PROTOTYPING ARCHITECTURE

The Conference Papers

Michael Stacey

Prototyping Architecture: The Conference Papers

Michael Stacey: Editor

The Architecture & Urbanism Research Division at the University of Nottingham with The Building Centre Trust, London, is pleased to present this book, which records the Prototyping Architecture International Conference at the Building Centre, London, held on 21 – 23 March 2013, to coincide with Prototyping Architecture Exhibition.

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Book Design: Nicholas Emblem and Andrew Tindale

Editorial Advice: Andrew King

Cover image: Image – Fig_0 Detail of adaptive gill like GRP solar shading of Ocean One, the Theme Pavilion of Yeosu Expo, architects Soma

to view the keynote talks go to:
https://vimeo.com/album/2162983

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INTRODUCTION

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Introduction

Michael Stacey

Prototyping Architecture: The Conference Papers records the Prototyping Architecture International Conference at the Building Centre, London, held on 21 – 23 March 2013, to coincide with Prototyping Architecture Exhibition. All papers have been peer-reviewed by an International Peer Review Committee. This conference was staged to coincide with the to coincide with Prototyping Architecture Exhibition. This exhibition explores the importance of prototypes in the delivery of high quality contemporary architecture - performative architecture that is inventive, purposeful and beautiful. Maximising the effective use of materials and resources whilst delivering environments that facilitate human well-being.

The conference and this book presents to opportunities, for exhibitors including James Timberlake, Philip Beesley, Mark White, Frank Barkow and Anne-Mette Manelius to set out their approach to architecture, research and the importance of prototypes in their practice. Thus deepening the understanding of their architecture and the prototypes within the exhibition. The conference is a platform for a wider range of voices within this material culture field, form experimental practice within architecture to the first use of carbon fibre in new build architecture. Widening the scope of this vital topic in contemporary architecture and practice by facilitating discourse between world leading participants in their fields.

The speakers range form architects, researchers, theoreticians, material scientists, industrial designers, engineers and students of these disciplines. Many of the papers are presented by multi or intra disciplinary teams, which are characteristic of contemporary scientific research teams and the design teams producing contemporary architecture, alike. However there is still space and respect for the individual scholarly research or practitioner and the contribution he or she can make to contemporary discourse about architecture. Potentially deepening our collective understanding of this topic, which retains its importance to humankind as it shapes and houses our lives.

Prototyping Architecture: The Conference Papers has been set out with the same running order as the conference. The conference has been structured in four themes: Resourceful and Inventive, Matter and Tectonics, Tectonics and Technology Transfer and Perfomative. In this book these become chapters. However these themes overlap, with prototyping in all chapters, the themes intertwine, for example biomimetic or bio-inspired design appearing in all four strands.

RESOURCEFUL AND INVENTIVE

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2 RESOURCEFUL AND INVENTIVE

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2.1
Fabric Formwork: Prototyping Concrete as Material, Process, and Context

Anne-Mette Manelius [i]

This paper in Prototyping Architecture discusses a research practice of making that aims at locating architectural potentials for fabric formwork for concrete, a construction method in which sheets of fabric are used as the main material for a mould. Fabric formwork has not found commercial implementation in architecture but has been used for a few projects by architect-builders. The built work as well as the research discussed here represents architectural prototyping as the experimental investigation of material and process. Based on the introduction of a series of experiments undertaken by the author it is argued that context is a key parameter of the investigation as well and may offer insight to future commercial implementation.

Description of the exhibited prototype

Fabric formwork is a new construction method for concrete structures that utilizes sheets of fabric as flexible, lightweight moulds. Based on a recently completed PhD project about the architectural potentials of fabric formwork for concrete, the fabric-formed column designed and constructed especially for the Prototyping Architecture exhibitions is the experimental investigation and material prototyping of a lightweight, prefabricated mould, which unfolds to be cast on site. The clustered concrete column is form-optimized for stability and constructed with minimal means. The principles of tensioning the fabric, of restraining it, and placing concrete have a direct formal consequence as a material dialogue between relaxation and control; thus the technique encourages an architectural understanding of concrete as material and as process. Essentially the exhibited prototype must then be understood as the formwork, the process, and the concrete object, and the contribution discusses the future of industrialized concrete architecture by emphasizing the prefabrication of intelligent, and lightweight moulds as an alternative to ‘dumb’ and heavy concrete elements. With the high ceiling of the exhibition venue at the Prototyping Hall of University of Nottingham the mould was exhibited, hung above to the concrete object and details of the sculptural concrete object could be compared with its two-dimensional textile origin.

Fig. 2.1.1 Trabeated PA Column at the Building Centre

Fig. 2.1.2 Undressing the PA Column at The University of Nottingham, Prototyping Hall

Background

Despite little commercial development and use of fabric formwork in construction, the history of the use of fabrics or membranes as the main material for concrete moulds shows several parallel and independent developments in the past century, and the principle has been discovered several times (Veenendaal et al 2011).[ii] From the use in 'fireproof construction' at the turn of the 20th century (Lilienthal 1889), [iii] to the inventions between the 1930-50s by the Irish engineer James Hardress de Warenne Waller who develops the Ctesiphon system, a construction method as well as a building typology for thin-shell, double curved concrete shells based on the 'sagging', under the load of sprayed concrete, of fabric tensioned fabric over a series of catenary-shaped arches as well as the rigidisation of the resulting double-curved surface, when the concrete/mortar hardens (Conlon 2011).[iv] Neither techniques survive. The introduction of plastics in the 1950s offers the major influence upon the availability of suitable and affordable membranes for construction. Developments and commercial applications in civil engineering include formwork jackets for the construction of underwater piles, as well as mattress types, mass-produced flexible formworks to reinforce revetments etc. (Lamberton 1980). [v] For architectural applications, the Spanish architect Miguel Fisac (1913-2006) invented a 'flexible formwork system' for the production of façade panels for which sheets of plastic suspended in wooden frames and restrained by patterns of tied wire or rigid line ornamental impactos.[vi] The façade for the Rehabilitation Centre for MUPAG (Madrid, 1969) is an example of a highly sculptural concrete envelope, where as Fisac's later use for a Cultural Centre (2000) is subtler (Fig 4).

Fig. 2.1.3 Facade panels dress all outer surfaces of a rehabilitation center in Madrid (1969) Miguel Fisac. Photos by AMM.

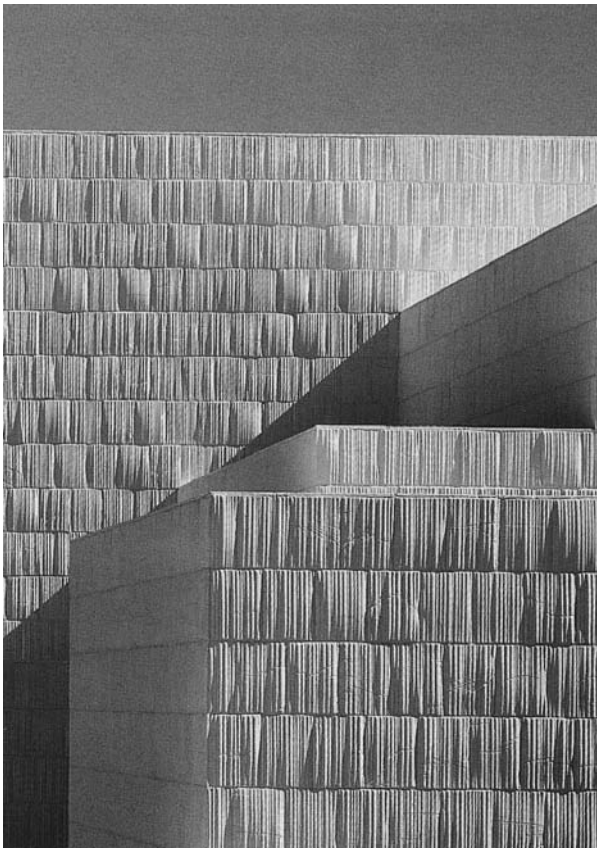

Fig. 2.1.4 Flexible formwork used for Cultural Center, 2000, Miguel Fisac. (Reprod. from AV 101)

The use of fabric formwork for architectural constructions is more recent and three key figures in the field developed independent, parallel practices in the 1980s and 90s. The built practice by the Japanese architect-builder Kenzo Unno, the sculptural practice by the Canadian architect, artist, and builder Mark West, and the construction products patented and distributed by the Canadian businessman Richard Fearn of Fabform Industries. The Centre for Architectural Structures and Technology (CAST) at the University of Manitoba was founded by West in 2002 as the first laboratory dedicated to researching fabric formwork. (West 2013).[vii] Here concrete columns, beams, walls, wall elements, shells, and rigid moulds have been cast and sprayed in fabrics (Fig. 6). West has also taught and constructed full-scale prototypes around the world. Today, an increasing volume of research is gathered in the International Society of Fabric Formwork (ISOFF) [viii] established at the World's First International Conference of Fabric Formwork (ICFF 2008). The current state of architectural research and teaching is roughly categorized by interest based on a material practice of making; [ix] in engineering by a combination of digital simulations and empirical testing and iterative development of construction techniques (Sang-Hoon Lee 2010 and Orr 2013); [x] and lately and importantly for the further development in the field and possible future implementation and commercialization, also on combinations of these fields of analogue and digital practices in architecture and structural engineering as discussed by Veenendaal and Block (2012). [xi]

Fig. 2.1.5 Unno Reinforced Concrete, Kenzo Unno, Japan Quilt-point method. Photo Tsunenori Yamashita

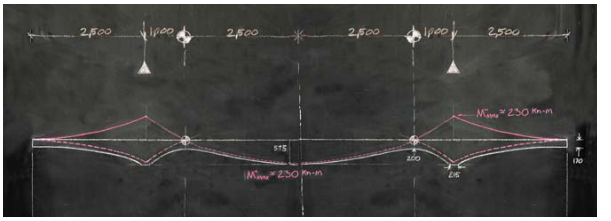

Fig. 2.1.6 Chalk drawing and form optimized concrete beam. Center for Architectural Structures and Technology (CAST)

Characteristics

Fabric formwork is characterised by the development of catenary curves, a filter effect during casting, and a particular expression of the materials and the principles of construction.

Catenary curves

The shape of a hanging chain is described as a catenary curve. Membranes deflect into catenary curves in all directions across the surface between points of restraint when exposed to an evenly distributed load such as hydrostatic pressure from freshly poured concrete. This material negotiation between the concrete and the flexible membrane allows the latter to structurally organize itself to a form that achieves equilibrium in relation to the load. The 'allowed' deflection of the surface under pressure makes the membrane an efficient formwork material.

Textile Filter Effect

The porous structure of woven fabrics acts as a filter that leads excess water and air through the formwork membrane, (see Fig.10). This happens immediately after fresh concrete has been placed, and the hydrostatic pressure is still high. The release of excess mix water from the fresh concrete mix lowers the ratio of water to cement in the concrete surface, reduces the amount of air bubbles and blowholes, and increases the surface strength of the cured concrete (Lamberton 1987). [xii] Fabric form liners, woven or non-woven, are placed inside rigid formwork systems to improve the water-cement ratio for concrete in harsh conditions such as salt water. With fabric formwork, the formwork itself has this filtering effect.

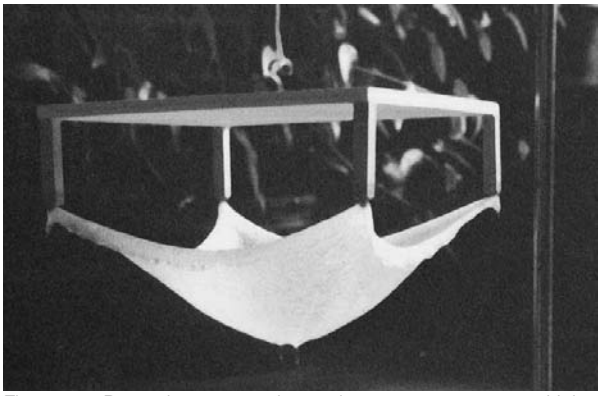

Fig. 2.1.9 Deflection of membrane into catenary curves, Heinz Isler

Fig. 2.1.10 Water pressed through geotextile during concrete pour, (TEK1 workshop)

External compaction

The membrane mould allows for direct physical interaction with the concrete as it is placed. One can feel where the concrete is, it can be compacted from the outside, and watching the filtering effect introduced above, it is possible to see where the fabric is and is not tensioned. The fabric bleeds when it is fully tensioned and if it does not, more concrete should be compacted or blowholes will be the consequence.

Expressed construction

Besides formal geometry, concrete takes on the characteristics and details of any formwork surface. For fabric formwork, the pattern of the weave, the fibre used in the fabric, the direction or tailoring of the fabric, and the shape and method of restraining and tensioning fabrics become evident in the form and surface of the concrete (Fig. 5). These formal consequences are very distinct in concrete cast in fabrics and demand a renewed understanding of concrete construction as well as the role of formwork. Where as the role of formwork technologies traditionally is to control a predetermined sculptural form, the roles of the formwork elements in fabric formwork deals with releasing fabric/concrete or restraining it. This entails that the technical role of the restraining form tie as well as other bracing elements of the boundary condition of fabric formwork also offers the architect a role of 'tying form' linking the designing with the processes of construction.

Fig 2.1.11-12 Form tie and tying form, student work RDAFA 2009, by : Katrine Dilling Holst, Magnus Maarbjerg, Iris Laxdal, Viktor Harald, Andreas Pilavachi Osterheld and Rebecca Nakayama Karstens

Stereogeneous construction – concrete as material and process

The dynamic and expressed relation between materiality and process for concrete described above, is coined by author in the concept of stereogeneity, which is based on the Greek words stereos, hard or solid, and geneity derived from *Gr. ginomai*, to begin to be (Manelius 2012). [xiii] Stereogeneity is the expressed manifestation into solid material form of a series of conditions from the construing and construction of structural formwork principles and concreting. In a more general term, stereogeneous construction is concrete as material and process and is linked to a way of thinking concrete in architectural constructions.

The material prototype is crucial in understanding and developing new methods of construction through making. The author and colleagues at the Institute of Architectural Technology at the RDAFA xiv have organized and taught several intense full-scale student workshops, in which the development of stereogeneous thinking is encouraged with the students. The direct relationship between the formwork-tectonic principles and the concrete pour has proven to be a remarkable didactic frame for teaching first-year students about architectural constructions directly through making, and for introducing the students to concrete in a way in which is ruthless in its direct material response to the varying levels and accuracy of craftsmanship, choices, and formwork principles designed and constructed by the student groups.

Where as a tight timeframe and the particular context of a large student workshop allows certain parameters of investigation, the experiments by the author investigate a variety of parameters and the work is formed in a complex web of reflections and influences such as responses previous work/student projects; to how previous work is received and discussed by industrial partners; to the specific context of the experiment, and so on. Based in parts on the lack of a concrete workshop facility at the RDAFA, an important reason for the change in contexts is the direct ambition of engaging in as many full-scale workshops as possible and thus allowing impulsive engagement.

Fig 2.1.13-14 Three fabric-formed columns at RDAFA, designed and constructed by CAST. The fabric for the moulds was brought from Canada. Creative Systems 2007.

Prefabricated formwork

A focus of the author's PhD work was the new architectural language of construction details as well as the expression of construction by experimental and analytical investigations of formwork-tectonic elements categorized as the frame, the form-tie, and the textile (Manelius 2012).[xv] The exhibited prototype is part of a series of experiments originally inspired by a practice at CAST of travelling with lightweight, prefabricated fabric moulds (West 2002) [xvi] and West literally did bring the first fabric formwork to Denmark in a duffle bag for the construction of three three-meter high columns at the RDAFA in 2007.[xvii] Throughout the PhD project the author has investigated the notion of prefabricated formwork further to encompass more than merely the fabric. As the following experimental cases will illustrate, it has been the experience that it is the boundary condition of the fabric formwork, which is the most challenging aspect of the construction method. Here, the boundary condition entails the bracing as well as the restraining/tensioning of the fabric.

The Ambiguous Chair Series

The purposes of making the *Ambiguous Chair* series for a special exhibition at a trade fair[xviii] included challenging fabric formwork in regards to sculptural and structural form, and surface, and thus to make a concrete object that could only be cast in fabrics; to produce a surprise encounter with concrete in order to open a discussion of what the material is or could be.

The experiment was basically an exploration of the oxymoron of the concept of fabric-formed concrete (Manelius 2009).[xix] The prototypes were designed as upholstered-looking chairs and cast in furniture fabrics to juxtapose the function to the scale of the object and to the soft look that stems from the quilt-point[xx] construction technique as well as from the fabric.[xxi] The initial purposes were intensified by the fact that fabric fibres and even patches of material remained embedded into the concrete surface. At the end the traces of the formwork materials appeared more present than the concrete itself to visitors. Despite a similar bulging shape this is a break from the expression of concrete plasticity, which Fisac was drawn towards in his flexible formwork (Soler 1996).

The *Ambiguous Chair* series also tested a notion of free-formed walls cast in basically endless lengths of fabrics. In practice, tensioning the fabric and restraining it using clamps in the quilt-point technique was very time consuming and the mould basically had to be managed through making. Furthermore, the sturdy rig produced for the *Ambiguous Chair* highlighted the importance of the boundary condition for construction method.

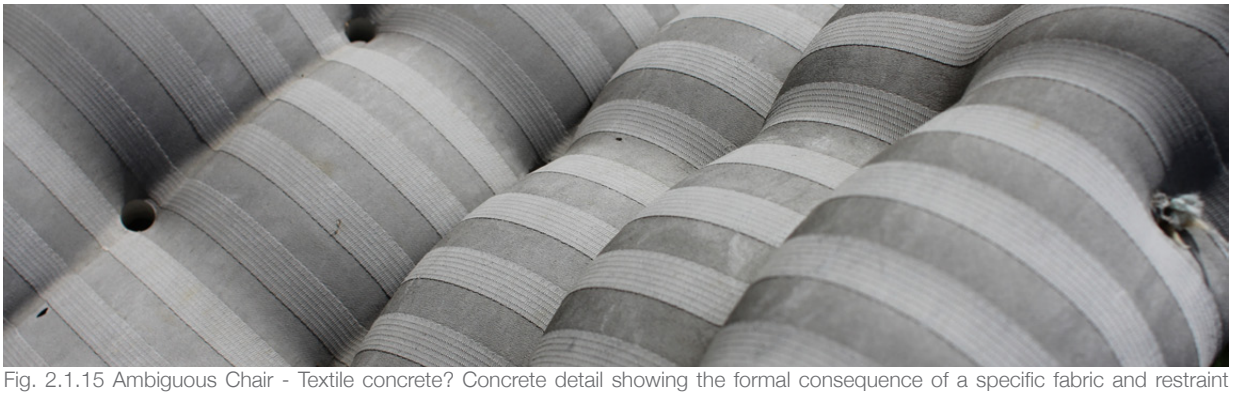

Fig. 2.1.15 Ambiguous Chair - Textile concrete? Concrete detail showing the formal consequence of a specific fabric and restraint technique. Manelius' Ambiguous Chair, 2009

Formwork-tectonic clarity

The intention of a formwork-tectonic approach to the following experiments is to eliminate bracing elements that do not also have a formal reason consequence upon the final concrete structure. A series of fabric-formed column experiments will illustrate this. The experiments explore the forming and structural roles of embracing textiles in fabric formwork.

Chalmers Column

The *Chalmers Column* (2009) is a 2-metre tall, unreinforced concrete column, made with architects Frederik Petersen and Kathrine Næss at the *Concrete Flesh* workshop at the Chalmers University of Technology, Department of Architecture. [xxii] The purpose of the curious experiment, which was also nicknamed the Sausage, was to use minimal means to obtain maximum formal expression and to test the sculptural potential of formties. The formwork is a combination of an elastic spandex material as the inner tube, with an embracing jacket made from glass fibre reinforcement mesh. The overall principle of combining a flexible inner tube with a pattern making outer corset was developed by Mark West with students in the 1980s but further parameters influenced the work at *Concrete Flesh*. The work was testing minimum control, and the embracing mesh, which was cut and altered, was close to bursting during the pour. The expressive organic character of experiments such as the *Chalmers Column* clearly blurred discussions about the implementation of fabric formwork with contractors at the PhD projects industrial part E. Pihl & Son. This influenced the next experiments.

Fig 2.1.16 The Ambiguous Chair, Photo by Rikke Grendal

Fig. 2.1.17- 18 Details of fabric-formed concrete

Fig. 2.1.19-20 Chalmers Column, 2009

Composite Column

The *Composite Column* (2010) is a 2-meter tall facetted column structure cast in a prefabricated formwork jacket of 'wood plank textile' and braced vertically. The approach is similar to the overall approach of the previous experiment: using only material, which has a forming role. That is to say – less bracing more forming. The intention on the other hand, was to produce a geometrically challenging column with no traces of fabric or bulging. The role of the fabric mould here was as an embracing pile jacket. Part of the prototype is the closing mechanism of the jacket, which turns a formwork plank into a form tie and combines it with the vertical braces. The introduction of the 'buttoned waist' furthermore investigated a very simple way to make a different sort of a column, an asymmetrical double-column with a direction.

While the principle of a prefabricated formwork system turned out to work well and could be developed with numerous inlays, the prototype wood-textile proved to be less generic as the boards needed faceting and the distance between them needed altering to enable the desired circumference of the columns. Furthermore, the composite textile had to be managed as one, which turned to be heavy with all the boards mounted. But while the formwork became heavier, the system and physical rigidity of the wooden boards provided something to handle and measure with on site.

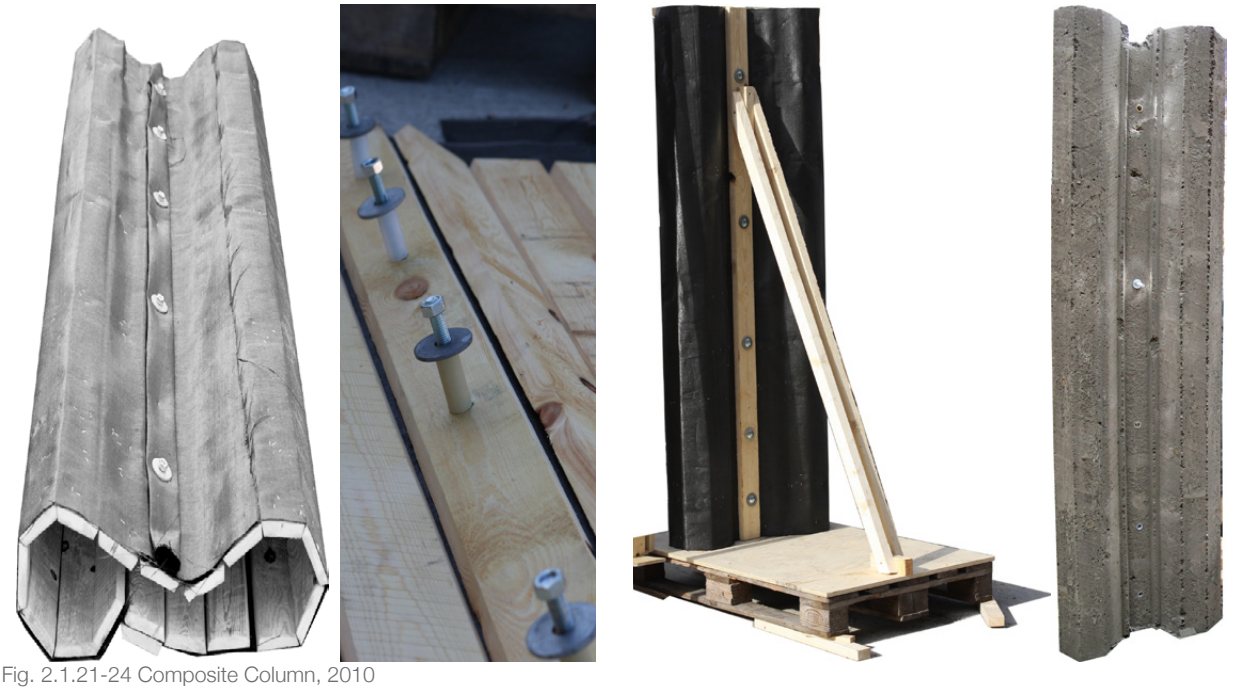

Fig. 2.1.21-24 Composite Column, 2010

PA Column

The trabeated or clustered *PA Column* (2012) is a two-meter high column cast in a prefabricated wood-textile in the prototyping hall at the University of Nottingham. The V-shaped wooden boards are forming and bracing elements for the advanced formwork jacket with three 'waists' as opposed to only one for the *Composite Column*. The prototype develops the formwork jackets from the previous experiments with the 'first settlers', namely the fabric-formed columns cast by CAST at the RDAFA in fabrics brought from Canada. Some practical parameters influenced the design of the *PA Column*. With the ambition of bringing the complete formwork to site as a composite wood textile ready to unfold and pour, the journey itself from Copenhagen to Nottingham became a design parameter simply because of the transfer from the airport to the university that involved several change of trains and taxis. The initial design for a maximum 200-litre pour resulted in 20-kilogram formwork. Instead the wooden braces as well as the proportions of the 'clustered' or 'cloverleaf' column formwork were slimmed down and resulting in a circa 140 litre pour and a formwork weight of 10 kg. Tools and special-made form ties were brought in the custom made flight bag.

Fig. 2.1.25 Demoulding the PA Column

Fig. 2.1.26-27 Details of the PA Column

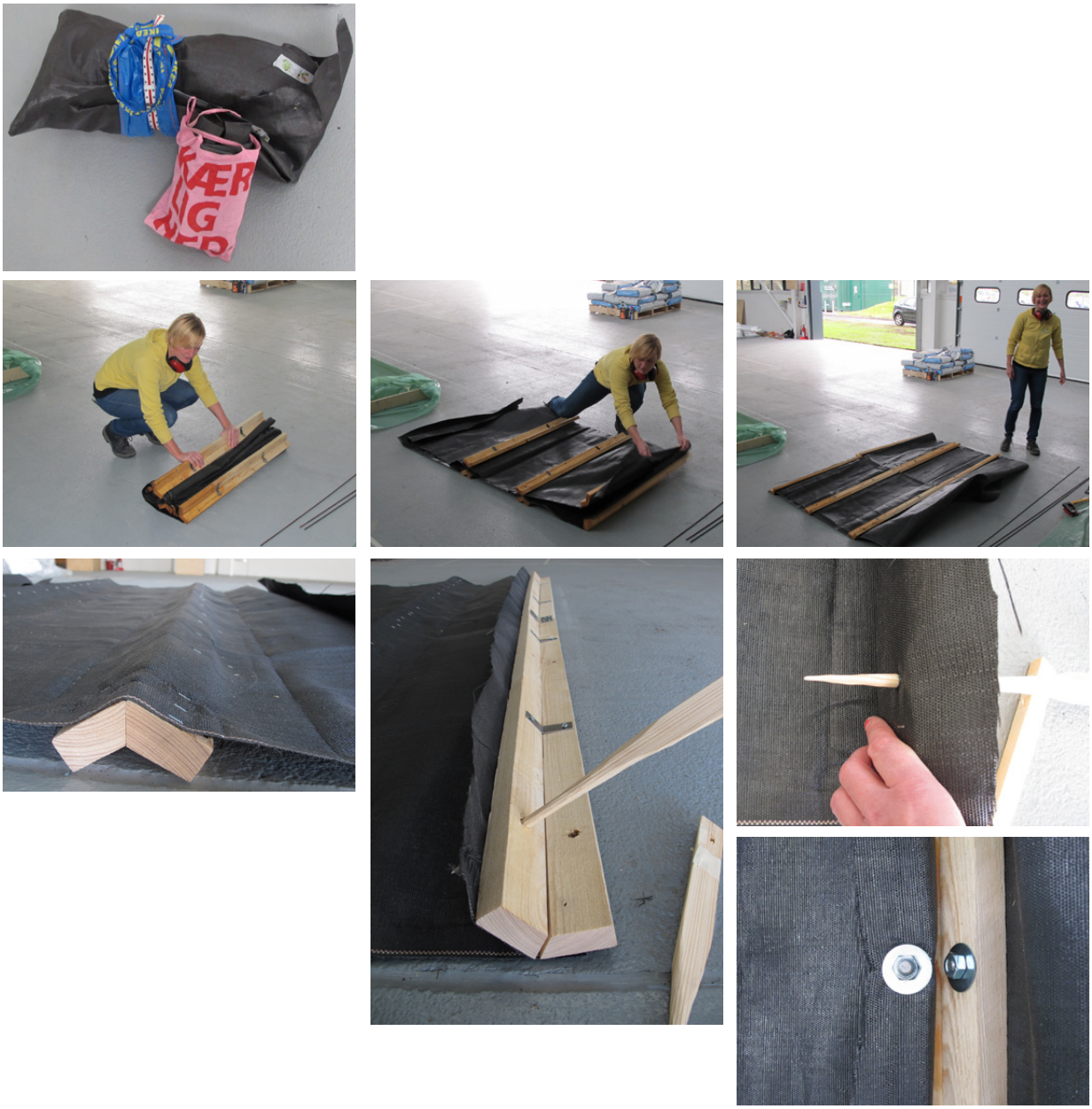

Fig. 2.1.28-35 PA Column - formwork assembly process

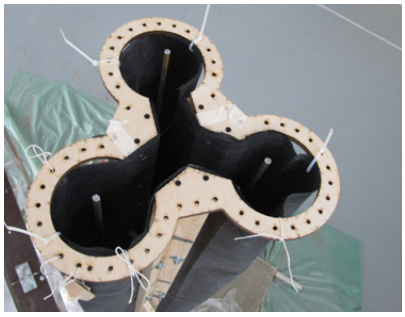

Fig. 2.1.36-43 Casting, revealing and displaying the mould of PA Column

Discussion

Fabric moulds and textile construction

The development of the Ctesiphon mentioned in the background section in the low-tech fabric-formed construction of thin concrete shells by the engineers, the Irish James Waller and German Kurt Billig, did not survive its inventors. Yet it did act as inspiration to the Spanish-born Mexican engineer Candela and he used it to build his first concrete shells in 1956 (Faber 1963) [xxiii] [Fig. 45]; but Candela moved on to other methods of construction when he adopted mathematic methods of design. A double-curved brick vault from 1974 by the Uruguayan engineer Eladio Dieste displays a similar structural shape [Figs. 46-7]. Dieste did not apply fabric as formwork; instead the innovative use of reinforced brick could be described categorized as a form of weaving and in this regard, the further developments of Dieste's corrugated brick structures are indeed very textile. Dieste's Gaussian vaults display a series of catenary curved sections (Pedreschi and Theodossopoulos 2007); [xxiv] just like fabric formed concrete. One can then speculate if a branch of the fabric-formed prototypes produced at the present time will also leave the fabric moulds behind and develop into more 'textile' constructions one way or another? Besides the practice by Kenzo Unno, the author is only aware of a few commercial applications of the technique, such as the construction of tilt-up façade panels in South Korea [xxv] [Fig 48-50] and a few small projects by the American architect and contractor Sandy Lawton of ArroDesign, in which the fabrics are used for load bearing concrete structures. The context for developing Lawton's practice in rural Vermont has two factors: The cost of hiring skilled labour to the site due to transportation, combined with unpaved access roads causing difficulty in for the delivery of materials (D'Aponte et al 2009). [xxvi] It highlights the low-tech aspect of the technology that the context allows few and relatively inexperienced builders to work with large concrete pours because it is "just so easy." [xxvii] This practice is prototyping at full scale as learning by doing, project by project.

The question is not whether fabric formwork can be used in construction. The future of fabric formwork as a way of prototyping concrete as material and process is likely to develop sporadically as parallel practices by design-builders and architect-researchers worldwide depending on a variety of economic or geographical contexts. The question remains how to implement fabric-formed elements for industrialized architectural constructions; prototyping may be part of it. An examination of the development and the roles of the formwork in a form-optimized fabric-formed concrete beam produced in a PhD project (Sang-Hoon Lee 2010), [xxviii] suggests that fabric formwork has a future for simple adaptations of mock-ups with complicated geometric shapes. The potential is that it is simple and cheap to adjust and develop complex concrete elements in a number of prototypes for empirical testing. The production of large numbers of identical concrete elements may however be cheaper by making a rigid formwork and is discussed by comparing Lee's work with similarly shaped T-beams in projects by Harry Seidler in collaboration with Pier Luigi Nervi (Manelius 2012). [xxiv]

On the other hand, a newly patented building technology called Superlight Structures by the Danish structural engineer, Professor Kristian Hertz, combines ordinary and lightweight concrete in a sequenced mode of construction. [xxx] With both technologies still in their infancy, the use of lightweight concrete may increase the possible scale of constructing fabric-formed concrete because the lower density concrete has a lower formwork pressure during the concrete pour. Discussed in the frame of context, the coupling of two novel technologies gives expression to something invisible. The construction method and the concrete technology complement each other and make visible something that may otherwise remain hidden. It may push the expressive nature of the oxymoron of fabric-formed concrete.

Fig. 2.1.44 Plasterer applying finishing touches of the Nofrango method to Ctesiphon shell construction. (Image reproduced from Conlon 2010)

Fig. 2.1.45 Early Candela Shell experiment based on Ctesiphon construction (Image reproduced from Faber).

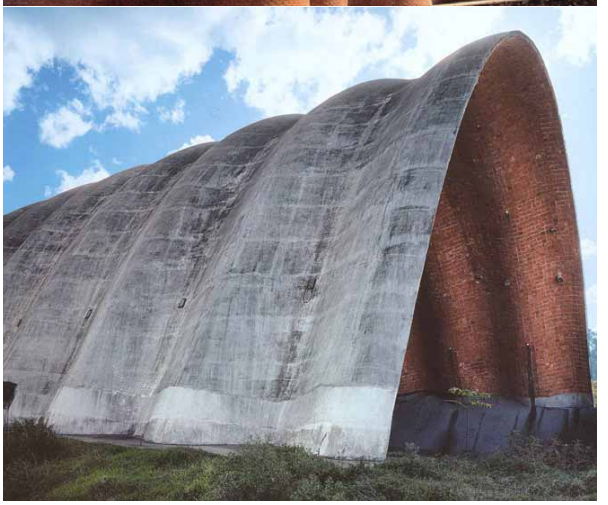

Fig 2.1.46-47 Dieste right: Double curved brick vault, Dieste 1974 and left: Church of San Juan De Ávila, Dieste 1993-98

Fig. 2.1.48-50 Hanil Visitors Center & Guest House, South Korea, by Byoung Soo Cho Architects (2008-09), photos by KimYong Gwan, sourced from CAST web site.

Fig. 2.1.51 Schultz House, Vermont, USA, 2008, formwork for walls and columns, image courtesy of Arro Design.

Acknowledgement
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iii Lilienthal, Gustav, Fireproof Ceiling, US Pat. 619,769, 1889.

iv Ciarán Conlon, The Innovations and Influence of Irish Engineer James Hardress de Warenne Waller. BA Architecture Thesis, University College Dublin, 2011.

v Bruce Lamberton, Fabric Forms for Erosion Control, Concrete Construction, The Aberdeen Group, 1980

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2.2
Clay, Craft, Culture: Material Explorations at Grymsdyke Farm

Samantha Oswald [i]

Grymsdyke Farm in Lacey Green, UK, operates as a prototypical architectural practice, enabling explorations in material testing, fabrication, and site-specific installation. It acts as a workshop for a variety of professionals and students with different backgrounds and affiliations. This allows the cultural and material heritage of the place, as well as the unique landscape to which it belongs, to provide the foundation for contemporary research. Two recent projects at the Farm have taken the clay brick as the subject of study. As a substance that can be sourced and processed entirely on-site, it offers an opportunity to investigate an integrative method of design and building. Both the method and the material reference the history of the area and question its relevance to current architectural issues.

The village of Lacey Green, around 56 kilometres northwest of London, is set in the rolling landscape of the Chiltern hills. Geologically, the Chilterns are chalk hills, but the dissolution of the chalk minerals and the weathering of Palaeocene-era sedimentary beds produced deposits of clay containing nodules of flint. [ii] The construction of local farm and town buildings reflects this subsurface condition; the primary construction is almost always brick, often with facades in filled using the 'knapped flint' technique of rendering. The lack of efficient transport networks and the availability of clay led to the establishment of multiple small-scale brickworks beginning as early as the eighth century. [iii] For convenience, brickworks were often located near the town or set of buildings they would have served. Remains of such sites from the 1800s can be found less than a kilometre from Grymsdyke Farm. Their legacy is evident in the village street called Kiln Lane. [iv]

Fig.2.2.1 The rolling landscape of the Chiltern.

Besides clay, the Chilterns were also a centre of woodcraft, with furniture-making being a primary industry in the town of High Wycombe until the 1990s. [v] Bodging, or pole lathe turning, was a craft particular to this area. Each season, a bodger would bid for a parcel of woodlot in which to work. Most would bring their own tools and set up a temporary workshop at the site, producing chair legs, spindles, and stretchers on their foot-powered lathe. [vi] This process of making on site had numerous advantages. The bodger would select and fell only the best trees for his purpose, ensuring that his time was not wasted and the health of the woodlot was maintained. [vii] The shavings and other trimmings could be burnt for heat, used to insulate the walls of his shelter, or simply returned to the soil. [viii] Transportation expenses were only incurred for the finished product, and not for the raw material. However, as mechanized production gradually replaced handcraft, this close relationship between the maker, the material, and its source was lost. The trade was virtually extinct by the 1950s, and furniture production was consolidated in factories. [ix]

Fig. 2.2.2 Traditional farmhouse construction - 'knapped flint' infill is preventant in the Chilterns

Fig. 2.2.3 Brick-drying shed

The formerly thriving brick-making industry has undergone a similar transformation, succumbing to mass-production and centralization. Today, of the 23 brickyards once operational in Buckinghamshire, only two remain, mainly supplying restoration projects. [x] Rising property prices and strict preservation regulations have made the opening of clay pits extremely difficult and costly, despite the fact that during new construction, many cubic metres of good quality brick-earth are simply excavated and removed. [xi] Although modified legislation would help revitalize the industry, it would also benefit from an experimental

attitude towards architecture that would take materiality and mindset, and not style, as measures of the identity of a place. This attitude is a key guiding principle of the work at Grymsdyke Farm.

London's ever-expanding sphere of influence is slowly shifting the demographic of the Chilterns from farming families to commuters and retirees. Large properties are being subdivided and sold off separately or redeveloped. It is in this context that founder Guan Lee acquired the farmhouse, cottage, stables, and outbuildings of Grymsdyke Farm in 2004. At the turn of the 20th century, this was a large working farm, with its manor house, barn, and many auxiliary constructions. [xii] Today, the property is shared by the farmer, who still raises livestock in the fields, small businesses, and the architectural workshop-studios that are slowly transforming the site. The facilities of Grymsdyke Farm have grown to include a full wood workshop as well as a laser cutter, CNC router, and 3d printer. The emphasis on fabrication and architectural installations is sustaining the craft-centric character of the rural community and applying these concerns to contemporary design. The resourcefulness and co-operation that would have characterized the actions on the farm and in the village are channelled into construction projects that link architects, designers, artists, and trades people through interaction with the site.

Brick, in particular, brings together a variety of disciplines, from the landscaper who drives the digger, to the ceramicist who programs the firing cycles, to the fabrication specialists who advise on the milling of the moulds, to the structural engineer who examines the strength of the terra cotta. Normally, innovation in brick is hindered by two conditions: first, by the sentimentality that keeps it firmly associated with the aesthetic of tradition, and second, by the industrial reality of mass-production. [xiii] The working environment at Grymsdyke Farm has liberated the brick from both of those constraints, allowing it to be freely imagined and manipulated. Digital fabrication facilitates the visualization and realization of new modules; hands-on interaction with the substance itself stimulates questioning about its response to heat, light, wind, and loads; the abundant clay and spectacular setting ground the projects in their location. In the two stories that follow, the development of these projects will be described, focusing on their engagement with the personal, technological, and material resources of Grymsdyke Farm.

Fig. 2.2.4 Aerial view of Grymsdyke Farm

Ascent- University of Waterloo workshop, April 2012

When we arrived at the farm for a week-long workshop, we already knew that there was clay in the soil, having been introduced to the project Hole by Guan Lee, but this clay's behaviour when fired had not yet been tested. [Fig. 5] The buildings on the farm and in the surrounding village, built mainly of brick, reassured us on this account. However, we should also have taken them as a warning of the true nature of the raw material with which we were going to work. Their structure and ornaments are indeed brick, but the facades are often infilled with flint pieces. [Fig. 6] This marriage of clay and flint, characteristic of the soil in the area, has profoundly affected the clay preparation process and will probably be the subject of future investigations at Grymsdyke Farm. For our purposes, though, they had to be separated. With no time to wet the clay to remove the stones by differential settlement or by screening, we had no choice but to pick over the material manually.

The task for the workshop was to create an 'ascent.' The desire for masonry to act as the primary spanning material led to the selection of timbrel vaulting as a technique. This method makes use of multiple layers of tiles, overlapping at different angles, to create an efficient load-bearing masonry vault. In parallel with research on this method of construction and experiments with the clay, we familiarized ourselves with the site to determine the best place for the vault. Initial aspirations to build a full parabolic arch were reduced by half, eliminating the need for the construction to be self-supporting and increasing its interaction with its surroundings. A steel beam supporting a brick wall in an outdoor covered area was chosen. The new clay tiles related to the existing brick, and aligning the top of the vault with a broken window added a touch of whimsy. Scale tests were cut using the laser cutter and the centring for the arch was developed in Rhino, but with continuing reference to the actual site.

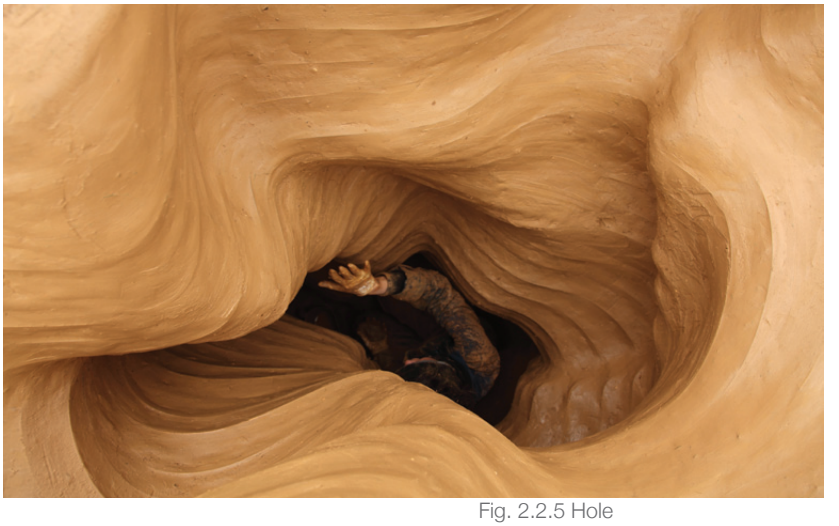

Fig. 2.2.5 Hole

Fig. 2.2.6 Brick and flint facade

The clay had to be dug from the ground, cleansed of flint, and consolidated in order to create a mixture appropriate for forming. Different consistencies lent themselves to different forming techniques: a drier clay could be rolled, like dough, but a wetter clay formed a sharper, smoother edge. [Fig. 7] It was decided that sheets of 10 tiles would be formed together using a moister clay for improved workability. These sheets could then be divided accurately with the help of a template. It became apparent that drying time was a limiting factor, since clay that dries too quickly will crack. [Fig. 8] The limited kiln space and drying time led to the choice of using two layers of concrete tiles and one of brick. In an attempt to keep clay as a linking material, some tests were executed using powdered clay as a substitute for some of the cement in the concrete; however, even the slightest addition of raw clay weakened the concrete, giving it a damp and brittle texture.

The moment when the kiln was opened after the first test firing was one of great satisfaction and relief. The bright orange colour and newly acquired resonance of the tiles affirmed the suitability of the clay for brick-making. For the operation of the kiln, the expertise of one of Grymsdyke's founding members was invaluable. We were able to rely on her experience as a professional ceramicist to determine to what temperature and at what speed the tiles should be fired. The modular masonry required only minimal support from plywood scaffolding. This structure, doubly curved for extra rigidity in the finished vault, was cut using the CNC router, assembled on the ground, then lifted into place. The top was notched to rest between the flanges of the beam, allowing the vault itself to rest on top of the beam.

Fig. 2.2.7 Shaping clay tiles

Fig. 2.2.8 Drying clay tiles

Fig. 2.2.9 Scaffolding for the vault

The difficulty of working with mortar on a semi-vertical surface was quickly encountered. The consistency of the mix was of great importance. It did not adhere if it was too dry, and slid off if it was too wet. As with most workshop situations, time constraints governed, and the three layers were laid almost simultaneously, with a reinforcing mesh between the first two. [Fig. 10] The true strength of the vault was not tested until months later, after the mortar had cured and the scaffolding could be removed. [Fig. 11]

Fig. 2.2.10 Ascent under construction

Fig. 2.2.11 Ascent

Terracott- Under Construction

Inspired by the Ascent experiment, I returned to Grymsdyke in July 2012 to further the research in clay. Making the tiles had taught us about the properties of the material, but its potential had not been fully realized. I wanted to construct something that would take advantage of the heat and light capturing qualities of terra cotta, as well as the plastic properties of clay. I decided to build a one-person shelter that worked on the principles of a Chinese *kang*, a sleeping surface under which a chimney flue is channelled. The shelter, however, would be primarily a showcase for the expressive potential of a non-standard brick module. I began by designing different bricks, attempting to create a single unit that would have very different effects based on its orientation. I also wanted to easily control the density and light permeability of the wall. Erwin Hauer's light-capturing screens and Eladio Dieste's inspired use of brick provided some precedents, but the best inspiration was to be found in the surrounding villages, where inventive bonding patterns and sculptural clay modules embellish the solid farmhouses. [Fig. 12] The iterations were tested using the farm's 3d printer; physical manipulation of the scaled units allowed me to evaluate different methods of assembly. [Fig. 13]

Fig. 2.2.12 Brick bonding in traditional construction

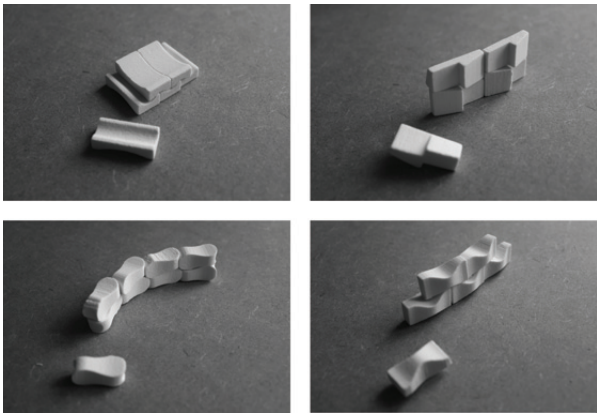

Fig. 2.2.13 Module iterations

In parallel with this search for form, I started to test the siting and scale of the construction, creating mock-ups in the farm's field and observing the light conditions at different times of the day. I was especially intrigued by a phenomenon I had observed on the wall of the farmhouse- the ability of the late summer sun to make the bricks glow orange in a predominantly green landscape. The final location was chosen for its relationship to the surrounding vegetation and the views out to the rolling Chiltern hills. The third element of this synthetic design process was the development of the brick forming technique. The knowledge acquired during the workshop as well as a visit to a local brick factory enabled me to refine the process. At H. G. Matthews, one of the two remaining brickworks in Buckinghamshire, bricks are made simultaneously in two ways, machine-forming and hand-forming. In both cases, the clay is thrown into a metal mould with a 'frog' on the bottom. [Fig. 14] Occasionally they produce runs of 'specials', for which bespoke wooden moulds are made. [Fig. 15]

The beauty and variety of these moulds served as an inspiration for my chosen moulding process, although the unusual brick shape required some key modifications to the traditional method. Regular brick moulds take the form of boxes enclosed on five sides; during moulding, the sixth side is scraped flush and the excess clay removed. Using a four-sided mould, I could more easily control the contoured profile of the brick by scraping both the top and the bottom. [Fig. 16] As well, the impact from the inversion of the mould is normally enough to dislodge the clay inside. Since the curved shape of my chosen brick precluded the use of this technique, I instead used the four-sided mould in conjunction with a secondary frame. Tapping the mould lightly on its corners, then knocking it on the secondary frame, demoulded the brick with minimal distortion.

Fig. 2.2.14 Traditional brick mould

Fig. 2.2.16 The moulding process

Fig. 2.2.15 The Mould Room at H.G. Matthews brickyard

The mould objects were developed in discussion with the fabrication specialists at Grymsdyke Farm. Their knowledge of wood's behaviour under the CNC drill bit guided my choices of orientation and sequence of assembly. Mould 1 was milled in two pieces, which were then permanently joined. [Fig. 17] Using this mould, I improved and adapted my moulding technique. The clay had to be pushed into the corners, then filled in the middle, the two sides trimmed, and the corners knocked to detach the brick before demoulding. For this process, the use of sand as a mould release was absolutely necessary.

Mould 2 was assembled from four separate pieces, for two reasons: first, the inside corners of Mould 1 were rounded due to the radius of the drill bit, and second, I wanted to test the working process using a mould that could come apart. The four pieces were assembled into two angles, which were held in place by a retaining ring. [Fig. 18] It soon became apparent that the additional time and effort needed to disassemble the mould were not compensated by a more precise brick, and the Mould 1 process was in fact more efficient.

Fig. 2.2.17 Mould 1

Fig. 2.2.18 Mould 2

I wanted to test if a mould made of a material other than wood might eliminate the need for sand in the forming process, and I also wanted to involve other expert makers in the community. Mould 3 was therefore designed to be cast in metal. Gommes Forge, about two kilometres from Grymsdyke, has been in operation since the middle of the 19th century. The forge still produces pieces in milled sheet metal, wrought iron, and cast metal. I created a plywood form for use in the process of sand casting aluminium, where a fine sand is packed around the positive pattern, which is then removed and the void filled with molten metal. The cast failed, however, because the initial form was too thin. I was informed by the blacksmith that although sheet metal can be very thin and strong, cast metal must be almost as bulky as wood to have the same strength. [Fig. 19] As well, since the clay adhered even to the metal, sand would still have been necessary.

The unusual brick shape also posed a challenge for drying, since the curve required support from underneath. A profile matching that of the brick was laser-cut and used as a rake to shape rows of sand, onto which the raw bricks were placed during the first day of drying. Once they had dried enough to hold their shape, they could be moved out to the covered passageway, where open shelves and continuous air flow aided the evaporation of moisture. [Fig. 20] After two weeks outside, the bricks could finally be loaded into the kiln. In traditional brick firing, the bricks must be carefully arranged to ensure air flow between them, but the shape of the new module easily accommodated this condition. The versatility of the module was apparent when I stacked the bricks after firing. Unlike the kiln arrangement, the stacking pattern could be very dense, permitting the efficient storage and transport of the units. [Fig. 21]

Fig. 2.2.19 The blacksmith examines the mould pattern

Fig. 2.2.20 Bricks drying in the old brick farmhouse

Fig. 2.2.21 Bricks packed for transport

I received a lesson from a builder on the skill of brick-laying. He was perplexed by the complex laying pattern, but gave me useful tips on the composition and consistency of the mortar. I had been using a fabricated guide to contain the mortar in the proper place on each brick; he suggested, instead, that I apply more mortar than necessary and strike it off as needed. Adapting this advice to the particular bonding patterns of the walls, I developed a technique of using a tool in each hand to finish and smooth the joints. [Fig. 22] Working extensively in situ allowed me to acquire a kinaesthetic, durational knowledge of the site. I felt the prevailing winds skimming over the hayfield, learned to anticipate the rain by watching the clouds on the horizon, heard the whinnying of horses from the nearby field, and traced the path of the sun as it shifted the shadow patterns on the walls. This sense of time and rhythm is then communicated in the built project, anchoring it in the continuous existence of its location. [Fig. 23]

The *Terracott* is not yet finished- and even once it could be considered 'complete', it will continue to be a source of observations and learning. There is still much to be discovered about the performance of this clay- the way it responds to weathering, the way its properties change with different additives, and the ways it could be digitally printed or tooled. Subsequent clay projects at the farm will no doubt build upon the knowledge of the *Terracott*, just as it was influenced by the projects Ascent and Hole before it. The brick projects at Grymsdyke Farm demonstrate how prototyping can actively contribute to the ethos of a place by bringing together a unique set of cultural and material sensibilities. Although the specific organization of the Farm is the direct product of its circumstances, the commitment to material, place, and cross-disciplinary research could provide a model for the architectural practice of the 21st century. The growing flexibility and variety of digital fabrication technologies is opening up the possibility of on-site making as a viable option. Only by engaging both the traditions of an area as well as the most advanced techniques can designers probe the limits of architecture's social, resource-efficient, and phenomenological performance.

Fig. 2.2.22 Brick bonding

Fig. 2.2.23 Terracott under construction14 [xiv]

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xiv Image credits: Emad Ghattas: Fig. 6, Guan Lee: Fig.2 and Fig. 5, Shane Neill: Fig. 9 and Fig. 12, Samatha Oswald: Fig.1, Fig. 3, Fig. 7-8, Fig.10-11 and Fig. 13-23,

2.3
Prototyping Sentinel: Studies towards an Interface Architecture

James O'Leary [i]

"Machines for seeing modify perception." Paul Virillio, *Guerre et Cinema.*

Interface Architecture proposes a constellation of 'sub-architectures', which are designed to allow intelligent observation and feedback; bridging the gap between sites of construction and the location of the architect at various phases of a design project. [ii] All components in the project are one-off bespoke items that explore innovative materials, intelligent systems and off-site manufacture techniques.

This paper focuses on the first of these, entitled *Sentinel*. The aim of *Sentinel* is to register the nuances of 'place' through intelligent architectural components. This work posits that the use of embedded performative technology in architecture can radically alter the scope of normative architectural elements to become intelligent, self-aware agents in a wider architectural system that seeks to understand the full complexity of its environment. *Sentinel* aims to document both the variety of external environmental conditions and the complexity of patterns of use to generate information fields that assist the architect in the design phase of the project.

Site Recording

The relationship between architect and site is a complex and troubled one. Architectural theorist Robin Evans carefully untangles these relations in his essay *Translations between Drawing and Building*. In this essay he identifies a certain unease in the relationship between architect and site, suggesting the source of this unease to be "the particular disadvantage under which architects labour, never working directly with the object of their thought, always working at it through some intervening medium, almost always the drawing." [iii]

The complex question of how the architect comes to an understanding of the specifics of a site is one with a long history. The answers to this question have changed over time and with developments in technology. However, regardless of the technology deployed, the trajectory of this process is consistently one of moving from the unfamiliar to the familiar, and from the familiar to the intimate – a tactile and very physically enacted love story between 'figure' and 'ground'. 'Figure' and 'ground' in this context enmesh the human figure and the physical ground being investigated, while also conjuring the 'figure' and 'ground' relationships described through drawing and representing the site in question. Slowly, the architect's understanding of the site develops over time. Traditionally, this would happen through a number of site visits, ideally conducted over a long period and through differing seasons to get a holistic understanding of the site in which the project resides. This process of revelation - the unfolding of the secrets of the site – is very tentative and incremental, requiring a deep registration of differing layers of information. Such recordings sit somewhat uneasily on the threshold of a need to register historical configurations of a site, while providing a base from which to project forward and provide instruction for new events in space and time, thus providing a kind of map and itinerary in one single document. The author has spoken elsewhere about the limitations of more traditional forms of architectural surveying and representation, particularly in its focus on the quantitative rather than the qualitative in design information. [iv] The current work under discussion aims to posit a new model for understanding site conditions using high definition video and computer programming and database technology. This paper will present reflections on the conceptual framework, design and construction process related to this current work in progress, a prototype entitled *Sentinel*.

Interface Architecture

Sentinel is the first of a series of inter-related works collectively entitled: Interface Architecture. These works literally and figuratively support the design and renovation of a stone building in rural Normandy, France, into a studio for an architect and a poet. Interface Architecture proposes a constellation of 'sub-architectures' [Fig. 1], which are designed to allow intelligent observation and feedback; bridging the gap between sites of construction and the architect at various phases of the project. All components in the project are one-off bespoke items that explore innovative materials, intelligent systems and off-site manufacture techniques. As the client is both owner and project-architect it continues a lineage of experimental one-off self-build projects as testing-ground for innovative new ideas in the discipline.

The aim of *Sentinel* is to register the nuances of 'place' through intelligent architectural components. This work posits that the use of embedded performative technology in architecture can radically alter the scope of normative architectural elements to become intelligent, self-aware agents in a wider architectural system that seeks to understand the full complexity of its environment. *Sentinel* aims to document both the variety of external environmental conditions and the complexity of patterns of use to generate information fields that assist the architect in the design phase of the project. One of the challenges of the project is the integration of hard materiality and soft intelligence, allowing for a synthesis of material and technological systems that are integrated into a site-specific situation. The piece will be continually exposed to the elements and will need to work in isolation and without maintenance for an extended period of time of five years.

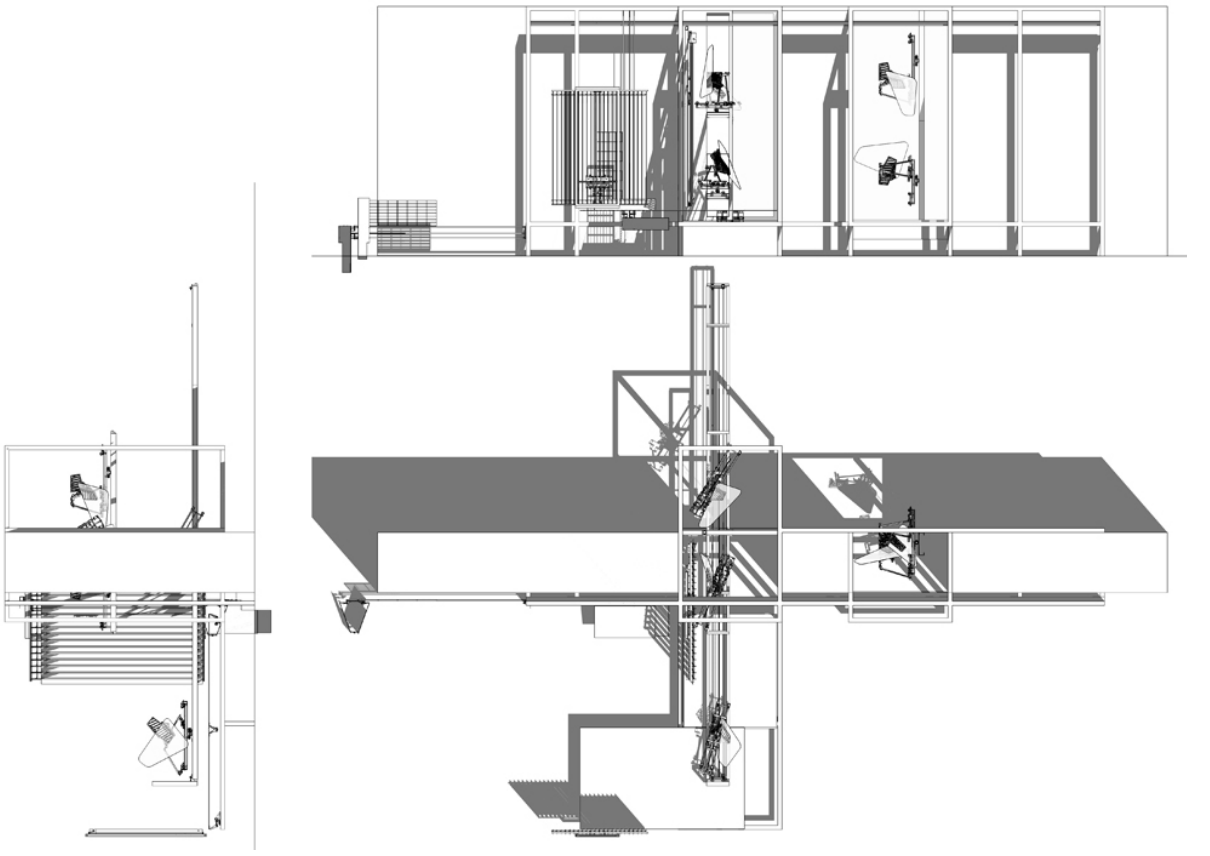

Fig 2.3.1. Kreider + O'Leary – SENTINEL, Sub Architectures - Plan, Section & Elevation Drawing.
© Kristen Kreider + James O'Leary, 2012

As the house is occupied seasonally, this first iteration proposes an *Interface Architecture* that performs the role of *Sentinel* of the architectural domain. Occupying the thick architectural space combining the approach, the threshold and the entryway of the main house [Fig. 2], *Sentinel* will perform a number of different roles across three main phases of its life span. During its first phase of life *Sentinel* combines the roles of guardian of the space, and of architectural probe that communicates real-time information about the site and its conditions to the architect during the initial design phase. During its second phase, the construction phase, the piece becomes an intelligent architectural filter, using embedded sensing and computing technology to monitor environmental conditions on either side of the building envelope as the building transforms from open ruin to closed occupied space. During its third and final phase the piece will take on the role of entry portal and main doorway once construction is complete, performing a timeless semiotic function of communication to visitors and occupants externally, as well as the more prosaic functional requirements of psychological security and physical closure from the perils of the outside world to its occupants.

This paper will discuss issues relating to a prototype constructed to interrogate the conditions of the first phase only. At the time of writing, the prototype has been constructed, and is currently undergoing iterations of programming design. It is scheduled for installation on site in Normandy in March 2013.

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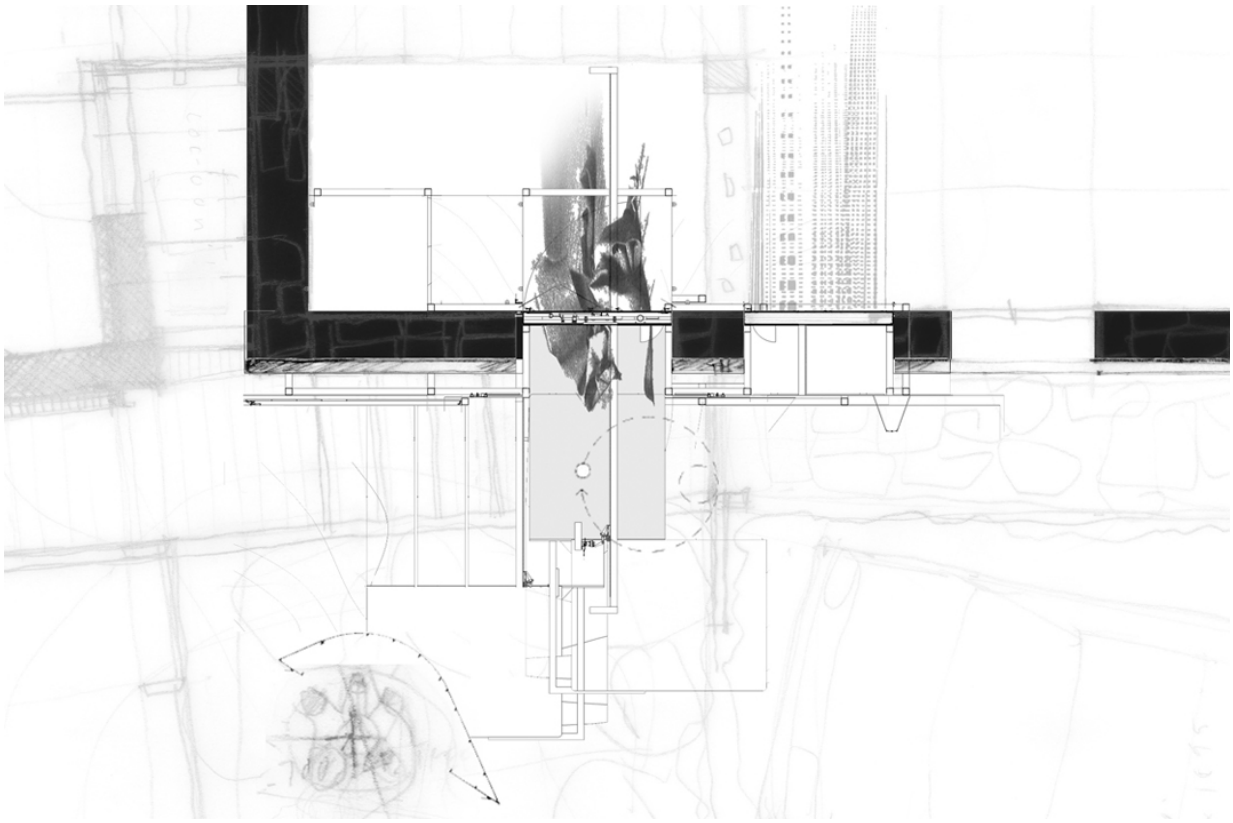

Fig 2.3.2. Kreider + O'Leary – SENTINEL, Sketch Proposal Entrance Plan.
© Kristen Kreider + James O'Leary, 2012

Property and Theft

On the 30th of September 2011, at 30 Place de Leveneur in Carrouges, Kreider + O'Leary finalized the purchase of a stone house at the offices of the local Notaire, Claudie Baudrant. On immediately driving to the property, they quickly realized that their neighbour had at some point broken in to the house and connected a wire to the electricity system, which had allowed him provision of free electricity through a cable that he had strung hidden across the road, and into his own house. Thus arose two conflicting emotions: firstly, pride in the realization of a long-held ambition to have a space to retreat to over the summer, and secondly, a strange unease about the necessity of the security of the house during the long months of their absence. Such are the conditions that gave birth to the current work under discussion.

The Security of the House

In O.F. Bollnow's *Human Space*, Bollnow takes the reader on a journey through our human relationship with our surroundings, from more philosophical understandings of the elementary structure of space, to the more prosaic aspects of spatial occupation, to thoughts about space as a medium. In the central part of this wide-ranging work, in a chapter entitled 'the security of the house' Bollnow discusses the vulnerability of the house, and the psychological need for a sense of security of the occupant, arguing that: "In the German language, as Heidegger has pointed out, the Frieden [peace] in which one lives is related to the *Umfriedung* [enclosure] of the dwelling area." [v] Looking more locally at the basic construction elements of the house, Bollnow identifies the external envelope as of

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primary importance, indicating that "[b]y means of the walls of the house, a special private space is cut out from the large common space, and thus an inner space is separated from an outer space." [vi] The enclosure of the dwelling area is thus central to a sense of peace and well-being. Critically, Bollnow acknowledges the need for a psychical as well as for a physical sense of separation from the outside world when he writes: "The outer space is a space of activity in the world, in which it is a question of overcoming resistance and defending oneself against an opponent; it is the sense of insecurity, of danger and vulnerability. … This is why he needs the space of the house". [vii] This turbulent sense of unease related to the outside world is calmed by the reassuring sense of separation provided by the physical enclosure of the house.

Man's psychological need for setting spatial limits, and the further need to transcend them, are explored further in sociologist and philosopher Georg Simmel's short but seminal essay Bridge and Door. In the opening section Simmel writes: "In the immediate as well as the symbolic sense, in the physical as well as the intellectual sense, we are at any moment those who separate the connected and connect the separate". [viii] He attributes the space of the external door with a particular power to connect to the external world, and even more than the wall, to engender a sense of enclosure internally. He continues: " By virtue of the fact that the door forms, as it were, a linkage between the space of human beings and everything that remains outside it, it transcends the separation between inner and outer. Precisely because it can also be opened, its closure provides the feeling of a stronger isolation against everything outside this space than the mere unstructured wall." [ix] The external door thus provides a powerful symbol of the porous relationship of humankind to the wider world, being the primary threshold between the inner and outer world in a spatial as well as a psychological sense. Our ability to allow the door to act as a kind of switch between our social and private selves is a recurring reminder of our freedom as individuals. He closes the piece with the following statement: "The enclosure of his or her domestic being by the door means, to be sure, that they have separated out a piece from the uninterrupted unity of natural being. But just as the formless limitation takes on a shape, its limitedness finds its significance and dignity only in that which the mobility of the door illustrates: in the possibility at any moment of stepping out of this limitation into freedom." [x] So the external door, of all architectural elements, particularly embodies this contradictory role of connecting and separating simultaneously.

Due to the significance of this contradictory threshold space, and its ability to act as a space of mediation between inside and outside worlds, the external door was selected as the site for the first of the *Interface Architecture* series [Fig. 3]. Assuming a similar role to the Roman god Janus, the god of beginnings and of transitions, who occupies the space of the threshold; looking without and within simultaneously, Sentinel will become both guardian and observer of this critical space, perhaps embodying Samuel Beckett's wish of fleeting occupation; to "live the space of a door that opens and shuts". [xi]

Fig 2.3.3. Kreider + O'Leary – SENTINEL, Sketch Proposal Front Elevation.
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Designing Sentinel

Sentinel was originally conceived as an architectural insertion that would occupy the main threshold space by an act of puncturing of the front door itself [Fig. 4]. As the design progressed, this interface element began to form part of a larger architectural assemblage that braces the ill-structured external front wall, frames the door and window openings thereon and forms new levels externally. In a more playful frame of mind, the piece is understood conceptually as a faithful resident of the space, one who would arise diligently at sun-up every morning, pop outside to gauge the weather conditions and observe the local area, and then dutifully record these observations for posterity, forming an archive of daily and seasonal recordings, which were relayed to the architect in London in real time. In terms of delivery, the piece would be manufactured off-site to high levels of tolerance and control, and then attached or inserted into the existing building fabric by the architect on-site as a self-build project. For the purposes of the *Sentinel* prototype under discussion here, the author choses to ignore the larger architectural elements and focus on examining how the observation machine might be designed and constructed, and once constructed, how to progress the programming of the machine to observe, store and relay information. The design was distilled down to four key operational components: a HD Video camera, a guide rail to allow it to move from inside to outside, a tracking system to move the camera along the rail with precision, and a computer to run procedures, store information and communicate to the wider world.

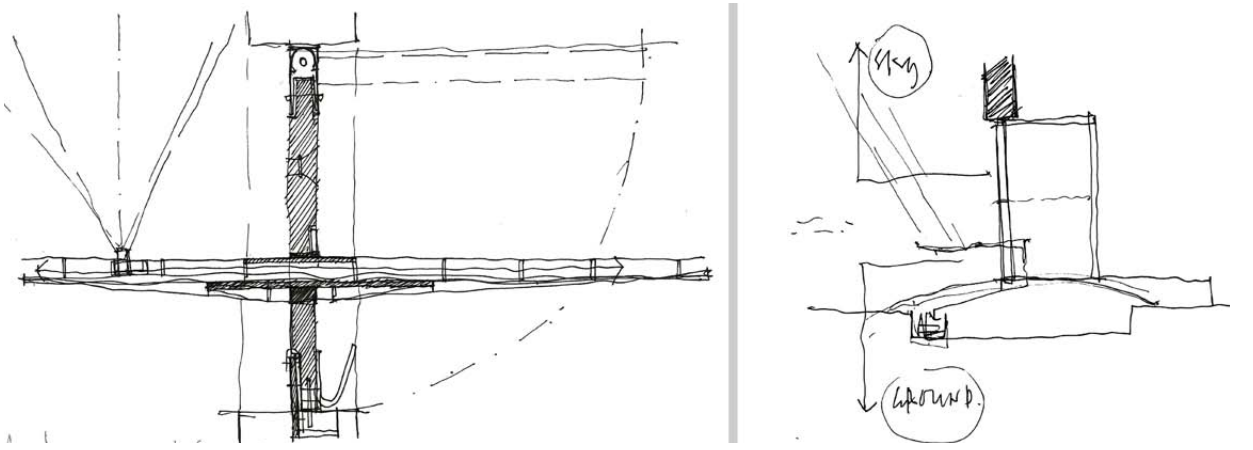

Fig 2.3.4. Kreider + O'Leary – SENTINEL, Concept Plan and Section Sketches.
© Kristen Kreider + James O'Leary, 2012

This gave a system to test what the author aspired to do in principle, before constructing the full architectural assemblage. Design constraints are provided by the fact that the piece needs to operate unaided and without maintenance for up to five years. Due to its location bridging between inside and outside of the existing stone house, it needs to be able to withstand elemental forces of wind and rain, and be designed such that it can continue to operate even when confronted by random events of interference by local humans, animals or matter such as falling leaves. Initial sketches showing light and delicate structural and architectural elements are quickly followed by more realistic drawings that acknowledge the degree of robustness with which it needs to sustain itself over the required timeframe.

Representation & Design Development

Looking at the developmental drawings, one is reminded of the fact that drawing is thinking made manifest: a graphic record of thought and intention. Peter Cook describes drawing as: "a spontaneous means of summarising immediate intention."[xii] The developmental drawings are in the main unselfconscious, spontaneous and mostly collaborative, used as a way of clarifying thoughts and ideas around the project.[xiii] Multiple hands draw numerous lines that draw distinctions, cleaving a space from the conceptual void; delineating entities, trajectories and boundaries. The lines are threads, propelled by thought, which move and mutate with the process of plastic creation. As a reflection of initial thoughts, the lines are loose, free and open, sometimes wildly and exuberantly speculative, sometimes coldly rational and utilitarian, only to become more defined, located and precise as the process continues.

However, as the scale of the *Sentinel* prototype is somewhere between industrial design and architecture, constructed of numerous specialist components that need to be carefully integrated to form a holistic piece of intelligent architecture, loose hand drawings inevitably make way for more precise and definitive computer drawings, which acknowledge the very tight tolerances at work in the piece [Fig. 5]. In order to respect the tolerances involved, laser-cut aluminium was selected to house the major elements of Sentinel and 3D printed components to generate millimetre levels of accuracy to ensure the requisite level of fit between components and their respective aluminium housings [Fig. 6].

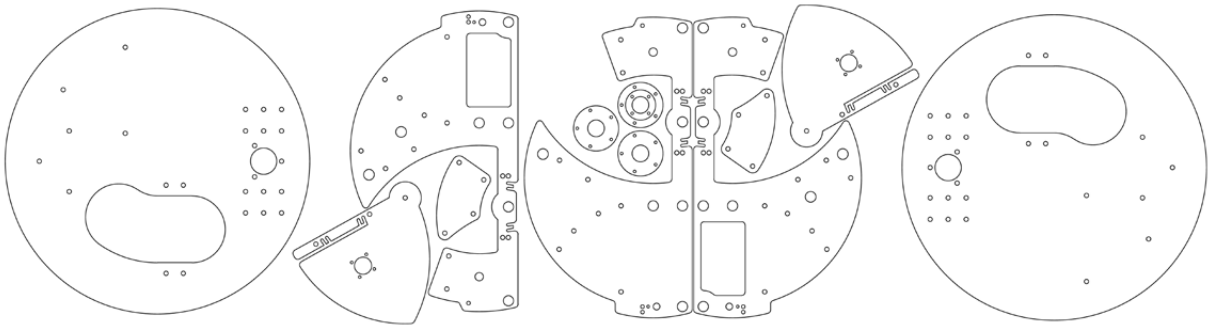

Fig 2.3.5 Kreider + O'Leary – SENTINEL, Aluminium Cut Drawing.
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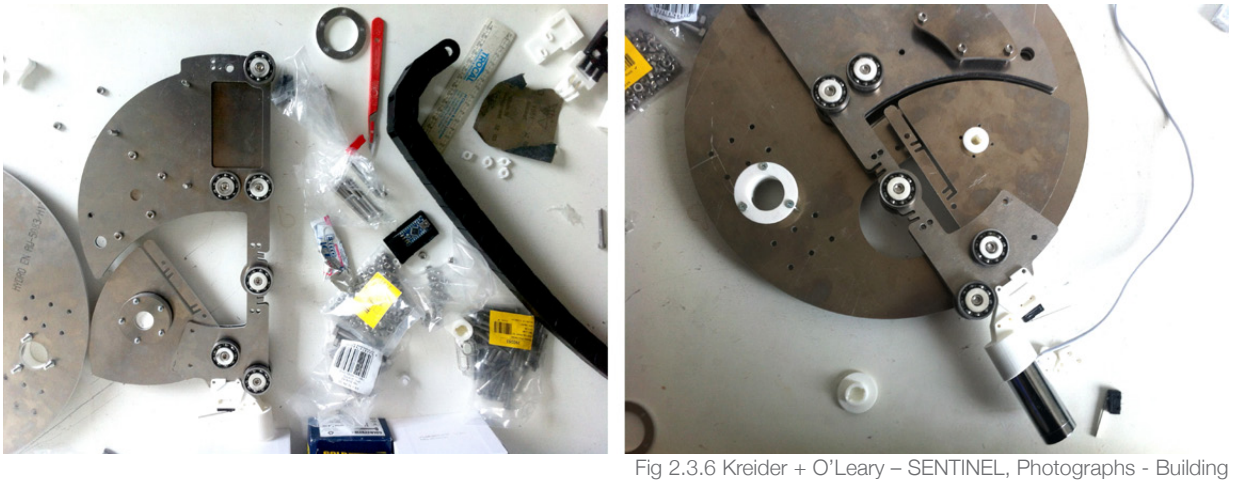

Fig 2.3.6 Kreider + O'Leary – SENTINEL, Photographs - Building the Sentinel Components.
© Kristen Kreider + James O'Leary, 2013

Constructing Representations

Sentinel is a machine for the construction of representations. In this, it follows in a long line of architectural tools that mediate between architect and site, and assist in the understanding and representation of space. Alberto Perez-Gomez and Louise Pelletier have carefully traced the development of these machines as part of their exhaustive survey of the development of perspectival representation in *Architectural Representation* and the *Perspective Hinge*. [xiv] Here they trace the incremental development of technologies of representation, from Fillippo Brunelleschi's ground-breaking hinged perspective machine for viewing the Octagonal Baptistery in Florence's Piazza San Giovanni of 1420 to Marcel Duchamp's Large Glass of 1915-23. Two moments are worth noting on this journey. The first is Girard Desargues's 1643 method for the accurate scientific calibration of sundials in his treatise on the subject. [xv] This, in turn, led to accurate projection of shadows on architectural drawings and perspectival representations, locking together for the first time a coherent inter-relationship of quantitative (hard) and qualitative (soft) information in the same representation, using the same projective techniques. In 2013, *Sentinel* aims to similarly fuse both quantitative and qualitative classes of information together, but through the use of digital video technology, calibrated using timecode of the sun's path around the earth defined by satellites orbiting in space.

The second piece worth noting is the construction of a large sundial, built in 1673 in the Jesuit College, now the *Lycée Stendhal* in Grenoble, France. This solar clock uses the reflection of the sun in a small mirror located at the window to reflect a spot of sunlight onto the ceiling of the interior to precisely indicate solar time, the month and the zodiac sign. This might well be the first example of a localised 'interface architecture' that occupies a threshold condition, positioned specifically to capture light information from without and projecting accurate information of the status of cosmological systems to the occupants inside the College. Critically, this system worked across diurnal, seasonal and yearly cycles, and was calibrated accordingly via drawings and charts on the interior. *Sentinel* aims for a similarly expansive timeframe of operation, but diligently captures this archive of daily local changes in condition, forming a comparative visual index of conditions on and around the site.

Constructing a Horizon

Sentinel is designed around the idea that a level datum is constructed, which punctures the membrane between internal and external environment [Fig. 7]. Periodically, at pre-programmed cycles, it scans this horizon using a long slow pan of the environment. In this action, the author is very much indebted to the techniques pioneered by Russian master filmmaker Andrey Tarkovsky, particularly in the 1983 film *Nostalgia*. In his collection of writings *Sculpting in Time*, Tarkovsky posits that the first principle of the cinematic image is observation. He arrives at this understanding through a more general discussion of what he terms the 'artistic image'. The artistic image is, for Tarkovsky, a means of capturing a singular and unique moment of existence. The artist's aim, he argues, is to make incarnate "a precise observation of life" by re-presenting it as image. [xvi]

It is this level of precision with regard to observation and the quality of its re-presentation that is useful in the current context. Tarkovsky's signature use of the long take and tracking shot suggest ways to attain this level of precise observation, initiating a scan of the visual

horizon. The long take registers changes within the frame as an 'imprint of time'. The tracking shot implies the movement of the apparatus *beyond the frame*, revealing closer and more expansive understandings of site. It is beyond the scope of this paper to fully examine this methodology in its full complexity. The author has written elsewhere about how Tarkovsky's theory and practice of the 'film image' facilitates closer readings of place and would like to draw from this practice here [Fig. 8], further extending it by utilizing the levels of precision and observational control available through the use of Digital Video. [xvii]

Panning between internal and external worlds in programmed cycles, *Sentinel* becomes a kind of remote mobile prosthetic of the architect's perceptual apparatus. In taking on the role of active moving occupier of space, in transforms the context into what philosopher Edward Casey, reading Merleau-Ponty would term 'Lived Place'. [xvii] In this sense, through the spatialising actions of the observing machine both quality and scale are perceived and recorded. Furthermore, a cyclical dimension is introduced, which sets up the possibility of a comparative mode of observation made possible by the temporal loops and cycles programmed through the *Sentinel's* code.

Fig 2.3.7 Kreider + O'Leary – SENTINEL, Photographs - Testing the Apparatus at the Bartlett, UCL.
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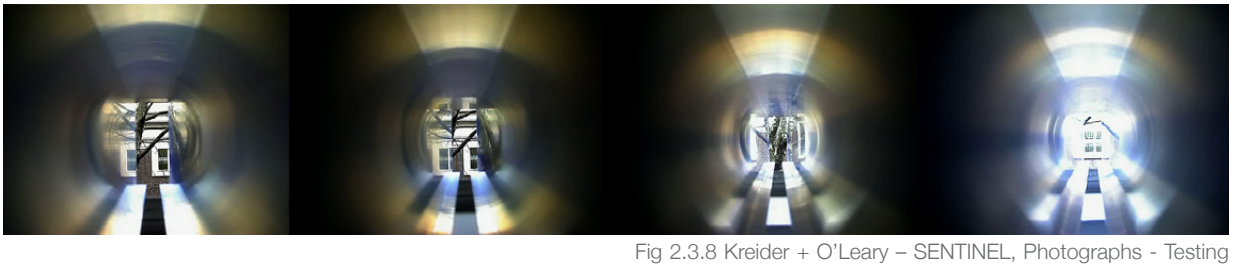

Fig 2.3.8 Kreider + O'Leary – SENTINEL, Photographs - Testing the Apparatus at the Bartlett, UCL.
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Coding a Cinematic Space

One of the key drivers of prototyping *Sentinel* is to be able to fully explore the possibilities of its programming. While it is readily possible to anticipate what the form of the architecture will look like through 3D modeling, how the different components perform and exactly what the camera records is very difficult to model until the piece is largely constructed and can offer the intended specific types of motion to the camera [Fig. 9]. For this piece a very consistent speed of motion of the camera is required, as well as for the tracking machine to have a sense of positional self-awareness in space. What digital video offers that film could not is an ability to be really specific in terms of what is recorded within the frame. Contrary to the frame in photography and film, the video frame is a completely linear scan of a scene. It is thus what Yvonne Spielmann, in Video: *The reflexive Medium* terms a 'processual' image. [xix] Both analogue and digital video are electronic signals, but since digital video derives from numerical code, it offers more possibilities in terms of signal processing. [xx] This possibility is exploited to the full as the design of the *Sentinel* code is developed, which can log a number of differing types of reading or recording simultaneously [Fig. 10], providing a more interesting comparative analysis of aspects of the site and patterns of use. How these edits are programmed can fuse two previously dislocated operations of filming and editing, constructing a 'cinematic' sense of space in the information in real time.

Fig 2.3.9 Kreider + O'Leary – SENTINEL, Photographs - Testing Code configurations at the Bartlett, UCL.
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Fig 2.3.10 Kreider + O'Leary – SENTINEL, Database Images - Testing Code configurations at the Bartlett, UCL.
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The Space of Memory

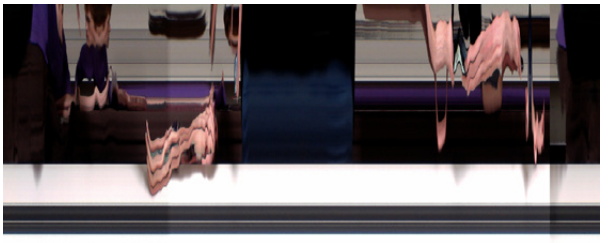
Film theorist Laura Mulvey isolates space as a special and privileged part of cinema's mode of representation in her paper: *Cinematic Space: Desiring and Deciphering.* Whilst Mulvey is concerned specifically with the inter-relationship between character and space, her isolated statements about the spatial condition shed light on *Sentinel* as a cinematic, spatial apparatus. She writes: "The screen image is always etched in space. … Furthermore, the cinema's ability to juxtapose places creates a further dimension of cinematic space." [xxi] Mulvey goes on to discuss the 'spatial resonance and reverberation' of particular places and how they may become anchor points for the localization of memories.

How these memories might be revealed through video recording is an interesting case in point with regard to *Sentinel*. The site where it is housed may well have memories to offer up, situated as it is in a direct line of attack around the notorious 'Falaise Pocket' the Battle of Normandy in 1945. [xxii] Mulvey invites closer and more analytical readings of this memory material to engage in what Bachelard might describe as the work of the 'topoanalyst' [xxiii]. It is interesting to think of the architect of the *Sentinel* becoming an analyst of this type, looking critically and analytically at the information that forms the Sentinel's archive, revealing histories, patterns and practices of the site itself.

The Poetry of Code

The *Sentinel's* archive is a product of recording and programming. These recordings that are generated, and the legibility of these patterns to the observer, are of course related to the coding of the patterns, so an ability to test the prototype in relation to an extended time-base is crucial at an early stage. In an essay entitled: Cinema, Architecture, Poetry, architect Peter Carl discusses the relationship of these differing practices, with particular emphasis on the role of time. He writes that: "[b]eing somewhere is always subject to the claim of what was there before we arrived and will endure after we have left. … We need to be there for the claim to arise, and the universality of the claim is necessarily contingent upon our imaginations and culture, so that the recorded presence is always marked by history and the observer's finitude." [xxiv] *Sentinel* hopes to tap in to this rich stream of time, to allow it to become meaningful, perhaps through the methods of 'topoanalysis' mentioned above. Here the act of coding takes on some of the technical rigour of poetry, instructing connections to specific passages of past, present and future [Fig. 11]. Only trial and error, testing and refining of coded instructions can lead to what Carl describes as: "a discipline or austerity of expression, a careful use of significant fragments." [xxv]

The potential of video to record expansive amounts of time is something that concerns video artist Bill Viola in his essay History, 10 Years and the Dreamtime. Viola posits that the artist needs to be more judicious in the management of information in the age of big data. He writes: "It becomes clear that the major task of today is not information production, but information management. … In this light, the main problem for artists using video these days is what not to record. Making a videotape, therefore, might not be so much the creation or building up of something, but more like the cutting or carving away of everything else until only a specific thing remains". [xxvi] Carving down to these specific elements is the task of the code, which itself needs to be sculpted in parallel with the material it produces, to engender relationships of information that become productive and meaningful [Fig. 12].



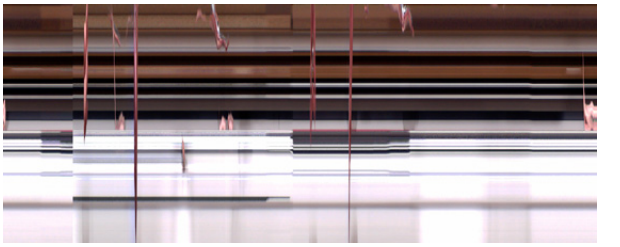


Fig 2.3.11-12 Kreider + O'Leary – SENTINEL, Database Images - Testing Code configurations at the Bartlett, UCL.
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The Aesthetics of the Database

For *Sentinel*, code shapes the form and composition of information in a number of differing ways. Code determines the moment of recording in time. Code determines the proportion of the image recorded. Code determines its composition as well as its adjacency to other recordings in a sequence or in a database. Critically, meaning is increasingly constructed (not found) through the comparing of self-similar elements in the database. As such, the management of the database is akin to a form of composition. In this database universe, the criteria for sampling and selection for particular clips is critically important. Lev Manovich has explored some of this territory with a number of works that are grouped collectively under the title *Soft Cinema*, where he compares the 'hard' aesthetic of a traditional cinematic narrative and the 'soft' aesthetic of a database narrative that he claims for these works. Writing about his piece entitled *Texas*, he describes the parameters of the database as follows: "Each video clip in the Texas database is described by 10 parameters that specify where the video was shot, the nature of the subject matter, its average brightness and contrast, the type of space, the degree and type of camera motion, and so on. These parameters are used by the software in assembling the movies. Starting with a particular clip, the software finds other clips that are similar to it on some dimensions. … Consequently it is possible to describe Texas as a media object that exists 'between narrative and search engine". [xxvii]

In these works he goes some way to answering a key question posed some years earlier in 1998, namely: "How can our new abilities to store vast amounts of data, to automatically classify, index, link, search and instantly retrieve it, lead to new kinds of narratives?" [xxviii] A decade later, it is now clear that the database is the new form of representation in its own right, with potential to update dynamically and deliver highly audience-specific streams of information to the viewer on request in real time. Once multiple presentations of this information are possible, the next question is one of composition. As David Claerbout writes of his own practice: "As a film-maker my tool is memory, not film. And memory likes a good composition" [xxix]

Presence in Absence

Sentinel is a work that deals with the condition of absence. In the same manner as a lover's token of a lock of hair provides a certain proximity to the material body of the absent lover, it aims to bridge the divide across a physical distance, becoming a locus of reassurance and remote contact. Sentinel aims to collapse two separate spaces, one being the architect's studio in London and, the other being a site for a projected house in Normandy. Through a connecting thread of data, it acts like the lover's lock of hair to enact a performance of proximity that is, at that particular time, impossible.

The works in the *Interface Architecture* series aim to facilitate the architect in the various phases of work in the design, construction and final occupation of the projected house. Throughout the design phase, *Sentinel* will become an interface between architect and site, registering the nuances of place and location through occupation and observation, in effect becoming a remote agent to the imaginative consciousness of the architect during the design phase. It will provide real-time information about site conditions, light quality, occupation, patterns of use and seasonal cycles – information that would otherwise be wholly or partially unavailable to the architect, who as per usual, is designing at a remote location from the site itself [Fig. 13].

Fig 2.3.13 Kreider + O'Leary – SENTINEL, Database Images - Testing Code configurations for Performing Architecture at Tate Britain, Feb 1, 2013.
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Architect, Site and intervening Media

To conclude, let us return to the certain unease in the relationship between architect and site. Robin Evans identifies the source of this unease to be "the particular disadvantage under which architects labour, never working directly with the object of their thought, always working at it through some intervening medium, almost always the drawing." [xxx] For Evans, the architect is always at a disadvantage, being in a state of near continual psychological displacement by labouring over the site of the drawing as opposed to the architectural site itself. Here the drawing takes on an aura of importance that transcends its material status, itself becoming a site of intense delineations, layering, textures, modifications and erasures. Evans suggests, however, an escape from this bind, by altering the definition of architecture to "insist on the architect's direct involvement, either calling the drawing 'art' or pushing it aside in favour of unmediated construction." [xxxi] He cites the positive aspects of this strategy as involvement, substantiality, tangibility, presence, immediacy and direct action: "the direct and experiential appears far more ethical, and far more interesting, far more at risk and far more real than the indirect and abstract approach." [xxxii] It is this strategy of direct involvement that we sought to engage when developing our work with *Sentinel*, in effect bringing architect and site closer together in a space of experiential engagement.

Fig 2.3.14 Kreider + O'Leary – SENTINEL, Testing Sentinel systems configurations for Performing Architecture at Tate Britain, Feb 1, 2013.
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i James O'Leary is an architect and installation artist. His work explores the inter-relationship between human beings and the spatial systems we inhabit, see http://www.kreider-oleary.net . He is currently a Lecturer in Innovative Technology and Design Realisation at the Bartlett School of Architecture, University College London, where he leads the M.Arch Architecture Design Realisation Programme and is Unit Master in M.Arch Unit 14. http://www.unit-14.net/

ii This project is partly supported by the Bartlett Architecture Research Fund, UCL. The Research Assistants on the project are Andrew Walker and Ollie Palmer.

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xxxi Ibid p. 160

xxxii Ibid p. 161

2.4
The Deceptive Ease of Folding:The Industrialisation of a Prototypical Product

Yves Ebnother [i]

This paper describes the process of industrialisation of a product whose development was aided and inspired by extensive use of computer-controlled processes, both in planning (modelling) and production. In particular, the notion of a seamless transition from prototype to product, as present in the current digital craft discourse, is critically assessed. The Zoid stool project was initiated some fifteen years ago while on an internship at Swiss design studio greutmannbolzern, Zürich. The brief was simply to design a promotional object for a sheet metal fabrication company which would showcase the various qualities of the material and its processing. The idea of a load-bearing object, a stool, was born, and it was to be folded from a single sheet of material. At the time, the idea was presented as a scale model (1:2) made from aero-ply, but, since the construction of the cutting and folding pattern for the flat sheet was not properly solved, its formal appearance was quite different.

The project was picked up again in 2005. The cutting and folding pattern could now be solved and computed using equation-based, parametric CAD, also making changes in the formal appearance possible (facetted). Access to digital prototyping equipment, in particular a cutting plotter, led to the current materialisation in anodised sheet aluminium. The sheet is scored and cut by the plotter and subsequently folded and riveted by hand. To date, the stool has been produced (on demand) about forty times and is available from a local shop_ specialised in small series objects and prototypes, as a so-called ‘prototypical product’.

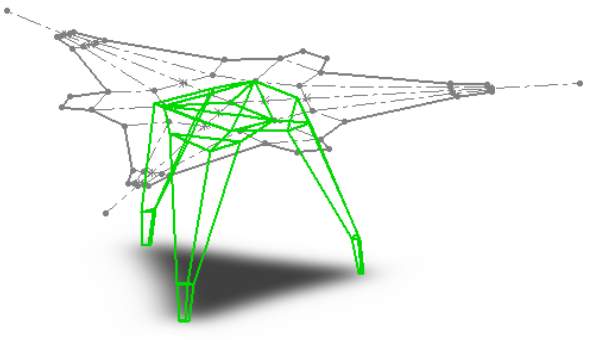

Fig. 2.4.1 Cutting Pattern Folding pattern and three dimensional body in CAD

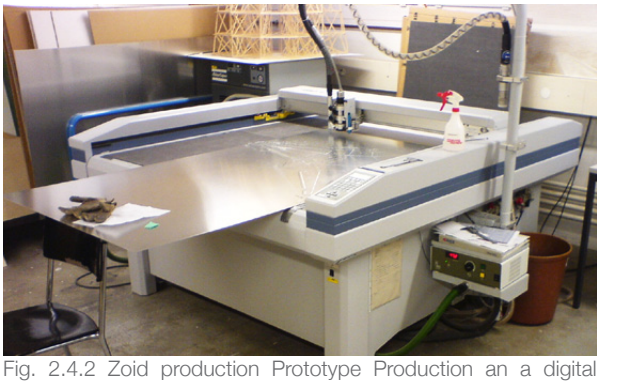

Fig. 2.4.2 Zoid production Prototype Production an a digital cutting plotter

Fig. 2.4.3 One Zoid The prototypical product

Fig. 2.4.4 Many Zoids Colour Range

Fig. 2.4.5 Zoid Shop Exhibited at Einzigart, Zürich

Problems

The project's reception in exhibitions and through user comments has been good, but it has so far not been able to attract a wider audience. This has supposedly been due to two reasons:

- high cost of small-scale production leading to high retail price
- material weakness in a heavily stressed spot leading (eventually) to brittle breakage

Based on this analysis, a manufacturing partner was sought and found, the German company Ackermann GmbH_, specialists in CNC-processing of sheet material.

First Industrial Prototype

The first industrial prototype was made using a wood-leather sandwich board, which Ackermann had developed for another project: the (rigid) wood layer is partially removed to reveal the (flexible) leather, which acts as a reliable hinge. In theory, this sounded perfect and elegant, because every material is used for its particular properties. However, the practical test revealed a formerly unknown, special condition in the back of the stool's leg, where compression loads are present in the fold itself. The fold, now materialised as a soft leather hinge, subsequently collapses.

Second Industrial Prototype and Preliminary Conclusion

The second (and third) industrial prototype was made using a readily available aluminium-polypropylene sandwich material, following the established manufacturing logic: the hard aluminium layer is partially machined away to reveal a fold line. Polypropylene, the core material, is ideal for this application as it has excellent hinge qualities. While the resulting prototypes did solve the initial problem of brittle breakage, they failed to convince in other aspects:

- due to the flexibility in the hinge, the prototypes have a certain amount of give, which is undesired in a stool;
- their materiality (look, feel, sound) appears plastic-like and "cheap".

Only, after several prototyping cycles, did the briefing for the industrialised product became clear:

- stability, sturdiness, longevity: needs to function well and be reliable as a piece of furniture;
- appeal: needs to convey a sense of high quality in all its visual and material aspects (design object).

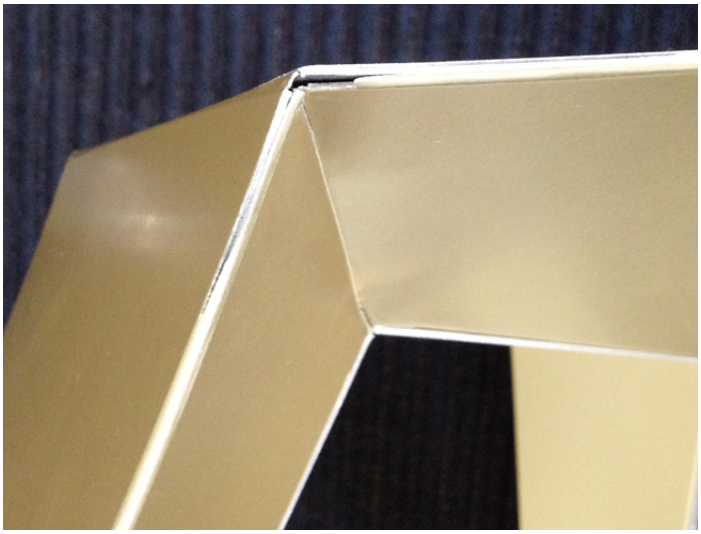

Fig. 2.4.6 Brittle Breakage Material fatigue

Fig. 2.4.7 Wood Leather prototype

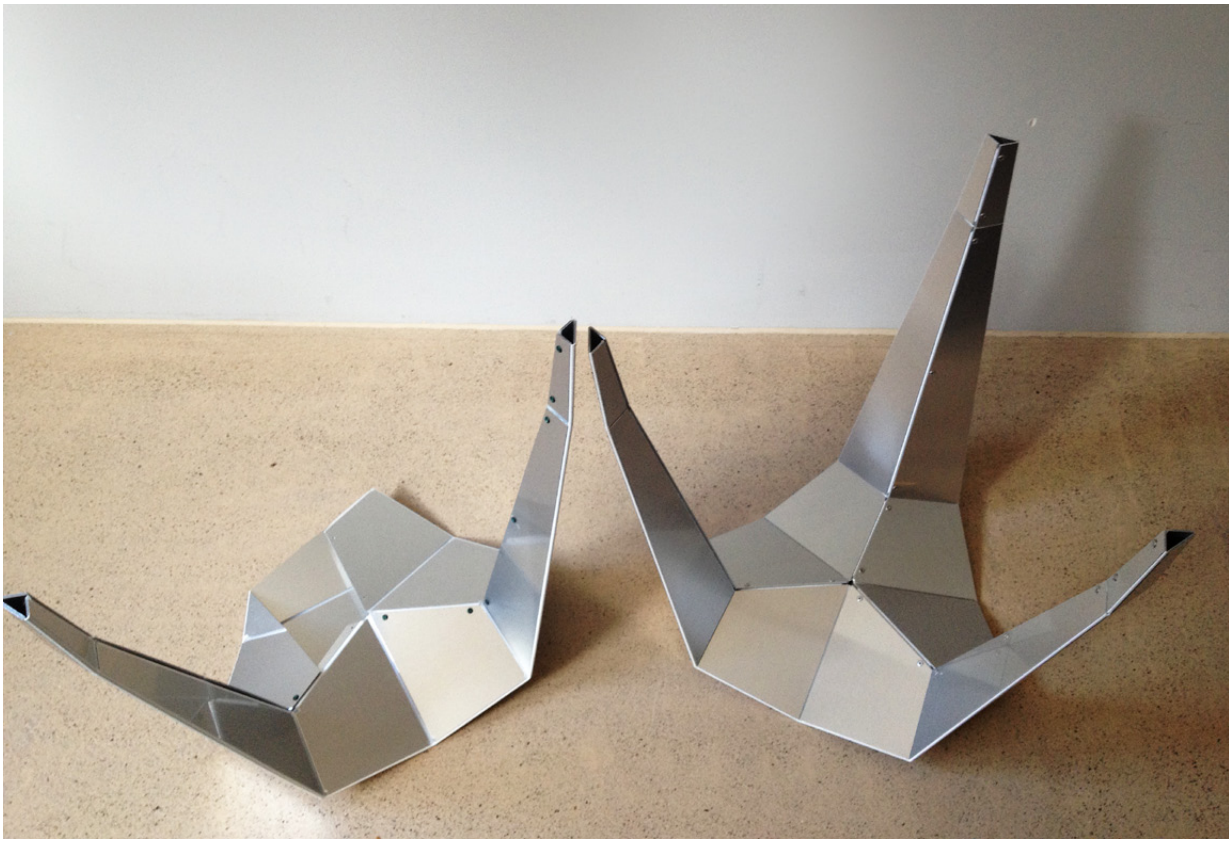

Fig. 2.4.8 Industrial Prototypes Aluminium-polypropylene prototypes

On Folding

To carry loads with a folded structure, there appear to be two principal approaches:

1. the structure is designed in such a way that the load bearing stress acts along the fold-lines;
2. the load bearing stress acts across the fold, effectively making it behave like a hinge.

Approach 1 is well known and documented and is present in the leg of the stool. A sturdy structure based on approach 2 as is present in the above mentioned critical spot, needs to fulfil the following condition:

FL {implied by the load} < FB {required to deform the fold}

In other words, the load bearing fold has to be made from material which requires more force to bend (in production) than it will have to withstand in use.

To fabricate structures based on approach 2 there are three strategies:

- manual production;
- machine assisted process;
- fully industrialised production.

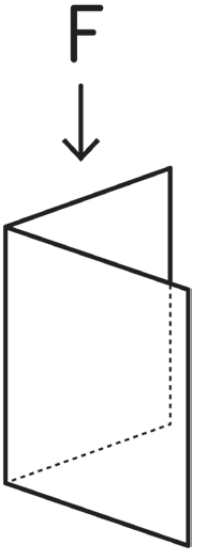

Fig. 2.4.9 Vertical

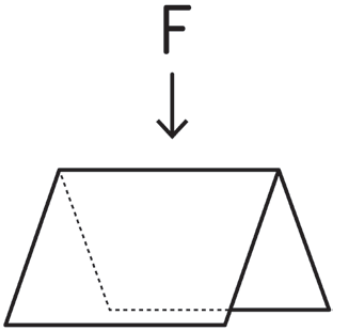

Fig. 2.4.10 Horizontal

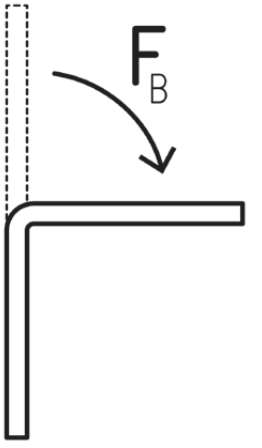

Fig. 2.4.11 Force required for bending

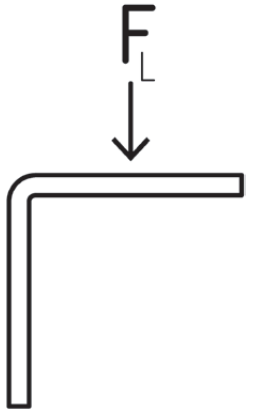

Fig. 2.4.12 Force imposed by load

Manual Production of Folded Structures

In manual production of folded structures, it is the actual folding that is carried out by hand. This method allows for the production of objects that are geometrically too complicated for the limited capabilities of standard bench presses. However, the problem lies in the limited force available for deformation. A common approach is therefore to perforate or score the sheet material thus allowing it to be bent manually, along a properly defined edge.

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Good examples of this technique are:

- The *BENT* family of furniture objects, designed by Stefan Dietz for Italian Manufacturer Moroso, made from perforated and powder coated sheet steel.
- The *Sputnik* table, designed and produced by Sander Mulder, made from scored and painted sheet aluminium.
- The NOM - Nature of Material furniture series, designed by Bakery Studio for Italian Manufacturer Cappellini, made from laser-perforated and painted sheet aluminium.

To achieve the required stability, these products are typically made using a bending mould or a jig, thus allowing the application of the required (substantial) force for bending.

Machine Assisted Production Of Folded Structures

Machine assisted production describes a hybrid scenario whereby some actions are carried out by hand whilst a machine does others. Typically, this could be used to overcome some of the limitations of a purely manual production, especially regarding the force required for bending. Towards this, Gregory Epps is doing pioneering work with his company Robofold (UK). Industrial robots are used to fold pre-scored sheet metal into free-form objects. While it seems that at present the process has limited abilities to bend thicker sheet and requires considerable effort to plan and set up, it may well be part of a future production scenario for the Zoid stool.

Fully industrialised production of folded structures

While there are numerous processes in industry to produce deformed sheet metal parts, there are two that seem particularly relevant for the discussed project:

- folding using a bench press;
- deformation with a die (deep draw).

Bench presses are used to put folds and creases in sheet metal. They come in impressive sizes capable of exerting many tons of pressure. Unfortunately, the Zoid stool cannot be produced using a bench press, because its folding geometry is too intricate. Also, due to the nature of its particular folding pattern, it cannot be folded sequentially (one leg after the other) but rather needs to be folded as a whole. In deep draw processes the sheet is punched into sturdy moulds (male and female). The advantage of this process lies in its ability to repeatedly produce identical parts in large volume production, at low part cost. For the discussed project, the construction of a folding mould can be envisaged, but at a cost which could almost certainly not be recovered by expected sales figures.

On Design

As mentioned above, based on the experiences made with both the small series prototype and the newer, industrial prototypes, one central question was raised:

- What are the expectations towards the design of this object?

The process of prototyping showed clearly, that while in the industrial prototypes some of the functional aspects of the stool were improved, others (appearance) had changed for the worse.

In traditional product design development, products are usually conceptualised based on market research, with a particular focus on consumer's expectations. Typical question might be:

- What will they want?
- What is important to them (features)?
- What other objects do they own?
- How much will they be willing to pay?

In the case of this project, this user-oriented view had never been a driving force. Rather the fascination for the folding mechanics, geometric transformation, material manipulation had been at the centre of attention, and of course an intuitive understanding of the desired design qualities. Faced with concrete questions in industrial prototyping it became clear that an explicit basis for design decision-making was needed.

A broad analytic look at reference design objects revealed some interesting facts: Isamu Noguchi's famous Prismatic Table, in production with Swiss furniture manufacturer Vitra_, will serve as an example. Noguchi's design from 1957 is a small coffee table made from painted sheet aluminium. While prismatic (hence the name) in appearance, it is made from three identical pieces which are invisibly connected. The pieces themselves are straighforward to make although of course they are finished to a very high standard. The result is an object that looks, functions and feels unobtrusively perfect. The effort invested in the piece's finishing to achieve this particular high-quality appearance is not perceived at first glance, but it is a key factor for the table's reception. Unsurprisingly, the small table's pricing fully reflects its laborious production and underlines its exclusivity. With Noguchi's table, Vitra do something simple, in terms of production technology, yet very well in terms of detailing, finishing, and sell it at an appropriate price.

The lingering presumption for the stool project had been that it had to be inexpensive in the market, maybe even offer the possibility for buyers to fold it themselves or to be sent as a flat unit. The analysis of Vitra's coffee table reveals the misconception in this line of thinking: the Zoid stool is far from simple to make (if it is to be stable) and one of its key appeal factors is the anodised finish. Therefore, it should be developed not into an inexpensive product, but into a perfected one that manifests the folding idea in a highly desirable object.

Live Sample

Faced with two unsatisfactory material options for further industrial prototyping:

- sheet aluminium, good finishing, structural weakness;
- aluminium-polypropylene sandwich, structurally strong, cheap appearance.

One stool was cut open to better understand what exactly the problem in the spot susceptible to brittle breakage might be. The live sample revealed that the issue was not so much the material's (lacking) flexibility as had been supposed previously, but rather seemed to be stemming from the actual cutting groove geometry. It appeared that the groove's particular proportion, its width to depth ratio was unfavourable and was indeed leading to a high tensile strain (tearing) in the fold itself.

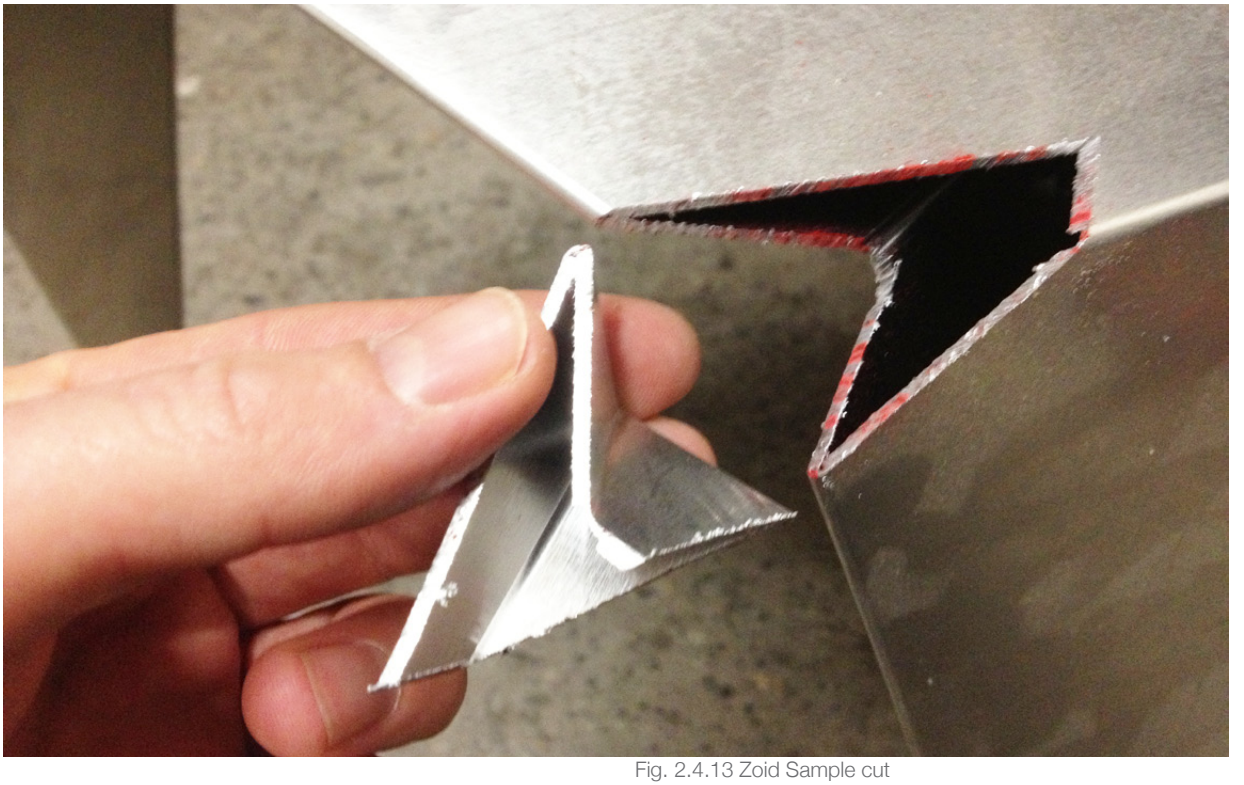

Fig. 2.4.13 Zoid Sample cut

Conclusion

The advent and increasingly widespread access to computer controlled design and fabrication processes has undoubtedly created a tremendous sense of excitement amongst creative practitioners. Whilst for many the new tools primarily offer myriad possibilities for aesthetic exploration, they also touch upon the underlying question of production. The fact that the same digital data can be used for prototyping as well as for production has led to the notion - and to many successful examples to prove it - that production of goods can be initiated by micro companies and then be scaled up to meet increasing demand. This model does indeed work well, but it implies tight constraints on the type of materials used and therefore the objects produced.

As is the case with the presented project, folding as a construction technique lends itself particularly well to this iterative way of working. Initial prototyping can be carried out in inexpensive paper and once CAD data is established it can be materialised and incrementally improved towards the final data set. While there are demands (on stability) in the industrial product that make it different from a prototype, these are detail particularities, which can be understood and solved. However, the real surprise in the development of the Zoid stool project was the fact the design brief needed to be made explicit. As shown above, and as is typical of ideas based projects (as opposed to marketing research based projects) the design brief and in particular the end user's requirements was not rationally understood. Of course, the project initiator has an intuitive comprehension of what the particular project is about, but this internal brief is often contradictory and has shifting priorities. In order to advance towards an industrial product it is therefore paramount to extract the intuitive briefing and to formulate it, to unveil contradictions and as a means of communication with project partners.

On a purely technical level, the transition from prototype to product - in this particular case, using a folded construction - can be said to be relatively seamless. It is the conceptual transformation from making one piece as a personal proof of concept to producing a serial piece of furniture for a distinguished market, which, disruptively, brings a whole new set of parameters and considerations to the process. Contrary to common opinion though, these constraints should not be seen as a threat to the creative expression, they are rather an untapped source of information, which, used sensibly, can be instrumentalised to clarify and strengthen the design itself.

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10 http://n-e-r-v-o-u-s.com

i Yves Ebnöther is a Swiss industrial designer. Upon completion of his BA Hons., studies at Ravensbourne, London, he returned to Switzerland to work at numerous design agencies, including Hannes Wettstein's office. In 2003 he enrolled on Prof. Dr. Ludger Hovestadt's MAS CAAD programme at ETH Zurich, where he developed his series of experimental prototypical products. He subsequently founded and directed the Rapid Architectural Prototyping Laboratory RAPLAB at ETH's Faculty of Architecture. In 2011 he moved to Singapore to set up the Prototyping Facility at ETH's Future Cities Laboratory. Currently he lives in Zürich with his family, where he runs his own design practice, works as a lecturer and is a founding member of FABLAB Zürich.

2.5
Prototyping and Prototypical: Two Models or Architectural Practice

Alan Dempsey NEX [i]

Prototyping in architecture is not new. The nascent years of the modern movement can be read through a series of prototypes and mock-ups. Yet once again, there is a renewed interest within architecture in the prototype as a tool, and prototyping as a methodology, for its promise to organise a design process that must integrate increasingly complex functional requirements and communicate to a more extensive design team. The prototype has long occupied a primary position in other design industries such as automotive, product design, shipping, or aerospace. All have undergone significant process reengineering in recent decades. Taking advantage of developments in CAD / CAM technology, each of them has dramatically increased efficiency and improved quality in their output. However, all of these industries share two key features: they benefit from economies of scale where investment in the prototyping of new models is offset by volume production; and their manufacturing process benefits from a closed supply chain. Architecture enjoys neither these economies of scale, nor a closed and controllable manufacturing environment. As has been observed elsewhere, architecture is actually prototypical in nature, as each building itself is a prototype that arises from specific circumstances, which are rarely if ever repeated. ii So how might our discipline learn to think prototypically and design through the prototype?

Research within Architectural Practice

Within our office we see two models of prototype use. The first we call the design prototype, which is an abstract model that has specific proto-architectural qualities that can be instrumentalised in differing ways across a number of projects. For us these models are prototypical. They are abstract and loosely describe particular spatial or organisational interests we have. When installed within a project they serve as a conceptual seed from which the project grows. They serve to structure an architectural agenda that can guide us beyond an understanding of design as a contingent solution to a specific one off problem.

Our second use of the prototype occurs during the design process itself, which we call the working prototype. The working prototype can be either digital or physical. A physical prototype is not necessarily a full-scale replica but it must have a specific performance that has a direct correlation to the performance of the full-scaled reality. [iii] A digital prototype is a constrained parametric model whose performance is driven by rules or specific relations among components. Gehry Technologies have pioneered this kind of prototype in architectural applications, and we have adopted full Building Information Modelling as part of our workflow. Both of these models of prototyping are used to structure an overarching

research agenda in the office. A core strand of this agenda focuses on the use of Modern Methods of Construction (MMC) and in particular using digital design and manufacturing in architecture to create extraordinary spaces, assemblies and components with ordinary means. That is, our aim is to investigate novel methodologies of creating bespoke designs which match or exceed standardised options in terms of cost, functionality, and performance.

A second and more focused line of research has been looking at the technical and aesthetic potentials of wood as a material because of its technical versatility, its positive environmental profile, and its potential range of formal expression. This paper focuses on recent applied design research on the above agendas, by Alan Dempsey and NEX, in three recent projects at the differing contexts of furniture, experimental structures, and building enclosure. Each project investigates the application of one of our design prototypes in to meet differing requirements of structural and functional performance, timber construction, and manufacturing approach. The development of each project makes extensive use of working prototyping as a core activity to enable design and progress our research knowledge.

Powerscourt Centre

A listed Eighteenth Century Building, Powerscourt Centre, is located in central Dublin. The building consists of a principal four storey townhouse and a three storey annex around a courtyard to the rear of the house. The entire building is Grade I listed. In 2010 NEX was asked to analyse the current use of the building as a boutique retail centre, and propose a contemporary but sensitive architectural intervention that would improve the buildings operational and environmental performance. Without going into detail, my purpose of introducing this project is to illustrate the two senses of the prototype I refer to in my introduction. The first is the design prototype, which in this case is what we call a deep surface. For some time we have been interested in exploring the status of the architectural surface, and more specifically the concept of a surface or envelope that has a deeper particulate structure composed of many elements. The particulate qualities of the surface have allowed us, in different projects, to explore new conditions of materiality, and create a system where multiple functions and performance demands are integrated within a single coherent system.

In Powerscourt, this deep surface takes the form of a new roof, which we proposed to enclose the central courtyard. The tectonic of the roof arose from a desire to create variegated light in the courtyard space within a system that echoed the rhythmical fenestration of the courtyard walls. In our first concept the roof structure spans the courtyard with a timber lattice where individual cells vary in size and depth in relation to structural and lighting needs. The smaller cells create a fine grain background of light and shadow, and the bigger cells framed clear class windows that admitted bright beams of sunlight into the space.

This design model was developed through a series of working prototypes. To maximise the variable qualities of light on the walls while minimising solar gain we undertook a detailed sunlight simulation and used genetic algorithms to help us determine the optimum position, size and angle for the larger sunlight apertures. The structure of the timber lattice raised interesting challenge of how to clear span the twenty-eight metres courtyard.

Fig. 2.5.1 Powerscourt

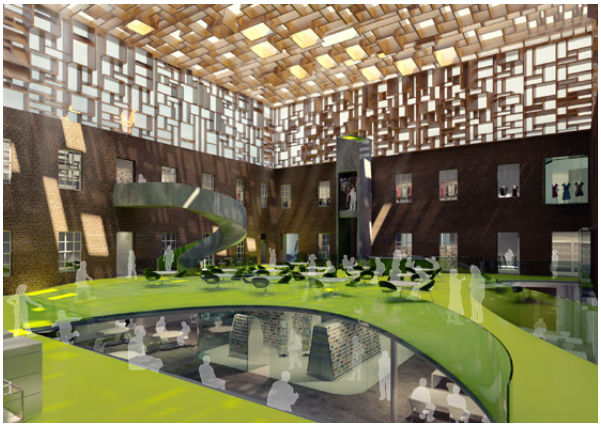


Fig. 2.5.2 Powerscourt – courtyard roof

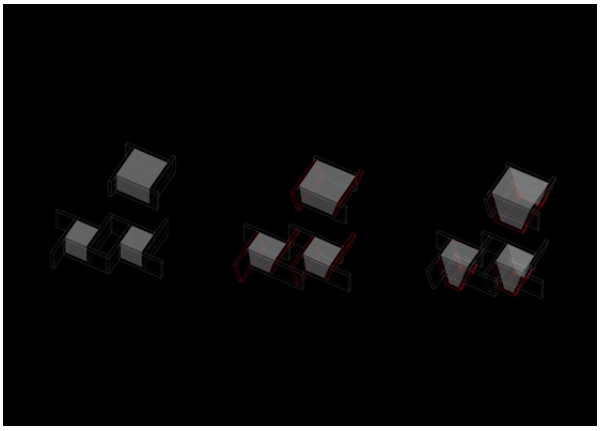


Fig. 2.5.3 Studies of the sunlight aperture, or roof lights

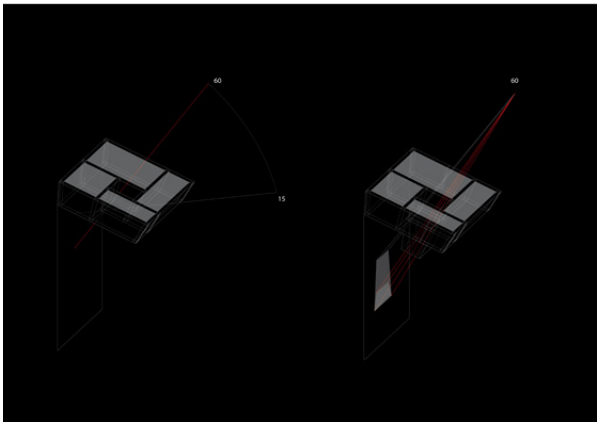


Fig. 2.5.4 Projected sun angles

Because NEX was working in a tight urban context there was no possibility of transporting and erecting full-length beams. Similarly the space for assembling the beams on site was severely limited. To try and address this, we developed the idea of using a reciprocating structure of four shorter beams that were lapped together in a cruciform arrangement. This assembly was applied to the roof surface repeatedly to transfer loads in regular spacing to the perimeter walls, while also accommodating the positions of the clear windows already identified.

As the practice developed more detailed prototypical structural models, we learned that the strength-to-weight ratio of timber was not sufficient to span the courtyard without overloading the existing structure. Further, the increased visual impact of massive timber beams created a roof that was unacceptable to us, and the planning and heritage authorities. In the end, the conceptual prototype of the deep surface with apertures was retained by switching to a structure of solid steel macalloy bars. This met our loading and construction criteria, while reinstating the delicacy of the lattice we originally intended.

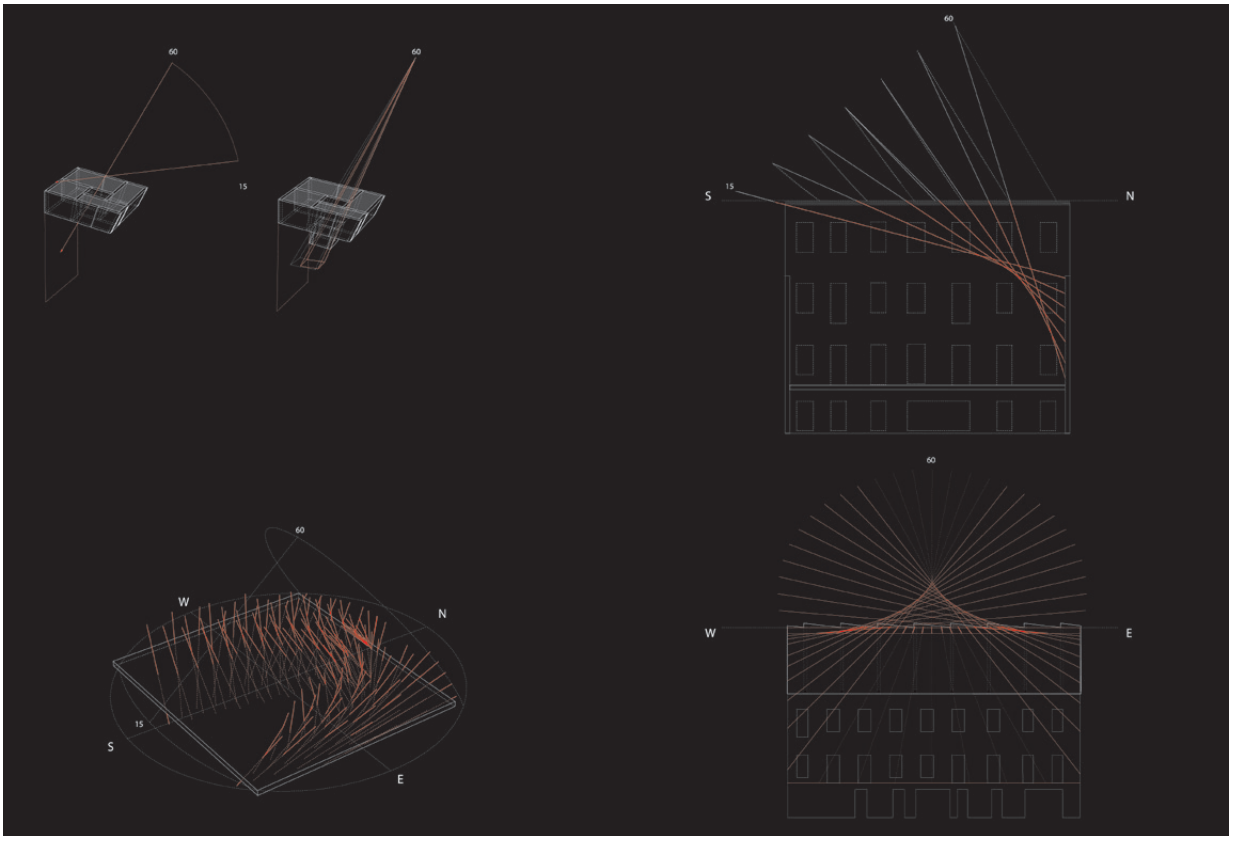
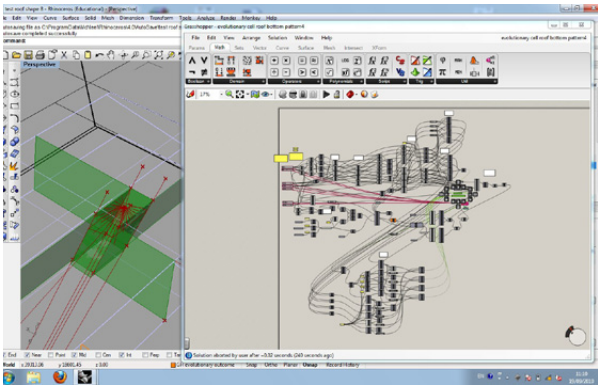


Fig.2.5. 5 Sunlight perpetrations over the seasons



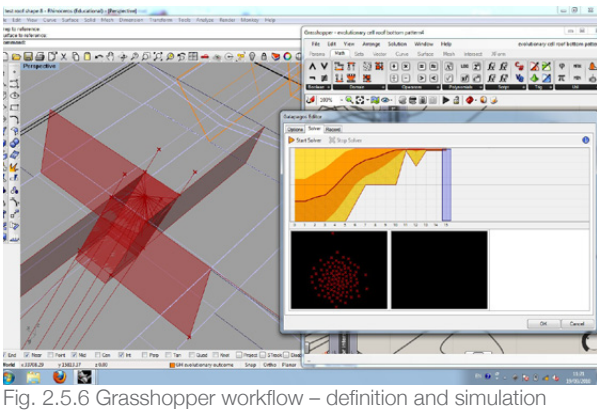


Fig. 2.5.6 Grasshopper workflow – definition and simulation

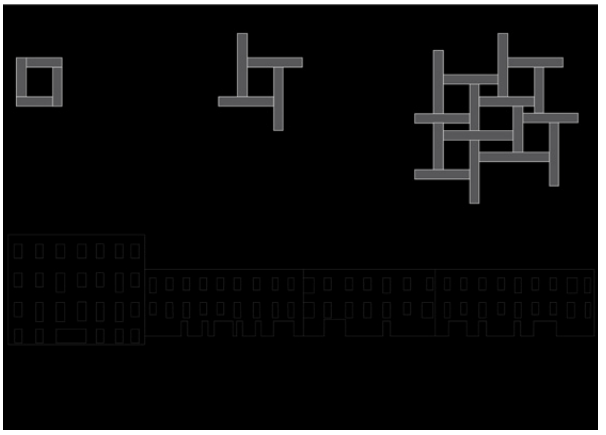


Fig.2.5.7 Reciprocating structure

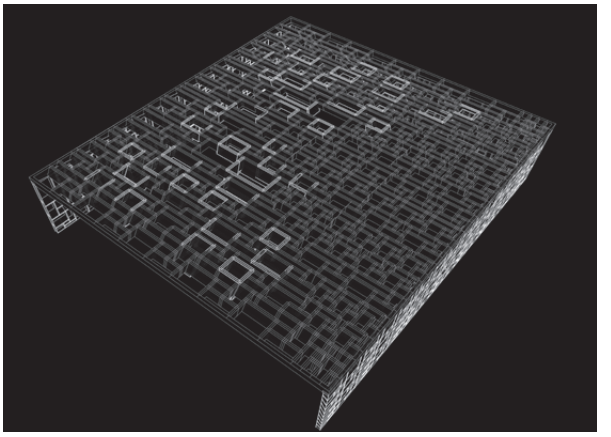


Fig.2.5.8 Courtyard roof perspective

Fig.2.5.9 Final courtyard proposal

To-and-Fro Table

Around the same time the practice began to develop the To-and-Fro Table, 2010. NEX entered a competition supported by the UK Technology Strategy Board and Metropolitan Works where the competition winners were awarded with the resources to develop a product proposal to pre-production stage. In considering a piece of furniture, I was very interested in the table. It is arguably the most important piece of furniture we use because it creates an immediate and comfortably intimate space that facilities social exchange. And yet social exchange is so subtle and nuanced. Evidently, what we say forms only a very small part of what we communicate to each other, with posture and gesture being equally important. [iv] So I was interested in exploring the concept of this mediating surface as something that wasn't so emphatic, but varied in its opacity and had a particulate quality so it became a more active mediator of social discourse.

Fig 2.5.10 To-and-Fro Table

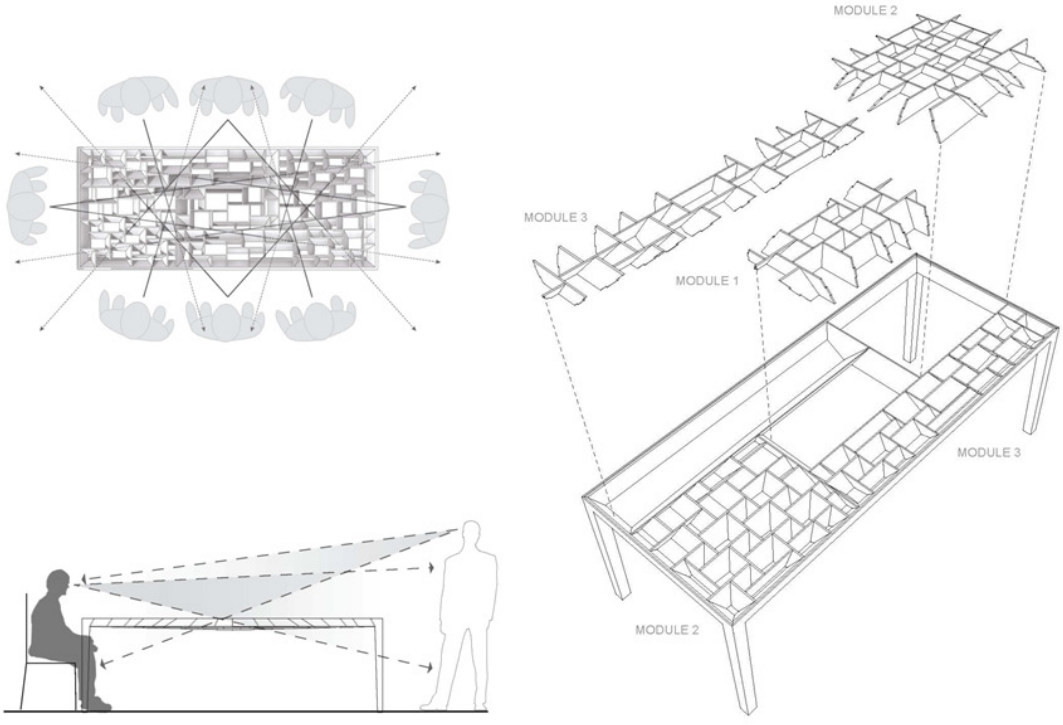
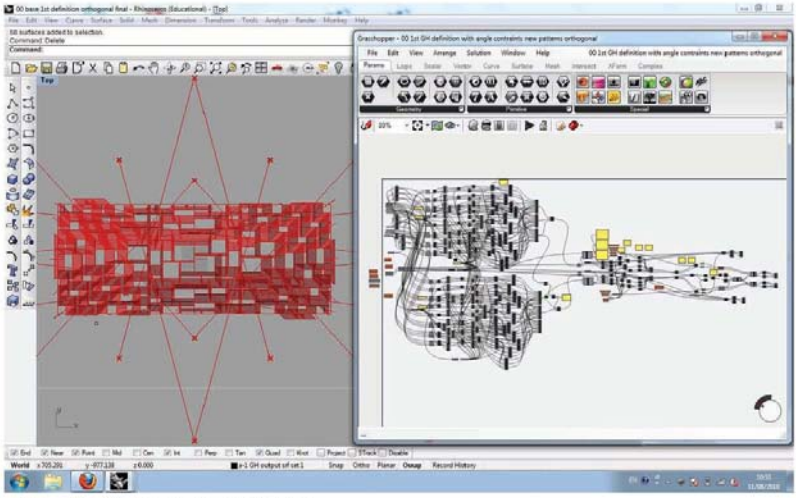


Fig 2.5.11 Table as a social space

To materialise this thinking, we took the design prototype of the timber reciprocating lattice from Powerscourt, and scaled it down to the size of a piece of furniture. In this instance, the driving parameters of the form of the lattice were not environmental but social. In place of studies on sunlight penetration, we looked at the human gaze across and along the table as drivers of the arrangement of material and structure. Like the reciprocating back and forth of a good conversation, the table is made up of a field of delicate wooden fins that vary to-and-fro in relation to each other and interlock to form this intricate lattice to appear most transparent in the vicinity of the person sitting opposite the viewer and increasingly opaque elsewhere. The complexity of the design demanded intensive prototyping from the beginning. The reciprocating fins were jointed with a very traditional mortise and tenon. However, the variation in the lattice meant that there was a maximum of two identical pieces out of some six hundred, and the angle of the joint continuously varied. The manufacturing approach therefore combined advanced five-axis computer controlled routers with skilled craftsmanship for the final assembly.

Initial full-scale tests led the practice to choose walnut wood for the entire piece. It is strong and sufficiently densely grained to accept a high level of detailed cutting for fine edges in the design and there it reduced the likelihood of the material warping while it was machined. Nonetheless warping proved to be a significant challenge to address. The fins were six millimetres thick, and the first prototypes distorted in plane as the fibre tensions in the wood were altered by the cutting process. To solve this, we switched to making the fins from a solid walnut laminate pressed from three two millimetre thick layers. The reciprocal pinwheel structure works at two scales – first at the scale of the component fin, and also the scale of the full length and width of the table. The larger scale provided some additional structural stability. More importantly, it allowed us to compartmentalise the assembly process into discrete bays, which maintained control over tolerance creep. The table was assembled by one skilled cabinetmaker over about three days. The completed piece demonstrates that while the variation of the transparency of the table can enable more nuanced social exchange, it is also produces a piece of furniture that actively contributes to the atmosphere of the space it is placed within by creating complex patterns of light and shadow when it is simply lit from above.



Screenshot: top view of the table and a parametric definition that controls the array of surfaces based on 8 viewer point.

Fig 2.5.12 Table as a field condition

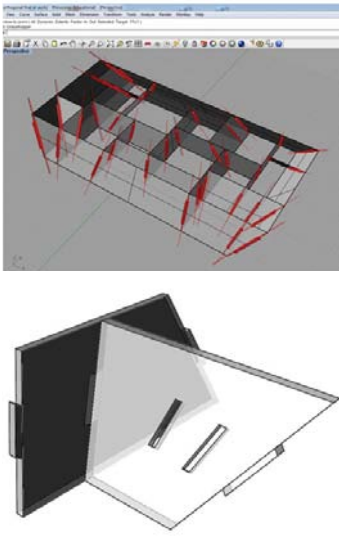


Fig 2.5.13 Variable tenon joint

Fig 2.5.14 Pressed laminate and cut fins

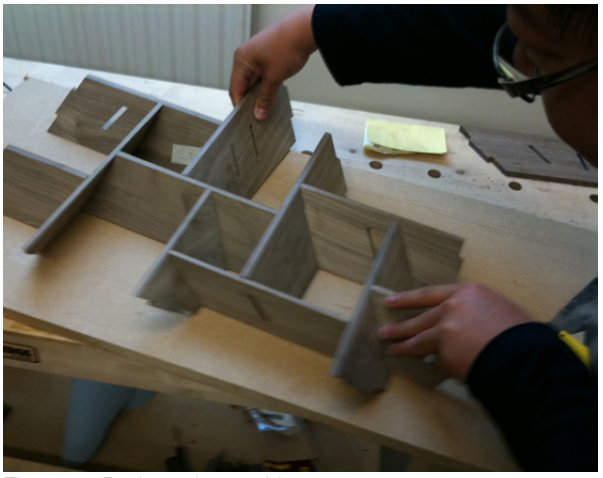


Fig 2.5.15 Reciprocal assembly

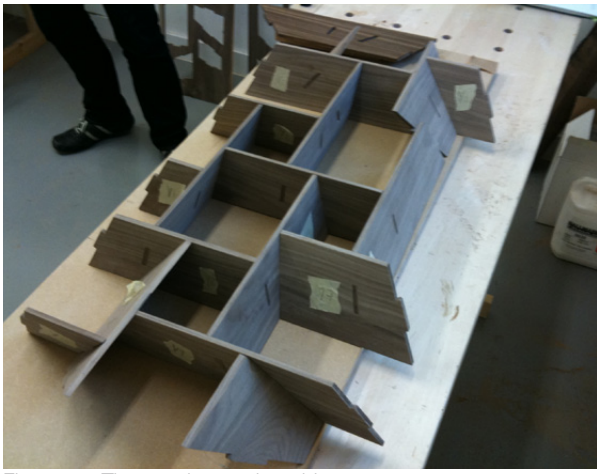


Fig 2.5.16 The next bay of the table structure

Fig 2.5.17 Machining the primary frame of the table

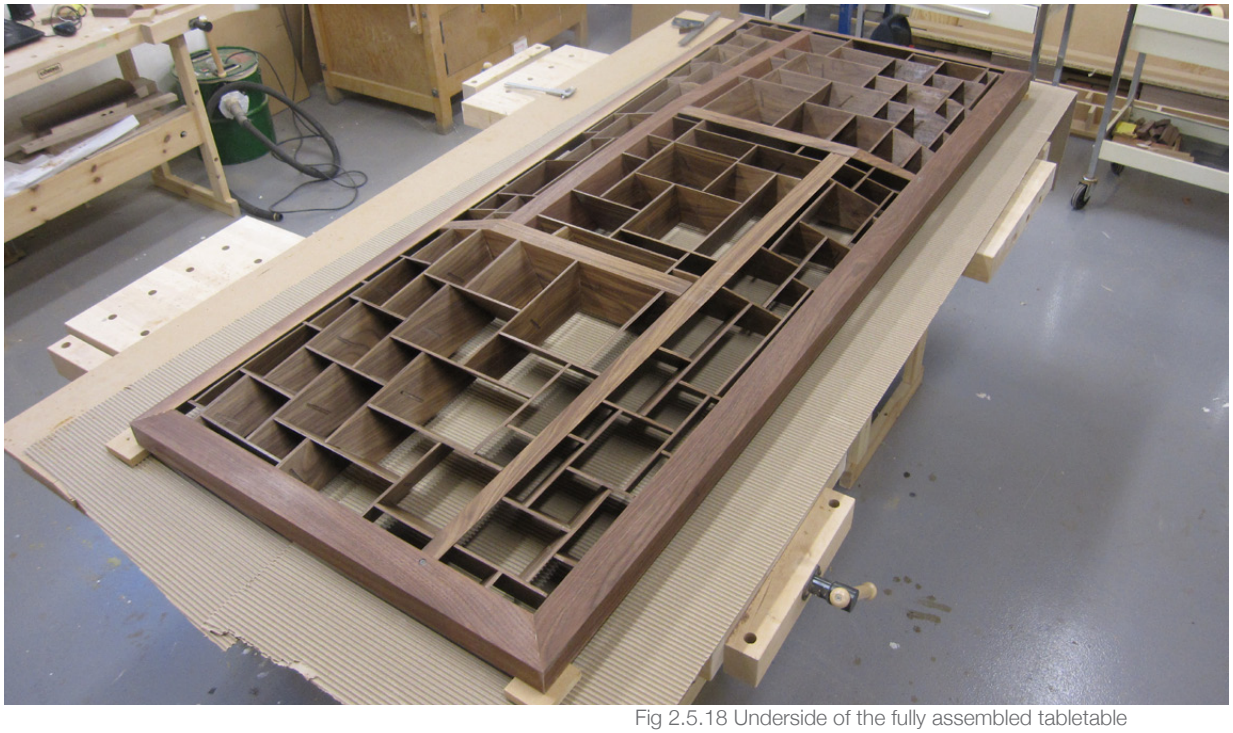


Fig 2.5.18 Underside of the fully assembled tabletable

Fig 2.5.19 Final adjsutments

Fig 2.5.20 To-and_Fro Table - elevation

Fig 2.5.21 To-and-Fro Table

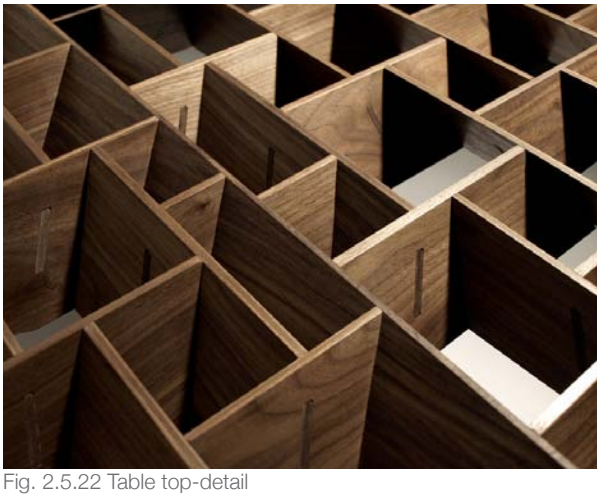


Fig. 2.5.22 Table top-detail

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Times Eureka Pavilion

This temporary garden and pavilion was designed in collaboration with Landscape Designer Marcus Barnett, and the brief was to explore the significance of plants to science and society. Commissioned by the Times Newspaper and Royal Botanic Gardens, Kew, *The Times Eureka Pavilion*, 2011, is an award winning structure. So in the garden, all plant species were chosen to reflect their medicinal, commercial and industrial uses in everyday life. Based on previous work the practice knew the pavilion to be ideal for prototyping an architectural experiment. "Freed from the performance requirements of weather tightness, environmental servicing and durability, which designers must address in larger buildings, a pavilion can become an experiment in new arrangements of material, space, and effect." [v]

Further, the explicit interest in the brief of the intersection between science and nature afforded us the chance to explore the distinction between the natural and artificial in an architectural space. Designing in the context of Kew Gardens also offered the opportunity to consider our proposal in relation to the history of the pavilion typology, which is well represented within the gardens. What is striking about these existing pavilions is the importance of their silhouette as incidents set in an Eighteenth Century pleasure garden landscape in the style of Capability Brown. When occupied by the viewer, they function as a meditative destination that frames the picturesque landscape.

Fig 2.5.23 Times Eureka Pavilion SLS Model: 1:20

Fig 2.5.24 Times Eureka Pavilion, Kew Gardens, London

Fig 2.5.25 The pavilion structure filters the surroundings London

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For the Eureka Pavilion, the practice was interested in subverting these two qualities of the typology. Instead of a strong silhouette we wanted to enmesh the project in its surrounding environment, through its siting and the texture of its envelope. By creating a route through the structure we intended it to form part of a thoroughfare rather than a destination. Finally, desired experience was for the inside to be more like a filter than a frame – to create an envelope that was porous, rather than filled with discreet openings, to filter the sounds and smells on the air while still offering shelter. Our design prototype of the deep surface became immediately instrumental in this context, and the knowledge we acquired of working with wood during the prototyping of the table suggested it was the best material to use. Using the prototype of the table as a precedent, the design of the pavilion explored the use of recursion as a generative process to evolve a three dimensional structure. The technique of recursion is the process of repeating actions or objects in a self-similar way in successive steps, and in our case at different scales. The development of the system is governed by a series of rules that define local structure without determining overall form in advance. Such mathematical growth processes offer an interesting alignment between computation and nature by producing unique and non-repeating instances of form that obey consistent rules of formation.

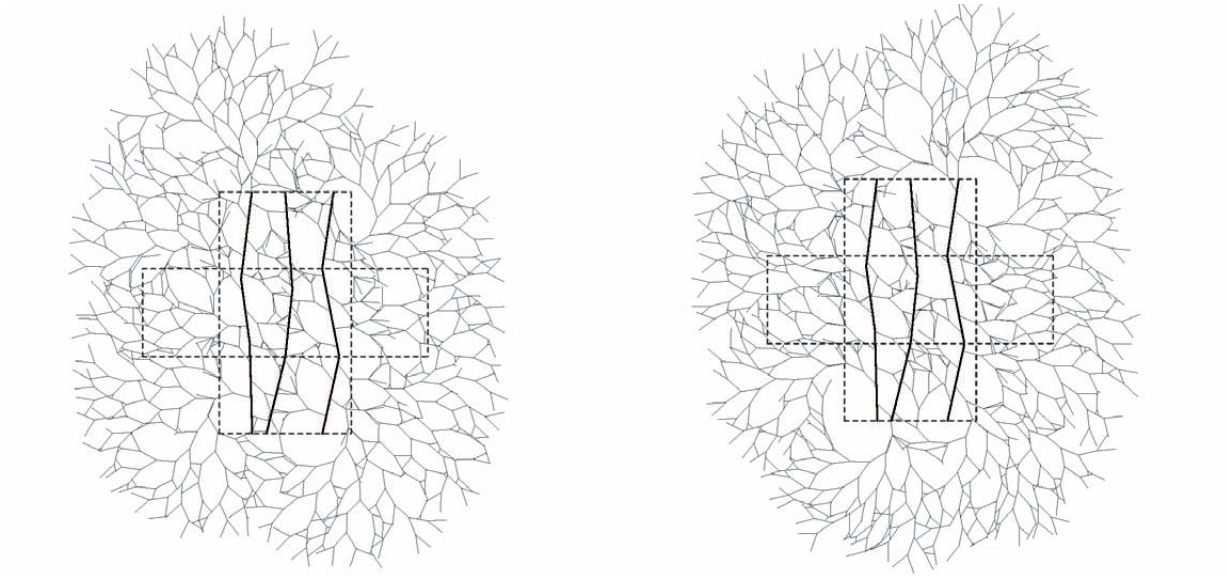

Fig 2.5.26 System bracing

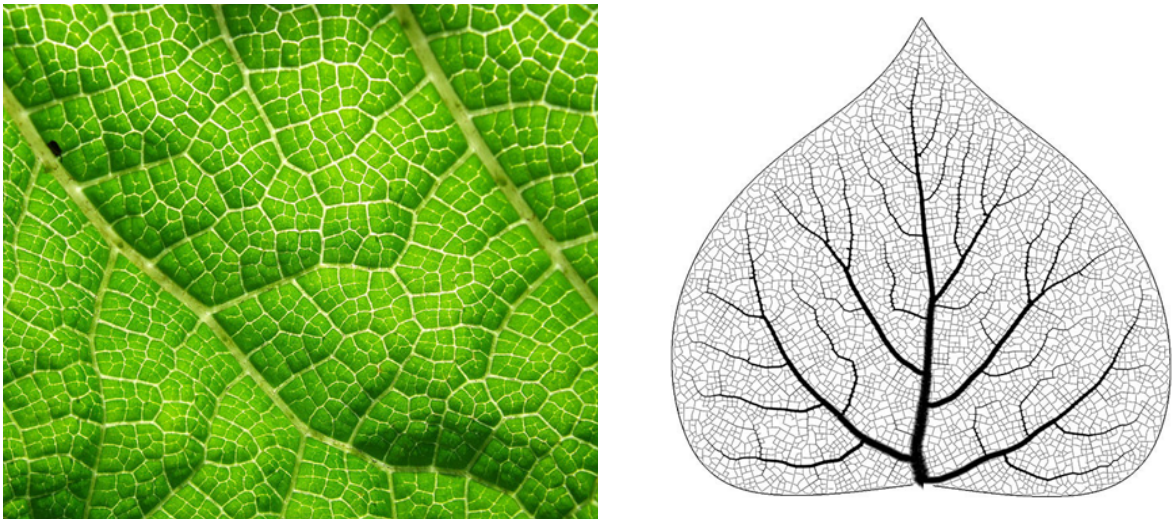

Fig 2.5.27 Leaf Venation

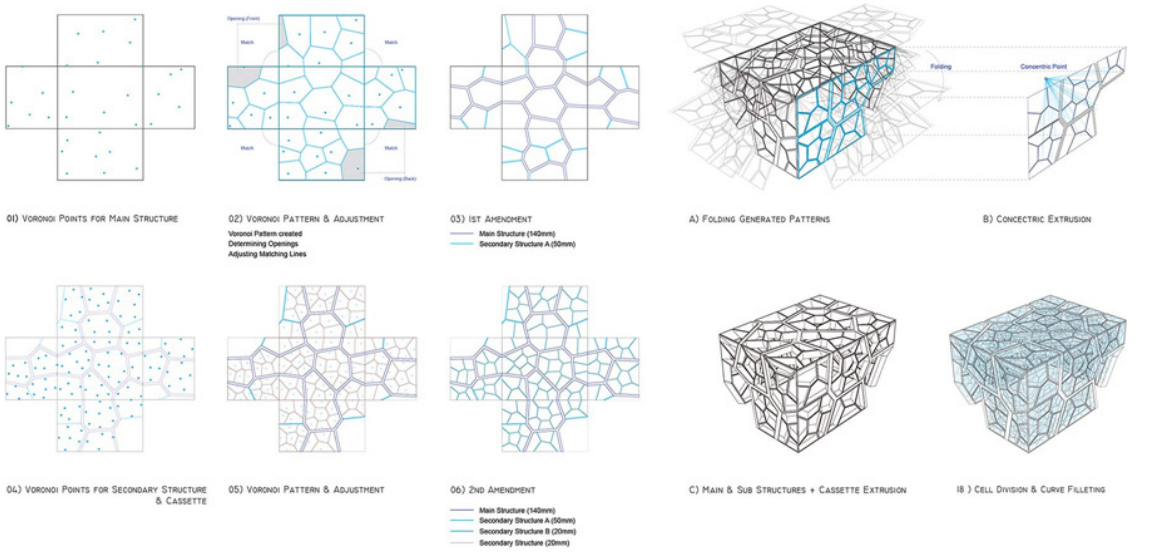

Fig 2.5.28 Design process - recursion at three scales and conical extension

The practice used two recursive approaches in the Times Eureka pavilion. The first experiments used a Lindenmeyer System (L-system) algorithm to generate a two dimensional pattern that was then wrapped over a 3D bounding box of the pavilion envelope. Versions of this were iterated many times using different values (initial length of the branches, number of branches branching out in every generation, range of angles between branches). While this exploration revealed a basic arrangement of the primary structure, we discovered it was difficult to control directional bias and it could not create smaller scale venation patterns between branches. In architectural terms, it tended to fix the pattern at a particular scale that made the structure appear too literal, meaning that there was a direct correlation between the scale of the branching in the pavilion and the scale of the branching in the trees in the surrounding garden. This was something we wanted to avoid, thinking it would be more interesting for users to experience the patterns of plant biology at an unfamiliar scale. To make this shift we began looking at techniques that could allow us to mimic patterns of venation. [vi] Though not a mathematical model of biological process, we eventually selected Voronoi procedures to subdivide the surface envelope. The process of division was recursive at three scales; the first division produced 21 cells of primary structure with 140mm beams; the second iteration produced 126 ‘cassettes’ with 20mm thick walls. The final iteration produced 586 cells that would be made from recycled translucent polypropylene.

The virtue of this approach was that it allowed us to establish a rule based process that constantly expressed differentiation at each scale and in each unit. Every cell was unique, just as you find in a biological system. A further level of spatial complexity was introduced by projecting the cell geometry to a single central point inside the pavilion to extrude the depth of the walls. While the aim of this was to produce a visually and environmentally more dynamic space, reinforcing the concept of movement through the structure, it also significantly increased the technical and manufacturing complexity of the timber elements. To be economically viable the entire structure had to be manufactured using a digital workflow and file to factory processes.

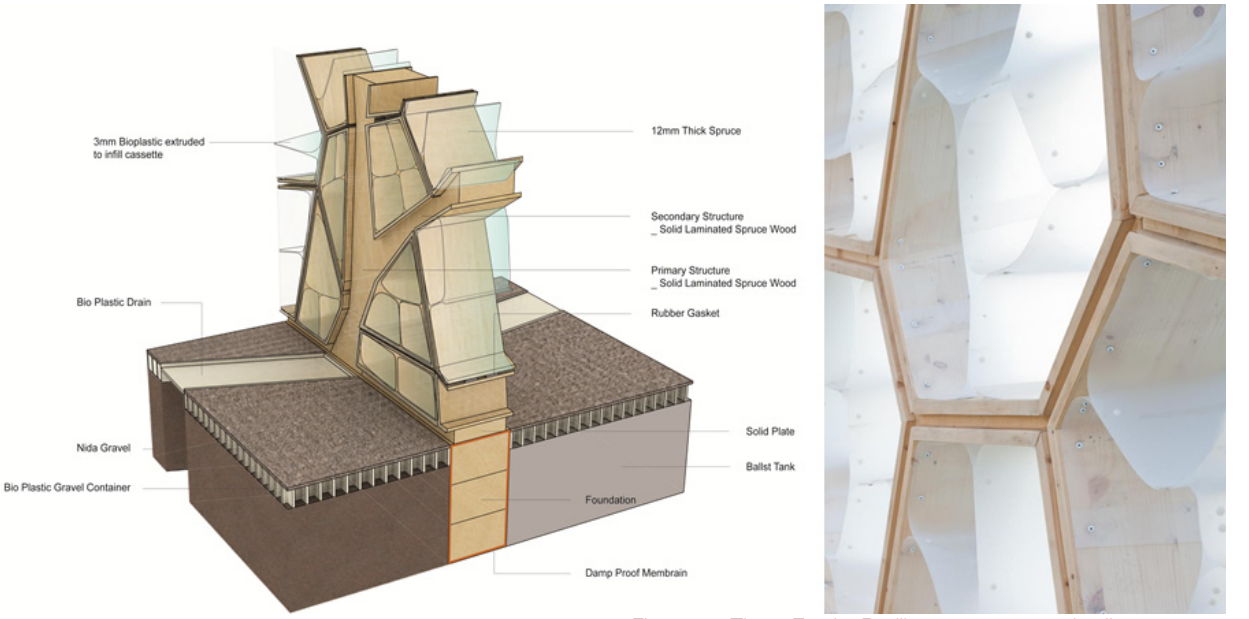

Fig 2.5.29 Times Eureka Pavilion – component details

For the timber structure, the 3D model constituted the full construction documentation, and it contained all dimensional and jointing information. The model was machined on a five CNC saw machine using FSC certified spruce. The primary structure was machined from block laminated lumbar, and the cassettes were cut from 20mm block boards, which was dimensionally stable and resistant to warping when cut. The cut boards were secretly screwed so that when assembled there were no visible fixings. Working tolerances for machining and assembly of all pieces was set at 2mm to ensure a tight fit of elements and to expedite on-site assembly. Intensive use of physical prototypes began with one-tenth scale prints and progressed to one fifth and full-scale cassettes.

The geometry of the infill cells were individually unfolded at cut from standard recycled polypropylene sheets using a CNC blade cutter. Each cell was numbered and reassembled on site with its nearest neighbours before being inserted into the cassette. The total site assembly time was four days. In the completed space quality of the patterning across the walls, floor and ceiling of the structure produced a powerful sense of occupying a biological structure. In operation the pavilion continued to mimic water transfer in plant biology. Rainwater literally runs off the roof infill cells into the main capillaries, down the walls and into the ground.

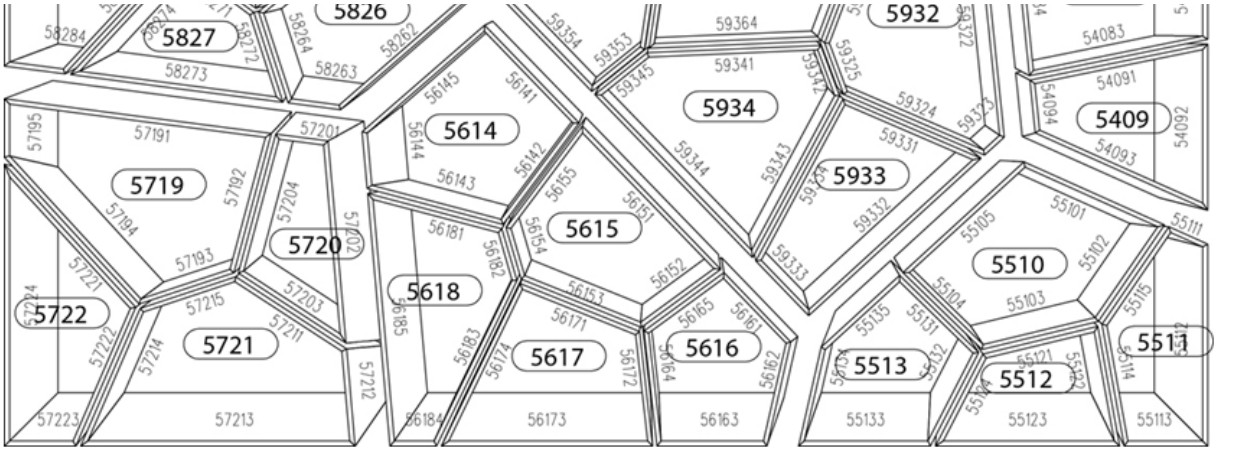

Fig 2.5.30 Times Eureka Pavilion – roof detail

Fig 2.5.31 Times Eureka Pavilion – 1:1 cell prototypes

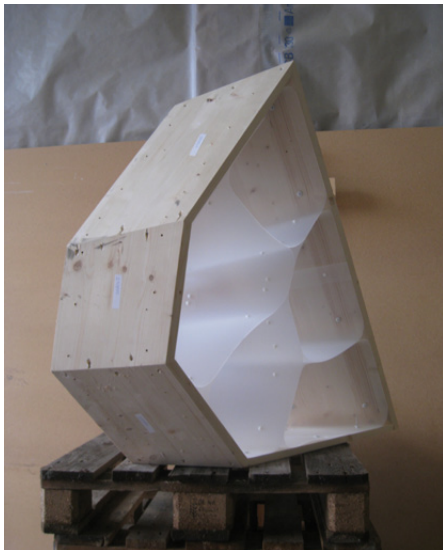

Fig 2.5.32 Times Eureka Pavilion – 1:1 cell prototype

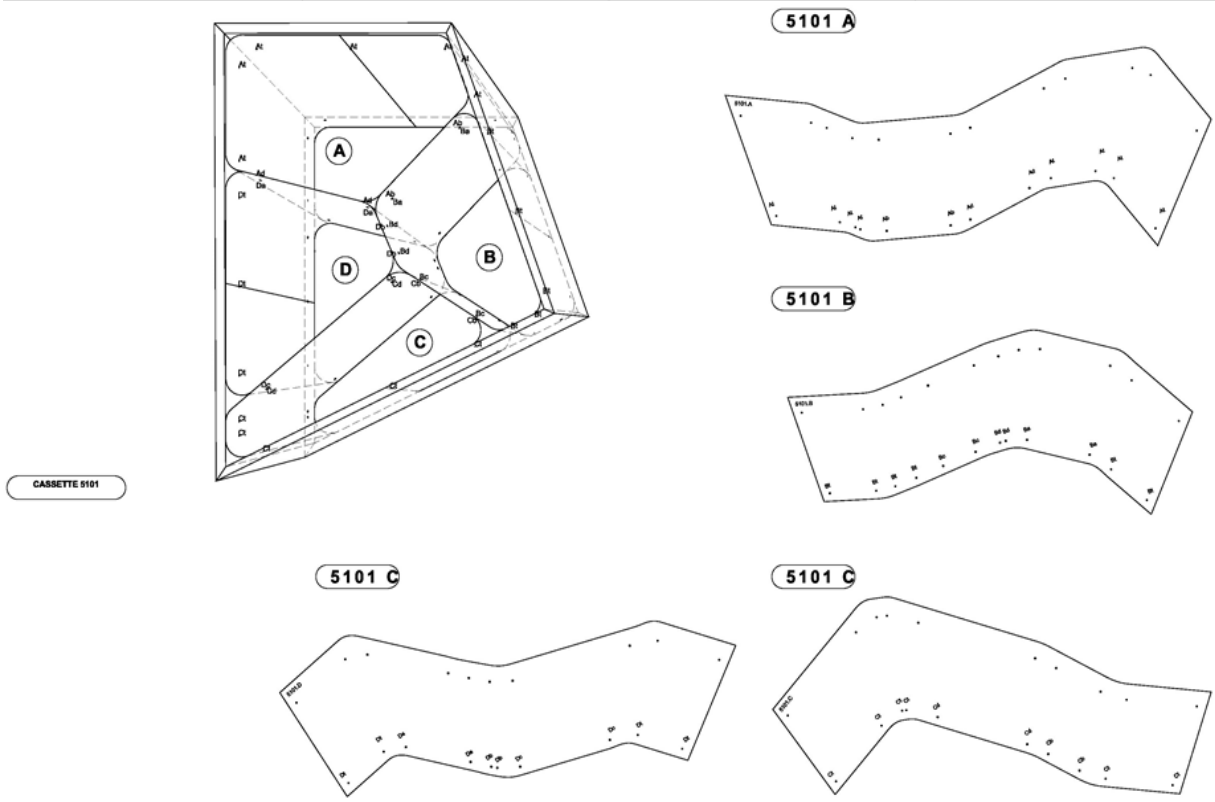

Fig 2.5.33 The completes Times Eureka Pavilion

Fig 2.5.34-6 Entrance and interior

Conclusion

Each of the projects above demonstrates how NEX made use of two processes of prototyping within our design practice. The Design prototype allows us to look for and identify conceptual models that we are interested in. These models are loose and abstract, yet have specific proto-architectural qualities that can be articulated in an extended variety of ways. The example of the deep surface prototype I have discussed here shows how it can be transferred from one project to the next with to achieve markedly distinct spatial qualities and functional performance. We use design prototype models like this formal seed to be cultivated in each project, and as a framework for research oriented practice to coherently develop a body of knowledge and push practice beyond mere design as a contingent solution to a given problem. These projects also illustrate how we have placed the working prototype – whether digital or physical – at the centre of our design process. While embracing the possibilities of working within emergent digital environments, we do not trust the representational seductiveness of the computer or indeed representational drawing. In particular, the development of affordable digital design and manufacturing tools has enabled us to re-assert making as a core activity within our architectural process. Through the creative act of designing through prototypes, we simulate a project in multiple parallel media and scales, to enable the continual improvement and discovery of novel architectural applications. An important implication of this is that it suggests a reversal of the design-test-redesign process. Prototyping Architecture enables us to test first and then design with a closer fitness to expected final outcome. This approach can be found in companies such as Toyota lean development process and it may offer an insight that could bring us closer to fully integrated design practice. [vii]

Fig 2.5.36 Times Eureka Pavilion, dusk at Kew

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i Alan Dempsey RIBA: is the founding director of NEX, an award-winning studio working at the intersections of design, architecture, and infrastructure.

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iii Heinz Isler's inflatable models are exemplar of the scaled physical prototype.

iv Desmond Morris, *Manwatching*, Jonathon Cape: London, 1977, p. 160

v Alan Dempsey and Yusuke Obuchi, *Nine Problems in the form of a Pavilion*, AA Press: London 2010.

vi For studies on venation patterning see Adam Runions & Martin Fuhrer, et al. *Modeling and visualization of leaf venation patterns*, http://algorithmicbotany.org/papers/venation.sig2005.pdf

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2.6
Kinetic Facade, Theme Pavilion Expo 2012 Yeosu, South Korea

Stefan Rutzinger, Kristina Schinegger, Jan Knippers and Florian Scheible [i]

The kinetic façade, just like the Theme Pavilion as a whole, emphasizes the experiential potentials of analogue architectural effects. Although movement is intrinsic to any media façade, architecture usually just provides the stable, immobile screen for digital motion. By facilitating actual movement, the kinetic façade exemplifies architecture as a medium in itself and creates choreography of dynamic patterns. To achieve the architectural intention of a seamless integration of the lamellae into the building skin, a mechanical solution that applies hinges and joints seemed inappropriate; therefore a biomimetic approach was pursued. The Theme Pavilion constitutes a completely new approach to kinetic structures in architecture. The innovation does not lie in the latest high-end technologies, but in a change of perspective inspired by and derived from the observation and analysis of natural role models.

Background

The Theme Pavilion is a major and permanent building for the Expo 2012 in Yeosu, South-Korea. soma's design proposal was selected as the first prize winner in an open international architecture competition in 2009. Its exposure in relation to the Expo's site designates the Theme Pavilion as a landmark building. Situated along a new promenade in a former industrial harbour and visible from all directions, the pavilion's exterior presents a multi-layered appearance, with many faces blending continuously into each other. The pavilion introduced its visitors to the theme of the World Exposition *The living Ocean and Coast* and housed two exhibitions, the Thematic Shows inside the vertical concrete cones and the *Best Practice Area* on the upper level of the building. After the closing of the Expo the permanent building will receive a new use.

Fig 2.6.1 Ocean One, Theme Pavilion, Yeosu Expo 2012, viewed from the shoreline, designed by soma architects

Design Concept

The pavilion's design is not aimed at a visual representation of the Expo's theme, but to transform it into a multi-layered architectural experience. Instead of proposing any fixed and symbolic meaning, it is meant to give rise to a multitude of individual readings. The varied forms of appearance of the pavilion are also due to the conditions of the site: Towards the sea, the aggregation of solid cones protects the pavilion from the impact of large waves. On the opposite side, facing the calm water basin of the Expo's Big O, the building develops out of the ground as an artificial landscape with plateaus and scenic paths. The roof merges into the lamellae of the kinetic façade that faces the Expo's entrance and draws attention to the pavilion by its moving patterns. The Expo's agenda, namely the responsible use of natural resources was embedded into the building, for example through the sustainable climate design or the biomimetic approach of the kinetic façade.

Fig 2.6.2 Ocean One, Theme Pavilion, Yeosu Expo 2012, designed by soma architects

Fig 2.6.3 Detail of the adaptive GFRP solar shading louvers of Ocean One, Theme Pavilion

Kinetic Façade

The seamlessly moving façade that is continuously integrated into the building's skin was already proposed in the competition and developed together with Knippers Helbig Advanced Engineering during the planning phases. To achieve the architectural intention a mechanical solution that applies hinges and joints seemed inappropriate, therefore a biomimetic approach was chosen. The technical solution was furthermore inspired by a research project at the ITKE University Stuttgart that investigates how biological moving mechanisms can be applied in an architectural scale. As a moving, emotional experience the kinetic façade combines sensations with the sensational, while communicating the Expo's theme in an innovative and investigative way.

As a counterpart to the virtual multimedia shows of the thematic exhibition taking place in its interior spaces, the kinetic façade like the overall building emphasizes the manifold potentials of analogue architectural effects. Although movement is intrinsic to any media facade, architecture is usually considered as the stable, immobile background for it. By involving real movement the kinetic facade aims to unify those usually isolated layers of architecture and media and define it as an interrelated and inseparable three-dimensional experience.

The façade covers a total length of about 140 m, and is between 3 m and 13 m high. It consists of 108 kinetic louvers supported at the top and the bottom edge of the façade. The lamellae are made of glass fibre reinforced polymers (GFRP), which combine high tensile strength with low bending stiffness, allowing for large reversible elastic deformations. The louvers are moved by actuators on both the upper and lower edge of the GFRP blade, which induce compression forces to create the complex elastic deformation. They reduce the distance between the two bearings and in this way induce a bending which results in a side rotation of the lamella.

Fig 2.6.4 Ocean One, Theme Pavilion with the adaptive shading closed

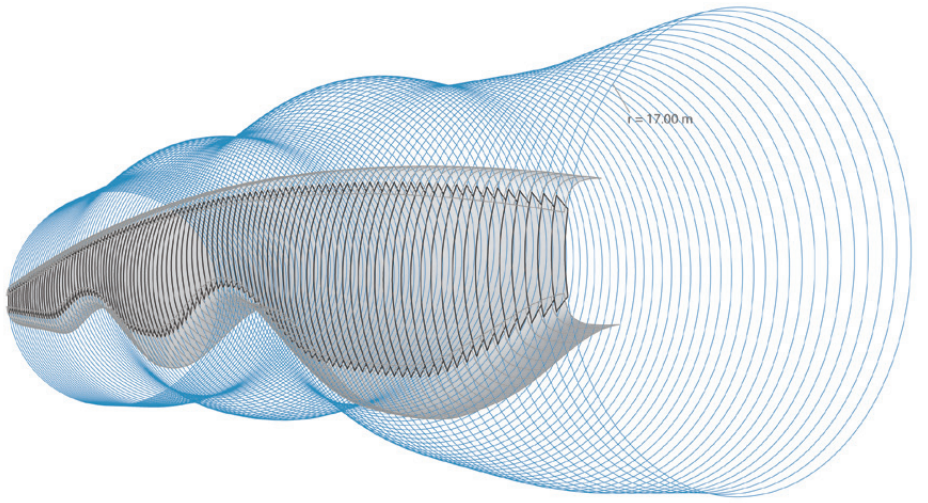

Fig 2.6.5 Digital exploration of the radial geometry of the louvers within the overall form of Ocean One by Soma

The actuator of the louvers is a screw spindle driven by a servomotor. A computer controlled bus-system allows the synchronization of the actuators. Each lamella can be addressed individually within a specific logic of movement to show different choreographies and operation modes. Upper and lower motors often work with opposing power requirements (driving-braking). Any energy generated can thus be fed back into the local system to save energy. In addition to their function of controlling light conditions in the foyer and in the Best Practice Area, the moving lamellae create animated patterns along the façade. The choreography ranges from subtle local movements to waves spreading over the whole length of the building. After sunset, the analogue visual effect of the moving lamellae is intensified by linear light bars located at the inner side of the front edge of the lamella. When in open position, they illuminate the neighbouring lamella, depending on the opening angle. The material performance of the biomimetic louvers produces an interrelated effect of geometry, movement and light: the longer the individual lamella, the wider the opening angle the larger the illuminated area.

Fig 2.6.6-7 Testing the 14meter high prototype GFRP lamellas of the solar shading

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Kinematic Engineering - Biomimetic Approach

Natural constructions show an almost infinite diversity resulting from mutation, recombination and selection. They essentially use a limited number of mostly light chemical elements and consist of fibres such as cellulose or collagen with direction-dependent properties.[ii] By combining different trajectories and the packing density of fibres, a number of finely tuned structural properties are achieved. Today, fibre reinforced polymers open up new methods of approaching natural role models. This means that the study of natural fibrous structures for architects and engineers is more promises than ever before.

For the Theme Pavilion in Yeosu the question arose how the morphological form and functional principles of nature could be used for a kinetic façade with the aim of increasing adaptability and energy efficiency, as well as reducing weight and maintenance costs. In deployable architectural constructions that incorporate shading systems or blinds, but also in retractable stadium roofs or bascule bridges, deployability is achieved by the use of technical hinges connecting rigid members and/or soft textiles and cables. Moveable structures in architecture are usually planned and built without reference projects or prototypes. This often leads to tedious experimentation involving the finished object and expensive maintenance including periodical replacement of parts. How can the mechanical complexity of kinetic systems for the façade of the Theme Pavilion in Yeosu be reduced? This question leads almost automatically to the study of natural role models. Botany provides the most radical insights. Many plants such as the venus flytrap move through the locally adapted and adaptive flexibility of their components and without any joints. Movements of this kind are caused by a change of the liquid pressure in the cells. Strategies to put such plant movements to technical use were first studied in a joint research project by the Institute of Building Structures and Structural Design (ITKE Stuttgart), the Plant Biomechanics Group (PBG Freiburg) and the Institute of Textile Technologies (ITV Denkendorf) by developing the elastic kinematics for a façade shading system as described in detail elsewhere.[iii]

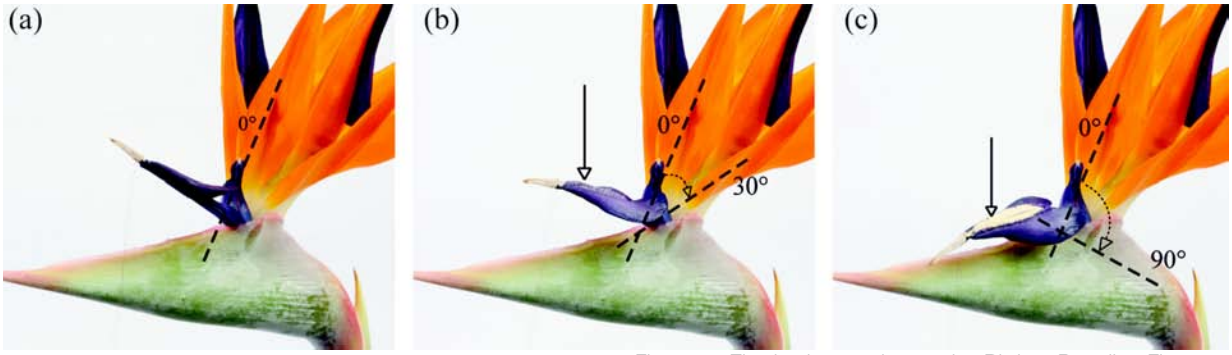

Fig 2.6.8 Elastic deformation of the Bird of Paradise Flower – when a bird lands on the petal, the perch bends down, the sheath opens and the pollen is exposed

The Theme Pavilion at Expo 2012 in Yeosu, Korea, provided an opportunity of introducing such systems on a larger scale for the first time. Inspired by this research a kinetic system based on the reversible elastic deformation of its components was developed. As their natural role models the elastically deformable fins are made of fibrous materials with locally adapted stiffness. They are up to 14 meters high and only 9 mm thick, with an additional stiffener on one side. A small compressive force is applied in the plane of the fin, which leads to a complex and large deformation, usually classified as buckling. In structural design buckling is usually considered as a failure, which needs to be prevented under any circumstances through design countermeasures and static verification. Nature, however, exploits this principle and uses it actively to mobilise large deformations by a small actuation force.

Even though the principle of the Yeosu facade does not follow the abstraction of a plant movement directly, the underlying idea was inspired and derived from the observation and analysis of natural role models. This encouraged the search for solutions outside traditional methods of design and construction and going beyond preconceptions, such as avoiding disproportionately growing deformations and stability failure modes. It turned out, that transferring the formal logic of the louver which have some similarity to fish gills into a large scale prototype would work perfectly well with the biomimetic engineering approach. A small model made of a simple rectangular strip of paper was the result of several abstract development steps and ideally merging the two approaches. Moving two opposite corners of the two short edges towards each other induced the same movement as it was built later in large scale. The advantages were large scale deformation with huge bending radii minimizing interlaminar stress, complex anticlastic bending leading to higher stiffness in opened movement positions, 1:1 reflection of the architectural concept and additionally it was easily adaptable to the complex overall geometry of the building.

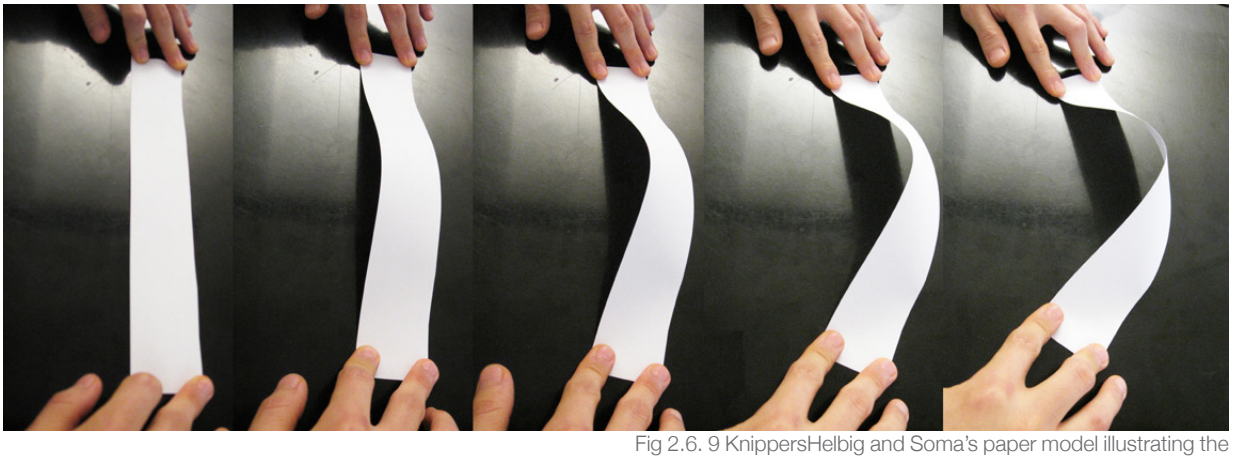

Fig 2.6. 9 KnippersHelbig and Soma's paper model illustrating the movement idea for the louvers

Fabrication and Testing

The fins were produced in a very simple hand lay-up process using conventional glass fibres and thermosetting resins. The stiffness of the louvers was locally adapted by the alignment, orientation and content of glass fibre mats. The laminate layout of the standard section is a combination of chopped mat and woven fabric in 0°/90° direction. The stiffeners are made of chopped mat and unidirectional rovings. Towards the bearings, the laminate is rotated by 45° and reinforced by additional layers. When open, the curved geometry, together with the residual stress state, results in a very rigid system that deforms only by a few millimetres even under high wind loads.

The actuator of the louvers is a simple spindle driven by an electrical servomotor. The driving power is converted into elastic energy stored in the deformed louvers. This internal energy is partially reconverted into electrical power during the closing of the louvers by using the servomotors as electrical generators. In the closed state, the adjacent louvers are stressed against each other by applying tension forces in the driving units so that the façade can withstand even the strongest storms on the South Korean coast under typhoon conditions without damage (wind speeds of up to 35 m/s). The pre-stress level of stress is actively adapted to the measured wind speed: an increase of the latter leads to an increase of the applied tension forces. This optimizes energy consumption as well as the mechanical loading of the various components and thus increases their life expectancy. To test the actual performance and durability two louvers of different lengths (14 and 5 metres representing the longest and the shortest louver) were manufactured, mounted to a steel rack, connected to drivers and servomotors and operated for a few months. Meanwhile fabrication and programming started. During testing it turned out that the concept of the louvers worked very well except the servomotors transferring some noise into the lamella creating resonance. Resonance was finally solved using some absorbers at the connection details. All lamellae are fabricated with a constant radius of 17 meters, therefore only one negative form was necessary; to speed up the production process 3 moulds were used simultaneously.

Fig 2.6.10 Fabrication of the GRP lamella louvers – the glass fibre with resin is being laid up by hand in steel moulds. [iv]

Wind Loads

The wind loads were derived from wind tunnel tests in order to achieve a safe and economic design of the louvers. The operational concept basically identifies two different situations: As long as the wind is less than 15 m/s (6 on the Beaufort Scale), the façade can operate. If the wind is stronger than 15 m/s, the façade will close automatically. In operating mode, the fins are individually actuated and create animated patterns along the façade. The potential choreography ranges from a subtle localized movement to wave patterns moving across the entire elevation of the façade. In order to reduce and homogenize energy consumption, moving all louvers simultaneously should be avoided. The kinetic façade is made possible by reversible elastic deformation and the locally adapted stiffness, associated with correspondingly large strains. They show nonlinear deformation which again, from a structural engineer's perspective, is usually considered to be a buckling failure that needs to be prevented; here, however, it is functionalized for the opening of the façade.

Conclusion

The analysis of the principles of natural form and function has the potential to stimulate architects and engineers to explore fundamentally new strategies in architectural design and technical implementation. The results achieved from this biomimetic research study have encouraged further investigation in the search for solutions outside traditional methods of design and construction that go beyond preconceptions such as the need to avoid disproportionately growing deformations and stability failure modes. The Theme Pavilion constitutes a completely new approach to kinetic structures in architecture, even though the materials and fabrication methods used are relatively simple and have been well known for many years. In this case, the innovation does not lie in the latest high-end technologies, but in a change of perspective inspired by and derived from the observation and analysis of natural role models.

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i Authors' affiliations: Stefan Rutzinger and Kristina Schinegger of soma, Vienna, and Jan Knippers, KnippersHelbig GmbH, Stuttgart and University Stuttgart, Institute of Building Structures and Structural Design, and Florian Scheible, KnippersHelbig GmbH, Stuttgart.

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iv Image Credits: Fig. 1, 3 and 4 Kim Yong Kwan, Fig. 8 and 9 Knippers Helbig Engineering, Fig. 2,5-7, 10 soma.

2.7
Adaptive Prototyping Process as Mechanism Towards a Holistic Architectural Design

Odysseas Kontovourkis, Marios C. Phocas and George Tryfonos [i]

In the history of architecture, biologically inspired design has been an essential and influencing component at various levels. Natural organisms' morphological or behavioural characteristics and their ability to transform and adapt to different conditions have been introduced in the design process using for example feedback loop mechanisms that iterate between creation and verification of design results according to external and internal conditions. Nowadays similar concepts are introduced for the production of prototypes paving the way for a comprehensive exploration that takes into account the adaptation ability of such systems in real time according to environmental conditions or human activities. This requires an integrated investigation into material behaviour, structural optimization and computation, aiming at effective performance based design solutions. The present paper exemplifies such an interactive performance based digital and physical design process from a holistic point of view, through presentation of the design and prototyping of an adaptive hybrid structure. In the case example presented various stages of the design process, from design to manufacturing, are developed from an early conceptual stage through consideration of material and structural aspects, as well as environmental conditions and human activities influencing criteria. In this frame 'soft' elastic material behaviour with embedded technology and computation, acting as integration mechanisms are applied throughout the design process of the associated digital and physical prototypes by using latest parametric-associative, fabrication and physical computing tools. The herein proposed continuous feedback loop design process that moves in a cyclical procedure from the investigation to the evaluation of intermediate real time results enables morphological configuration, kinetic behaviour simulation and data transition from the digital to the physical environment and vice versa.

Architectural design processes have been highly influenced from natural principles and in particular, from the way biological organisms behave with regard to their ability to survive and reproduce. A ground-breaking work that examines organisms' morphological characteristics through transformations with regard to their ability to adapt to different environmental conditions is provided by Thomson (1992).[ii] Such principles have been applied in architecture to examine the potential of designs, or other systems and structures to be developed and reproduced by adaptation processes that presuppose a direct connection between design decisions taken at various levels on the one hand and adaptation processes according to environmental, human activities related or other influences on the other hand.

Architectural theorists discussed the role of biological analogy in architectural design stressing out the significant influence exhibited by nature in the design development (Steadman 2008).[iii] This is considered to be one of the most influential directions in the future of architecture (Jencks 1971).[iv] The responsiveness and adaptation of designs and processes according to various influences with well fitting results may be found in real architectural precedents (Alexander 1964),[v] as well as in other related works, whereas design adaptation mechanisms are used as new approaches that allow design processes to respond and adapt to the context of the design problem under investigation (Negroponte 1973).[vi]

Concepts taken from nature have become a significant source of inspiration influencing design at theoretical and practical level. Biologically inspired designs range from examples, whereas morphogenetic principles are mimicking organisms' growth and behaviour, or natural principles are translated and applied in computational design processes expanding the ability of computers to be used in design investigations (Frazer 1995).[vii] As a result, such directions influence significantly the way architecture deals with design processes paving the way for new interactive approaches with regard to the ability of computers to be used as a creative design medium. Gradually, computational principles emerge while considering biology to be a source of inspiration and influence of the way architecture is investigated. Nowadays, such approaches deal with the notion of feedback loop, an idea that trades back to the work of cybernetics (Alexander 1964, Sterk 2006).[viii] In this frame mechanisms and processes alternate between design investigation and evaluation of results according to external or internal conditions.

Currently, a number of architectural design examples follow similar principles in the design investigation and physical prototype development. The idea of adaptation is applied in the development of systems at a theoretical design level, as well as in the adaptive design and prototyping of systems, while involving investigation into real time physical behaviour according to environmental, human related or other conditions. The idea of applying natural principles in real time problems is examined in the present chapter through the interactive development of an adaptive hybrid structure that combines digital and physical adaptation processes in a multi-objective performance based context.

Related Applications

In architecture, different definitions may relate to adaptable behaviour, such as adaptive, interactive, or responsive, which describe systems and structures' behaviour influenced in real time by external and internal criteria and conditions. Fox and Kempt (2009)[ix] explained in their work on interactive architecture that in order to achieve an adaptation behaviour due to environmental and human related influences, two areas are combined and investigated in parallel; kinetics and embedded computation. Embedded computation involves the use of sensors, microcontrollers and actuators and functions as the technological medium that collects physical information, processes and responds by controlling the system's behaviour in mimicking the behaviour of physical organisms. The behaviour of kinetic structures is influenced directly by its embedded technology and its application distinguishes structures into different categories.

In kinetic structures, embedded technology is used to activate their behaviour, while focusing mainly in the application of the actuator mechanism, for example of pneumatics and hydraulics. Such mechanisms enable the motion and transformation of structures in real time based on specific functional or structural requirements. The Expanding Geodesic Dome and the Expanding Helicoid by Hoberman, or the Bascule Bridge by Knippers are examples of deployable structures following such principles (Asefi 2010).[x] In these case examples, responsiveness is achieved by the control mechanism, although environmental or other physical influences in the form of inputs are not taken into account for the investigation of the overall structure's behaviour.

In examples where environmental or other external influences are part of the responsive system's behaviour, sensors are used to collect information in real terms, process these to the system and finally activate the system's behaviour respectively. The Institute of Arabic Studies in Paris is classified within this category of systems that adapt to external environmental influences (Herzog, Krippner, Lang 2004).[xi] In this case the responsiveness of the facade elements due to sunlight changes induce a responsive behaviour through their rotational motions. In the same direction, addressing spatial conditions in interior spaces, the Emergent Surface by Hoberman and the Ageis Hyposurfaces by dECOi change their geometrical configuration influenced by human activities related conditions (Schumacher, Schaeffer, Vogt 2010).[xii]

Currently, the tendency to use 'soft' materials and similar technological principles in order to achieve responsiveness emerges, an idea that trades back to the work of Negroponte (1973),[xiii] who initially discussed the use of 'soft' materials and their relation with responsive structures. The Hylozoic Ground, the Canadian pavilion at Venice Architectural Biennale 2010 by Philip Beesley (2010)[xiv] and the Applications Gallery project by Michael Fox (Fox, Kempt 2009)[xv] are examples, whereas 'soft' materials are used for the development of architectural installations influenced by human related conditions. The work Muscle by Kas Oosterhuis (Oosterhuis 2003)[xvi] applies a similar technology to achieve responsiveness in a complete structure due to human influences. Finally Tristan d'Estrée Sterk (2006) combines in similar architectural case studies environmental and human related influences.[xvii]

Structural prototypes apply soft material principles that exhibit a passive adaptive behaviour, similar to the behaviour of biological systems and organisms. The use of bending-active members and their ability to move and change their shapes due to natural adaptation processes is discussed in Knippers, Speck (2012).[xviii] Elastic kinematics as found for example in complex plant movements may act as role models for the development of new bio-inspired adaptive systems. Compared to technical systems, adaptive structures in nature replace local hinges by elastic deformations of their members and thus distribute the acting forces over a wider area in which bending takes place. This alternative approach renders the possibility to form complex single- or double-curved primary structures from straight or planar members. Sufficiently thin component thickness thereby allows for small bending radii and thus results in low bending stresses. Structural rigidity can be either increased by the combination of bending and tension prestress stored within individual elements, or by coupling of multiple elements to a hybrid system. The use of bending principles enables not only initial complex geometries and their subsequent stabilization through additional prestress, but also the capability of the members to undergo reversible

deformations (Schleicher 2011).[xix] Therefore bending-active kinematics define the systems deformation sequence by taking into consideration geometrical relationships, as well as coupled internal forces that are responsible for the transformation pathway. Bending-active members are triggered by active or passive control mechanisms and their application in architecture can be enhanced due to their ability to accelerate feedback loop mechanisms during the adaption process (Khoo, Salim, Burry 2011).[xx] Applications of such principles can be found in Reither and Jolly (2011)[xxi] and Khan et al., (2009), whereas the elastic properties of polymers are utilized in architectural installations.[xxii]

The design and prototyping of an adaptive hybrid structure is presented in the current paper to exemplify the holistic architectural design that takes place in a cyclical and interactive process between design and manufacturing. The investigation tries to cover all aspects of the design process through the application of environmental and human activities related conditions that influence the development in different phases, from the conceptual to the detailed design phase. The hybrid structure consists of lamellas of fibre composite material of high tensile strength and low stiffness, positioned in the weak axis to allow for adaptability and reversible elasticity. A secondary system of struts and cables is integrated to the lamellas with embedded technology and computation. The performance of the adaptive structure in real term conditions led to intermediate design decisions at various levels of the development. In this frame digital models and physical small scale models were developed and investigated in parallel through the use of parametric design software for the simulation of the structure's kinetic behaviour and direct correlation between the digital and the physical information.

Adaptation Development Process

In the current section an adaptation development process is proposed and applied for the design and physical prototype development as substantial part of a holistic design approach. This is described by using a general flowchart as shown in Fig. 1 that contains diagrammatically the various parts and necessary steps undertaken throughout the development process. This flow of action is structured into three basic parts that reflect the basic steps undertaken in the adaptation behaviour: The physical data acquisition, the mechanisms of controlling intelligence, in order to achieve a specific behaviour, and the outputs that actuate movement behaviour of the physical prototype.

The process of adaptation is considered to be substantial part of a holistic design approach that involves methods and principles found also in other conventional design approaches. The general design process proposed incorporates the adaptation feedback loop mechanism within a performance based design process initially proposed by Phocas, Kontovourkis, Ioannou (2012).[xxiii] In this case the control mechanism and intelligence of the system are incorporated to provide a holistic design approach represented as a cyclical process that moves repeatedly from creativity given by the physical prototype to accuracy given by digital simulation and real adaptation processes. These are represented in different stages of the process, including the conceptual outer loop design stage and the detailed inner loop stage. The process is repeated in an open loop procedure, moving back- and forwards for re-examining aspects of physical development and simulation until a desirable solution is achieved.

In the input stage, the collection of data in real terms is achieved through application of sensors and a microcontroller (Arduino Microcontroller) embedded in a parametric-associative design software (Firefly plug-in in Grasshopper for Rhino). In the control or computational stage, the adaptation behaviour is programmed and developed by taking into consideration material behaviour and structural performance. The synthesis of the collected input data with parametric and programming principles based on the adaptation algorithm provides responsiveness and movement of the system. In the output stage physical behaviour of the system is generated and examined. Throughout this process, different parts are organized in a feedback loop, cyclically iterating between the output motion results and their control mechanism. In this way, continually changeable outputs become the new inputs that feed the control mechanism and in combination with the external and internal inputs, influence the physical behaviour of the structure, Fig. 2. The adaptation process offers thus a form of intelligence that allows adaptability to be accelerated.

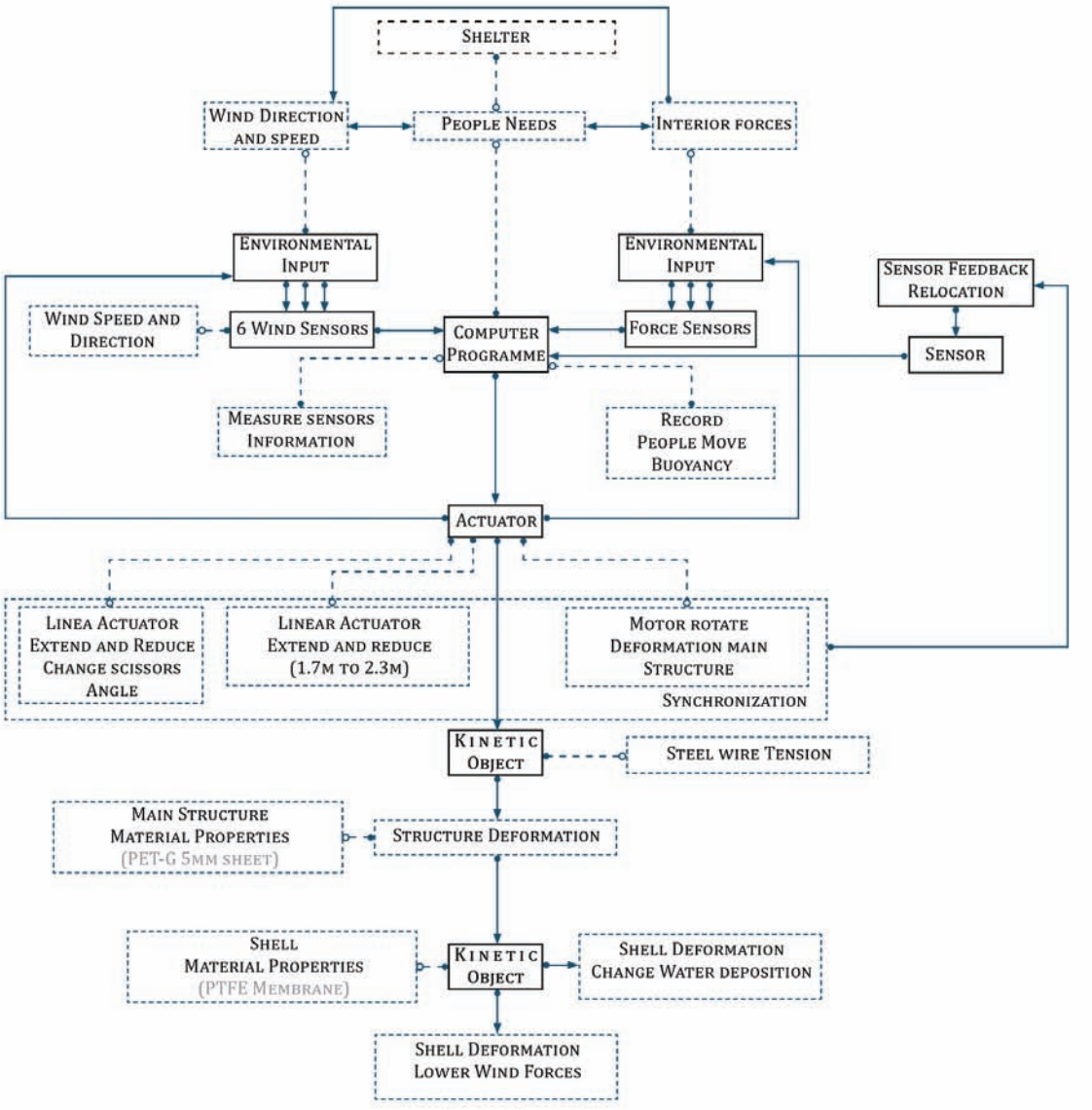

Fig 2.7.2 Flowchart of the adaptive hybrid structure process

Adaptive Hybrid Structure

Hybrid systems are defined through linkage of different components in parallel and/or in series that are combined to resist forces by developing a specific mechanical behaviour due to their different resisting nature (Schlaich et al. 2005).[xxiv] Precondition for the hybrid system is that the parallel components are basically equipotent in their load-bearing function and dependent upon one another in their novel behaviour. The potential of hybrid systems lays in the synergetic possibilities emanating from exploiting the systems disparities: reciprocal compensation of critical stresses, system-transgressing double or multiple function of individual components and increase in rigidity through opposite systems deflection (Engel 2009).[xv]

The primary members of the structure consist of lamellas of polyethylene terephtalate glycol, PTEG, a translucent co-polyester product that offers high elasticity and strength and ease of fabrication. The lamellas with 5.83 m length, 60 to 200mm width and 8mm thickness, are strengthened through a secondary system of struts and cables. The struts cross section consists of glass fibre reinforced polymer, GFRP. The connection points of adjacent lamellas forming scissor elements through their bending and outward rotation are at distances of one third of the total members length on both sides. The lamellas obtain an initial bending deformation and are interconnected at their upper and lower edges through vertical members of the same elastic material. The positioning of the secondary members in the longitudinal direction of the lamellas follows respective geometrical and structural considerations with regard to minimizing the bending stresses in the primary members and enabling the kinematics of the system with minimum energy consumption through activation of the cables. As a consequence the outer lamella areas form with the secondary members trusses with increased stiffness properties. The inner lamella areas comprise hybrid systems through integration of three struts with continuous cables in the longitudinal direction, Fig. 3. In these areas the secondary system is responsible for the reduction of the bending stresses developed in the lamellas through respective increase of the axial forces introduced in its members with the deformation of the former. Six interconnected scissor elements comprise the circumference of a unit that comprises a symmetrical hexagonal hollow structure. The diaphragm constraint is obtained through horizontal circumferential members connecting adjacent scissor hinges.

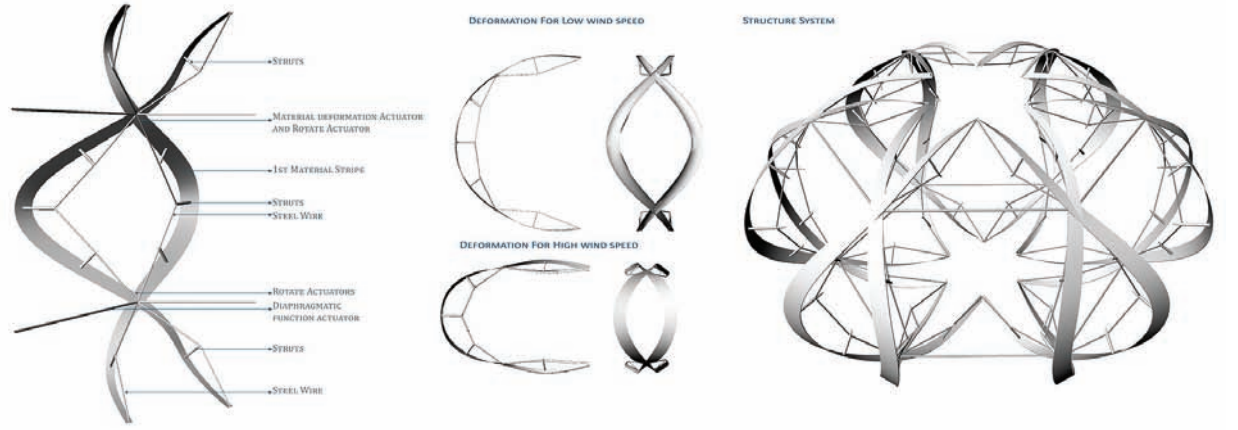

Fig 2.7.3. Detailed three-dimensional model of the scissor elements

In terms of the kinetic operability of the hybrid structure, different geometrical configurations of the lightweight components may be developed through their autonomous and non-autonomous movements. In this frame variable stiffness is achieved at the level of the primary members' physical properties defined through the material and sections used, and at the level of the kinematic system activation parallel to the primary members, through alteration of the cables' length and the application of pulleys with electromagnetic brakes at the internal cables' joints. The cables edge connection points are fixed and integrated with actuators for the control of the overall members length, as described in the following sections.

The structures envelope consists of single PTFE membranes at the scissor elements areas and the inner hollow core area formed by the vertical interconnecting lamellas. PTFE cushions span between adjacent scissor elements, Fig. 4. In all cases the membranes are considered to be flexible enough to accommodate the movements of the primary structure without having any interaction on the transformation process of the primary members. For exploiting to a high degree multi variable external and internal influence factors that should determine the behaviour properties of the structure's adaptability, in the specific case example the unit is situated in an open lake site with prevailing winds of variable direction and intensity and water level of variable depth throughout the year.

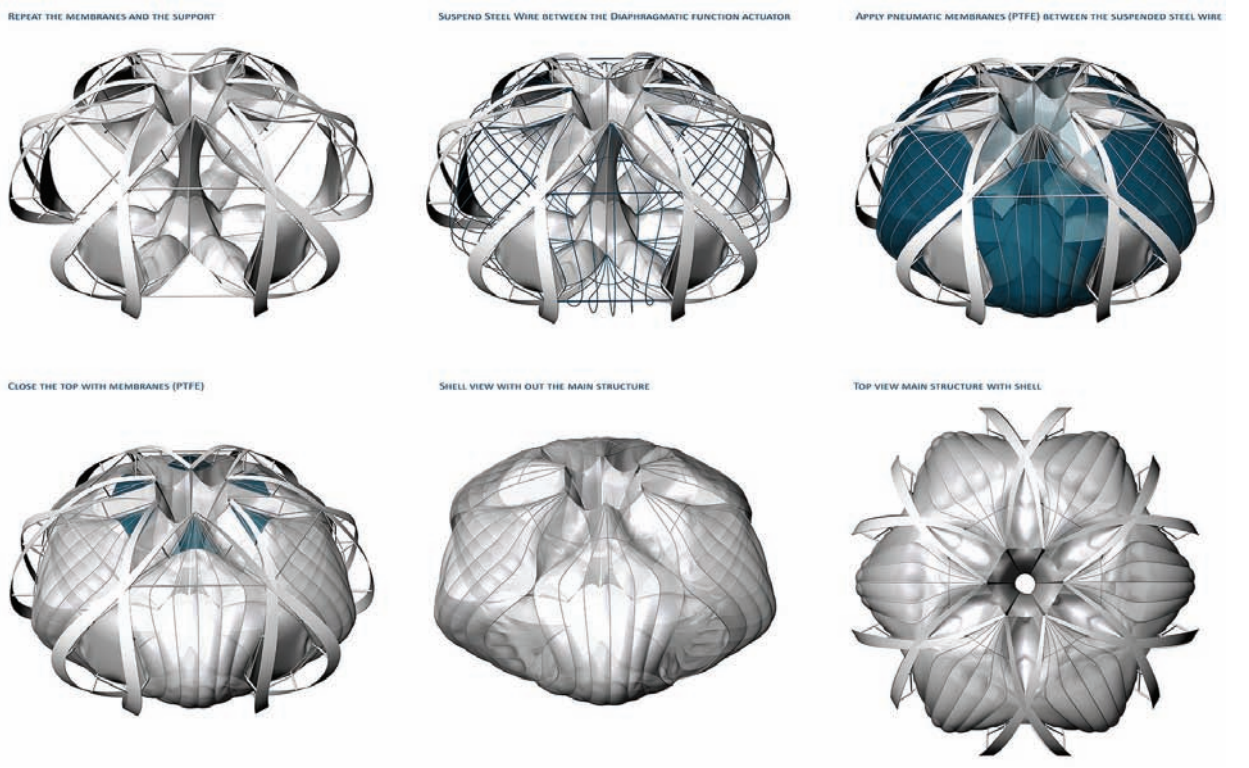

Fig 2.7.4 Structure and envelope system of membranes forming the overall unit shape

Physical Prototype Development and Simulation

The three basic steps in the procedure of the physical prototype development and simulation are described as part of the general flowchart shown in Fig. 1 of the physical adaptation process. Physical prototyping and simulation are conducted in parallel starting from the conceptual development in smaller scale up to the detailed development in larger scale. The process of development can be briefly summarised in three stages exemplifying the progress and the decisions taken throughout the development of the physical and digital prototypes.

Parametric design and simulation procedure

The digital prototype is developed with the parametric-associative design software Grasshopper (Plug-in in Rhino). The material and structure behaviour is simulated in the Kangaroo physics software (Plug-in in Grasshopper). In the simulation process, physical properties of the structural elements and materials are taken into account, in order to capture the systems behaviour in real terms. The structural systems behaviour is primarily

characterised by the bending elasticity of the PTEG-lamellas, the axial stiffness of the GFRP-struts and the elastic tensile strength of the cables. The geometry of the structural system is broken down into the individual scissor elements that are parametrically controlled throughout the transformation process. The elements physical behaviour simulation is organized in three categories with regard to bending, compression and tension, according to the type of forces and behavioural rules applied. Following the idea of the part-to-whole simulation process, behavioural rules are applied for each structural element at local level in generating the overall systems behaviour at global level through the resultant force of the structural elements behaviour. In parallel, following each transformation process, the relaxation behaviour of the structure while reaching its equilibrium position is investigated.

The bending behaviour of the structural elements is simulated by using sets of continuous three points as input components (Ahlquist, Menges 2011).[xxvi] Therefore each lamella is parametrically divided into segments and points. In order to activate the bending behaviour of each scissor element, the upper and lower hinge connection points are defined and controlled parametrically. The respective elements bending behaviour is obtained through parametric modifications of the distance between the two points, in compliance to the function of the actuators that control the vertical deformations of the elements.

The physical simulation of the struts is achieved by applying spring behaviour on the basis of Hooke's Law of elastic stress-strain behaviour (Ahlquist, Menges 2011,[xxvii] Phocas, Kontovourkis, Ioannou 2012).[xxviii] Spring behaviour is controlled by a number of input parameters that influence the members' behaviour under compression or tension including the 'rest length' and the 'start length'. If the rest length is equal to the start length, the member is considered to be under compression. When the rest length has a value, close to the start length (this can be parametrically controlled by multiplying the start length with a value from 0 to 1), the member is under tension.

Stage 1: Conceptual physical prototype development and simulation

Initially, the simulation examines the elastic behaviour of the material under the influence of bending forces, aiming to capture possible deformations of the scissor elements. In parallel the hinge connection point positions of the elements are controlled parametrically through a linear actuator for possible modification of their distance and control of the elements' height. In addition, this preliminary simulation attempts to exemplify how the respective deformation behaviour at local level can influence the deformations of the overall structural system initiated by modifications of the hinge connection points' relative distances. Finally, first correlations with possible future results derived from the actual scale simulation can be observed. This requires further investigation in terms of accuracy needed in the development of the physical and digital prototypes, in order to achieve close relations with the actual elastic material simulation.

Stage 2: Refined physical prototype development and simulation

In the second stage, the digital prototype is refined by modelling the lamellas according to the physical prototype. The nonuniform section width along the primary axis of the members allows a more uniform bending stress distribution and reduced torsional stresses concentrations. It supports also the respective modification process of the relative angles of the scissor elements, since it reduces the number of friction points into two and provides

wider openings when the scissor elements are further deformed. At the hinge connection points of the lamellas, an actuator is positioned that controls the members' deformations in vertical direction and the relative angle of the element. Finally as mentioned in the previous section, linear actuators connecting horizontally the lamellas' hinge points are responsible for the diaphragm of the structural unit.

Through the simulation procedure it is observed that the system has the ability to sense high wind loading values and transform its shape by reducing the unit's height and the relative angle of the scissor elements. In cases of low wind loading values, the system has the ability to increase its height and the relative angle of the scissor elements. Diversity with regard to the application of input parameters in each of the six structural elements as to wind direction and speed induces different respective deformations of the material and the overall unit.

Stage 3: Detailed physical prototype development and simulation

The detailed simulation stage aimed at finalizing the physical prototype and examining its behaviour through the simulation process. Close relations between the physical and the digital simulation results are expected to be acquired henceforth. In order to achieve this, the physical and digital prototype solution concentrated on the detailed development of the overall structural system, including aspects of sensors and actuators positioning, virtually described and closer examined through simulation studies. The respective intermediate results obtained from the previous investigations led towards the development of the adaptive hybrid structure that integrates elastic material properties, the secondary system of struts and cables, as well as sensors and actuators, Fig. 5. Analytically, rotation actuators are positioned at the hinge connection points of each scissor element that control the release and lock of the continuous cables running along the struts' pulleys. The rotation actuators enable modification of the cables' length and in parallel, control of the lamellas deformations, as well as the relative angles of the scissor elements. Having established the diaphragm of the structural unit through the aforementioned linear actuators and the synergy of the sensors and actuators of the system, an adaptation algorithm applied, as described in the next section, provides motion and responsiveness of the system based on environmental and human activities related influences.

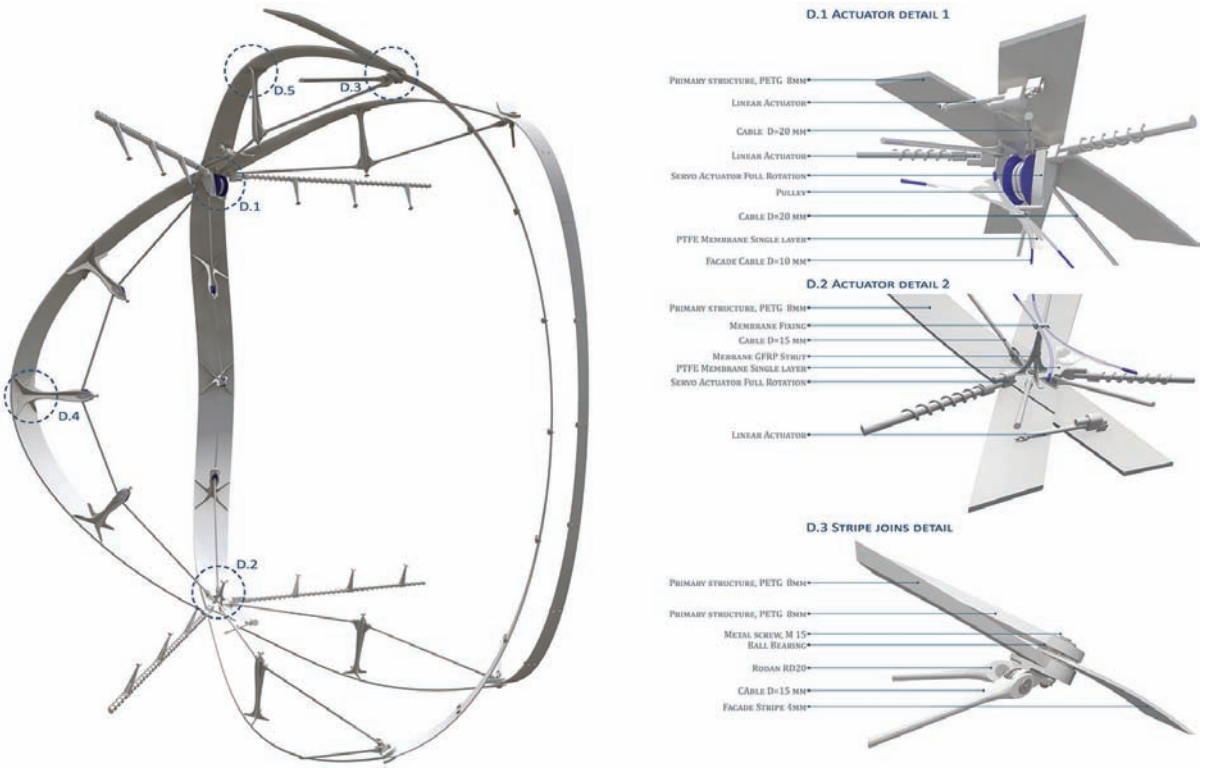

Fig 2.7.5. Detailed drawings of actuators and their positions on the structural element

Physical Prototype Adaptive Behaviour
Embedded technology

The application of embedded technology is regarded as an acceleration mechanism that allows responsiveness of the structure under physical input influences. Therefore the proposed scenario introduces two basic parameters that might influence such a behaviour: Firstly, speed and direction of wind loading, which influences the systems morphology. Wind loading sensors are embedded into the system acting as information collectors of the wind forces and direction. Secondly, the movement and the position of the users in the interior of the unit, respective movement and position sensors refer to the human presence within the unit. Such inputs are collected via movement and loading sensors in the interior of the structure. Both criteria act as input parameters for the adaptive algorithm responsible for the transformability of the structural unit, as shown in Fig. 6. This behaviour is physically simulated using a microcontroller that activates the actuators for respective responsiveness of the structure, providing thus an equilibrium stage. In this way, a dialectic relation between external environmental and internal human presence related influence parameters is achieved. Through transformability and deformation, the structure is able to adapt to different environmental conditions in reducing the wind forces acting on the unit envelope and to achieve human comfort according to the users' activities in the interior.

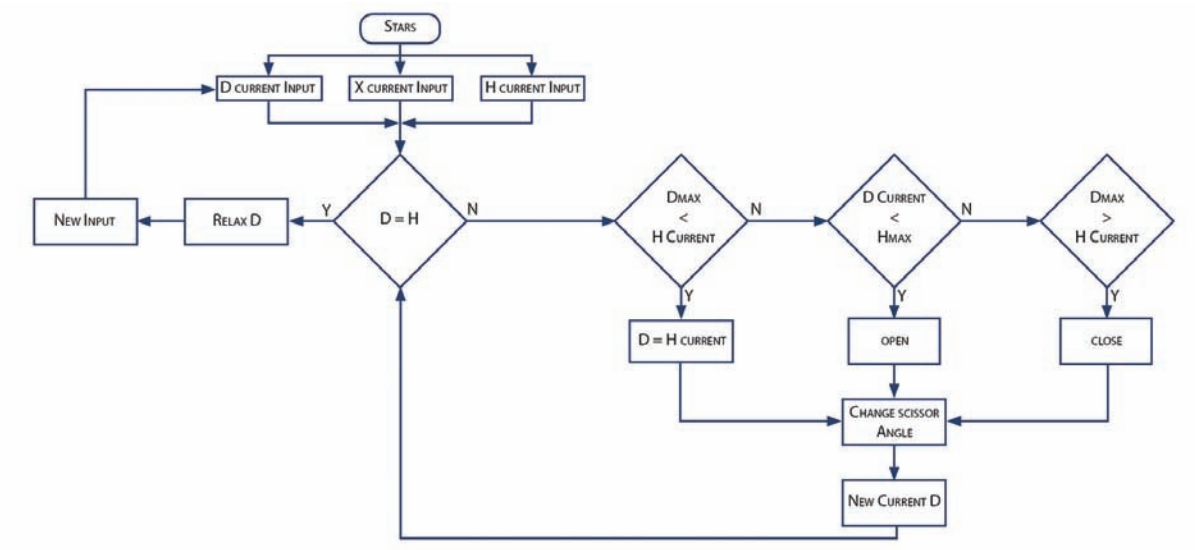

Fig 2.7.6: Flowchart of adaptation algorithm

Adaptation process

The software Firefly (plug-in in Grasshopper) is initially used, in order to digitalize physical conditions as real term environmental, human and structural inputs and subsequently to actuate mechanisms of system motion, in order for the structure to acquire an adaptive behaviour. The control system of sensors and actuators works in an integrated parallel manner, in order to achieve the feedback loop mechanism. Thus, three types of sensors are used: A first group of sensors measures physical information derived from the environment; in this case air pressure. This information is related to airflow, direction and pressure and recoded in Bits/V, fitted in turns to the digital environment. A second group of movement and load sensors records human movement in the interior of the unit. These two groups of sensors are complimentary with a third one that measures the motion of the structure with regard to its deformations due to external airflow conditions. The latter consists of sensors that measure the rotation angles of the scissor elements and distance sensors that measure the height of the elements in each deformation.

In taking into consideration the actual physical model scale, the sensors are calibrated according to the working space environment. The airflow sensors ranging from 0 to 1024 Bits/V are calibrated from 300 to 800 Bits/V. In addition the linear actuators that control the relative angle of the scissor elements are replaced by circular mechanical motion servo standards, able for 180 degrees rotations. For achieving the respective transformations, the scissor elements are calibrated for rotations in the range of 30 to 100 degrees. The three groups of sensors provide all information necessary for the adaptation algorithm to be created in order to actuate the structures motion and control mechanism. Analytically, input data obtained from the air-sensors is compared with the data obtained from the users presence and the height of the elements. With no users and external high-speed airflow, the structural transformation is maximum, with 1.20 m scissors height and smallest possible

relative angles. With external low-speed airflow the structural transformation is minimum; the scissor elements have 2.40 m height and maximum relative angles. Otherwise, the structural transformation is defined according to the usage in the interior, with the perimeter as reference for minimum height. Consequently, the relative angles of the scissor elements are adjusted according to the distance of the users from the centre of the structure. Fig. 7 illustrates some examples of responsiveness of the physical prototype to such conditions.

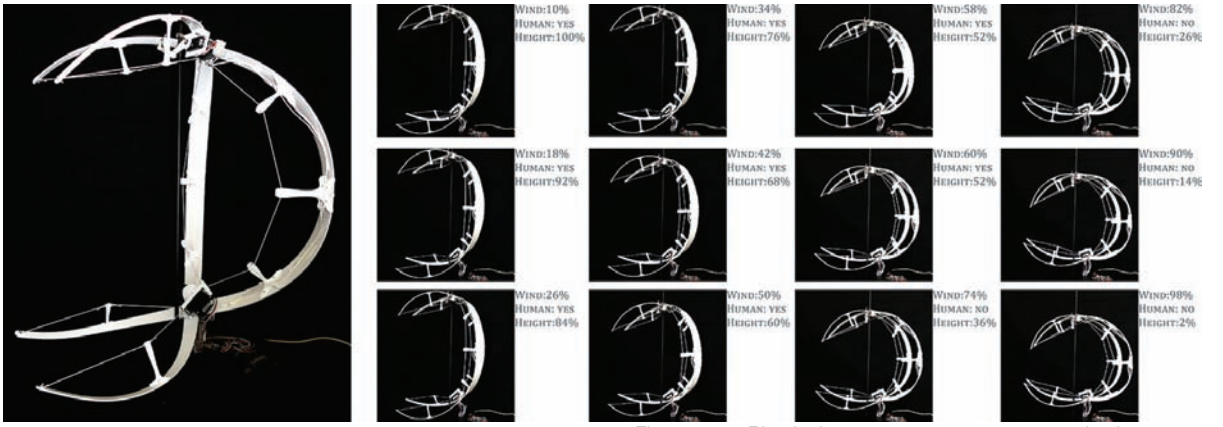

Fig 2.7.7: Physical prototype of a structural element and possibilities of adaptation

Conclusions

The development of an adaptive hybrid structure presented in the current chapter supports a holistic design approach, whereas the prototype is generated and tested using physical models and digital simulation procedures from an early conceptual stage. In this frame, kinetic structural and elastic material behaviour are combined with embedded technology applications. The adaptive hybrid structure consists of PTEG-lamellas with a secondary system of GFRP-struts and cables for strengthening and controllability of the primary members. Embedded technology in the form of sensors, microcontroller and actuators is added to the system for providing adaptation behaviour in responding to the influences of the environment and the users activities as a natural organism with senses and actions. The combination between 'passive' and 'active' control of the structure that applies to the material adaptive structural behaviour and embedded technology respectively provides effective responses against real term conditions considered herewith.

The application of multiple criteria in the structures development comprises an essential part of the specific development process, since it allows a holistic design approach to be thoroughly examined, including design and physical development on one hand and digital simulation of structural performance and adaptation behaviour on the other hand. Furthermore, the integration of different disciplines dealing with various aspects of the design and simulation process enable new technologies to effectively assist design and simulation investigations of novel adaptive structures and materials, a research direction that was difficult to be traced in the past based on conventional digital simulation tools and physical computing processes. Similar holistic design approaches could be further applied in prototype experiments for enabling future related developments and solutions in actual scale architectural problems.

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2.8
Keynote: Architecture in the Prototyping Age: Thinking Ahead

James Timberlake [i]

Keynote: **James Timberlake** FAIA is a partner at KieranTimberlake, a prominent architecture firm noted for its integration of research and practice guided by a deep environmental ethic. The firm is the recipient of the 2008 Architecture Firm Award and the 2010 Cooper-Hewitt National Design Award. In addition to his practice, Mr. Timberlake teaches at the University of Pennsylvania. He is the co-author of five books on architecture, including refabricating ARCHITECTURE, an examination of the manufacturing methodologies poised to transform building construction.

Fig 2.8.1 Smartwrap Cellophane House Kieran Timberlake Architects

MATTER AND TECTONICS

3
MATTER AND TECTONICS

PANEL CHAIR: ALAN JONES

3 MATTER AND TECTONICS

3.1 Compagnon 1:1
3.2 Open Matter(s)
3.3 Robot Manufactured Formwork for Doubly Curved Concrete Surfaces with Precisely Embedded Optical Fibres Displaying Live Images
3.4 Learning by Doing: an Imersive Manufacturing Experience with Undergraduate Architecture Students
3.5 Knitectonics
3.6 Exploring Material Reciprocities for Textile-Hybrid Systems as Spatial Structures
3.7 Proto-materials: Material Practices in Architecture at Molecular and Cellular Scales
3.8 Prototyping Biomimetic Structure for Architecture
3.9 Autarki: Coupling a 1:1 Cross Laminated Timber Building Prototype with Parametric Energy Simulation to Investiate Scenarios for Energy Self-sufficiency

3.1
Compagnon 1:1

Nathalie Rozencwajg and Michel da Costa Goncalves, RARE Architecture [i]

The prototype plays a vital role in the architectural process by means of coupling designing and making strategies, in a repetitive, iterative and informative process. The performance of the prototype is most clearly realised at the one-to-one scale where the designer's idea is tested by construction, both physically and digitally.

Undisturbed by technological evolution, the French tradition of compagnonnage or labour fraternity, active since the Middle Ages, still gather to set the highest standards for craftii. After several years, an apprentice would prove his status as a worthy compagnon through the production of a masterpiece – his 'chef-d'oeuvre' - in the form of a 1:1 building detail. In this exacting and tediously iterative tradition merging learning and making, appears an immediate relationship between making and thinking. By contrast, abstraction is where the architect traditionally exists. The designs begin as depictions of an edifice that is not yet real and architects are not involved in physically producing the object of their design, but are concerned primarily with its codified design information. Thus, the architect has spent a large proportion of history out of direct contact with the making process, arguably increasing his reliance on abstracted concepts and dogmatic use of techniques and materials through the centuries.

Challenging this dichotomy, contemporary prototyping opportunities may redefine the designer's role in generating a design that apprehends and anticipates the challenges of conveying that specific condition. This includes both the planning of how an object might be built, piece by piece, as well as how the entirety of the project might be perceived in its full scale. Prototyping techniques allow for ideas that may not have been born exclusively of a conceptual process to surface. Thinking through the sketch or a conceptual model offers limited insight and options into how a product might be assembled, reconfigured or behave materially. Digital platforms however, generate new conditions bringing the designer back closer to the traditions of craft, of knowledge through making, of repetition and first hand experience. With scale-less modelling, the shared and embedded manufacturing expertise and iterative processes, form an associative platform that mimics the founding of a millennium old guild. Furthermore, in our exploration of digital craft, the use of prototypes reveals the manner in which the design information triggers novel technological and phenomenological responses. The architect is now more informed on the production of his design, like the craftsman.

The compangnonnage was a three-tiered hierarchy. A young man started as an apprentice (garçon), then after at least one year - and up to twelve years - he became a journeyman (valet or compagnon) which lasted an indeterminate period of time and meant working under the instruction of their senior, the master who would have by then proved his skill and established his authority as an exemplary craftsman.[iii] Nevertheless, the making of buildings has always been reliant on each of the members, at any level of the order, efficiently reproducing each necessary step from designing to making not only for the achievement of the final product but also to determine their status and skill within their respective disciplines. In this long, personal and geographical journey (compagnons typically travel between 'maisons') the value given to practical knowledge is engraved in the intelligence of one's hand. It is as much a physical knowledge, literally embodied, as it is a theoretical one. The production exists within the full knowledge of its quality and pertinence. The making is informed by the knowledge of how it should be, of how it has been passed down.

In reference to the mediaeval workshop, Richard Sennett remarks that, "none is more important than its foundation of authority, the knowledge it could pass on by imitation, [and] ritual."[iv] Thus, in the fraternity's frameset, education and production merge in the practice and making of full-scale replicas. As the object of learning is also the learning instrument, there is no detachment equivalent to the architects' abstraction. The feedback between the mental conception of construction and its practical realisation is achieved within the compagnon by way of its painstakingly acquired specialisation as a piece of articulated division of trade within the fraternity. The final test however remains often away from the reality of construction. The realisation of each compagnon's "chef-d'oeuvre", the one-to-one building detail, remains educational in its purpose and often infinitely exquisite in its complexity. The "master's" singularity merges with technical knowledge of thousands before him. The "chef-d'oeuvre" as both fully informed and prospective object, is a prototype.

As defined by the UK Crafts Council, the creative process of making that develops practical, conceptual and visual understanding through direct engagement with tools and materials in response to human needs5, has supplied design with conceptual models that undergo evolution, representational models that do not change but communicate an idea and prototypes that are able to perform in the same effect that the finished product is expected to. The prototype, almost by its very definition, invokes the innovation by which one explores spatial, typological, urban and structural systems for a prototype is only built for an object not yet conceived. However, the design generation process and the design production process have been distinctly separate in architecture6 chiefly due to the problem of size and scale. Despite their grandness, the master's 'chef-d'oeuvre' remains a detail. As part of a building, this architectural element of the highest standard is set to coexist besides elements of equal quality hence passing on by trade the fraternity's training. For architects, the distance to making has further increased by the very disappearance of the craft's model.

> *"Prior to the industrial era, architects were the purveyors of the built. As a result of the industrial revolution, industry itself became the purveyor of the built."*[vii]

The lost relationship between the designer and the craftsman has furthered the gap between conception and making - arguably insomuch as the contractor to the principles of his trade, as in the architects from the physicality of his concepts. Whilst the technological knowledge exists, it relies on creative assemblages of existing procedures. By the evolution of materials and techniques as well as the complexity of building and procurement, the generalisation of the architect's role has, it seems, continuously increased. Beyond rare historical examples in the 20th century[viii], the loss of the direct command of 'making', and subsequently of its understanding, has further abstracted the designer's realm. Architectural detailing is yet another higher level of abstraction through codified drawing. Unlike the product designer, the architect never could and most likely never will be able to prototype the entire product physically at one-to-one. The full-scale physical prototype will only ever be a generation of a building detail while the scaled down physical prototype must perform the same way the building would for it to be useful (which is rare on an architectural scale).

The prototype is the tester of the viability of a project and the prototype either physical or digital is a full description of that part of the building. Within a new digital paradigm, it is potentially the performative unit in the generation of a project that defies indeterminacy within a chosen design process. The complexity of the design process requires not only that there is a need for a finished product, but also that the methodology itself is well crafted. That is, not only does the practice aspire for a constructed result but also that our process of achieving this result is well organised. A prototype simulates the physical form and can then be evaluated in relation to its simulated context. The prototype in this process can, arguably easily, offer many and multiple figures and the results formed are largely unforeseen otherwise.

At RARE prototyping is used in the conception of our projects, not as a means of mere verification but a tool within the looping design process. It attempts to bridge these two models of conception, which have in recent history systematically drifted apart. Whilst the compagnon retains his specialised knowledge embedded within the individual and the fraternity, the architect's role is increasingly fragmented to orchestrate a host of specialised threads of knowledge into the complex whole, that is the contemporary building. The bridge the practice is attempting to construct between these two models is therefore fundamentally a bridge of informed conception, wherein the prototypes are not simply a mute representation of the idea; but rather a living; working; breathing component of the whole to come. The fraternity is a closed collaborative platform set for specific purposes with an active feedback cycle between making and conception done by intrinsic individual expertise or between the knowledgeable tiers of the organisation. The conception is derived, informally and hierarchically, by the constraints of the making and helped by the visualisation - or ability to foresee, due to the direct subjective experience – of the intended result.

In a new design approach one would be able to operate on both these levels allowing learning, designing and making to take place simultaneously. Arguably, BIM software, or associative modelling has the potential to be a digital replica of the medieval guild. The scalelessness of the digital model enables to combine conception with the iterative nature of 3D models; this is aided by real-time feedback, which is in itself both technological – by embedding manufacturing constraints – and experiential – through the testing of otherwise

intangible considerations. The opportunities of the modelling platform combine with those of digital fabrication to offer additional benefits in the product directly linking material and manufacturing and feedback as well as the first hand physical experience. The processing and craft of the prototype at the one-to-one scale of the building is our closest answer to an augmented design. By means of the one-to-one scale, thinking by doing, designing by fabricating, prototype and product are barely differentiated. Continuously, each one informs and is informed by its representation and construction as part of a non-linear design process.

Considering the iterative aspect as the learning process in the case of associative modelling, we find that a single alteration initiates an automatic synchronisation of all the systems of elements within the model replacing the old mechanical operation of setting up conditions in each respective representational document of the project. It is the master of the guild passing down his knowledge that will be gradually embedded within other generations of apprentices. Whereas repetition is the means of passing learning from one generation of compagnon to the other, from one tier to another, the iteration allowed by digital simulation allows for the painstakingly acquired specialisation of the building to equally become an articulated division of trade not within the fraternity but within the design team. Sennett's notion of the "Intelligent Hand", suggests that the work of the hand, at 1:1 scale, is where learning from repetition and iteration replaces abstraction[ix]. In the same way but virtually, this repetition and variation can be constructed in a much shorter time span, with palettes of materials, options of structural elements and distorted dimensions viewed as multi-informational systems that have concurrently advanced architectural language. The gap between conception and making is not dissolved and the architect is as close to the craftsman in relation to material, but a transformation has nonetheless occurred. Introducing our own platform for feedback has reduced the distance between abstracted conception and reality.

Computational software, whether it serves two-dimensional or three-dimensional stages of design representation, is categorically scaleless. For this reason, the practice is liberated to include as much a level of real detail as possible, irrespective of the inconvenience of their actual size and this becomes reproduction and conception at a one-to-one scale. When working with a digitally fabricated model on associative CAD modelling, information is introduced at one-to-one, therefore the model itself can be considered a one-to-one prototype.

> *"When an author produces a drawing that becomes the information that drives the machine, it compresses the world of design and fabrication into a single process, thereby yielding efficiencies not realised in the industrial era."*[x]

It is a conception with a memory: the historic of its generation and through embedded constraints the memory of the construction constraints. By means of digital prototyping the practice mimics production at the study stage of a project, taking the design approach from a largely speculative process into a more physically creative and experimental process spanning and recurring more frequently in all the stages of architectural production.

Digital fabrication, in addition, is therefore the design approach and the generation of the prototype by which the practice is able to simulate, analyse, model and produce within the stages of our designs. Similar to traditional orthographic representation, digital evolution promises the definition of a project by way of direct relation between design and making, as is practiced among the compagnons. Although 3D printing as a digital fabrication technique, distances the architect from the components that make up the building, all sheet based cutting and assembly demand an alternative strategy of construction, which might be employed in reality. The recent facilitation from a computer fabricated model to a built form is brought about by digitally controlled technologies such as CNC milling machines, laser-cutters and 3D printers that comprehend the architect's representational formats. Subsequently, architects are thrust into direct involvement with production processes, as they are eloquent in providing the information that used to be translated by fabricators into the data that operates digital fabrication equipment.[xi] Our understanding of structural tolerance and mechanical margins of errors is much more precise in response to the manufacturing requirements of the machines. Overall, these technologies reunite the schism between digital and "real" processes and also include the test of physical construction that gives the architect a greater responsibility with a stronger input within the construction process itself.12However the one-to-one prototype, as the engenderment of representation and production, reminds us that architects are still drawing according to the limits of digital fabrication machines. As Paul Virilio accurately notes, "it is man who gives himself wildly extravagant dimensions and the earth that reveals its limits."[xiii]

Furthermore, it is the full-scale prototype that invites the construction industry into the project because it is at this point that materials and assemblage are defined by the real-life constraints. This forces a reciprocal relationship between simple construction and conception arguably resulting in intelligent design. "The fact that complex geometries are described precisely as NURBS curves and surfaces, and, thus, computationally possible, also means that their construction is attainable by means of CNC fabrication processes."[xiv] The efficient prototype in modern day practice is not the 1:1 production or the 1:1 simulation but rather 1:1 production and 1:1 simulation in shorter and recurring steps until the project is realised. If the prototype is successful it can even be considered a finished building element.

But as the repetition is key to gradual improvement in the guild frameset, the digital fabrication has more to offer than the change in understanding of scale and production constraints. The fraternity does not solely educate but improves the making by making. The embedded method of knowledge transmission seeks more than a quantitative educational idea synthetized into a set of listed skills to be acquired. The guild sees itself as an elite, a tool made of additive excellences. It is telling that the apprentice can evolve slowly in accordance to his skills but he can only become a compagnon through the realisation of his chef-d'oeuvre or nothing less than a masterpiece. The merged platform and education that forms the guild is geared towards its own improvement by individual creation. Likewise, the digital simulation is required to be more than the automation of existing processes – mere set of skills – but a way to generate augmented designs. Digital simulation makes iteration feasible through its speed and tolerance for the resolution of complexity, which the traditional model-making method of the compagnons simply cannot absorb. As such, the prototype becomes an enhanced conception of detail and understanding of both

construction and experience enabling a much more bespoke response to the demands of a project - it is for us a vector to augmented forms of design.

RARE Architecture directs its work towards the experience of phenomenon where one-to-one testing - the making of “chef-d‘oeuvre” - exists as a learning tool to refine our works based on contextual and phenomenological perception, which escapes codified representation and traditional simulation. The synergy of method and form, not only brings us innovation but permits us to produce effect. In the course of enhancing standard building materials by new modes of production, the perception of the finished product becomes entirely reformed. Our Town Hall Hotel project challenges the dichotomy between scale and complexity. An inverted approach was proposed, where the detail, the material and the perceptive, were guided by an overall coherent design informing the conversion of the nine thousand square metre Grade 2 listed structure into a Hotel & Serviced Apartments, Conference facilities and a fine dining Restaurant & Bar.

Through the early consideration of different scales, the project illustrates how the preconception of this hierarchy can be inverted as a design process and along the way question the notion of composition and perception, where the physicality of space is enhanced by other qualities. The sensitive design aims to preserve the building’s original features while equally integrating contemporary inserts, including tailored furniture elements and a bespoke roof extension. After abstracting the eclectic original design, digital prototyping brought about the development and interpretation of traditional techniques and motifs, which resulted in the balanced contrast of renovation with restoration.

The extension’s uniqueness is defined by the adjustment of its global geometry and the local transformation of its skin to adapt to its context. The volume was first deliberately formless and followed the various cavities and discontinuities of the existing floor plan. Its refined shape subsequently emerges from a careful study of environmental factors and adjustment to the existing structure and functional requirements. Working through parametric software required an open approach that allows the design to undergo several operations that could produce highly unexpected results. Here, the practice combined iteration and feedback together with simulation – we are learning as we are designing. The uncertainty of the outcome is not a limit but rather a liberation. It creates an opportunity to seek new forms, which cater to the dynamic factors of a specific project, opportunities, which computational techniques were designed to offer.[xv] The aspiration for a final form, the prototype accepts the accumulation of variables - with the architect still in control - until the optimal result can be chosen from multiple generated iterations. The making of iterations is reciprocated by the iterations of making where a prototype is made digitally, then made again physically as an analysis of what was first made digitally.[xvi] The mimicry as expected does not replace nor fully imitate real processes, but rather its value beyond visualization becomes the new relationship to conception – a new understanding of making beyond the merging of abstraction, craft and experience. In other words, with a raised consciousness of material and method, the issue of real and virtual is diminished, only the augmented value of form and experience remains.

All of this in turn is the introduction of additional opportunities in the design process. The general facetted shape dictated by rights of lights and natural light intake, in the patios for example, also responds to the historical composition and Heritage concerns, with the resulting profile additionally shaped to disappear from certain angles coinciding with original perspectives while creating a prominent new façade from others. By mapping the various environmental constraints and local needs of the site digitally, the form of the new extension is not generated as a composition but as the sum of punctual requirements further assembled to regulating the skin's porosity. Digital prototyping enabled us to merge these variables together to produce the bespoke laser-cut skin that mediates both the internal functions and the neighbouring buildings. Defining this as performative ornament – where the ornamental design also performs a function – the adaptive pattern deploys itself over 300 linear meters and regulates solar gains, views and privacy according to the different spaces it is set against. Derived from an art-deco pattern, the new functional ornament was developed into a digital grammar system merging functional and historical aspects. The design is generated through a set of steps that enable the proliferation and scaling of a square along a set of required performances. The process started with guiding curves and paths established at key height lines in relation to the overall shape and structural requirements. These were then intersected or deterred according to the desired degree of openness thus responding to the internal function and cardinal orientation. This hierarchy of views and sun gain established the rule of the overlap and scaling up or down of a singular component, whose coverage and intricacies constantly evolve.

This associative digital modelling allowed the scale of the ornament to be reintroduced and expanded beyond its decorative quality: the aluminium laser-cut skin of the new extension is decorative but it also performs. From within, the skin creates a protective envelope, which filters and edits the surrounding views. The ever-changing shadows create a moirés of reflections that enrich the spatial experience. From outside the depth of its special coating generates nuances of colours that respond to the changes in the light condition throughout the day. In contrast, at night, its silhouette reveals a mysterious presence, evolving in accordance to the life within. Achieved through the iterative production of various physical and associative digital study models, our design process preserved the constant link between the urban scale and the user's experience through the envelope's geometry and porosity. It is the detail that defines the guest's perception of the surrounds; his perception of the context is diffracted in multiple frames defined by the adaptive local geometry. As such it is by approaching the design through the parameterized proliferation of a simple shape that the overall skin of the new extension is generated but by extension also the desired relation to the context. Digitally prototyping the inverted scale functions as adaptive architectonics but in turn it is also the pattern - the ornamental feature, the lower order of scales, using classical terminology - that defines the overall perception. Thus, the small-scale element, stemming from the existing decorative feature found in the building, initiated a thorough study to produce the new vocabulary for many interventions in the building - this is our digital craft.

Compositional studies of existing and derived features were the basis of a decomposition to generate a new ornamental vocabulary. The results produce patterns with a variety of qualities that can be aesthetically as well as functionally assessed and provide in addition to the new performative skin, interpretative marquetry, ventilation outlets, service

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enclosures, and so on. The development of these elements relied on advanced modelling and computer-aided manufacturing helping to reintroduce the uniqueness of design within a controlled budget. They enable a reflection on the particular, the one-off, where the process remains the same but the outcome can be different. Here the efficiency of the digital prototype allowed us to assess the imbrications of economic value, as cost is a direct factor of machining time – the scale and design of the cuts, scores and milling is inherently correlated to the cost of production.

Digital evolution though, has projected us to a platform that the physical prototype has not traditionally. The practice is able to prototype not only the product but also its effects. Understanding the digital prototype as an opportunity to simulate both the tangible and the intangible such as a 3D model with which heat and sound mapping can test atmospherics but equally light conditions can be tested through a digitally produced physical model. Now that the prototype exists digitally, the prototype can potentially take us to a scale beyond one-to-one. The one-to-one digital prototype is a (one-to-one) generation of the whole building. Our ability to quantify a building's structural and environmental performance allows the designer to account for site-specific differences of use and behaviour. The one-to-one prototype generates a play of variables within the architectural design process. It is not only a factor of innovation and learning but can also in itself be appreciated as a finished product to be used in the completion of a project, in the same way that the compagnon's one-to-one detail would certify his training and be of the most skilled products of his time.

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3.2
Open Matter(s)
A community approach towards smart materials and their potential for architecture and design

Manuel Kretzer [i]

This paper is inspired by a number of historic precedents and compares their theories to recent developments in information technology and digital fabrication in order to establish a different approach towards (smart) materials than the predominant one. Kurt Schwitters' emphasis of the process versus the final result is paired with Yona Friedman's urge towards an architectural system that leaves space for individual self-expression and an interest towards collaborative methods that emerged during the OpenSource movement at the end of the '90s. The article then looks at more recent developments, like consumer focused 3D printing techniques, and how they will influence architectural practice but most of all education. It is then realized that the continuous quest for standardized and homogeneous composites, that conform with digital design and fabrication methods, greatly simplifies materiality and in turn leads to a loss of variety and knowledge to design in accordance to a material's characteristics. To propose a possible solution, the beginnings of mass production and concomitant counter positions are evaluated and the formation of a recent community network, based on an interest in experimental investigations in smart materials, is presented. The paper concludes with an overview of materials and projects that were developed as part of this initiative.

Schwitters

Kurt Schwitters, born in 1887 in Hannover, Germany can be considered as one of the most remarkable artists of the 20th century. He is probably best known for his epic architectural construction the "Cathedral of Erotic Misery", which he began around 1923. Over the following 20 years this gradually transformed his private apartment into the Dadaist walk-through sculpture that today is usually referred to as "Merzbau". Although the project unfortunately was completely destroyed by bombing raids in 1943, and the knowledge about its true form and extent remains limited to a few photographs that have survived, its influence on contemporary issues in art and architecture is exceptional. The spatial installation, which he built up from randomly found elements and without being trained as a craftsman[ii], was not approached by him with a preconceived vision of what it should become, but was rather developed through the particular qualities and properties of the materials and artefacts he incorporated and their inherent interrelations. Seen in this context Schwitters' piece of art was never about its finished appearance, but more about the dynamic, constantly evolving and changing process of its creation[iii]. These continuous modifications spanned through several personal periods of interest and research, different artistic phases and a variety of spatial explorations and expressions.

Some accounts actually indicate that in certain areas the transformation was up to six layers deep and incorporated moveable walls and columns in order to reveal its insides. So even though the installation changed its visual appearance and physical manifestation over the course of time, it still contained its beginnings and rather than replacing parts that had become obsolete they became ingrown into the larger assembly, materialising his idea of the house as body and the body as house[iv]. It was through this process of assemblage and growth that Schwitters wanted to prove Merz, the name he had given to his personal artistic principles, as a spatial and temporal model for architecture and urban planning. In his own words he declared in 1924: "Merz means creating relationships, preferably between all things in the world.[v]" Even though the project remained mostly hidden and only visible to a number of invited people it inspired generations of architects to follow.

Friedman

Roughly 15 years later, in the early '60s, Yona Friedman, born 1923 in Budapest, developed his vision of the Ville Spatiale - the spatial city, on the idea that architecture should solely provide a framework for self-expression and self-fulfilment and liberate the inhabitants from master planning and spatial paternalism. Like his Dutch colleague Constant Nieuwenhuys, he believed in the progress of automated production and the resulting increase in leisure time that would change and transform society. Although there is a whole range of formal similarities between the two projects, New Babylon and Ville Spatiale, like the lightweight structural system that allowed them to float above existing cities and landscapes or the collaging style of representation and sculptural model making, Friedman insisted in his approach, like Schwitters before him, on the importance of the process rather than the final result[vi]. He later coined the term "Merzstrukturen", which are merging the – in his eyes – two most significant impulses to 20th century architecture, namely the benefits of industrially fabricated space-frame structures, popularized by Konrad Wachsmann, and the extreme emotional individualism of the Merzbau. By setting this idea into the social context of our time, which he characterized as a culture of people desperately trying to express their personal difference, he encouraged the users to create their own environments - based on trial-and-error. Since each of the spaces would then be different and personalized by the respective tenant, this approach is coherent with his manifesto on mobile architecture (1956), in which he refused the concept of an average man, but rather focused on the individual whose interest and future behaviour cannot be predicted[vii]. He believed that guidelines to these kinds of improvisations couldn't be described by standard architectural means of expression, like plans or drawings, but rather through "cooking instructions", recipes or tutorials in the form of comics, that would allow for interpretation and experimentation within a manageable framework.

In order to prove his visions in a real world context he established simple architectural systems for developing countries, using locally available materials and traditional building techniques, and visualized them through sets of self-explanatory comics. His aversion towards a top-down dictatorial design, with the architect superimposing his ideas of form, function and aesthetics over the immanent needs and desires of constantly evolving individuals has strong similarities to fundamental principles of the Open Source Initiative that started in 1998 at Palo Alto, California. With free redistribution and unlimited access to information being one of the keystones of this philosophy it rises through the collaborative efforts of a multitude of users that continue developing the ideas within the specific

communities[viii]. The power of joint development has led to software ranging from operating systems (Linux), server solutions (Apache, MySQL), web browser (Mozilla Firefox), CMS systems (Wordpress, Joomla), productivity suites (OpenOffice), image manipulation (GIMP), 3D creation (Blender), video player (VLC) to design related projects like Processing, Arduino or Grasshopper all the way to the legendary Kinect Hack[ix].

Anderson

Just a couple of months ago, long-time Wired Magazine editor in chief, Chris Anderson left the journal in order to become CEO of 3D Robotics. The company, that produces autopilot modules to turn RC vehicles into drones, actually sells these components through one of his other projects, the online community "DIY Drones". This continuously growing, very active social network, explores the creation of Unmanned Aerial Vehicles (UAVs) in an amateur and homemade manner. His decision, to leave a well established position at a renown journal, in order to start-up a firm based on the demands of a self-initiated community, is similarly characteristic as well as pioneering for our time, which Friedman actually calls the epoch of "mass-individualization". In his recently published book Makers, he goes even a step further and argues, that the current do-it-yourself and hacker movement, which manifests itself in communities like the above, is strongly driven by the emergence of consumer focused digital fabrication tools as well as instant access to cloud-based manufacturing stores. He further states that this transformation, from bits back to atoms, forms the logical extensions of the digital revolution that marked the beginning of the Information Age, and will replace mass production through mass customization.[x]

The manifestation of online strategies, based on networking, exchange and open ownership, into a global movement that enjoys physical making and prototyping has found a number of fertile grounds, both in the digital and the physical world, and concurrently proved to have great influence on architectural design. Through the access to new tools, community-based software and scripting languages as well as CNC and rapid prototyping machines we're today witnessing a great amount of generatively designed and digitally produced forms at all scales. What's sometimes lacking in these explorations however is a thorough understanding and examination of materiality, which with the prevalent tools, that process sheets or print powdered granulate, is not only unnecessary, but becomes almost impossible. Albeit the idea of collective sharing and development is certainly something the architect, especially during his education, intuitively identifies himself with, the praise of these machines, and in particular 3D printing techniques, bears some questions, if not doubts, especially when it comes to leaving the representational scale of model making. But it is exactly this threshold, the scale in between models and real buildings, the scale of temporary installations, pavilions and sculptures that provides an enabling opportunity to experiment, express and experience architecture. It is through these 1:1 prototypes that the designer can verify whether his abstract ideas can be realized; but only through hands-on experience he can draw conclusions on how to improve the operation of tools and especially the application of materials.

Ruskin

A few hundred years back, in 1849, a similar dispute arose as a response to the Industrial Revolution and the concomitant redundancy of universal craftsmanship through the transition towards automated machinery. John Ruskin (1819 - 1900), a leading English art

critic during the Victorian era, became a fierce opponent of mass production and demanded the truth to materials, their "appropriate" use and the honest display of construction[xi]. He despised modern materials and believed that machine made and even cast ornaments would defame craftsmanship and similarly that the painting of surfaces would disguise materiality and create an intentional illusion[xii]. His appreciation of traditional methods of construction was funded in his deep believe, that the success of a project was dependent on the spirit and attitude of the performing labourer. Gottfried Semper (1803 - 1879), a German architect and engineer, shared some of Ruskin's ideas, especially the truth-to-materials aesthetic[xiii], but more in an interest to reveal the procedure of how something was made, since this would emphasize its meaning and function. Both writers – with their aversion towards automation and standardization – had a strong influence on art and architecture. Ruskin's ideas initiated the international design movement Arts and Crafts (1860 - 1910), which advocated traditional craftsmanship and the creativity of the individual, and in turn inspired such styles as Art Nouveau, the Dutch De Stijl and eventually the Bauhaus. Semper's functional approach to modern architecture and his demand for a reconsideration of the notion of style created an international following that convinced such iconic personalities like Frank Lloyd Wright (1867 - 1959) or Adolf Loos (1870 - 1933) to argue for the appropriate use of materials and creation of form in accordance to their properties[xiv].

While the developments during Industrialization undoubtedly led to modern times, a stronger, taller, lighter architecture and most of all a better, healthier, more comfortable and longer life, its quantification, norms and standards also resulted in a massive simplification of content for the sake of comparability. In the field of architecture and design this becomes especially obvious in today's attitude towards materials. Even though material libraries, consultancies, catalogues and online explorers certainly provide a profound database and offer various ways in order to experience, search and sort materials in relation to specific properties and applications, they foster the already prevalent preference of form and surface over structure and materiality[xv]. This in turn leads to a material usage that reminds more of applying textures in CAD programs than a thorough understanding of a material's inert properties. It is surprising as well as reassuring that Anderson refers to today's Maker Movement as the "new Industrial Revolution", which in his eyes rises through the liberating powers of 3D printers and the alike. Comparing this particular development to ground-breaking historical events like the invention of the Apple II or the birth of the laser printer and its effects on the publishing industry, he predicts it will convince consumers to move away from cheap mass produced products towards niche designs and the work of artisans.

It might however be rather counterproductive to simply adopt this thesis to the applied area of architecture and design. Especially in education the back and forth between digital and physical, between representation and manifestation or drawing and making and the experimentation with tools and materials for form-finding, structure-testing or appearance-evaluation plays an essential role and shouldn't be replaced through fully automated additive fabrication processes. Obviously this in no terms means to promote ancient craftsmanship and back-to-the-roots, but rather encourage a comprehensive and design accompanying understanding of material characteristics. Since no matter how homogeneous or solid a material might appear, it is under no means finite, as it is always built-up from certain mechanisms occurring at atomic or microscopic scales[xvi].

This critique of a falsification and disguise of materiality becomes even more important when dealing with new and especially dynamic materials of which the amount of empirical knowledge is limited or simply non-existing. In order to understand these performative materials in relation to time and space and hence develop novel concepts for architectural applications, it is advantageous to cultivate a general understanding of their molecular composition, internal chemical reactions and behaviour in response to energy fields. Through this basic knowledge the designer will not only comprehend why the material behaves but also how its internal structure can be modified in order to enhance particular processes that vary from standardized market solutions. As long as efficiency and durability don't become crucial factors he will consequently be able to test and prove his visions in a prototypical but applied manner.

Materiability

In order to encourage and share this process-based approach towards smart materials, but also to break the prevalent myth that surrounds these, I have recently founded the *materiability* research network, a community platform and growing database that reveals advanced materials, showcases their production process as tutorials and simple instructions and promotes their assembly in temporary and speculative spatial installations and artistic explorations. The educational network, which emerged from a joint initiative between the Chair for CAAD, ETH Zürich and Interaction Design, Zurich University of the Arts, is funded in a belief of unrestricted access to both information and knowledge and is strongly driven by a community that finds equal inspiration in digital creation and physical making.

The current database includes do-it-yourself instructions for:

Electroactive Polymers

An electroactive polymer exhibits a change in size or shape when stimulated by an electric field. The most common applications are in actuators and sensors. The basic unit of electroactive polymer actuators consist of an elastomeric film sandwiched between two compliant electrodes. When an electrical voltage is applied between the electrodes the film is squeezed which leads to a planar expansion.

Aerated Bioplastics

Bioplastic is a kind of plastic based on sustainable biomass sources, which can (bio) degrade much faster than fossil-fuel plastics. Common mixtures are made from vegetable fats, starch or microbiota. In this case a gelatine-glycerol solution was chosen, which can be turned into fairly solid compounds. The bubble pattern was created through introducing air into the liquid while it was drying.

Electroluminescent Displays

Electroluminescence is an optical and electrical phenomenon in which a material emits light in response to an electric current or to a strong electric field. An electroluminescent display is basically a luminescent capacitor. It is produced by screen-printing several functional layers on top of each other and activated by an alternating voltage that excites the dispersed phosphor crystals.

Dye-sensitized Solar Cells

A dye-sensitized solar cell is an economic solar cell, which belongs to the class of thin film solar cells. It is based on a semiconductor formed between a photosensitized anode and an electrolyte. A dye-sensitized solar cell is fairly simple to make and can be produced as flexible and semi-transparent sheet.

Phosphorescent Soft Actuators

Soft robotics is an emerging area of research based on the idea to create a robot that consists entirely of soft and flexible components. One approach focuses on embedded pneumatic networks within a silicon skin that lead to kinetic movement by pressurizing the channels.

Bioluminescent Algae

Bioluminescence is a natural phenomenon that concerns the emission of light through a living organism. Pyrocystis Lunula is a particular bioluminescent alga with crescent-shaped cell morphology of 0.15 mm in size. In low light conditions, the cells produce a bright blue light when irritated or mechanically disturbed.

The smart material projects that have emerged from this initiative and were realized during workshops and student courses as part of my research include:

Phototropia

Phototropia was a project by the 2012 MAS class at the Chair for CAAD, ETH Zürich and was realized from in March 2012. It merged self-made electroactive polymer membranes, screen-printed electroluminescent displays, thin-film dye-sensitized solar cells and eco-friendly, gelatine-based bioplastics. While the bioplastic formed the structural foundation and connected all elements, the solar cells and electroluminescent displays were joined together into a tessellated origami surface, hovering above the electroactive polymers that populated the ground. The autonomous installation produced all its required energy from sunlight and responded to user proximity through moving and illuminating elements. The generated energy was stored in batteries below the platform and – once fully charged - redistributed via Arduino microcontrollers to the respective elements.

The project found its inspiration in participative and transient systems, proposed by visionaries like Yona Friedman or Constant Nieuwenhuys paired with a naive curiosity for self-made (smart) materials and an aversion towards mechanistic kinetic systems. It was a proposal for an experimental architecture that can decay while actively being renewed, as a response to times of tremendous globalization, increased connectivity and digital identity within an information based society.

Supervision: Manuel Kretzer

Students: Katia Ageeva, Diana Alvarez, Orestis Argyropoulos, Stella Azariadi, Tianyi Chen, Yun-Ying Chiu, Ivana Damjanovic, García Pepo Martínez, Melina Mezari, Bojana Miskeljin, Evangelos Pantazis, Stanislava Predojevic, Stylianos Psaltis, Meda Radovanovic, Daniel Rohlek, Miro Roman, Castro Mauricio Rodríguez, Teemu Seppänen, Grete Soosalu

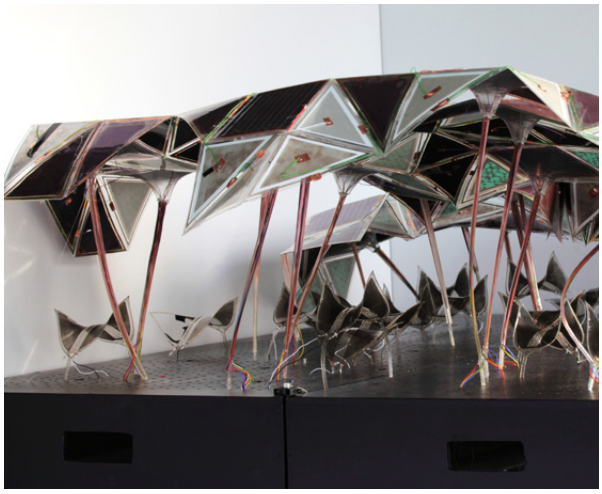
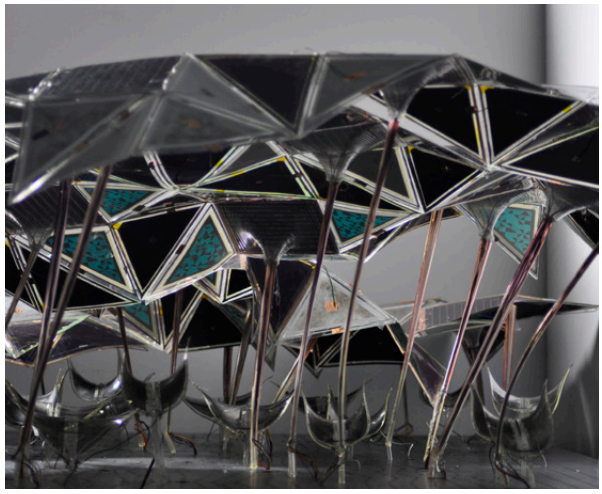
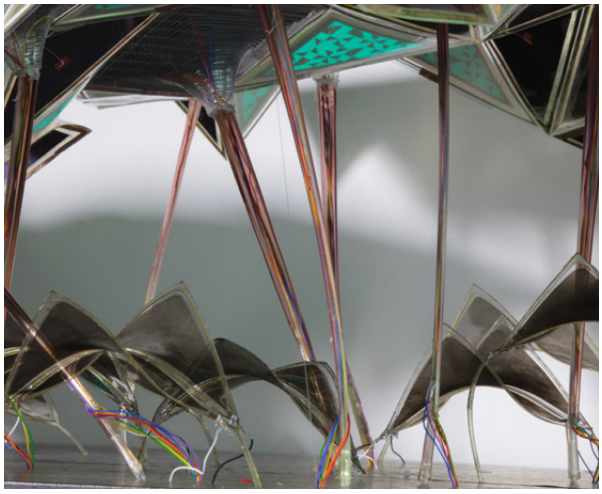
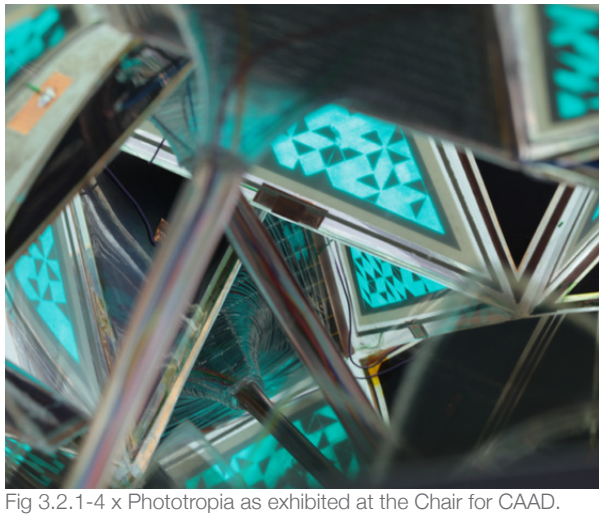





Fig 3.2.1-4 x Phototropia as exhibited at the Chair for CAAD.

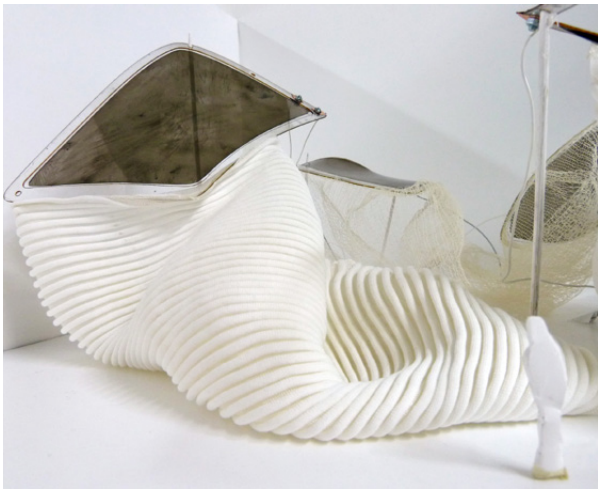
Animated Textiles

Animated Textiles was a five-day workshop held at the Swedish School of Textiles at the University of Borås from Sept. 17th to 21st 2012. Within this workshop the combination of soft electroactive polymers with various lightweight textile systems to create animated surfaces, structures and assemblies was explored. The workshop participants, both Master and PhD students, worked in three groups of four people each. After a generous introduction into the techniques of producing electroactive polymers, each group created their own membranes based on iterative mutations of a previously defined working component. The necessary support frames were cut using a laser cutter from Polycarbonate sheets. The components that exhibited the best behaviour and strongest deformation were picked and attached to textiles and fabrics in order to form animated ecologies of moving textile assemblies. At the end of the workshop each group had successfully built a physical prototype, which was then presented to a larger audience.

Supervision: Manuel Kretzer, Ivana Damjanovic

Organization: Delia Dumitrescu

Participants: Astrid Mody, Felicia Davis, Una Baldvinsdottir, Joanne Kowalski, Inese Parkova, Emelie Johansson, Riikka Saarela, Christina Maschke, Stella Katsarou, Nilla Berko, Justien De Bus



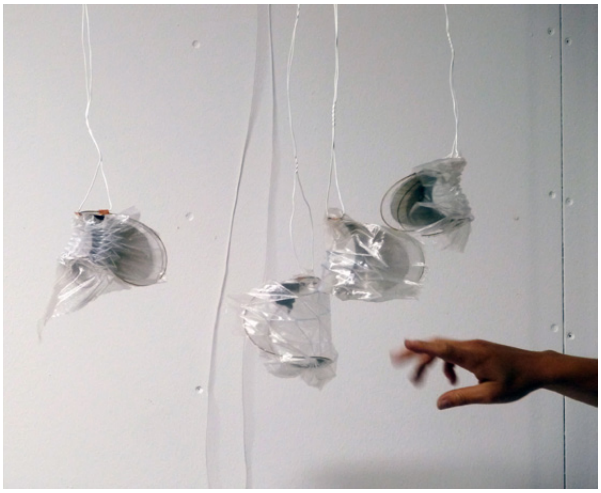


Fig 3.2.5-8 Different prototypes that were built during the Animated Textiles workshop.

Material Animation

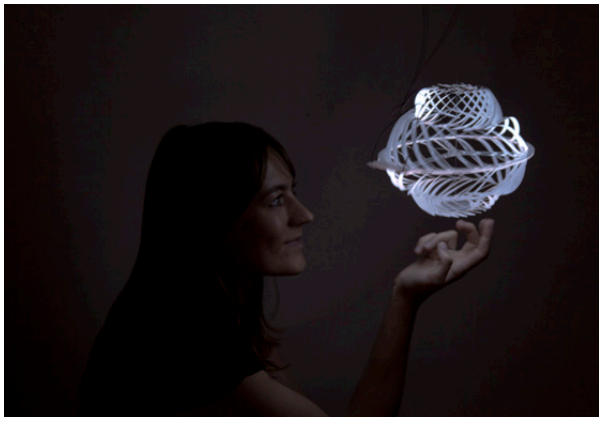
This was a kinetic light installation, produced within one month by the 2011 MAS class at the Chair for CAAD, ETH Zürich. The intervention was made from laser-cut electroluminescent foils, which responded to the location, number and velocity of human occupants.

The experiment was situated in three interconnected rooms of an idle emergency bunker below ETH Zurich's Science City Campus. Each room reflected a different theme and approach to physically animate the material in an architectural context. EL foils are extremely thin, flexible and lightweight screens, which emit a homogeneous cold light across their surface without the need for additional infrastructure. Room one was "Vapor", a fluid space consisting of eight floating elements that were expanding and contracting in response to human interaction. The second space housed "Open Wires", which aimed to realize an environment based on ephemeral and unpredictable three-dimensional shapes. The system consisted of 31 EL strips that revolved and flickered at high speed. Located in the third room was "Insomnia" which focused on the flexibility, thinness and homogenous illumination of the material. These properties were used to provide backlight for two optical animations based on moiré patterns. The position and movement of the visitors in between the spaces was constantly tracked through Kinect Sensors and fed wirelessly into a remote server that compiled the information and redistributed it to the respective installations. This system was used to organize the dynamic variation of different behaviours that were designed to encourage people to further engage with the installation while getting a real time feedback on their actions within the space.

Supervision: Manuel Kretzer, Ruairi Glynn

Students: Agata Muszynska, Aleksandar Lalovic, Hideaki Takenaga, Jesper Thøger Christensen, Jorge Orozco, Magda Osinska, Mihye An, Nikola Marincic

Course at MAS CAAD, ETH Zürich (2011)



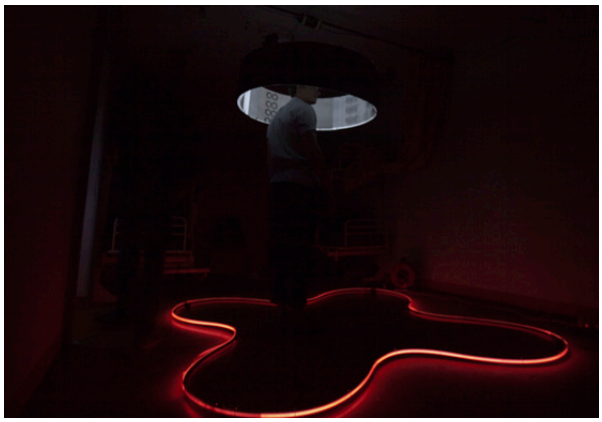


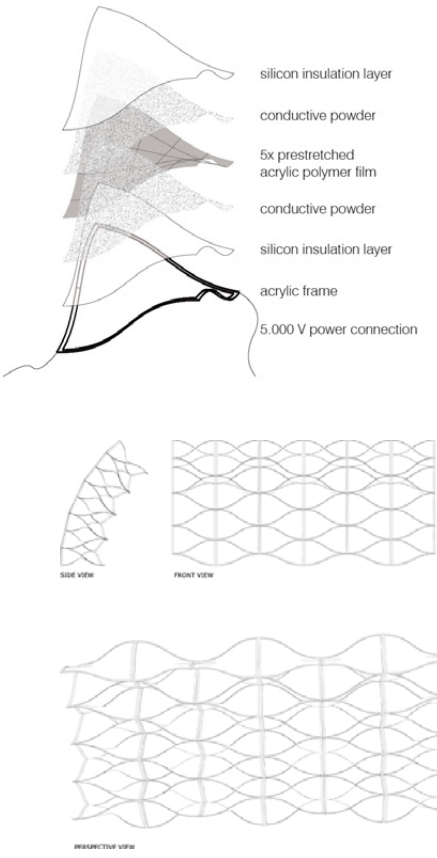
Fig 3.2.9-11 Material Animation, as exhibited at ETH Hönggerberg in April 2011. From Left to Right: Vapour, Insomnia and Open Wires.

ShapeShift

The thesis project *ShapeShift* was realized in fall 2010 by a group of MAS students at the Chair for CAAD, ETH Zürich. It investigated the potential of electroactive polymers in an architectural context and suggested novel possibilities of architectural materialization and 'non-mechanic' kinetics. In this project, the focus was not to use the materials as mere actuator replacements but rather enhance their aesthetic qualities. The component based shape emerged from the material's particular properties to go back to its original form. Each module was made from a very thin layer of elastomeric foil, a flexible acrylic frame, which kept the membrane material stretched, and two electrodes that sandwiched the entire system. In parallel to the design of the individual elements, several investigations into different structural assemblies and tessellations were performed.

Supervision: Manuel Kretzer

Students: Edyta Augustynowicz, Sofia Georgakopulou, Dino Rossi, Stefanie Sixt



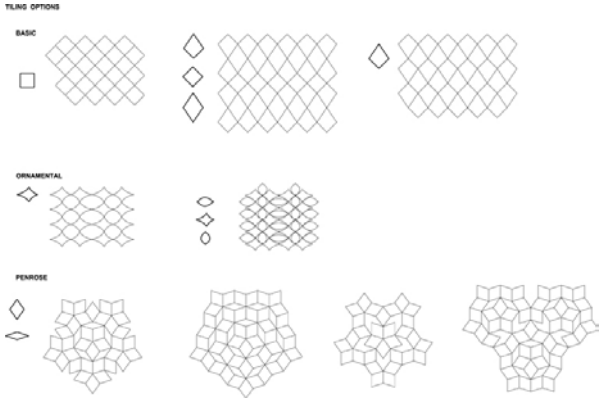


Fig 3.2.11-13 Left: Diagram of Different Component Layers; Middle: Various Tiling Options; Right: Final Structural Arrangement.

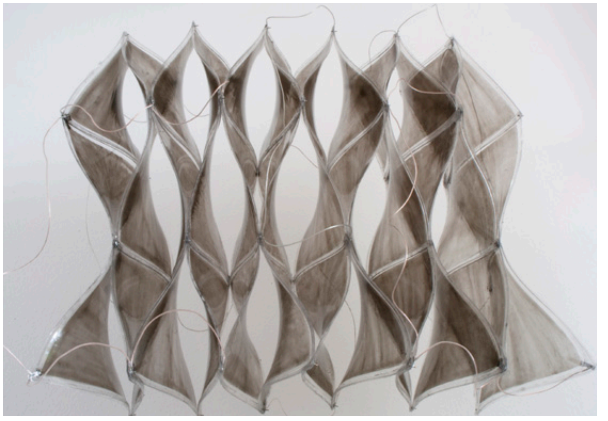


Fig 3.2.14-16 ShapeShift final installation, exhibited at Starkart Gallery, Zürich in October 2010.17

An in depth focus was placed on the potential of dynamic structural arrangements. In these constellations, no static support structure was necessary, since individual elements were connected to each other to create self-supporting organizations. As with the single modules, the dynamic structures maintained their shape based on the relationship between the pre-stretched electroactive polymers and the enclosing acrylic frame. Through these direct connections an extra layer of complexity was achieved. Every unit influenced the form and movement of its neighbours, and therefore, the overall system behaviour.

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xvii Image Credits: All photographs by Manuel Kretzer, ShapeShift Diagram 01 by Manuel Kretzer, ShapeShift Diagram 02 and ShapeShift Diagram 03 by Edyta Augustynowicz.

3.3
Robot Manufactured Formwork for Doubly Curved Concrete Surfaces with Precisely Embedded Optical Fibres Displaying Live Images

Johannes Rauff Greisen, Lars Nyholm Thrane, Claus Pade [i]

Optical fibres transmitting light through concrete can be used to show live images on concrete surfaces. The display technology has been developed for planar concrete screens by DuPont Lightstone. The display technology requires that the optical fibres are embedded precisely into concrete and therefore the formwork must provide a high level of spatial control of the fibres during casting. Applying this display technology on doubly curved surfaces involves major challenges in achieving accurate fibre position and angle: Formwork rigidity is critical in order to maintain fibres orthogonal to the surface during casting and yet allow reasonable ease of removing formwork. The research conducted at Danish Technological Institute solves these challenges by utilizing a new composite concrete formwork material and three and five axes robotic milling and drilling operations. The presented prototype is a final cast result of this research and development of the next generation of formwork technology for optical fibres.

The research shows that utilizing robots within concrete building opens new perspectives: Controlling and embedding a hitherto unseen amount of delicate inserts is now technically possible, and when the efficiency of robot manufacturing is combined with the flexibility of craftsmanship the embedding can be customized and executed within a reasonable economy. Concrete as building material is a composite, but has sometimes nevertheless been conceived as a homogeneous grey mass. Optic fibre concrete is to be conceived as a composite material with translucent and opaque components controlled by computer tools to a degree resulting in a new form of transparency.

Introduction

The research described in this paper has two motifs: Firstly, to prototype the fabrication method for a doubly curved concrete screen, and if a fabrication method was found. Secondly, to obtain a physical concrete specimen – a prototype – that could demonstrate the architectural appearance of such an optic fibre concrete surface. The prototyping work aims to make concrete buildings show light driven live images on freely formed curved surfaces. Its potential role in architecture is to integrate technology in concrete building and thereby challenge traditional projecting technology. Furthermore, traditional projecting onto curved surface comprehends image distortion due to linear trace of light, focusing problems due to the projecting devices focus plane, and risk of shadows due to objects between the projecting device and the projecting surface [Fig.1]. The described research takes point of departure in an optic fibre based concept [Fig. 2], and aims to develop

a doubly curved concrete screen, that solves the addressed problems with distortion, focus and shadows. The research deals with a palette of issues ranging from production technology over resolution and pixel luminance to architectural appearance.

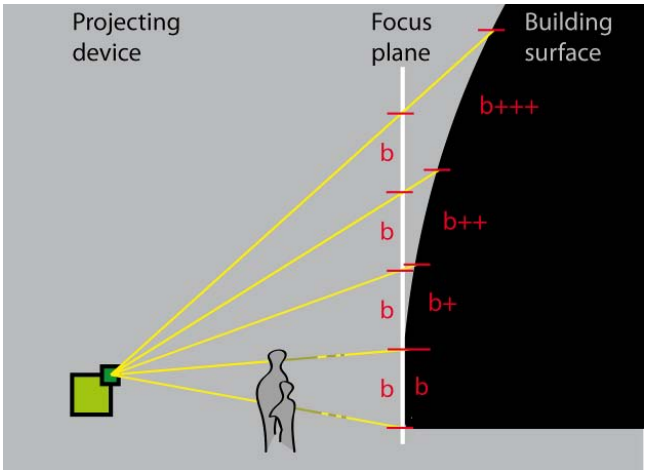

Fig.3.3.1 Projecting on curved surface comprehends image distortion (various b-distances), focusing problems and risk of shadows

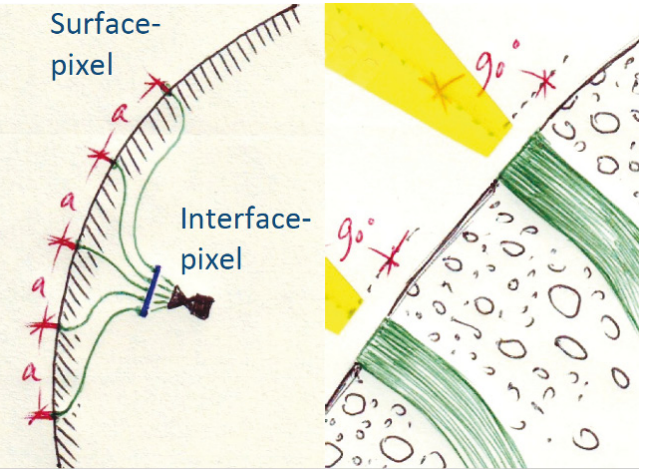

Fig. 3.3.2 Double curved concrete screen concept solves distortion (constant a-distances), focus and shadow challenges.

The experiment builds upon existing production technology based on Danish Technological Institute covering robot fabrication of freely formed concrete geometries (Thrane, 2008). The display system is developed to be embedded in concrete by Dupont Lightstone, who also holds the world patent (DuPont, 2008). Traditionally, formwork based on metal sheets with two axes laser cut fixing holes for positioning of optical fibres is used, but this technology can only produce planar surfaces, because the planar surface is the only case where the fibres are parallel. When the optical fibres are parallel, they have a common direction in which the formwork and the cast concrete specimen can be removed from each other, without damaging the fibres and/or the concrete. A non-planar cast concrete item have optical fibres pointing out into the formwork in non-parallel direction as a result of fibres being orthogonal to the curved surface geometry at the point, where they penetrate the surface. A curved or a doubly curved surface needs a new formwork concept, because any other geometry than planar results in a mechanical interlocking.

<<

A soft formwork material is an option, but the optical fibres must be positioned precisely and angled orthogonally to the surface to provide sufficient image quality. This means that the formwork must be rigid enough to withstand concrete flow and pressure keeping the optical fibres fixed in place and angle during casting. This interlocking and demand for rigidity makes non-destructive removing of formwork impossible. This is an unavoidable premise deriving from geometry and the optical fibre based display technology and a new generation of formwork technology is required, to deliver precision at a cost permitting destructive removal. Six formwork concepts were developed, three were tested for feasibility and one was chosen to be developed to full scale. This successfully resulted in three spherical concrete objects with altogether approximately 6000 optical fibres embedded.

The aim of this paper is to give sufficient description to cover all aspects in the conducted prototyping experiment, connecting the research to actual present and possible fabrication methods in architectural practice.

Objectives and Research Questions

This experiment addresses two objectives: Fabrication of concrete formwork and architectural appearance of a hitherto unseen concrete surface. Regarding fabrication of concrete formwork the display technology demands precision at millimetre-scale, which for planar screen is executed by a laser cutter with two degrees of freedom. The medium duty industrial robot, which has been used in fabrication industries for half a century and for the last decade has been used to fabricate freely formed concrete formwork, has more degrees of freedom. Today six degrees of freedom is standard. The specific industrial robot used in this experiment works on a larger scale, with a working envelope of two by three metres and payloads above a hundred kilograms. Industrial robots are cheaper, moves faster and more flexible compared to traditional Cartesian manipulation systems, for example the traditional CNC milling plant. Generally, building has tight budgets, is large and complex so it requires high speed and high degree of flexibility. Therefore robot milling is relevant to architectural practice, challenging traditional CNC milling facilities. A disadvantage of using an industrial robot is that it is less precise than a CNC milling facility. The robots tolerances are larger and varying depending on the position in the working envelope, due the fact that industrial robots consist of rotatory axes, while the Cartisian CNC system consist of three linear axis. The control interface of the robot provides spatial control with five degrees of freedom.

The first research question is:
Are the robot operations precise enough to place relatively small optic fibres?

The screen concept requires a succession of operations. Some operations will be digitally performed and some operations will be manually performed. The amount of operations must be limited in order to limit overall complexity, and the operations must be organized in order to simplify fabrication.

The second research question is:
Is it possible to establish a reasonable workflow, which indicates industrial feasibility?

Regarding architectural appearance the doubly curved optical fibre concrete screen is hitherto unseen, so prototyping it raises new questions upon the spatial appearance of the optical fibre based display system. Most of the light leaves the optical fibre in prolongation of its direction (Fig.2), and therefore it is expected that the concrete screen will appear most luminous on areas facing towards the person viewing it, and thereby the geometry will compromise the image quality.

The third question addresses this local small-scale issue:
Will the curved geometry result in highlights and influence image quality?

The fourth question relates to larger scale issues about architectural space, time and movement. It deals with the spatial appearance of the entire screen through qualitative and/or subjective evaluation of the concrete screen as an architectonic element.

The fourth question is:
How will the curved concrete screen appear in architectural space?

The sequence of the four research questions corresponds with the chronology of the experiment and the sequence of the five phases to be mentioned below.

Materials and Methods

The experiment consisted of five phases in total. Phase 1, 2 and 3 covered the research and technology development. The subsequent phase 4 and 5 were of more practical nature.

1. Pixel-pattern. Input image was divided into interface-pixels and each pixel is passed through its respective light optic fibre and became a surface-pixels. Pixels should be placed in a pattern that was able to transfer the two-dimensional input of the interface to a correct three-dimensional image output on the concrete surface.

2. Formwork-System. The metal plate would probably be replaced by a material that was stiff enough and could be shaped three-dimensional, so that the large quantity of optical fibres could be fitted effectively with a tolerance of less than 1mm (position) and 2 degrees (angle), and maintained so during casting.

3. Concrete. Low viscosity and small aggregates was necessary to ensure complete enclosure of fibres and avoid blocking between them. The concrete must be self-compacting (SCC) because previous experiments with vibration showed that air bubbles formed around the fibres. The requirement was a concrete surface of high quality, with uniform colour and without blowholes, which were suitable for subsequent grinding and polishing.

4. Removing formwork and surface finish. Critical to getting access to cast results to evaluate and achieve a satisfactory surface quality. The stage was research, but based on well-known manual technologies, which at the most could be automated.

5. Interface and projecting device. Necessary to use display technology to display images on a concrete screen. The stage was not a development, but based on the available projector technology having obsolescence thus should be regarded as interchangeable.

Pattern

First phase investigated different patterns and was solved with a triangular pattern [Fig. 3 and Fig. 4]. The interface was defined as a circular plane with a 60 degrees grid of interface-pixels.

The distance between the interface-pixels was kept as small as possible, in order to capture as much light as possible from the projecting device [Fig.5]. The concrete screen consists of the same triangular grid of surface pixels with varying angles and distances [Fig.6]. The two grids are connected with optical fibres, so any optical fibre endpoint in the interface (interface-pixel) refers to the same optical fibre endpoint in the surface (surface-pixel). The triangular pattern offers thereby true correspondence between the two-dimensional image and the three dimensional concrete surface. It is important to emphasize that this pattern is different from commonly used triangulation (also known as polygonal tessellation) because the amount and position of triangles must be identical in the two-dimensional interface as in the three-dimensional. This is a crucial point in order to obtain pixel correspondence between interface and surface resulting in correct image display on the concrete surface.

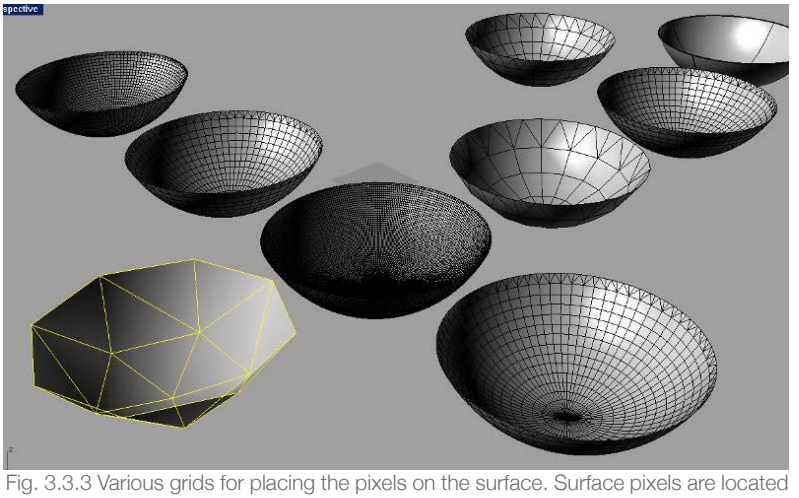

Fig. 3.3.3 Various grids for placing the pixels on the surface. Surface pixels are located at gridline intersections.

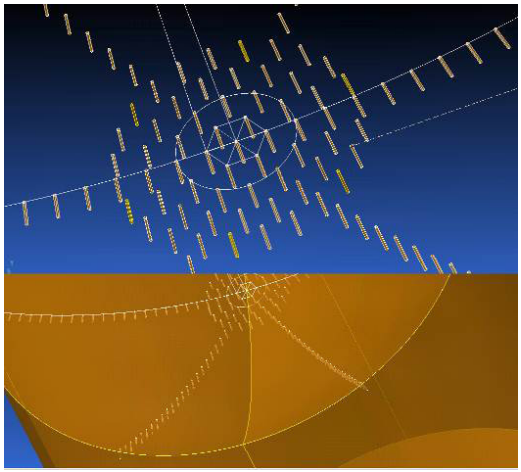

Fig. 3.3.4 Digital model of the fixing holes for the optical fibres in a double curved surface

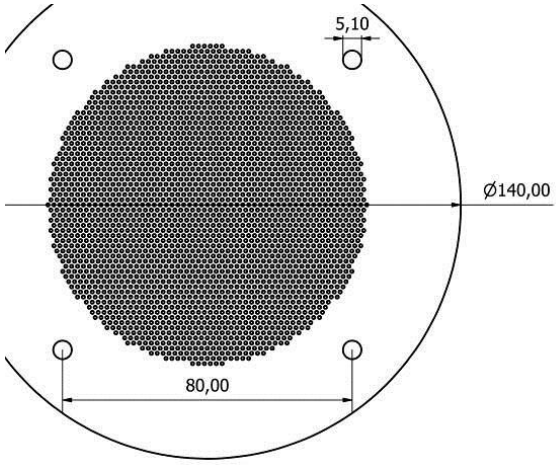

Fig. 3.3.5 Technical CAM-drawing of interface being used to instruct laser cutting of 8mm acrylic plate, into the interface plate.

Fig. 3.3.6 Flat interface placed upon double curved formwork to illustrate the pattern correspondence.

Formwork

Development of a new formwork system started from the known formwork solution consisting of laser-cut metal sheets. Various possibilities of forming metal sheets into desired shape were investigated. Hydro-forming and cold pressing were workable, but useless in relation the specific use and rejected for three reasons. Alternative formwork concepts were found. These formwork concepts were all based on block material being robot-fabricated by milling the geometry and drilling the holes for the optical fibres. Finally three formwork concepts were tested: A: Casting sand, B: Thermoplastic sheet vacuum coated expanded polystyrene, and C: Epoxy resin coated expanded polystyrene.

Formwork concept A [Fig.7] was acceptable in regards to milling geometry precision, but in regards to drilling millimetre-scale holes, the casting sand showed to be all too brittle resulting in un-precise holes, without sufficient ability to fix the optical fibres to maintain required position and angle precision. Furthermore, the hardness of the sand would wear out the drill after repetitive operations, and the weight of the casting sand blocks gave handling troubles. The solutions based on expanded polystyrene were both far easier to handle than casting sand due to an approximately 75 times lower density. The lighter and softer material characteristics of expanded polystyrene resulted in faster and better milling and drilling operations, but also in a need for strengthening the surface. This surface reinforcement should provide sufficient rigidity to fix optical fibres, without interlocking the formwork and the cast concrete piece after curing. Two surface reinforcement systems were tested: Thermoplastic solution (B) and a chemical hardening solution (C).

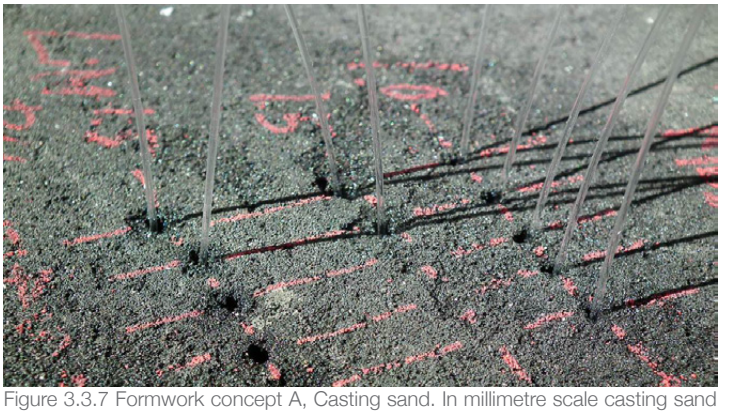

Figure 3.3.7 Formwork concept A, Casting sand. In millimetre scale casting sand showed not to be firm enough to fix and control optical fibres. Various drill sizes and types of glue were examined.

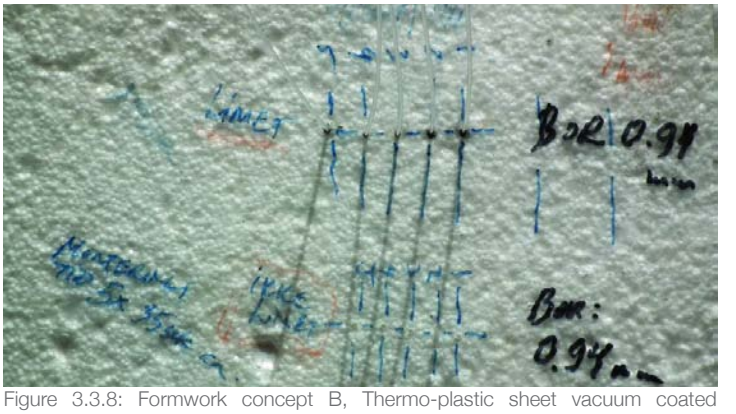

Figure 3.3.8: Formwork concept B, Thermo-plastic sheet vacuum coated expanded polystyrene. Holes in coating were fabricated with a 0.94mm drill to increase friction. Gluing showed nevertheless to be necessary.

The formwork concept B [Fig. 8] was not performing well in regards to geometry. The warm plastic-sheet combined with the vacuum, applied an amount of pressure on the milled expanded polystyrene so cavities were developed, and the material texture of expanded polystyrene was articulated. The rugged surface and especially the slopes of these cavities obstructed the drilling operation, since the drill was deflected as a result of not approaching the plastic-sheet orthogonally. Experimentally, this deflection lead to only slightly un-precise placement of holes, but statistically the deflection would result in breaking the drill during the required 3000 operations per prototype. The plastic sheet performed almost acceptable in regards to positioning the optical fibre but in regards to angle, the fixation was not deep enough resulting in un-precise angles. Forces along the fibre will occur during casting, and the frictional resistance between the chosen the 1.00mm optical fibre and the plastic sheet was too low to secure the fibre. This made gluing necessary. Gluing is an extra operation that has to be executed manually simultaneously with the fibre mounting. The worker will be in long-term contact with the gluing solvents, which definitely made formwork concept B not desirable.

The formwork concept C [Fig. 9] was developed to the far best performance of the three formwork concepts. Regarding geometry C-solution presented a better surface finish and its epoxy surface reinforcements was more gentle to the geometry, than the B-solutions warm plastic sheet and vacuum. Regarding the fixing holes C-solution showed to be better for three reasons: Firstly, the epoxy surface was trouble free to drill. Secondly, optical fibre positioning was accurate and the resin had penetrated into the expanded polystyrene resulting in deep reinforcement, which controlled the optical fibre in depth and maintained an accurate angle.

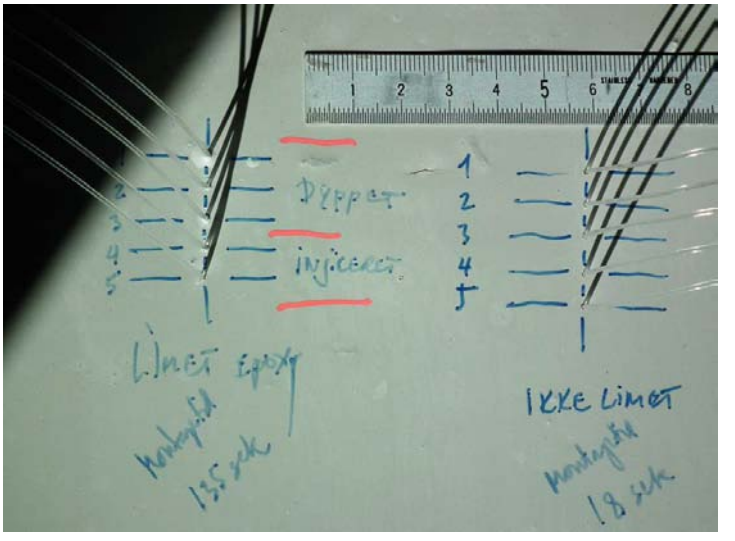

Figure 3.3.9: Formwork concept C) Epoxy resin coated expanded polystyrene. Five optical fibres mounted by gluing in 135 seconds(left) and five optical fibres mounted by friction only in 18 seconds(right)

Thirdly, the friction resistance between the optical fibre and the epoxy, combined with the increased contact area due to the increased reinforcement depth, lead to a fixing by pressure and avoiding gluing. This formwork concept C was taken further to full-scale development. The prototype formwork consisted of expanded polystyrene, grain size 250 and density 0.035 kilograms per litre. The formworks geometry was robot fabricated with a 40millimetre ball nose milling tool, operated with three degrees of freedom [Fig. 10]. The milled geometry was surface reinforced with an epoxy resin characterized by low viscosity to ensure penetration into the expanded polystyrene, and a grey colour to make fixing holes more visible to human eye to ease manual mounting of optic fibres. This resin strengthened the formwork in ten to twenty millimetres of depth and the formwork was reinstalled in the robot cell and carefully aligned according to the robots coordinate system. A specially made tool with a drill-tip of a 0.95mm in diameter was mounted on the robot and operated with five degrees of freedom fabricating the mounting holes for the optical fibres [Fig. 11].

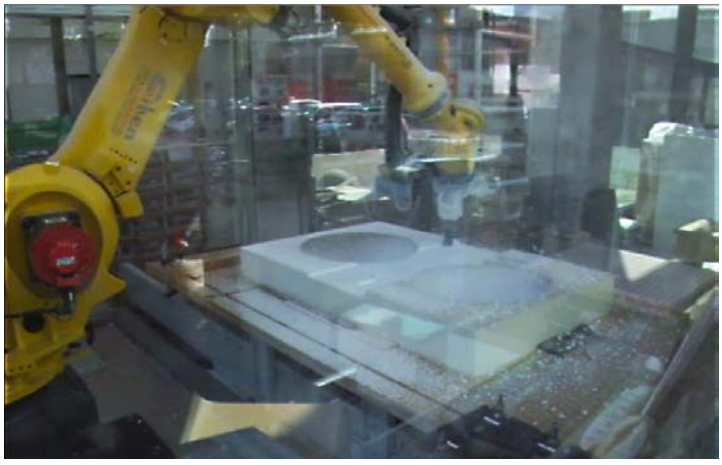

Figure 3.3.10. Formwork geometry fabricated by a six axes industrial robot milling the geometry in expanded polystyrene.

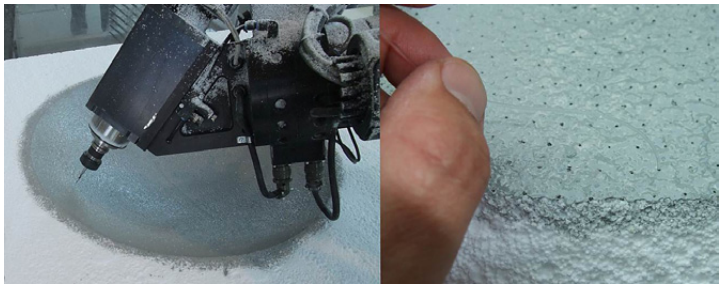

Figure 3.3.11: Robot drilling mounting holes (left), Manual mounting of optical fibres (right). Horizontal surface shows that epoxy resin has penetrated and reinforced the EPS in 10-15 mm of depth. This deep reinforcement improves friction and secures the angle of the optical fibre.

Approximately 3000 optical fibres with a diameter of 1.00 mm were manually inserted in each prototype formwork and connected to the interface. One fibre by one fibre, so each specific surface-pixel corresponded with its proportionate specific interface-pixel. After inserting the optical fibres in the spherical formwork a top was fabricated to give the cast concrete item a cylindrical bulk, which covers the fibres entirely and provides structural strength and rear-side suspension. The formwork was carefully filled with self-compacting concrete (Fig. 12). To obtain maximum binding between optical fibres and concrete, no release agents were used. In order to avoid formation of bubbles around the optical fibres no vibration was carried out during casting or after form filling. After form filling anchors were inserted into the fresh concrete of the cylindrical bulk, to provide hidden fixing points for projection device and for lifting, handling and suspending the cured concrete screen.

Concrete

Experiments were carried out with two types of certified self-levelling dry-mix mortar, referred to as self-compacting concrete. The two types were differentiating by the maximum size of aggregate and surface durability. According to their certifications, EN 13813, the

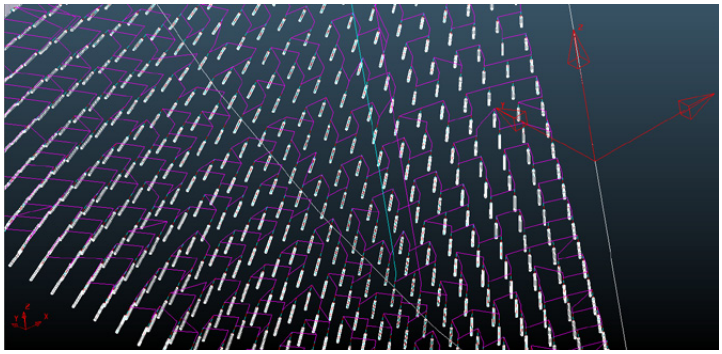

Fig. 3.3.12 Trajectories for drilling operations with five degrees of freedom, resulting in mounting holes for optical fibres.

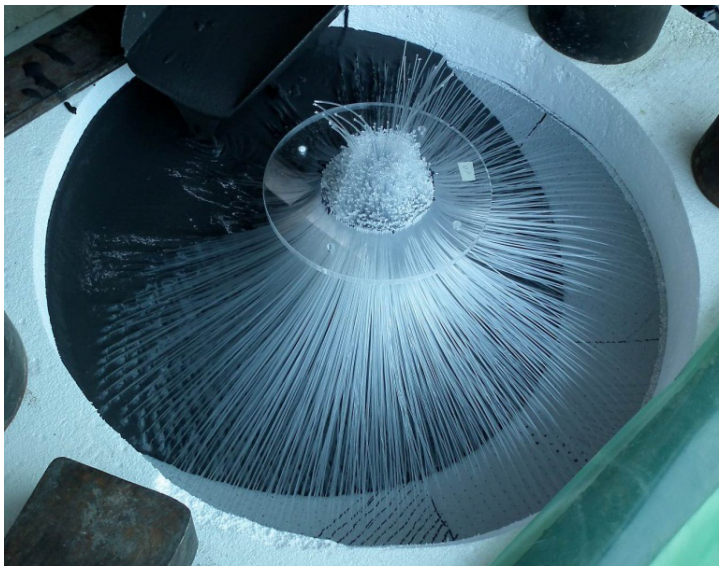

Fig. 3.3.13 Final formwork being carefully cast. Note the guidelines in formwork to maintain track of pixels positions during optical fibre assembly.

fine mortar was slightly stronger and lighter than the coarse mortar [Table 1], but only a difference in surface appearance was tested.

	Aggregate size	Surface strength, 1 week	Dry density
Mortar 1, Fine	< 1mm	>1.0MPa	1600 kg/m3
Mortar 2, Coarse	< 2mm	>0.7MPa	1700 kg/m3

Table 1: Key parameters of the two dry-mix mortar types used.

Fig. 3.3.14 Concrete shaded by different degrees. From left 9%, 3% and 0% Ferro-oxide pro rate share of estimated cement quota of dry- mix.

Ferro-oxide was blended into the dry-mix to shade the concrete darker [Fig.14]. A handful of blends were casted without fibres, to facilitate choosing the best blend for the final prototypes.

Three combinations were chosen to be tested with optical fibres.
Concrete 1: Coarse dry-mix without ferrous oxide
Concrete 2: Fine dry-mix without ferrous oxide
Concrete 3: Fine dry-mix with 9% ferrous oxide pro rate share of estimated4 cementquota of dry-mix.

Concrete 1 was used in a limited sample with 50 optical fibres (Sample 1) to demonstrate the interplay between coarse aggregate and optic fibre pixels. Concrete 2 and 3 was used in full screens with 3000 optical fibres (Screen 2 and Screen 3, respectively), to demonstrate the different appearance of light concrete and dark concrete. Afterwards casting all three concrete specimens were covered with plastic to secure hydration and cured for 24 hours at 20 degrees centigrade.

Fig. 3.3.15 Easy form releasing from the Concrete 3 (with ferrous oxide).

Fig. 3.3.16 Formwork sticking to Concrete 2 (without ferro-oxide).

Fig. 3.3.17 Optical fibres being cut. Formwork and concrete surface being grinded using dry rotating disks

Removing formwork and surface finish

After curing the formwork was removed destructively. It was observed that Concrete 3 containing ferrous oxide was easier to release from the formwork [Fig.15] than Concrete 2 not containing ferrous oxide [Fig 16], both without ferrous oxide. This difference in releasing properties was not investigated any further, because the optical fibres anyway had to be cut along the concrete surface, as close as possible, so removing the remaining formwork was not an extra operation not of importance. Sample 1, cast with coarse concrete without ferrous oxide, was given a coarse dry surface grinding and finish. Screen 2 and Screen 3, cast with fine concrete of different blends, were both given dry grinding followed by a wet polish. Finishing was executed manually with flexible rotating discs: For grinding sand/silica-based abrasive disks were used with a grit-size of 80, and for wet polish diamond-based abrasive disks were used with a grit size of 60-800 [Fig.18 and 19]. The finished concrete screens were let dry under normal indoor conditions and were not given any further surface coating or proofing within this experiment.

Fig.3.3.18 Final concrete surface after wet polishing with rotating abrasive diamond disks

Fig.3.3.19 Interface cut into a plane.

Completing interface and aligning projection device

The void between the concrete and the interface was filled with polyurethane foam, to fix optical fibres and the interface. The optical fibre length remaining outside the interface plate was cut away along the interface, using an electrically heated cutting wire [Fig.20], and the plane interface surface including the optical wire ends were sealed up with cyanoacrylate glue. The interface was ground [Fig.20]. A standard projection device was placed underneath the interface pointing upwards towards a mirror reflecting the projection onto the interface. This arrangement was necessary with the specific projection device to maintain focus without occupying too much space behind the screen.

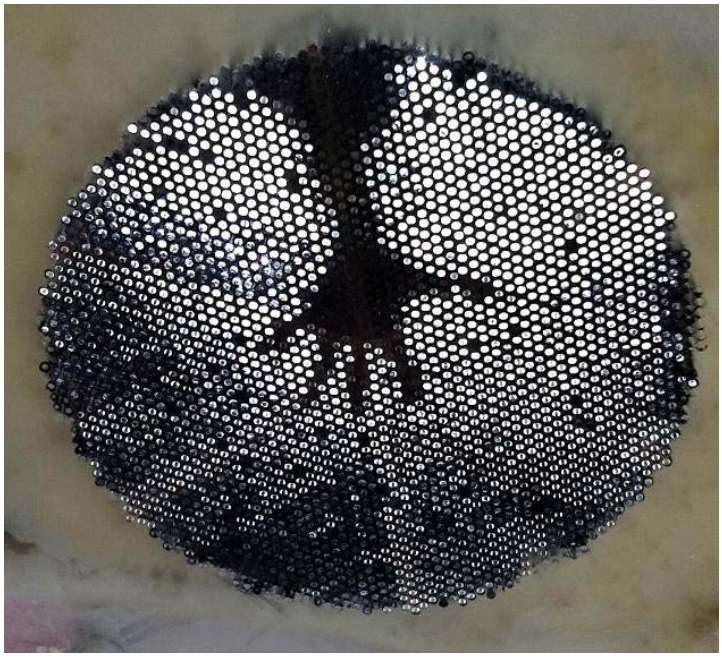

Fig.3.3.20 Final ground interface surface

Results and Evaluation: Fabrication and Appearance

For evaluation of the cast specimens were used and quantitative methods to evaluate the efficiency and accuracy in production. To maintain the general view at the experiment and cover the range of different issues the evaluation was done using a mixture of quantitative and qualitative methods. Quantitative methods assessed the efficiency of the fabrication process and precision and functionality of the resulting prototypes. Qualitative methods evaluated the appearance of concrete surfaces. The evaluations were partly made during the experiment informing the iterative technology development.

Fabrication and process complexity

The evaluation of the prototyped fabrication process showed that the industrial robot handles tolerances less than 1 mm, in spite of its relatively large working envelope and relatively large payload. It also showed that the robots head size limits it operational freedom, since the large robot head needed space to operate, which was the direct reason that the formwork had to be divided into screen and a formwork top. The combination of CAM-operations and manual operations proved to be feasible, when CAM provided precision and efficiency at well-defined tasks and handwork provided flexibility and solved less well-defined tasks.

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The formwork concept C, based on epoxy resin coated expanded polystyrene, proved to be rigid enough to control concrete and optical fibres during casting and yet relatively easy to remove after curing without damaging fibres and concrete. Ready-mix mortar proved to be useful in experimental setup regarding form-filling, surface quality and colour, but for larger application a mix design must be developed. The polished concrete surface was visually evaluated in different light conditions and in wet and dry condition. When the concrete surface was drying out micro cracks were revealed [Fig.21]. Apart from these temporary visible micro-cracks, the final surface appeared smooth and delicate, and the micro cracks had no constructive implication. If dark lines following the micro cracks when the surface is semi-wet would be regarded an aesthetic problem, this could be solved with a hydrophobic surface treatment. Hydrophobic treatments are well documented and will prevent the micro cracks to become visible due to water, and will also serve as a safeguard against dirt and smudging.

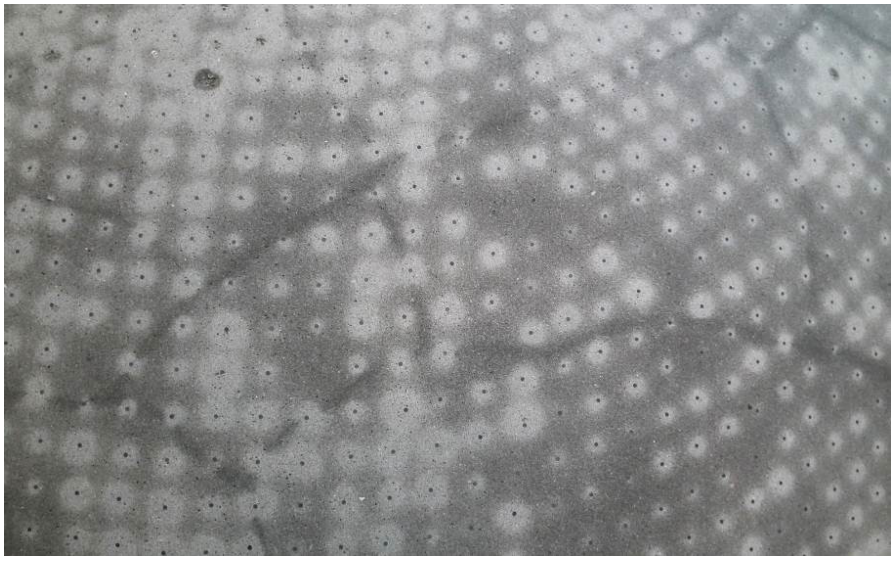

Fig. 3.3.21 Drying process revealed micro cracks in the concrete screen surface.

Concrete screen precision and performance

The position of surface-pixels were evaluated by spot checks where distances between surface- pixels in the cast concrete screen were measured with a flexible steel ruler [Fig.22] and compared to respective distances in the digital model. Furthermore the alignments of surface- pixels were measured. It was found that distances between the optical fibres corresponds with the distances defined in the CAD model within less than one millimetre, and the displacement from their average line was less than half a millimetre. Regarding the optical fibre position and geometry, the formwork system tolerance was established to be +/- 0.5millimetre. Variations in measures and alignment appears to be randomly distributed to both sides of the reference, so it is concluded to derive from the interaction between the epoxy coatings uneven surface and flexibility of the drilling tool, rather than from CAD-CAM errors.

Fig. 3.3.22 Measuring the relative position of surfacepixels, by alignment and mutual distance. 10 mm +/- 0.5mm

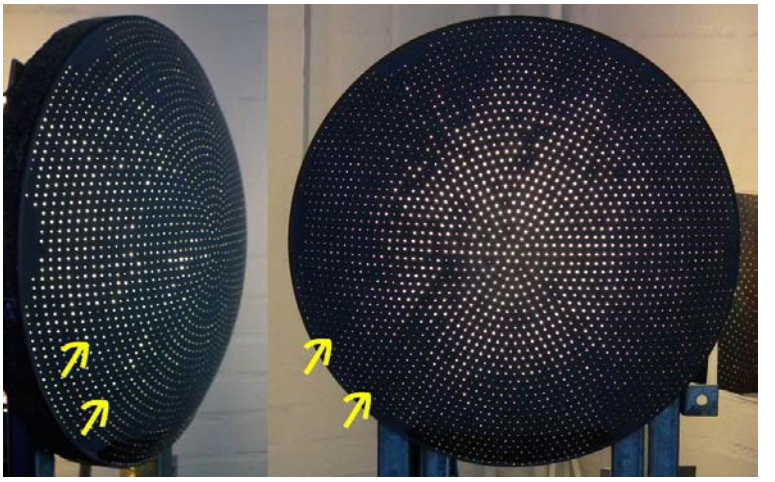

Fig. 3.3.23 Comparison of pixel luminance in side view (left) and in front view (right). Two rows of pixels seems to be 'pointing side-wards' indicated by yellow arrows

The angle between the optic fibres and the concrete surface was more complicated to prove.

Since the optical fibre is a cylinder, the surface-pixel is an ellipse created by the surface cutting through the optical fibre. By virtue of this, the angle of the optical fibre could theoretically be measured by the ratio of the surface-pixels widths and its length. If the cylinder (the optical fibre) is cut in a right angle the cross-section becomes a circle. A circle is an ellipse with equal length and width. So, if the measured ration is 1, it can be deduced that the optic fibre is cut (and cast) in a right angle. The more the fibre deviates from being cut in a right angle, the more the surface-pixels width deviates from its length, and the ratio deviates from 1. Practically it was not possible to measure width and length of the surface pixels, due to their small millimetre size, so light intensity in different viewing angles [Fig.24] was used to determine optical fibres orientation due to their light concentrating character. This evaluation method also aligns with the overall goal of obtaining surface pixels with equal luminance.

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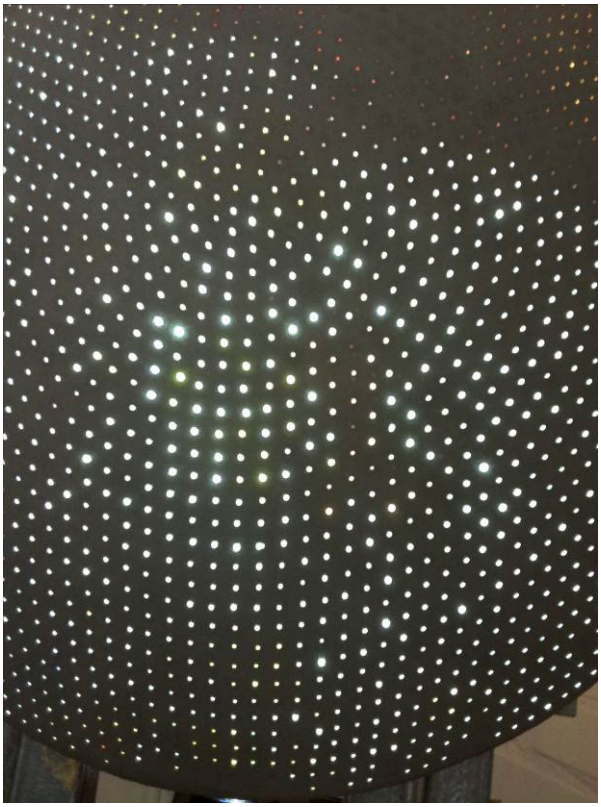

Fig. 3.3.24a Cast screen lightened with white light. Variations in pixel luminance

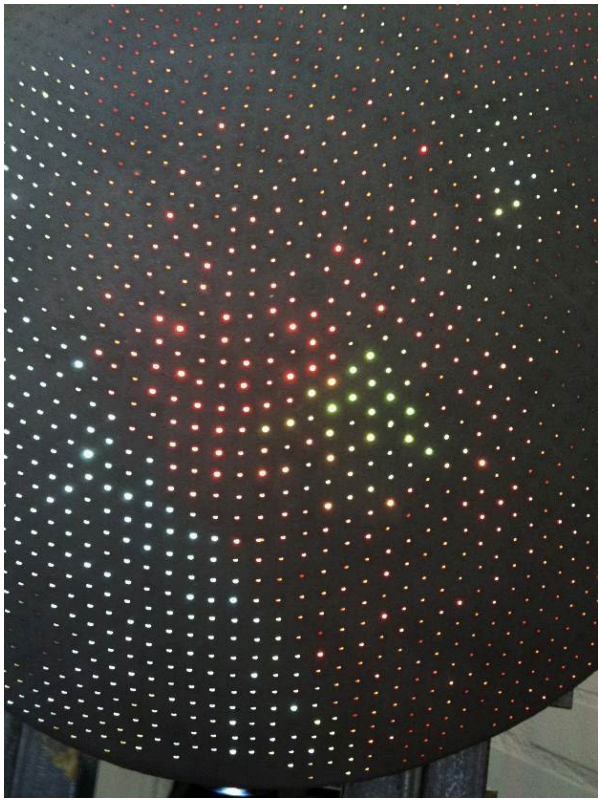

Fig. 3.3.24b Cast screen lightened with coloured light. Variations in pixel luminance.

Screen 2 and Screen 3 was investigated leading to ambiguous results, defining two sources of error. Firstly, optical fibres that were cast in un-precise angles were discovered [Fig.23]. The luminance of these two rows peaked about 35 degrees from right angle to the surface. This luminance variation, which is directly connected to different viewing angles establish certainty that these two rows of optic fibres have an irregular angle to the concrete surface. Secondly, the evaluation pointed out variations in luminance, which were not dependant on viewing angle [Fig.24]. It was found that these differences derived from un-even grinding of the interface.

The interface-plane and the correspondence between surface-pixels and interface-pixels were investigated by the surface being lighted from outside and a hand affording shade upon the surface-pixels. The interface-plane on Screen 3 had two dozens of dead pixels. Half of the pixels were lost into the interface due to insufficient gluing, the other half suffered from no connection to their surface-pixel. It was concluded that their fibres had been damaged or broken during concrete casting or more probable by high frequent vibrations during sanding of the interface. The Interface-plane on Screen 2 [Fig.25] had five dead pixels – all caused by insufficient securing. Furthermore Screen 2 suffered from an area of scrambled pixels caused by erroneous manual fibre mounting, and a displaced row of surface pixels caused by erroneous laser cutting of the acrylic interface plate.

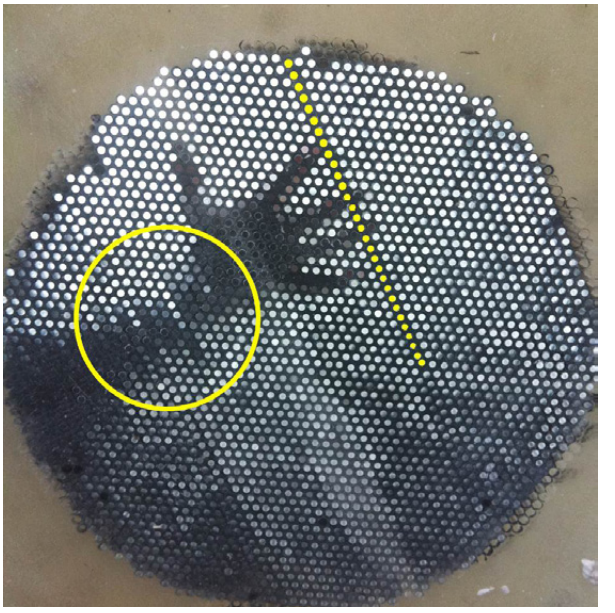

Fig. 3.3.25 Investigating pixel correspondence (below). Interface of concrete screen 2 (left) showing scrambled area (yellow circle), a displaced row of interface-pixels (yellow dots) and five dead pixels (black).

A summary of the evaluation results accounts:
Lost interface-pixels were thirty out of six thousand, approximately 0.5 percent;
Lost surface-pixel was one out of six thousand, less than 0.02 percent;
Scrambled area as result of fibres being transposed during mounting was estimated to five percent of the area;
Uniformity of pixel luminance was considered not quite acceptable.

Concrete screens appearance and image depiction

In general it was obvious that moving images appeared as better quality, than still-images. This phenomenon is described in literature (Fausing, 1999), and is caused by interplay between technical and perceptual phenomena. Technically, because the image moves across the display and the limitations and errors of the display is spread evenly over the image, because the human eye is not locked to the screen, but follows the image. Perceptually, because human vision works dynamically by over time storing what it sees, and thereby the human eye is able to fill out the blanks and compensate for low resolution or poor image quality. A still-image does not have these advantages and will appear with errors and holes, which the human sight even keeps it-self busy over time by investigating.

The triangular pattern demonstrated ability to maintain pixel position and but yet allowing variable distances between surface-pixels, and therefore offering form freedom to design the concrete surface. The two-dimensional was successfully transferred to a three-dimensional output displaying a correct image depiction [Fig. 26]. This depiction wraps around the concrete surface like a mapping wraps around a digital model. Furthermore, evaluation of the displayed image showed on one hand that the experienced image quality profited from the three major directions in the pattern (compared to a regular pattern with only two directions). On the other hand, the centre of the pattern was visually compelling, locking the eyes to the screen.

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Fig. 3.3.26 Concrete screen displaying a flower, reference on the computer screen, the 2D input (interface-pixel) is transferred to the to 3D output(surface-pixel)

Simple images perceived from a distance, was appearing with a highlight on the top of the surface, the area facing directly towards the observer [Fig.27]. This highlight confirms the expectations presented by research question 3. The evaluation result was that the triangular pattern and developed formwork system offers a non-distorting concrete screen with a high degree of formal freedom, but the highlight on the areas facing towards the observer poses a limitation upon this forms relevance.

Fig. 3.3.27 A simple image of traffic sign displayed on the concrete screen. It illustrates the highlight occurring on the part of the surface facing directly towards the viewer due to the light leaving the optical fibre in prolongation of its directions and the optical fibre being cast in right angle to the surface.

By the three evaluated concrete surfaces it was noted that aggregate size was a very important parameter in relation to surface-pixels and material texture. Larger aggregates were beneficial in order to camouflage the surface-pixels when un-lit. Sample 1 showed that using larger aggregates poses an important potential for utilizing optical fibres in architecture, because when the optical fibres were unlit they simply disappeared among the coarse aggregate [Fig. 28]. This ability to disappear was resulting in a more surprising concrete surface with hidden display technology than the fine concrete mixes (2 and 3). It was also judged to be a respectful application of the technology, showing deference to the aggregate and to potential tranquillity of architecture. Due to the limited size of Sample 1, more experiments in larger scale must be undertaken in order to inform any further result and even conclusions.

Fig. 3.3.28 Unlit pixels disappears in the surface camouflaged by coarse aggregates

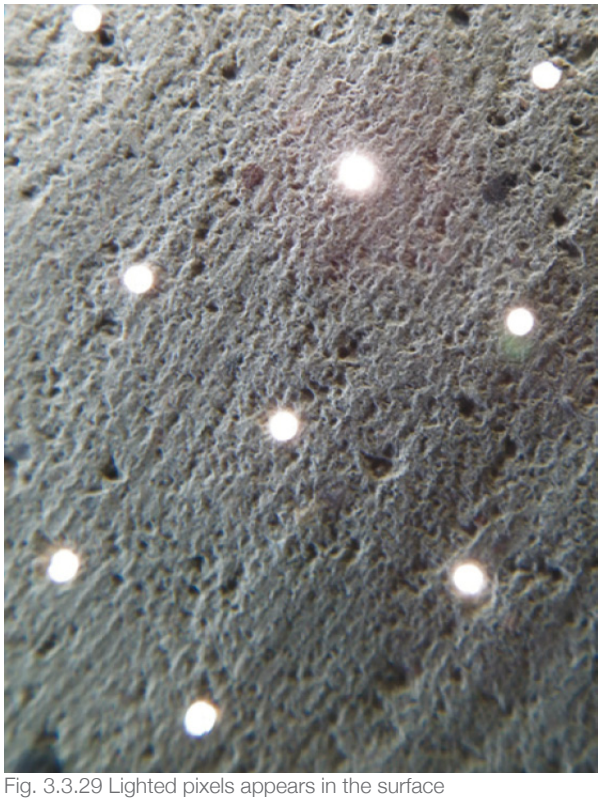

Fig. 3.3.29 Lighted pixels appears in the surface

Results and Discussion

With the evaluation results in mind, the research questions can be answered.

The first two questions were dealing with fabrication of the concrete formwork:
Are the robot-operations precise enough to place relatively small optic fibres?

Yes. Bridging precision and efficiency is possible. Fine tolerances can be fabricated utilizing a medium duty industrial robot, which also can be used to fabricate the geometry of the concrete formwork.

Is it possible to establish a reasonable workflow, which indicates industrial feasibility?

Perhaps. It is possible to combine the flexibility of manual operations with the precision of computer-aided manufacture and provide a feasible fabrication process for a small scale or experimental setup. If the demonstrated process is feasible in larger scale is not proved, and at least implementation would require expertise from relevant industries like textile or composite material industry.

The third question and fourth question were regarding architectural appearance of this hitherto unseen concrete surface.

Will the curved geometry result in highlights and influence image quality?

Yes. Curved surface geometry influences and reduces image quality displayed on the optic fibre concrete surface. A highlight cause different luminance and furthermore the curved surface causes a perceived distortion of the image. This distortion is similar, but reverse, to the distortion the embedded display system was meant to prevent.

How will the curved concrete screen appear in architectural space?

Ambiguous. As a result of the highlight occurring upon the areas facing towards the observer, the doubly curved optic fibre concrete screens appear transparent. When the viewing angle is changed the highlight follows the viewer. So not only the live images are moving but the optic fibre concrete surface itself seems to be moving. This causes on one hand a vibrant and perhaps intimidating appearance. On the other hand the material texture of the surface causes a calm and solid appearance, which apparently results in tactile curiosity and draw people to approach and touch the optic fibre concrete surface.

Regarding an architectural context and the considerable size of buildings it is important to note that the amount of surface pixels will grow exponentially with the size of the cast concrete surface, so the manufacturing process must embrace project specific adjustments when going into architectural scale (Scheurer, 2008) Pixel size can be changed by altering the diameter of the fibre and of the drilling device. The amount of pixels and distance between them can be changed by CAD. The formwork can easily be divided via CAM. This division will optimize manual mounting of optical fibres, and the final grinding and polish will insure a seamless surface. With some adjustments the demonstrated manufacturing process might be termed new industrialization, and is able to deliver mass customization

(Jørgensen, 2007) for high-end concrete buildings, but in spite of these potential improvements, obtaining sufficient resolution still seems to be the bottleneck: 3000 pixels is equivalent to a resolution of 55x55 points within a traditional regular grid. To put this into perspective, the screen on a normal hand held device has a 200 times higher amount of pixels [Fig 30]. Therefore, it is not likely that optic fibre concrete will be able to compete with contemporary fast moving information technology.

Fig. 3.3.30 The covered area of 3000 pixels on a smart phone illustrating today's standards of density within information technology. 2009. Apple Iphone4 960-by-640-pixel resolution at 326 points per inch.

On the other hand when the prototypes resolution is compared to a contemporary state of the art building, it apparently belongs to the leading field. The Ganterbein Vineyard is a brick building envelope with embedded images showing stylized grapes, built in 2006. The bricks were rotated and placed by a robot, with sufficient accuracy to turn every brick into a single pixel forming an image covering the facades. The amount of pixels embedded in one façade [Fig.31] is equivalent to the amount of pixels embedded in the optic fibre concrete prototype.

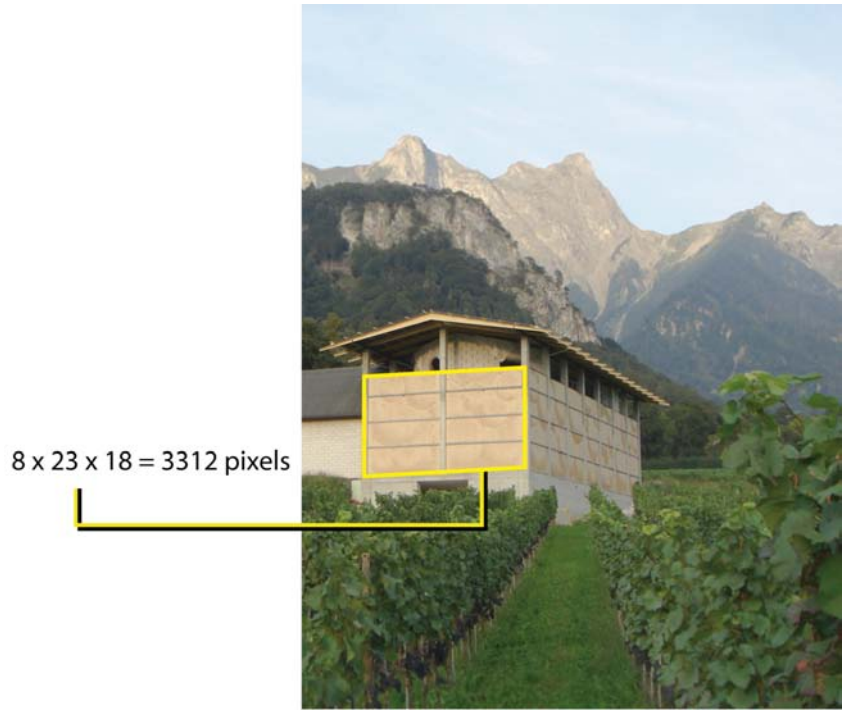

Fig. 3.3.31 The covered area of 3000 pixels on Ganterbein Wineyard façade illustrating resolution in state of the art building. Fläsch, Switzerland, 2006, Gramazio & Kohler.

Traditionally brickwork is a composite material consisting of brick (stone) and mortar (binder).

Likewise concrete as building material is a composite consisting of aggregate (stone) and cement paste (binder), but concrete has sometimes nevertheless been conceived as a homogeneous grey mass since its material composition is not conspicuous. The innovation that is illustrated with Ganterbein Vineyard and with the optic fibre concrete prototype concerns a new type of composite material made possible with robots engaging in operations which is falls more in the category of material processes, than in the category of geometric fabrication: The brickwork in Ganterbein Vineyard is not utilizing mortar to adhere the bricks, but epoxy resin as adhesive. This binder is not visible, and the building surface appears to be composed by small transparent elements and small opaque elements. Or, in direct light conditions, the building surface is a composition of small light elements and dark elements created by shadows. The changing light conditions let light and shadows interplay, and gives the building surface a dynamic textural effect. Likewise, the optical fibre concrete prototype appears as a composite material with translucent elements and opaque elements. The translucent elements, the optic fibres, are mainly lit from behind, but they also intercept surrounding light causing local textural highlights. This materialized texture results in an interplay with the concrete and especially the polished natural aggregate. We would argue that the optic fibre concrete should be conceived as a building surface with a dynamic textural effect, deriving from the interplay between opaque subdued concrete and the light fibres, rather than being conceived as a piece of information technology.

Conclusions

The conclusion of this paper is that utilizing robots within fabrication of concrete building, opens new perspectives: The research shows that robots have already been applied in building practise, and that controlling and embedding an outstanding amount of delicate inserts is now technically possible. This technically possible fabrication method procures a new potential architectural appearance of concrete architecture. The demonstrated optic fibre concrete could technically be applied in any concrete surface – both prefabricated elements and in-situ cast. It could be applied on a large area like a screen or a smaller area as a part of a larger uninterrupted concrete surface.

The prototyped fabrication method shows that it is possible to use a medium duty industrial robot for CAM-fabrication of delicate and complex concrete formwork. The robot demonstrates both precision and speed. This finding is based on drilling holes with a diameter of one millimetre for placement of small optic fibres, but there is no reason to believe that this finding should not apply to other types of concrete formwork, and that the embedding can be customized and executed within a reasonable economy. The general crucial point is that the efficiency of computer aided manufacturing, must be combined with the flexibility of craftsmanship. Specifically, the robot can be used in combination with manual operation to fabricate expanded polystyrene formwork with rigidity and precision enabling replacement of the traditional metal sheet based formwork. This method can provide hitherto unseen geometrical freedom for concrete surfaces with embedded optical fibres. The amount of inserts combined with the geometrical freedom illustrates how industrial robots are able to work beyond geometric fabrication and attend to material processes.

The prototype shows that optical fibres are a feasible technology to make concrete surfaces display images and thereby offer future architectonic and spatial possibilities. Scale, size and information density are crucial factors in the challenge of bringing these new possibilities into architectural practice, and further investigations are required to understand these new spatial possibilities. Moving images are a way to increase the perceived image quality, but moving images must be used with care due to architectures tradition of standing still. Optic fibre concrete surfaces must not be employed as traditional information technology, but must be comprehended as a new transparent architecture.

Johannes Rauff Greisen M. Arch. Ph.D. scholar at CINARK, RASA, finalizing his work on architectonic potentials in utilizing robot fabricated formwork for concrete building. He is a university teacher and author of five articles on concrete and architecture. He also provides commercial consultancy on robot driven concrete solutions. Johannes is employed by the Danish Technological Institute and provided contributions to the Danish research project UnikaBeton. He is currently engaged in three EU-FP7 research projects: TailorCrete extending form potentials for concrete building, Light2Cat embedding solar driven catalytic systems into concrete surfaces, and DigiStone making digital signage applicable within concrete street furniture.

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3.4
Learning by Doing: an Immersive Manufacturing Experience with Undergraduate Architecture Students

Guillermo Guzman Dumont [i]

Context

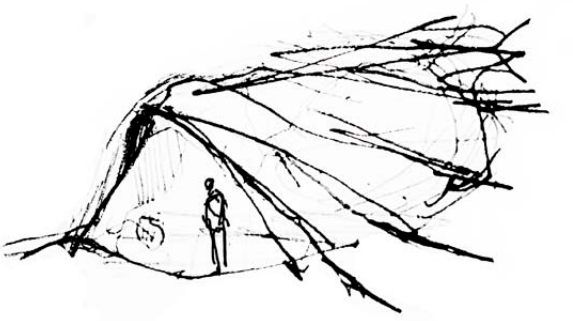
There is an ongoing debate in schools of architecture about how effective is the transfer of knowledge and skills from taught modules into design applications in studio for undergraduate students, before they got into their year out in practice. How much of it is internalised and made applicable into real experiences, and whether current studio assignments are allowing this to happen. This paper describes a pedagogic experience at the department of Architecture and Built Environment of the University of Nottingham, in which various prototyping strategies were implemented in order to optimise the design and manufacturing of a pavilion that was presented at an international exhibition: The Nottingham Shipping Shelter: a fleeting retreat. The invitation came from Ecobuild, the world's largest sustainable construction fair, and consisted in delivering, in a very short period of time, an efficient and attractive structure to become a visitors resting area, consisting in sheltered seating plus information displays at their event in London on March 2012.

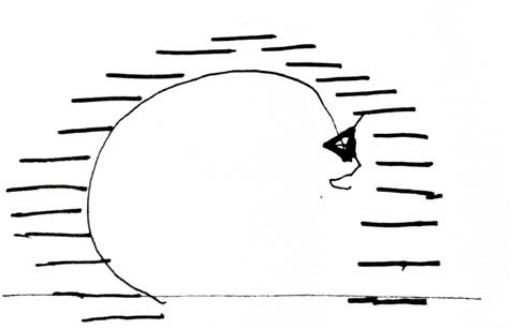
Fig 3.4.1 The Nottingham Shipping Pavilion being presented at Ecobuild

Competition

A design competition was organised across the 2nd year of Architecture course as part of an integrated design module, in order to make it a wide opportunity for engagement in a live project. The project brief emphasised on the location flexibility, rapid assembly, transportability and economical feasibility, specifically in the source of materials. 22 proposals were presented and after tough deliberation, two design proposals were chosen, both using the same material but with different conceptual and physical approaches, so they could be integrated and built as one concept. Fourteen students integrated the two designs and developed a final concept, which was completed through the fabrication of the pavilion at university facilities during February 2012.

Fig 3.4.2 Nottingham School of Architecture Students defining the geometry of the arch





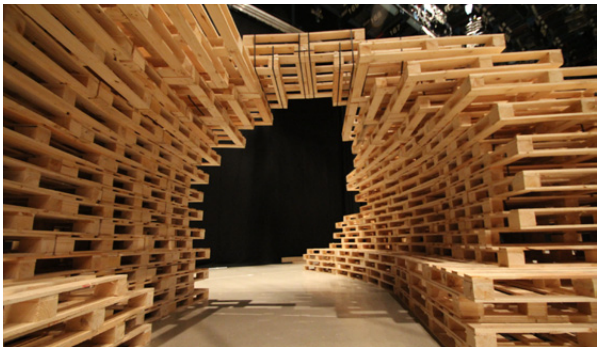


Fig 3.4.3-8 Sequence of images from the conceptual sketches to the final piece

Constrains vs. opportunities

The exercise was designed to put to test, the knowledge and skills learnt at previous year's theoretical modules and to deal with time, logistics and budget restrictions as design enabling factors rather than constrains. The idea of appropriateness and feasibility were taken at an ingenious context as the sourcing of the materials and the operative logistics took a massive role. Special encouragement was given to the possibility of engaging with industry to source materials through sponsorship or to identify opportunities of adding value to discarded elements from the construction industry by recycling them. It was also very important to conceive an assembly and montage strategy that required not only limited time to be done, but also less equipment, implements or machinery.

The parametric design: repetition vs. replication

Made from reusable timber pallets, the structure of the Fleeting Retreat is scaled and sculpted from something once linear and static into something organic and flowing in form. A curled leaf inspired the form of the pavilion and the leaf's arbitrary and transient nature paralleled the journey of the shipping pallet. It was that movement of people and their journey between buildings and places, which provided the link to the choice of material. The design approach started with an exploration on digital 3D models (CAD) using Rhino, then through scale physical models to culminate with the 1:1 scale modelling to consolidate the design.

Repetition in parametric design is the multiplication of an object, with specific properties, for the production of a whole. The form and main characteristics of the pavilion were generated using this approach. This repetition was ruled by a pattern of association between the parts, where an essential connection was defined to achieve structural integrity between them, which was then tested in different angles and displacements towards the achievement of its particular geometrical organic integrity. Several full-scale mock-ups were built to test the structural behaviour, resistance of the units and the strapping system.

On the other hand, the replication of the model, understood as the process of multiplying an object while altering its properties to produce an evolved version of it, occurred when a number of versions (iterations) were developed in preparation for the event at Ecobuild. This was initially aimed to rehearse the assembly process, but it also generated remarkable improvements to the aesthetics and efficiency of the geometry from version to version. In this process the relationship between the 1:1 scale assembly and the CAD model was fundamental. First to inform the tracing of the starting points for the assembly, and then to record the steps made during it, both the successful and also the mistaken ones, so this as-built record could assist the production of the following version incorporating improvements to it. This generated a fluid bi-directional dialogue between the CAD and the real model. In this process it was fundamental for the students to use their knowledge in structures, construction and architectural theory in order to debate and resolve the challenges that were arising along the live construction process.

Fig 3.4.9 Students learning the use of the strapping system

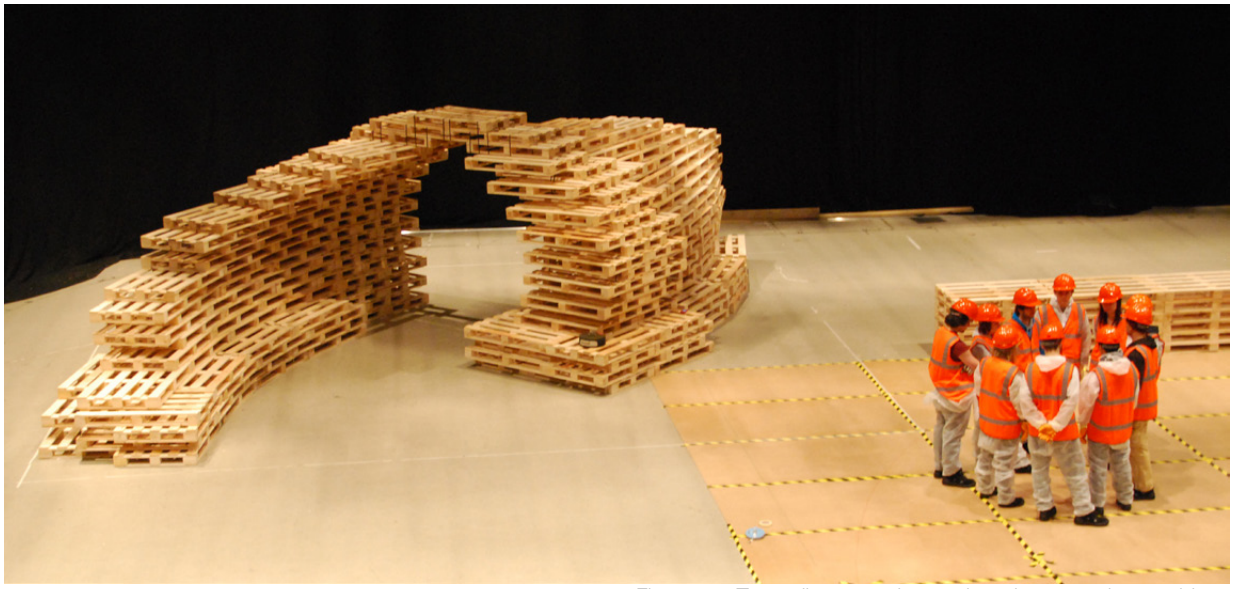


Fig 3.4.10 Team discusses the result of the second assembly at The University of Nottingham

Fig 3.4.11 Assembly process

This has been successfully tested when the pavilion received an invitation from Nottingham City Council to be re-assemble and adapt its design to different contexts: first at the Nottingham Castle for the Olympic torch relay event in July 2012 and recently at the Light Night event in the Old Market Square, Nottingham in February 2013. This last event represented an additional challenge for the project, as there was a new group of students to assemble it. Guided by a few members of the original team and supported by drawings and photographic records of the previous events, this new group was able to confidently join the task and fulfil the time and resources requirement.

Fig 3.4.12 People visiting the Pavilion at the Nottingham Castle

Fig 3.4.13 The design and build team at the Nottingham Castle

Fig 3.4.14 Nottingham Shipping Pavilion being assembled at the Old Market Square in Nottingham's city centre

Fig 3.4.15-16 Nottingham Shipping Pavilion in Old Market Square, Nottingham

With the belief that by combining digital exploration with the capacity of building the designed forms, a precedent is set up for all future attempts of using the potential of the digital resource more consciously and with full awareness of the spatial and formal implications of their design decisions. This establishes a rich interface, an open dialogue between the different mediums of exploration towards a high quality product, as well as a sensible process. This also allowed the group of designers/builders to be immersed into a more participative environment, generating an inclusive and rich debate during the production of the proposals, which extended their engagement into additional roles like: graphic and web design, communications and social media, clothing design, etc., all in preparation for presenting the pavilion at Ecobuild. The pavilion received the runner up prize for sustainable stands, awarded by the Green Building Council UK at Ecobuild.

Further stages of this research consider the elaboration of a full set of plans and instruction manual for further events that would involve the pavilion and the monitoring and assessment of the results of the students that participated in the project in their final year of their undergraduate course, both in studio and taught modules, in order to determine the real contribution of this pedagogic experience.

Conclusions

This experience demonstrates that a project like this can effectively enhance the learning capacity and theoretical knowledge integration of the students involved, and set a different attitude towards future, more complex design assignments, including important elements of recognition, public engagement and therefore to become an even more competent professional.

Fig 3.4.17 Nottingham Shipping Pavilion at the Light Night Festival [ii]

References

i Guillermo Guzman Dumont is a Lecturer in Architecture at Department of Architecture and Built Environment in the Faculty of Engineering of The University of Nottingham.

ii Image Credits: Fig. 1-2, 9-20 © G. Guzman and Fig. 3-8 © James Brimble.

3.5
Knitectonics

Sanhita Chaturvedi, Esteban Colmenares and Thiago S. Mundim [i]

"...techniques that operate on a material level, if we need ideas, will follow from techniques and techniques follow from matter..."

Gottfried Semper[ii]

Can a simple household craft facilitate a proto- tectonic system? The research aimed at exploring digital fabrication systems that facilitate optimized, adaptive and specific integrated architectural solutions[iii]. The project explored on-site fabrication of *monocoques*[iv], thereby integrating skin and structure along with services and infrastructure. It is inspired by the beauty of nature systems with their inherent efficiency and performance and strives to embody a self- organized micro system of textures and a macro system of structure. This paper elaborates how a textile technique instigated a pristine approach to real- time design and customized production. Material research and technical experimentation were followed by application of the associated numeric aspects of the technique, first to digitally imitate the process of assembly and further exploited to develop and visualize the novel fabrication system. The digital machinic system was then deployed on a test site to demonstrate the tectonic capacity of the method developed.

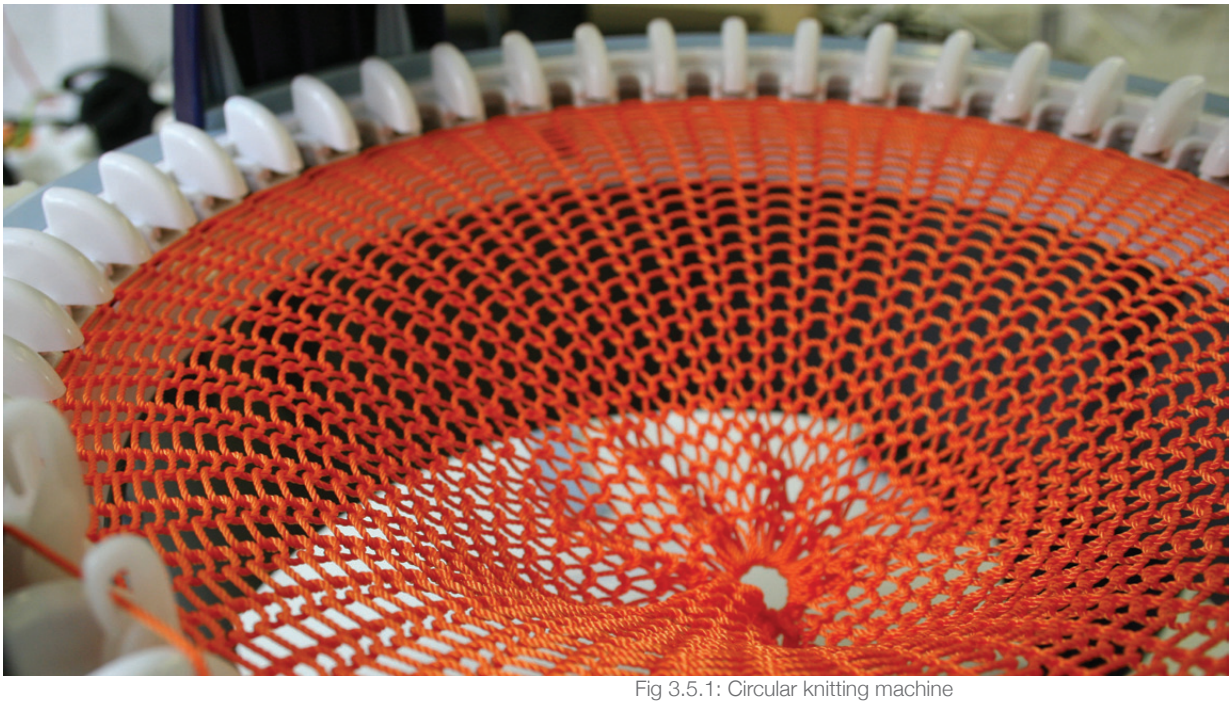


Fig 3.5.1: Circular knitting machine

Knitectonics commenced at the Design Research Laboratory at the Architectural Association as a part of the Proto – Design Agenda. The agenda investigated analogue and digital forms of computation in the pursuit of systemic design applications; wherein materials and production processes perform as active agents to accomplish an architectural approach that is both adaptive and hyper specific.[v] In the last few decades, material and manufacturing research has been increasingly multidisciplinary and poly- scalar in an attempt to imbibe efficiency and performance across disciplines. Within the design-based disciplines also boundaries have blurred and diluted as high- tech digital fabrication processes are utilized in all stages- from conception to materialization.

The project premise for the project was to re-engineer standard design and construction processes to achieve *economy of means*. Economy of means can be defined on various parameters, as efficiency of material, machine, infrastructure, energy, time etc. The research initiated with study of monocoques in nature as well as the man- made world, where the skin is the structure to achieve economy. Concrete shells are the most exemplary examples of monocoques in architecture; however due to elaborate formwork the use of shell construction techniques declined over time. The challenge was to identify a new system, beyond the limitations presented in existing construction technology by reviewing the need for formwork and proposing a self-structuring prototypical system, which can be fabricated on- site.

The biological world is an unsurpassed source of ideas of generating and sustaining integrated solutions. While attempting to emulate similar forms, the major hurdle for designers is to achieve complex forms with proficient use of resources. In nature things are manufactured molecule by molecule; human artefacts are constrained by practical and economic limitations of our construction technology.[vi] A significant observation through the research was that in nature self-structuring form is one of the most prominent methods to economise on time and energy and eliminate material waste. By extrapolation, *self-structuring forms* can be achieved in the man-made world by employing a continuous fibre so that the material could be placed optimally; this continuous membrane allows structural loads to be transferred evenly across the surface.

Design Research

The initial experiments were to study fibres and matrix composites and their behaviour to form structural skins, followed by an attempt to eliminate formwork. The inference from the experiments was that material behaviour depends on the type and density of fibres, while surfaces can be optimized by organizing and differentiating fibre-matrix material distribution.

Textiles have often coincided with architecture throughout history; today with the emergence of composites they are predicted to be at the core of a revolution in architecture. [vii] Gottfried Semper located textile as the first technical art in his book -*The Four Elements of Architecture* (1851)[viii] and recently Peter Testa Architects proposed a textile prototype tensile building system for a 40-storey carbon fibre tower. The potential of textiles becoming tectonic elements is apparent in the quote by Lars Spuybroek, *"soft elements will become rigid through collaboration, by teaming up, weaving, bundling, interlacing, braiding, knotting and knitting."*[ix] Enquiring into the production processes in the textile industry provided an insight into techniques used for mechanically manipulating fibres into three- dimensional fabrics. The techniques are interweaving (fibre placement, 3D weaving, stitching), intertwining (twisting, braiding) and inter-looping (knitting). Technique of knitting was desirable as the continuity of material gave the opportunity to create structures without any formwork.

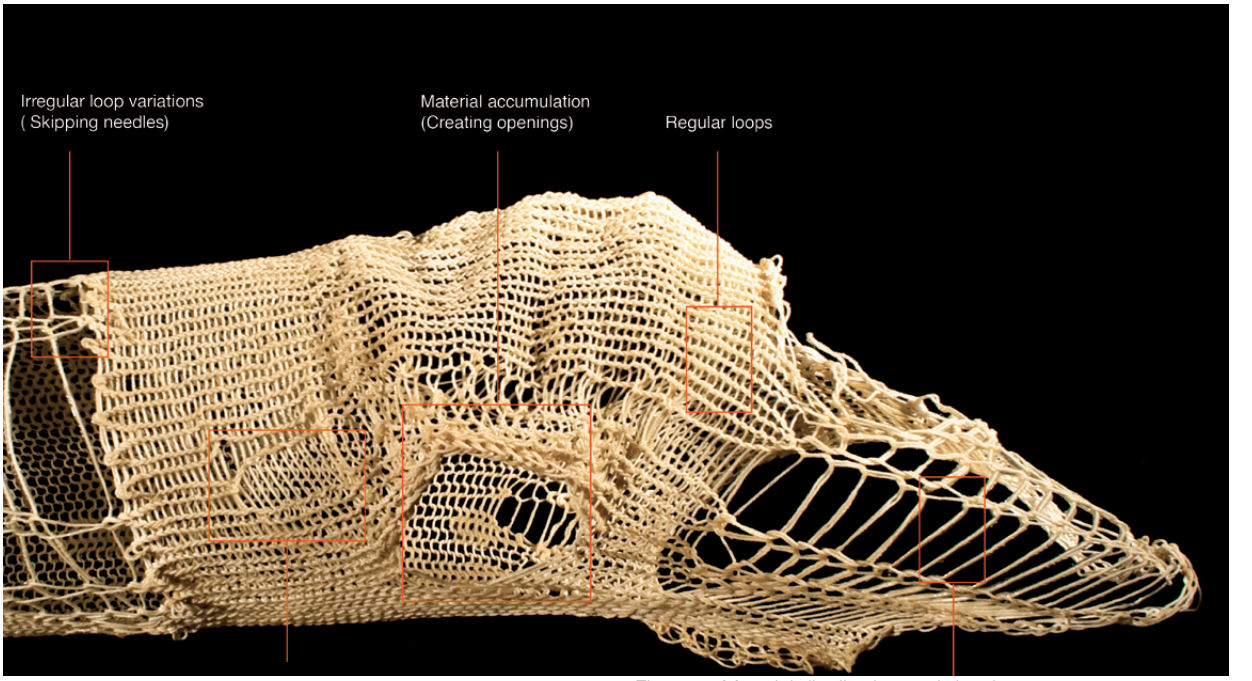


Fig 3.5.2 Material distribution and density

Knitting can be described as a technique for constructing a two-dimensional fabric structure from a continuous length of one-dimensional yarn, which allows creation of flexible fabric with different patterns and the capacity to create to shape. Knitting machines work on the same principle as traditional hand knitting. The machine used for analogue experiments was a household circular machine and the two basic topologies created are cylinder and flat. The first experiments were aimed at understanding machine mechanics, material combinations, knot variations, topological connections to create holes, differential deposition of materials and patterning of the surface. The inference was that the topology, density and rigidity of the knitted output are dependent on these parameters: machine (size), track (shape), head (movement), yarn feeder, yarn (thickness and number of strands), knot (size), gravity, tension, resin type and solidification time.

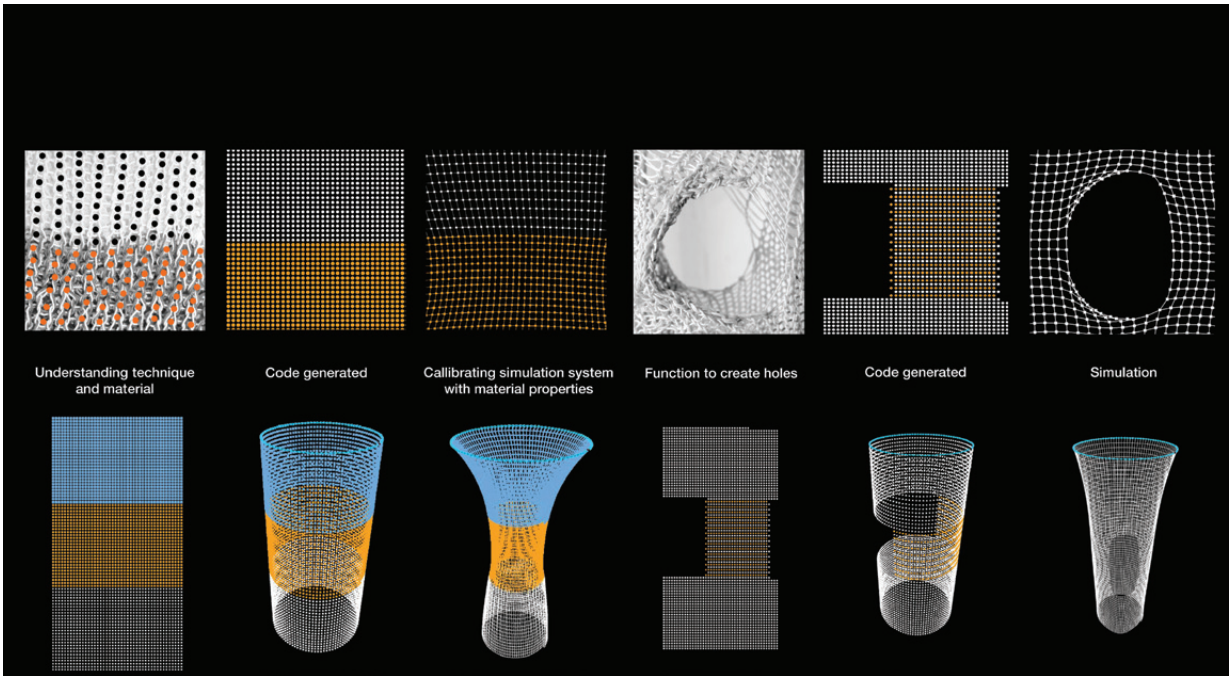


Fig 3.5.3 Knitting decoded

CNC Knitting: In order digitise the process the mechanical machine was translated into a CNC machine. This required hacking in two aspects, firstly digital control of the knitting process using G-Code and secondly, digital needle counting, control and selection.

Digital Machine: The machine was converted into a digital machine to study the implication of real-time scale and to create complex geometries. Analogue models were translated into digital codes that depict the numeric rules for the machine and material properties were simulated as the yarn governs the behaviour of the fabric. This enabled to create forms that were not possible with the analogue machine and to use multi-materiality and patterning to achieve porosity, rigidity, structure and openings.

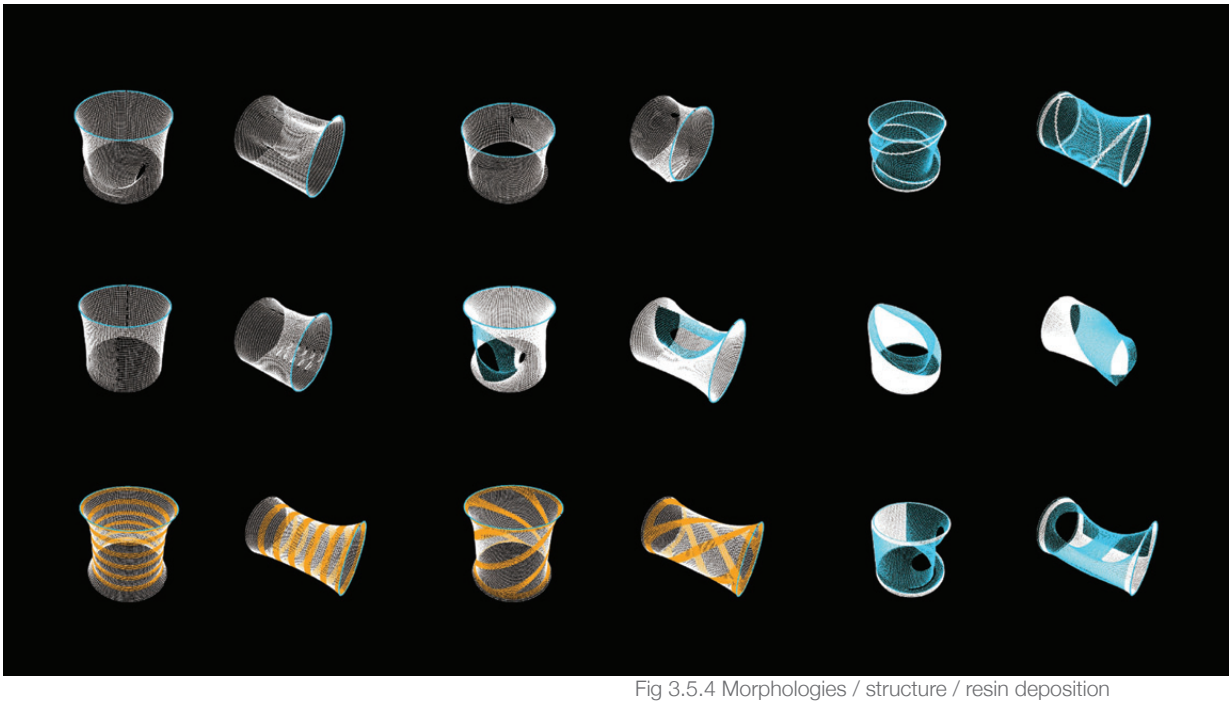


Fig 3.5.4 Morphologies / structure / resin deposition

Plural machines: After researching the possibilities and limitations of a single machine, next step was to speculate the implications of introducing a second machine. Interaction of multiple machines of varying sizes presented the possibility of having hierarchical spatial configurations, double skin structures and other tectonic and topological possibilities.

Any material system for novel tectonic intentions requires structural validation, so a modest knitted and solidified model, weighing 100 grams was put to test strength against 700 times its own weight.

The structural validation, along with the understanding of rule systems and ability to program knitting, brought forth the evidence that an everyday craft of knitting, on simple household machines, could indeed facilitate envisioning the possibility of an integrated proto-fabrication system.

Fig 3.5.5 Structural validation and 1:1 prototype

Machine Design Evolution

After understanding machine, method and metaphor of knitting, the challenge was to explore the tectonic possibilities presented by the technique, resolve the issue of scale as an architectural prototype and adapt the system for on-site deployment.

Knitting machines have been an integral part of the 200-year-old textile industry. Existing industrial knitting machines and patented machine proposals were investigated to understand large-scale production of fabrics and knitwear. The evolution of the conceptual prototype design of the machine began with a circular machine and through a series of developments eventually came back to a circle. The process facilitated in incorporating and evolving patented designs and geometry optimization in the configuration and also in reducing the machine to its simplest functions. Certain conclusions were established through this evolution; starting with the fact the shape of the knitted fabric is independent of the track shape.

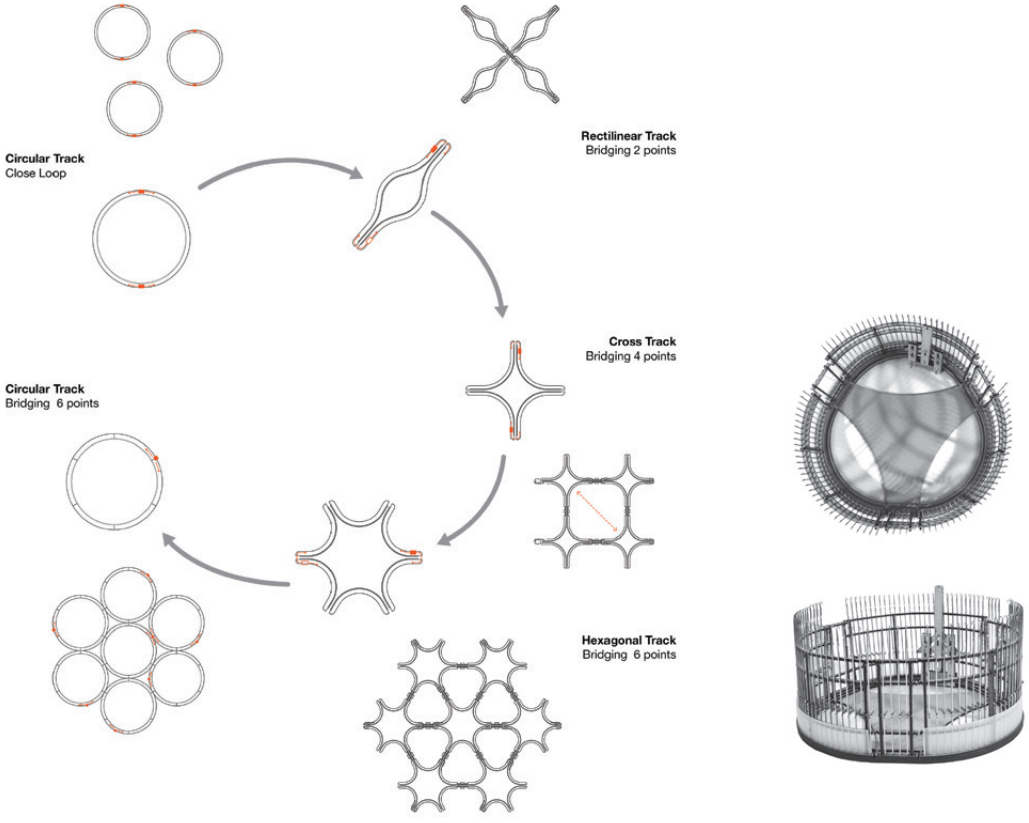


Fig 3.5.6 Machine evolution

In the final conceptual prototype, each singular machine is composed of six needle beds, separated by track connection points. Multiple machines are arranged in hexagonal circle packing, as it is the most optimal arrangement. This *part and whole* approach allows flexibility in the number of tracks and configuration to be used. Contrary to the analogue machine used, the separation of the mechanical elements of the machine that is the CAM system and the yarn feeder, allows to choose a connection point to be activated or deactivated, along with the flexibility to use different materials on different yarn feeders. The connection points activated by the yarn feeder agent, govern the topologies created. This makes the fabrication a dynamic time based process, wherein connections and bifurcations could be introduced actively.

Soft textiles unite structure, geometry, aesthetics, material sciences, parametric design and digital fabrication, but to compete with hard construction materials, they need to be reinforced with stiffener materials and can be reinforced during the assembly of form. The proto system permits to be addressed, specific tectonic issues with generic techniques of knitting; the system has the capability to be singular and modular, micro and macro, continuous and transformational.

Digital Machine

To investigate and simulate systemic aspects and topological complexity with the knitting-solidification machine, it was imperative to construct a digital machine system. The aim of this digital system, used as a real time simulation tool, was to generate design solutions by developing a digital interface, which embodied all the machine knowledge attained through research and experimentation. The system represents a new language of assembly and comprises of decoding, design and generative tools.

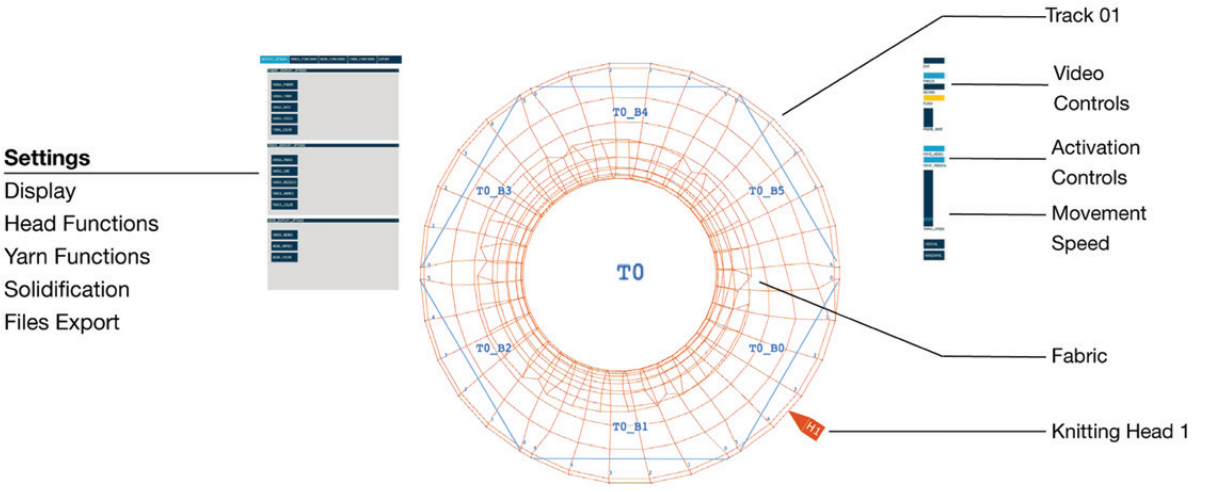


Fig 3.5.7 Digital machine interface

Decoding Tool

The first phase of developing a 'decoding tool' involved understanding and decoding the knitting action of the machine, the material properties of the fibres used and behaviour of fabric produced. The tool facilitated in appreciating and speculating patterning and topologies beyond the capacity of the analogue machine. To create a simulation system that could digitally imitate all parts of the machine and their actions, which together would create a knitted structure the parts of the machine executing different functions, were split into tasks in the simulation system. These were developed individually and later combined together to form the complete system. The simulation was scripted in Java language using software *Processing.*[x] For simulation of physics an additional library *Toxiclibs*[xi] was used. Parts of the System: Needle, bed of needles, track and bridge fulfil the functions as described in conceptual machine.

Knitting Action

The knitting process on an analogue knitting machine involves each needle to create a loop. Each knot on the needle is represented by a *particle* and is singularly active on the needle. These particles are then dropped similar to the knots and the resultant fabric can be described as a *number of particles*. Particles are connected with *springs* that are the digital equivalent of the yarn. These springs are subjected to forces of gravity and other springs around them, as the knots are relational and impact each other.

Knitted Fabric

Each yarn used in knitting has specific properties and it was imperative to embed this data into the simulation to get a real picture of the material behaviour. As the knitted fabric falls with gravity, the yarn governs the behaviour of the fabric. Each yarn was imparted with the characteristics of yarn strength and weight. The yarns are differentiated by the strength of the 'spring' of each yarn, such that the springs under all forces are always attempting to come to that rest position.

Machine Dynamics

In conventional knitting, the machine is stationary and the knitted fabric is pressed under rollers and pulled down. In the conceptual machine, the machine moves up while knitting and gravity and ground are utilized to attach and tense the fabric. The following functions are used for simulating real time dynamics of the system:

- Fabric Attachment: allows attachment of the fabric to the ground or any other horizontal plane and setting the distance for attachment;
- Machine Movement: enables movement of the machine vertically upwards and adjusts the required tension by establishing movement speed;
- Tension: the tension derived is a combination of machine movement speed and the friction caused by the attachment plane.

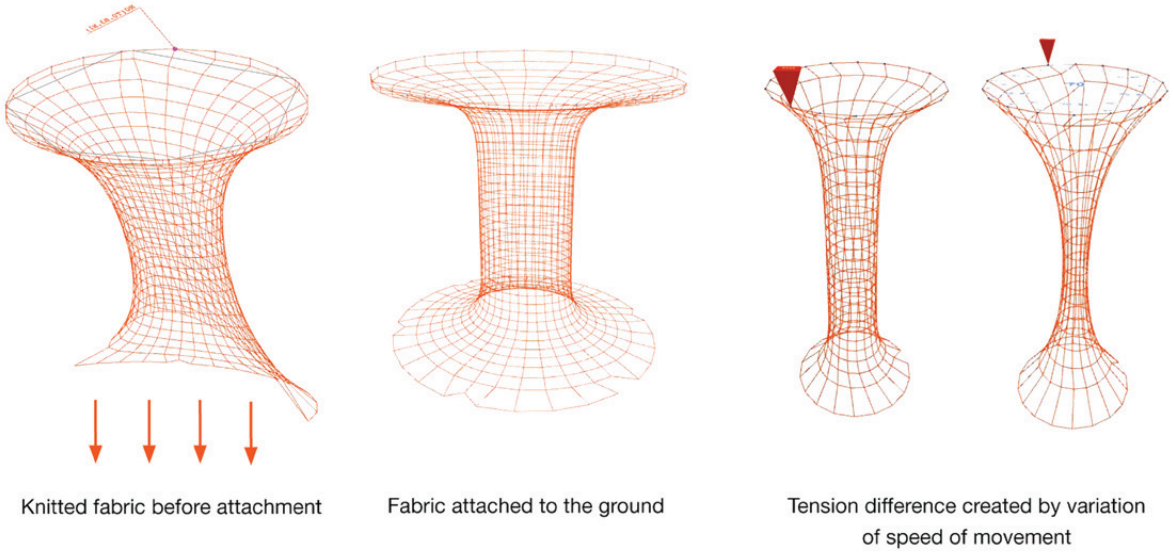


Fig 3.5.8 Physics simulation for knitted fabric

Materiality

The implications of knitting multiple yarns simultaneously were studied in analogue experiments. Being in the realm of fibre composites, matrix material for solidifying the yarns was used. Later the possibility of the fibre and matrix combination in a single material i.e. the pre-impregnated yarn was explored. Integrating the physical properties of these materials into the simulation.

- Multiple Yarns: Each single yarn had selected properties and for combining multiple materials, the simulation creates a new material with a distinctive identity and combines the properties of all the different yarns used.
- Solidification: It instigates the process of solidification of the yarn after it has been knitted. The time between the knitting and solidification can be regulated on the interface. For solidifying a knot, the simulation freezes the springs of the 'particles' involved
- Pre-impregnated Yarn: The knitted fabric can be soft and rigid; hence the digital system also needed the flexibility to selectively solidify a specific yarn and not all yarns.

Design Tool

In the second phase, simulation helped conceptualize the 'design apparatus', with the interface as a fabrication blueprint. Design apparatus is based on the systemic comprehension of a simple machine, wherein it allows selection of size and configuration of machines, type and properties of fibres, dynamics and equilibrium of the system and the course of action of the fibre feeding 'agent'. The algorithmic routines facilitated the option of pre-programming or real-time sequencing of heads and visualizing the outcome. The tool was used to design topologies, wherein multiple heads were choreographed to knit along tracks and respond to bridges, as per the structural, environmental, aesthetic, infrastructural and lighting requirements.

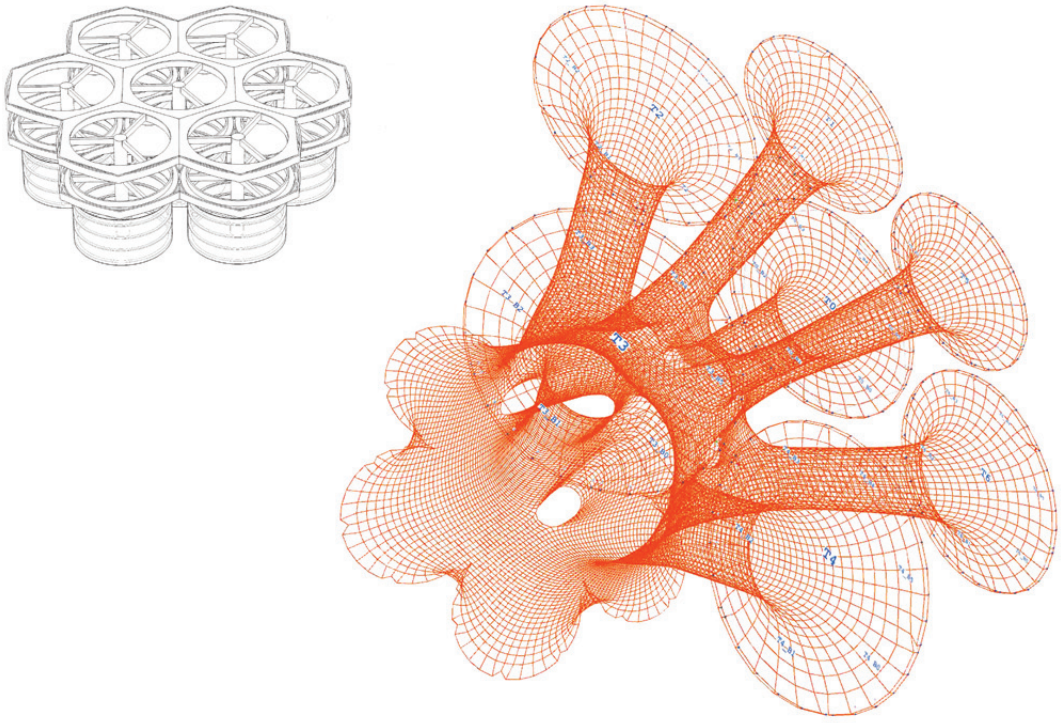


Fig 3.5.9 Knitted topology with 7 Machines

Head Sequences

The bridge activation and routine can be predefined on the script or can be modified in real time on the interface. Routines of bridge activation – deactivation and bridge- cross bridge, facilitate in creating connections, bifurcations and topologies. On further improvement to the machine, the deduction was that the bridge was not required as a physical element; but rather as an action of the yarn head. At any connection point of two tracks, the yarn head could perform any of the four prescribed actions referred to as sequences:

- Sequence 0: for the yarn head to bypass;
- Sequence 1: for the yarn head to return back;
- Sequence 2: for the yarn head to bridge across;
- Sequence 3: for the yarn head to cross-bridge;
- Sequence 9: Void function.

Yarn Head Initiation Point

The starting point of a yarn head can be directed, by giving it a location and also the direction of movement. As the yarn head path is prescribed by the routine of sequences, the knitted outcome is specific to the initiation point in the configuration of tracks.

Dropping Knots -The knit density can be changed and holes can be created by dropping knots.

Yarn Head Paths -The tracks in a hexagonal grid enclose an external perimeter and an internal perimeter. These perimeters the track itself (large perimeter) and the interstices created (small perimeter) can both be employed as paths for the yarn heads.

Attachment Control -The option to attach or not attach at any specific moment and the possibility to attach to the ground or another horizontal plane, opens up a new domain of topologies and morphologies. If more tracks are added without attaching them to a horizontal plane while moving the tracks vertically at a reasonable speed, cantilevers with interesting cross sections can be achieved.

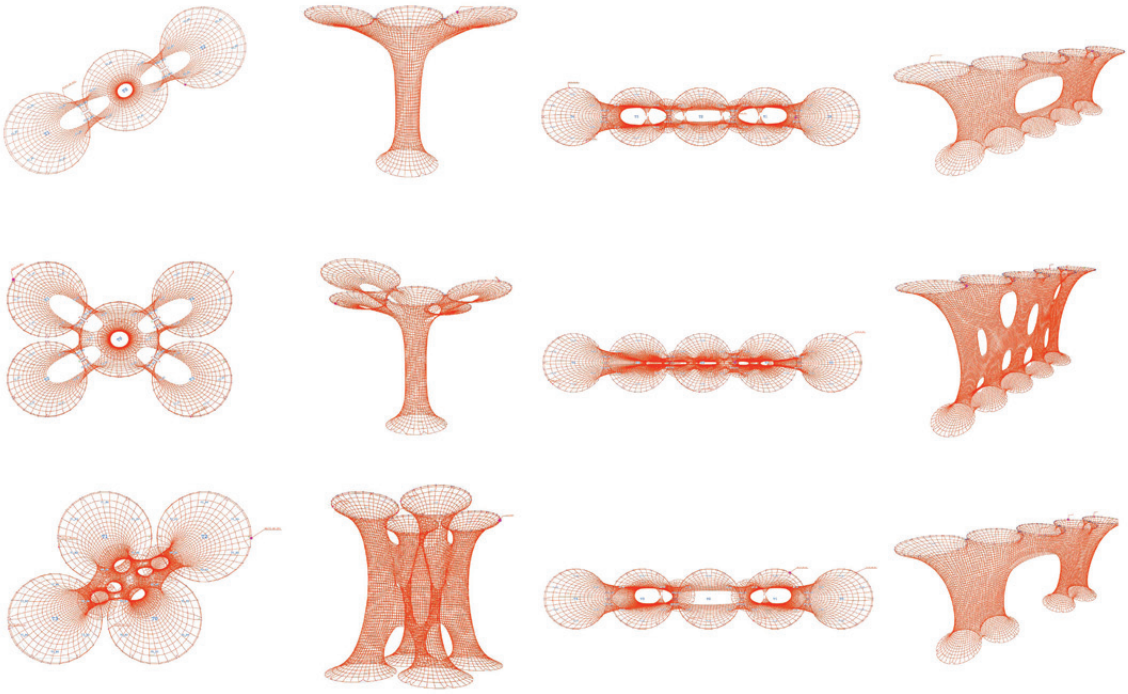


Fig 3.5.10: Monocoque Section Prototype

Generative Tool

The digital systems thus facilitate in realization of most of the tasks dealt with conventional materials and machines in architecture. It offers various ways to setup up the sequence and controls the machine, such that the system does not provide a single accurate result, but endless permutations and combinations. The system provides multiple solutions with equal suitability and not a unique solution, thus making it impossible to solve in a linear manner.[xii] So the third phase proposed a *'generative tool'* to locate appropriate architectural solutions by evaluation, selection and optimizations. The constants of the system i.e. the 'chromosomes' are varied to achieve a random population. These iterations are evaluated against the prescribed parameters and then bred over ten generations to obtain appropriate architectural solutions. *'The Generative Multi Performance Design System'* proposes a framework to generate solutions within design space defined by the system's design language, with the integration of various performance criteria. The system is composed of four phases, namely, synthesis, analysis, evaluation and optimization. Within these cycles modules store parameters, constants and constraints.[xiii] To compare different iterations and find the most optimum, these were applied to the digital machinic system proposed.

Synthesis: The basic architectural parameters of structure and space were established as the design intentions.

Analysis: Since the forces of gravity and pull on the knitting system control the fabric, the structure is characterized by the tension in the knots. The space is embodied in the dimension of the enclosure created.

Evaluation: To understand the stretch in different regions and the cross- sectional changes in the knitted fabric along both axes, analogue models were studied. Computationally, for structural evaluation the system measures the tensile forces (spring strength in comparison to the rest position strength) acting on each knot and categorizes them to be: over stretched, under stretched and ideally stretched, on the basis of analogue calibration models. From analogue models it was also concluded that a knitted fabric typically stretches up to a third of its original length. So for spatial evaluation the minimum dimensions for a habitable space were established.

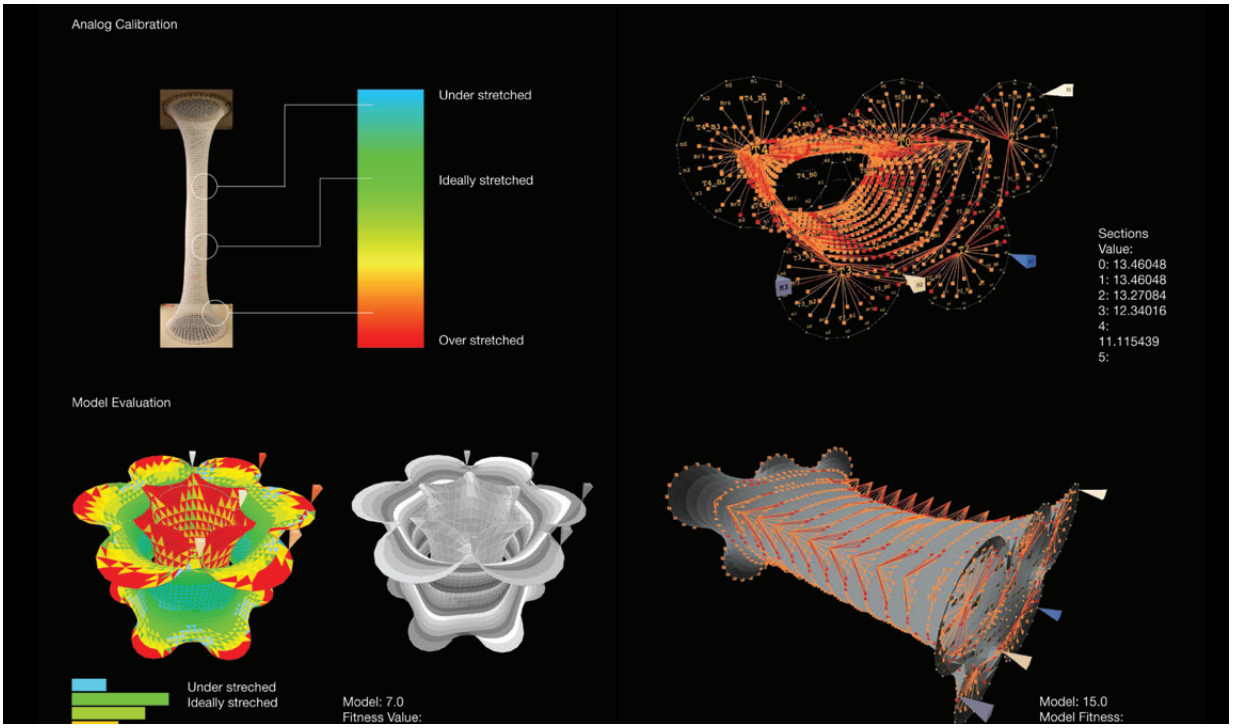


Fig 3.5.11 Structural & spatial evaluation

It is important to note here that all parameters are relative, without unit and are based on analogue calibration models.

Optimization: Typically the most optimum solution could be chosen by comparing it against a *predefined* best solution. But since in the proposed system there are no preconceived ideal solutions, the challenge was to locate the most optimum solutions. Genetic Algorithm was seen as a potential optimization tool. This genetic or evolutionary algorithm can be decomposed into five stages: fitness function, selection mechanism, coupling, and mating and mutation introduction.[xiv] Applying these principles to develop an optimization tool for the proposed digital machine, first the constants or the chromosomes were set which are comparable to the genes or the DNA in biological evolution.

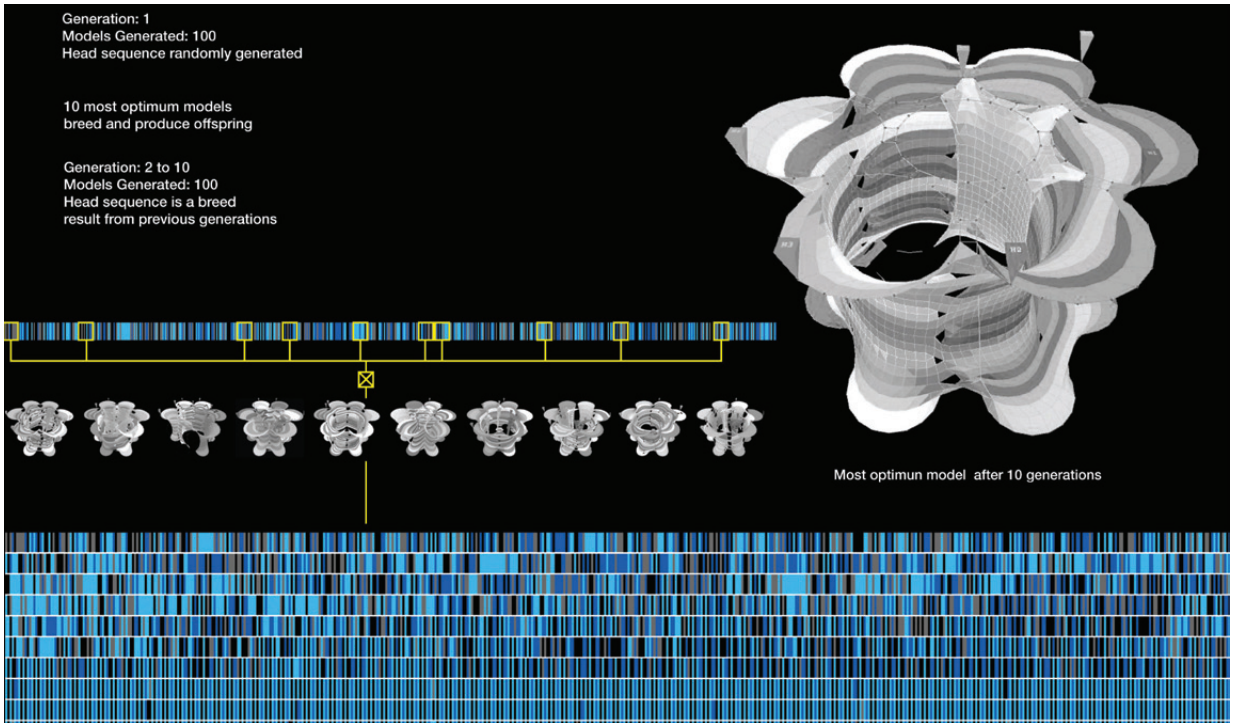


Fig 3.5.12: Genetic algorithm

The iterations were evaluated against the parameters of structure and space and assigned a fitness value. Of the hundred iterations, ten iterations with the highest combined structural and spatial fitness value are selected as the best. Each of these then mates with all the other ten iterations, to generate offspring or the second generation. The process of selecting ten iterations with highest fitness values and then mating amongst is repeated for ten generations. Interestingly, the resulting tenth iteration tends to become self-similar by the sixth generation. So to interrupt the self-similarity, a mutation in the genes was introduced i.e. some iterations are replaced with iterations with a random sequence, every now and then.

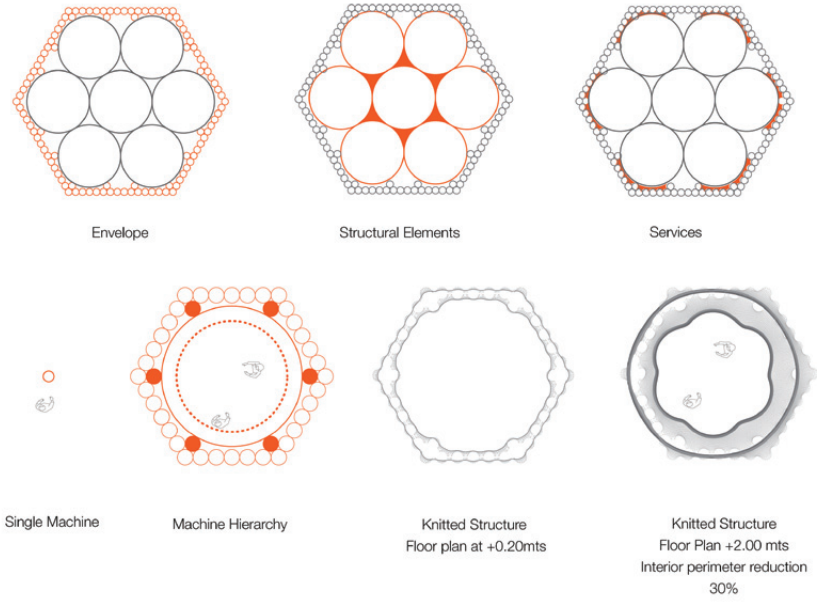


Fig 3.5.13 Machine scale resolution and module

Tectonics

The digital machinic system imparts us the opportunity to envision knitting as a principle of construction. The machine has a one to one relationship to the material result, as there is no manipulation involved in the process. In order to visualise it as a formal language for a programmable architecture, it was critical to explore the three dimensional and topological aspect of knitting. By definition, topological surfaces are smooth manifolds, so their construction should have no seams; this makes knitting a potential tool, with its continuous yarns interlocking to form complex surfaces. Every topological surface has a local coordinate system at each point. Knitting creates natural local coordinates in the form of rows and stitch columns. All knitting is the creation of global structure via choices made in the local stitch creation.[xv] Thus, the digital system enables creation of a macro system of structure and a micro system of textures. The development of a tectonic system began with explorations of the digital machinic system in following realms:

Configurations: The organization of hexagonal circle packing, gives six connection points to each machine. Multiple machines can be arranged in hexagonal, linear and organic configurations.

Hierarchy: The aim was to address multi- scalar issues with the knitting system, so it became crucial to introduce the idea of machine of variable sizes, such that the hierarchical tracks deal with the macro issues of space and at the same time undertake the micro issues of envelope.

Module: Considering conventional construction as a starting point for the standard thickness of building envelopes used for structure and insulation, the desired thickness of the envelope was calculated. The analogue experiments informed that on tensioning, the cross- section of the knitted tube reduces by 30% – 35%. It was vital to take this into account in determining the size of the machines. In hexagonal circle packing grid, each circle with a diameter of ‘d’ has six points of connection. Interestingly beyond this, only a circle of diameter of ‘9d’ on this grid has six connection points. So the machine diameters were deduced as d for small and 9d for big machine.

Resolution: The small and the big machines, along with the voids of different dimensions created between them, give an opportunity to employ them for envelopes, structural elements and service core and shafts, of varied resolutions.

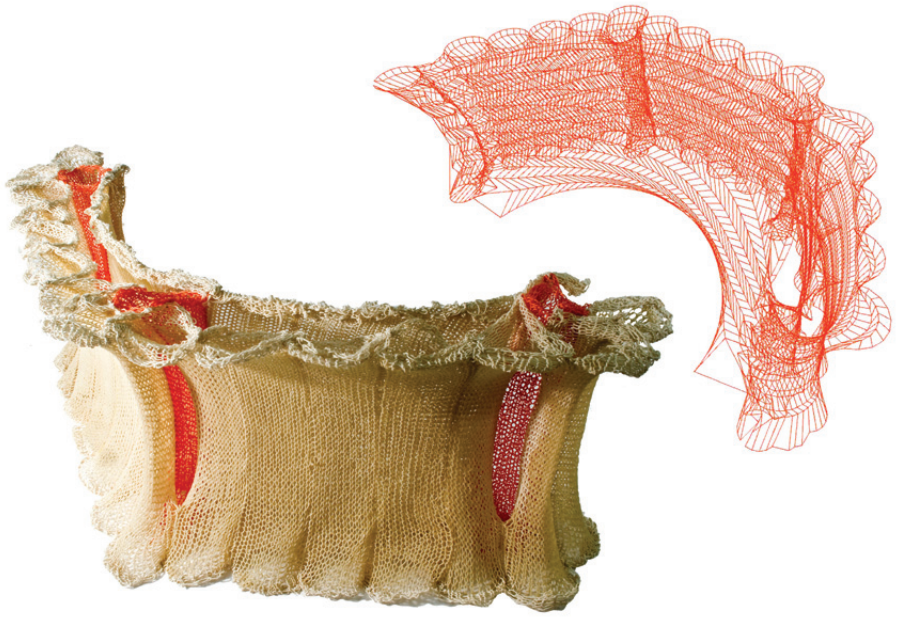


Fig 3.5.14: Knitted Prototypes

Tectonic elements

The proto system being a mono-system has the capacity to integrate multiple scales and resolutions and functions.

Spatial variations: The macro machine set up of tracks can be combined in a multitude of ways to attain a hierarchy of spaces. With the skin as the structure, continuous column free spaces that can connect and bifurcate to form networks and nodes can be achieved. The structure is continuously embedded into the spatial envelopes to maintain integrity through continuity and connectivity.

Columns: The structural elements like columns could be fabricated using one or more small machines. As the elements created have no joints or seams, the forces are spread evenly across the shell without being concentrated on the joints, thus making it structurally efficient and lightweight.

Apertures: Can be created using both the machine sizes, depending upon the size requirements. It is interesting to note, that all the openings and punctures compute their own structure; by accumulation of material around them and also by the self-regulation of knots with their inter-relationality.

Layering: The combination of machines help in configuring singular architectural elements and or multiple layers. Various structural elements, namely the foundations, walls, columns, beams, and also circulation elements i.e. corridors, ramps become a part of the knit structure. The possibility of introducing a new material at any point of the process and directing it to a certain local or global path is to be used to embed services' infrastructure effortlessly into the layers.

Details: Along with designing tectonic elements, it was necessary to detail three junctions of critical importance in all construction i.e. the detail at the junction of the structure to the ground, the detail at the junction of the envelope and intermediate floor and the detail at the roof level.

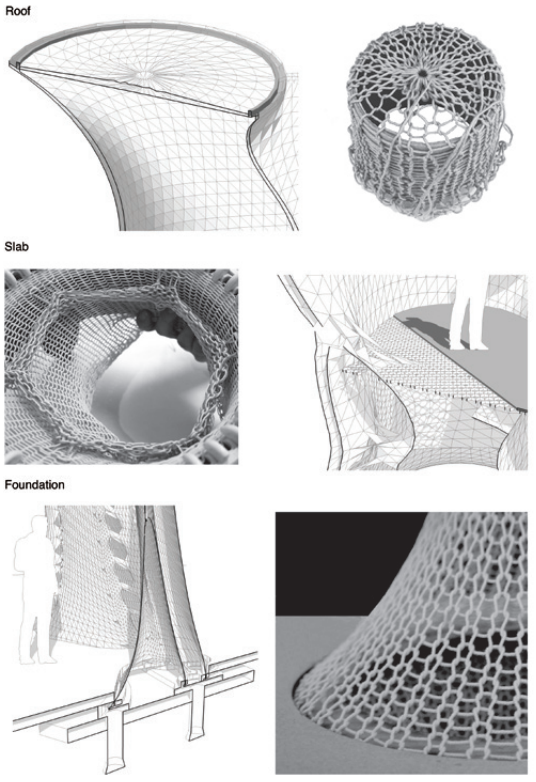


Fig 3.5.15: Prototype junctions

Fig 3.5.16 Knitted prototype

Materials

The tectonic application of the digital system requires imparting materiality and also identifying the on-site deployment procedure. High performance textiles are amongst the most innovative fields of material research. The materials employed would belong to three families: structural, infrastructural and performative materials. Fibres are knitted into soft fabric, but require a reinforcement material to form strong composite structures. The epoxy resin impregnated carbon fibre, merges the characteristics of both fibre and reinforcement into one and is thus ideal for knitting and solidifying for structural performance. The soft envelope could be knitted in the *Gore Tenara* yarn and vapour barrier sealed with silicone for waterproofing. Performative and smart techno-textiles are being extensively used in architecture. For instance, silicon optical fibres could be an efficient medium to transfer data, fibre optics could be embedded for lighting, flexible organic cells can be used to retain the solar energy in the day and convert it to emit it as light energy. Another systematic advantage of knitting is to create multiple levels of performance with a mono fabrication system. Hence infrastructure can be embedded into the skin and layers. For instance, electric conductive wires and hydraulic systems could run in the envelope and provide electricity, heating, hot water etc.

Deployment

The site constraints and programmatic needs determine the most favourable deployment technique for a particular scenario, depending on different attributes i.e. the scale, resolution, richness of the topological space created and volumetric possibilities.

The deployment process is to be executed in the following stages:
Firstly, the machine is placed on its location by a construction crane, a certain height above the ground. The machine then knits and lets the knitted fabric fall with gravity, which is attached to the ground.

Attachment: The knitted fabric can be attached directly to the ground. The initial process for this set up is the fixing of the knitted dense foundations to attachment rings and this solid base then becomes the support for the whole structure. The geometry of the attachment ring and the scaffolding is a replica of the machine configuration i.e. hexagonal close packing. Each machine track would have a corresponding steel ring on the attachment, allowing a clamped connection.

Movement: The vertical machine movement is a synchronized process, which can be provided by a construction crane.

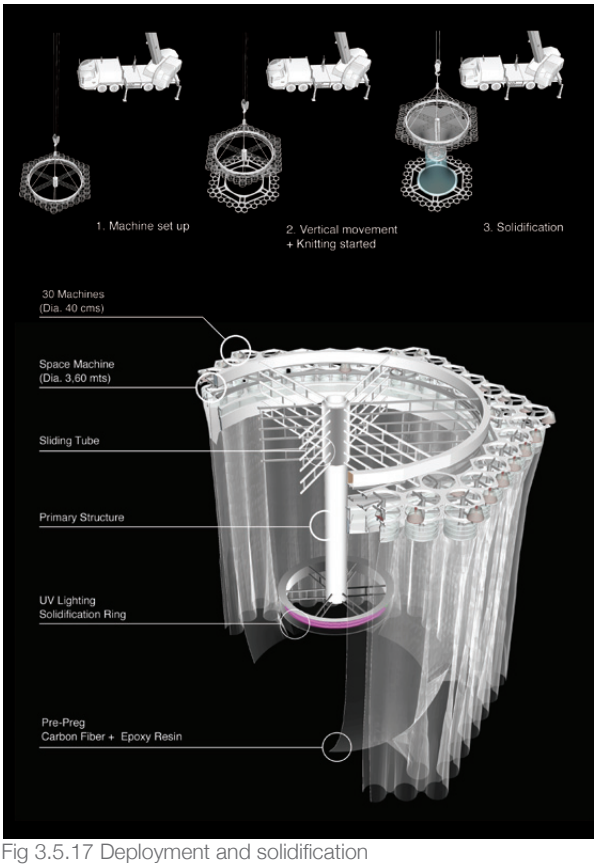


Fig 3.5.17 Deployment and solidification

Solidification

After knitting the prepreg carbon fibre, solidification is crucial, as it becomes a structural support to reduce the tensioning of the system. The machines have two rings, the upper one for knitting prepreg carbon fibres and the one below with UV light, to solidify the knitted structure. The curing ring activates the pre-impregnated fibres structural properties and the time taken depends on the density, thickness and conductivity of the resin. The distance between the two rings and the diameter of the solidification ring were determined by doing analogue tests. The test was done in three phases with two parameters; fixing diameter and stretched length of knitted fabric and the distance between the knitting and the UV ring was determined to be equal to half the diameter. The analogue test also reinforces the idea of stretching and solidifying in phases, contrary to the idea of solidification following the knitting and stretching process.

Termination: when the machines end the knitting cycle, the process can be terminated in two ways, either by articulating the UV lighting ring so as to solidify the last section or by leaving the last section of the knitted structure as a soft surface and then enclose the termination.

The deployment possibilities of the on-site knitting system make the system flexible and adaptable to various scenarios and sites.

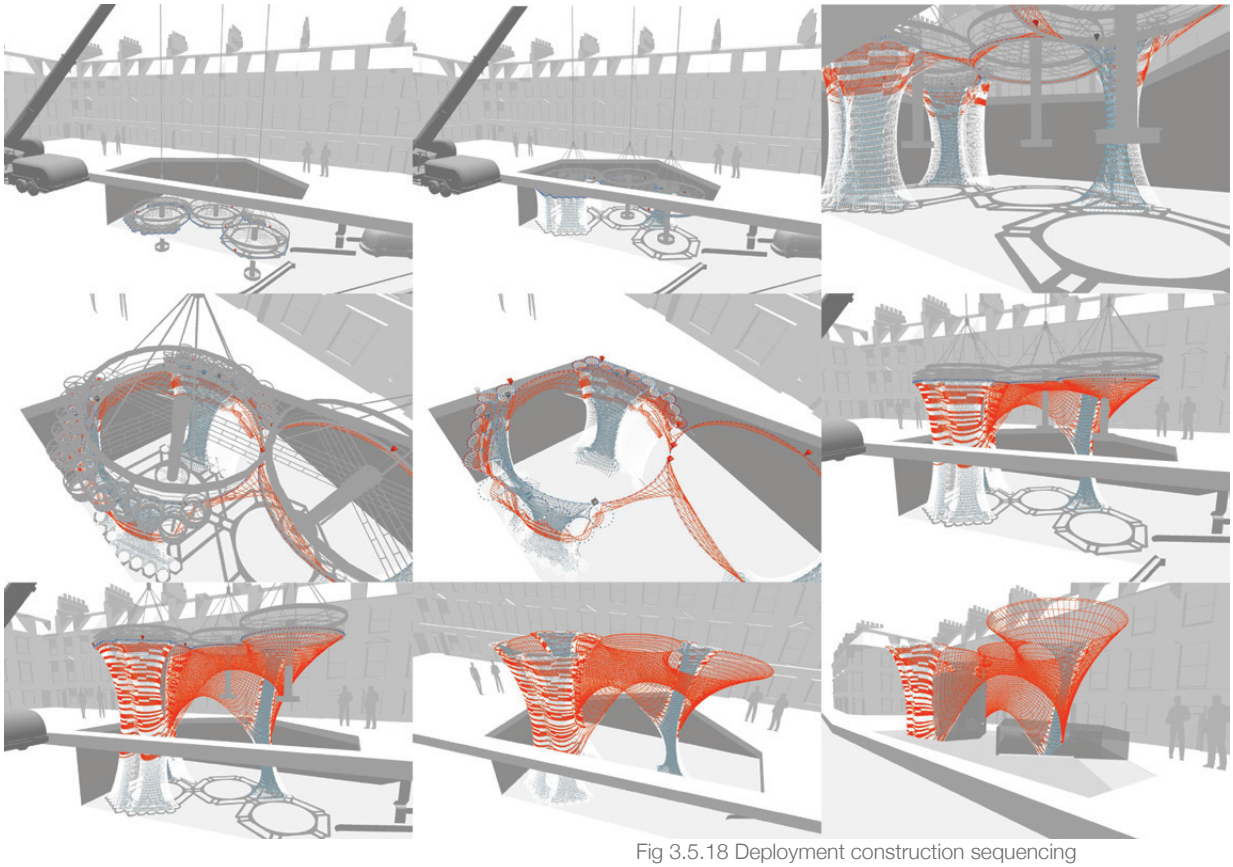


Fig 3.5.18 Deployment construction sequencing

Scenario

To summarize, the setup enables one to achieve complex topological surfaces as the machine has a one to one relationship to the material result. The natural local coordinates create a global- local structure and indicate the possibility of multi- scalar, dynamic and flexible results. Additionally, to address macro level and micro level issues with the system, the idea of a machine of variable sizes within the hexagonal grid was introduced, hence imparting it the capacity to integrate multiple scales, resolutions and functions. The tectonic aspects are addressed at two levels by the system, firstly at the spatial or programmatic level, providing space, structure and punctures, and secondly at the functional level, providing micro infrastructure, embedded services and performative skin.

The system was analyzed to appropriately locate the application of the reinterpreted method. Being multi-scalar, modular and collaborative, it has the potential to attend to various scales, programmes and sites and can adapt to site constraints with the flexible deployment and material usage approaches available. The nature of the system establishes its prototypical application in the realm of quick deployment, minimal impact and integrated mono-system. The multiple interconnected layers give the opportunity to embed micro infrastructure and services into a unified structure, making it suitable for macro level infrastructure.

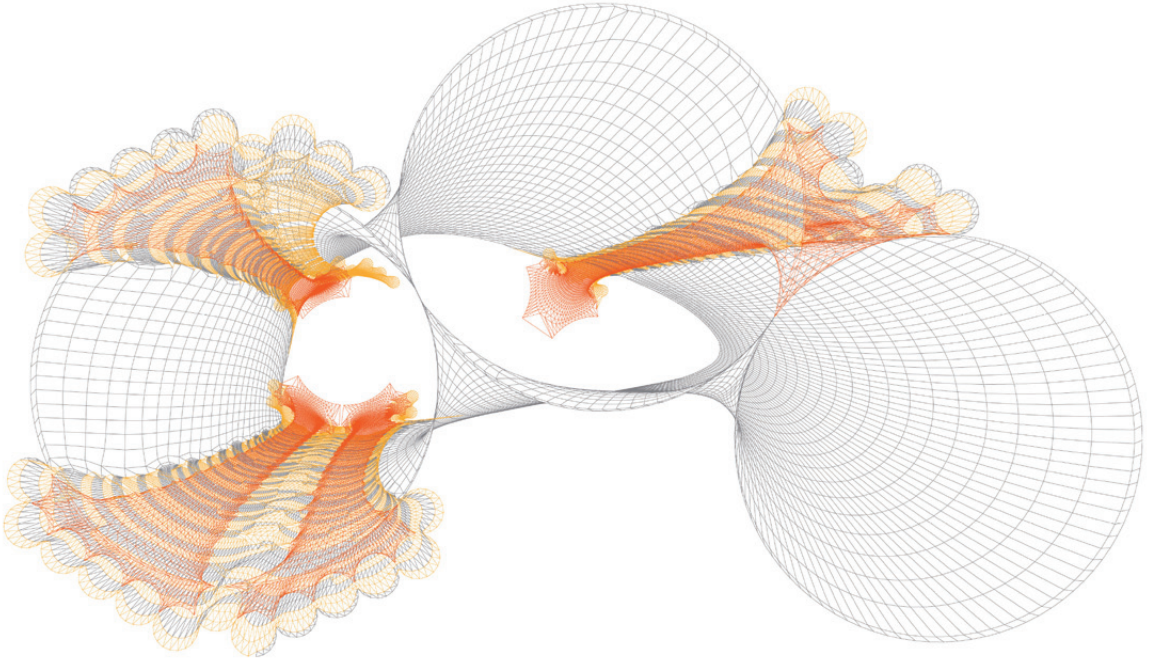


Fig 3.5.19 Deployment plan

To test the system, the infrastructure development for a new transport technology - Personal Rapid Transit (PRT) system in Bath - was chosen as the application scenario. The PRT, being high-tech and lightweight with its complex connections, continuity and bifurcations, networks and nodes, adaptability, demonstrates resonance to the proposed machinic system. The aesthetics, lightness and transparency of knitted fabric, aptly situate it in the deep-rooted culture of textiles in England's historic towns. The system was employed at different sites to explore the prototypical nature of the system on the basis of programme, scale, context, machine configurations and material. Though all sites use the same system, the design and deployment approach to each varied, thus testing and demonstrating the feasibility of the system and also defining its limits and ranges.

Fig 3.5.20: Deployment test scenario [xvi]

Possible Futures

With the jacquard loom, the pre-designed technique through pre-programmed instructions, gave way to computation. Inspired by a textile technique the three tools use computation to design, visualize, instruct and fabricate in real-time, with an on-site fabrication machine, such that it gets feedback from and responds to materiality. The choreography of the way the material is deposited in the proto system, defines a new vocabulary for architecture, thus becoming a proto tectonic system. These are the initial steps in the research and development of a knitting-based parametric system that enables real-time fabrication to intelligently interact with the parameters, propose an *optimized* solution bracket within which the designer could design and then communicate said design to the deployment machines. But most importantly, this parametric process of prototyping could be utilized with any other machinic process to develop novel fabrication methods.

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3.6
Exploring Materials Reciprocities for Textile-Hybrid Systems as Spatial Structures

Sean Ahlquist, Julian Lienhard, Jan Knippers and Achim Menges [i]

This paper describes research in developing design frameworks and materialization methods for forming intricate *textile hybrid* structural systems. Characterized as a force-active system, a textile hybrid structure is comprised of tensile surfaces operating in equilibrium with networks of elastically bent elements. The complexities of such material-inherent behaviour necessitate a coordinated series of multi-scalar prototyping processes. Executed effectively, such a methodology establishes fundamental methods for material behaviours made accessible for early design investigations of force-active materially-informed architectures. Complexity, in this instance, is innate, a repercussion of the inextricable relations between topology, structural behaviour and materialization. Prototyping serves to simultaneously resolve such mutual relationships. In placing primacy upon the processes that span across a series of diverse prototypes, the approach yields increasingly generalized methods, establishing fidelity between the processes of computational formation and material operation. As an active evolving agent, the accumulation of diverse design instances helps develop purpose-built procedures into robust generalized frameworks, by combining both computational intelligence and physical feedback. This paper shall describe a series of specific exemplars, of differing scales and degree of performative and geometric complexity, which realize a versatile design framework addressable to a wider range of behaviour-based structures beyond iterations of the prototypes themselves.

Introduction

The particular approach outlined in this paper addresses the limitations of a single prototype to predict collective material behaviour beyond its own specific scale. A prototype, in this case, refers to a design space, which induces a new vocabulary of form, performance, and generative means (Coyne 1990).[ii] An exemplar is a single iteration of a complete system that activates a select set of parameters and design functions, as defined by the prototypical design space. When interacting multiple materials, the parameters, relationships and predictability of the outcome are increasingly elusive. In such a scenario, the methods, computational and otherwise, which generate the prototype, are solitary to the narrow set of possibilities and material choices that the single prototype implies. To overcome this, prototyping is suggested as a process which envelopes multiple prototypical design spaces. Project-specific methods are encapsulated into robust computational design environments made applicable to a broadening range of material-based schema (Attar et al., 2009).[iii]

In this sense, a meta-prototypical design space is generated relating learned conditions, techniques and material logics across ever-diverse behaviours of structural performance and material form.

In addressing increasing sophistication of material relationships, iterations of physical exemplars provide scale and material specific data, while the intent is for the methods of design generation to grow progressively fundamental, uncovering the most basic functions, which relate material make-up to behaviour. This plays out in the coordination of physical experimentation and computational simulation, registering the degree of robustness related to scalar conditions and fidelity in calibration between virtual prediction and real performance. Specifically, the projects documented in this paper describe the transformation of singular methods for the design of tensile form- and bending-active structures into programmable behaviour-based modelling environments integrated with explorations in physical form-finding. The interaction between the various modes of design addresses critically the interrelations across the conditions of textile-hybrid structures and generally any force-active system: topology, structural behaviour and materialization (Ahlquist and Menges 2011).[iv] Ultimately, the design framework seeks to manage material differentiation in minimal material means, structural robustness, and varied spatial characteristics. The explicit implementation of the design framework in this research explores such capacities through instrumentalising textiles from homogeneous membranes to variegated CNC knitted textiles and glass-fibre reinforced polymer (GFRP) elements of varying cross-sectional dimension.

The exploration of tensile capacities and bending behaviour of materials that combine high strength with low bending stiffness is implemented across multiple design platforms between a springs-based solution, methods in finite element analysis (FEA), and procedures for physical form-finding. This paper compares the implementation methods in their relation to the design of multiple form-active and complex textile-hybrid prototypes. The coalescing of methods into design frameworks is documented in these projects, where each contains differing degrees of bending- and form-active relationships, yet all focus on examining differing scalar and spatial aspects. Two projects, in particular, serve to explore the meta-design space uncovered through multiple prototyping efforts. The M1 Project in Monthoiron, France, a collaboration between the Institute for Computational Design (ICD) and Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart, explores variability in the networks of bending-active GFRP elements ranging from the global structure to more intimately scaled cells purposed for the articulation of spatial effects. An installation for the gallery in Copenhagen institutes variegation in the textile structure through means of CNC knitting, activating the behaviours of force to drive the surface articulation of the textile. The surface itself is an exploration of a continuous global surface topology and variegation in the local knitting structures. The research outlays an approach whereby these increasingly minute descriptors of fibrous logics, across textiles and composites, can be explored in their capacities and materialized for their effectual and interrelated behaviour, and done so across multiple scales.

Fig 3.5.1 M1 Textile Hybrid at La Tour de l'Architecte in Monthoiron, France, 2012 (photograph by Julian Lienhard) and Semi-Toroidal Textile Hybrid Installation at ggggallery in Copenhagen, Denmark, 2012, (photograph by Sean Ahlquist).

Prototyping in Material Behaviour

This research examines the potentials for structural performance and spatial differentiation in textile hybrid systems. Following the classification by Heino Engel, a *hybrid* structural system intermixes various types of structural action, of relevance here are form- and bending-active conditions (Engel 1990).[v] Specifically, a textile hybrid system develops from the equilibrium of tensile form-active surfaces and bending-active beams. Materially, both structural capacities are realized with textile-based materials and material composites. Form-active tensile surfaces are developed with either textiles, where performance is based upon knit structure and yarn capacity, or membranes, where a coating is added to waterproof, protect and further structure a woven textile substrate. Bending-active behaviour is enabled by composites of glass-fibre and polyester resin. Specific to this research, textiles range from woven and custom CNC knitted composition to PVC coated membranes and open-web meshes. The bending-active elements are pultruded GFRP rods and tubes. As linear elements exposed to bending, they are structurally referred to as beams. The hybrid nature of the system is also expressed in the global structure where at moments equilibrium is found in gridshell-like arrangements of bending-active elements while also in other areas the mutual exchange of tensile and bending-active forces stabilizes long cantilevering conditions.

In a true lightweight structure, all components of the structural system are connected in an inseparable relationship of form and internal forces. Each component is individually designed and sized to its permissible minimum that accounts for the various external loads.

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Consequently, each component of the system is stressed to its '*ultimate limit strength* at least once in its lifespan, leading to what can be described as a fully stressed design. In addition it is the desire of the textile hybrid system, and certainly in this research, to minimize if not eliminate externalized stresses, removing the need for anchorages to resist pre-stressing forces so that they only serve to hold the structure against external loads. Modern camping tents utilize such structural logic of bending-active elements stabilized by tensile surfaces, though are studied solely through means of full-scale modelling. In this idealized condition, all geometries are determined and *resolved* via the mutual exchange of structural forces within the textile hybrid system.

Traditionally, modern camping tents are explored and specified through full-scale studies and within a particular size based on mobility and weight. There are minimal precedents for such systems at larger scales. This could be attributed to two inter-related factors. First, while physical form-finding produces valid simulation of interacting structural behaviours for textile hybrid systems, there are noticeable limits to what the scaled model may predict for implementation at larger scales. While the geometry of the scaled simulation may be concise, the rigidity of the model is often exaggerated as dead load at this scale is insignificant. At larger scales, this factor becomes increasingly influential in geometry and material specification. As such, the means of prediction are significantly limited to exemplars at or as close to full scale as possible. Second, as form arises from material and force interaction and is particular to scale, a complete system has to be simulated physically in order to evaluate its behaviour. Where a mock-up may traditionally provide insight at full-scale, the partial construction of such an interdependent system cannot provide an exhaustive enough investigation.

In the exemplars shown in this paper, the aspects of topology, behaviour and materialization are explored amongst methods of physical form-finding and computational methods of simulation, intending to foster knowledge and prediction of textile hybrid systems at expanding scales. The coordination of these methods serves as the genesis of a meta-prototypical design space. While these three states of the textile hybrid system have been distinguished from each other, they are in fact highly interdependent. Depending on the design medium, either *virtual or real*, the simultaneity of the states can be, to certain degrees, integrated or unravelled. Topology describes the number of elements, their interconnectivity and their implicit geometric type. Globally, the simplest levels of topology are dealt with, the plane, cylinder and torus, understanding that highly advanced topologies can be accomplished through various interconnections of these basic types. Also, this respects fundamental considerations of materialization where elements are often panelised, though in advanced knitting techniques, textiles of tubular and toroidal topologies can be generated. Behaviour then defines the relationship between topology and materialization to compute a specific description of geometry and internalized forces. The ability to both disentangle and integrate, with agility, these factors is a critical component defining the fidelity of a cohesive design framework for textile hybrid systems.

In Fig. 2, relationships are defined between: 1, the exemplars developed in this research, 2, the implementation of three modes of design in physical form-finding, springs-based simulation, and finite element analysis, and 3, how these modes influence topology, behaviour and materialization. While there is a linear fashion in which these projects,

methods and aspects of textile hybrid system are documented, the integration is far more fluid and reactive. While physical form-finding offers information in topology, behaviour and geometry, finite element analysis offers controls for geometric variation through manipulation of structural and material characteristics. Such reconfiguring is then confirmed and re-explored in physical form-finding. The genesis of a formal concept often emerges through the physical modelling experiments, yet exploration and testing of that concept happens more adeptly and expediently through a computational environment. In this case, the springs-based simulation offers means of generation, modelling and manipulation, efficiently studying variation at grand and/or minute degrees. As means of approximating behaviour, information is sourced from the physical explorations and later transferred into finite element analysis. The fidelity of the collective process is grounded in the feedback and interchange between these critical modes of design.

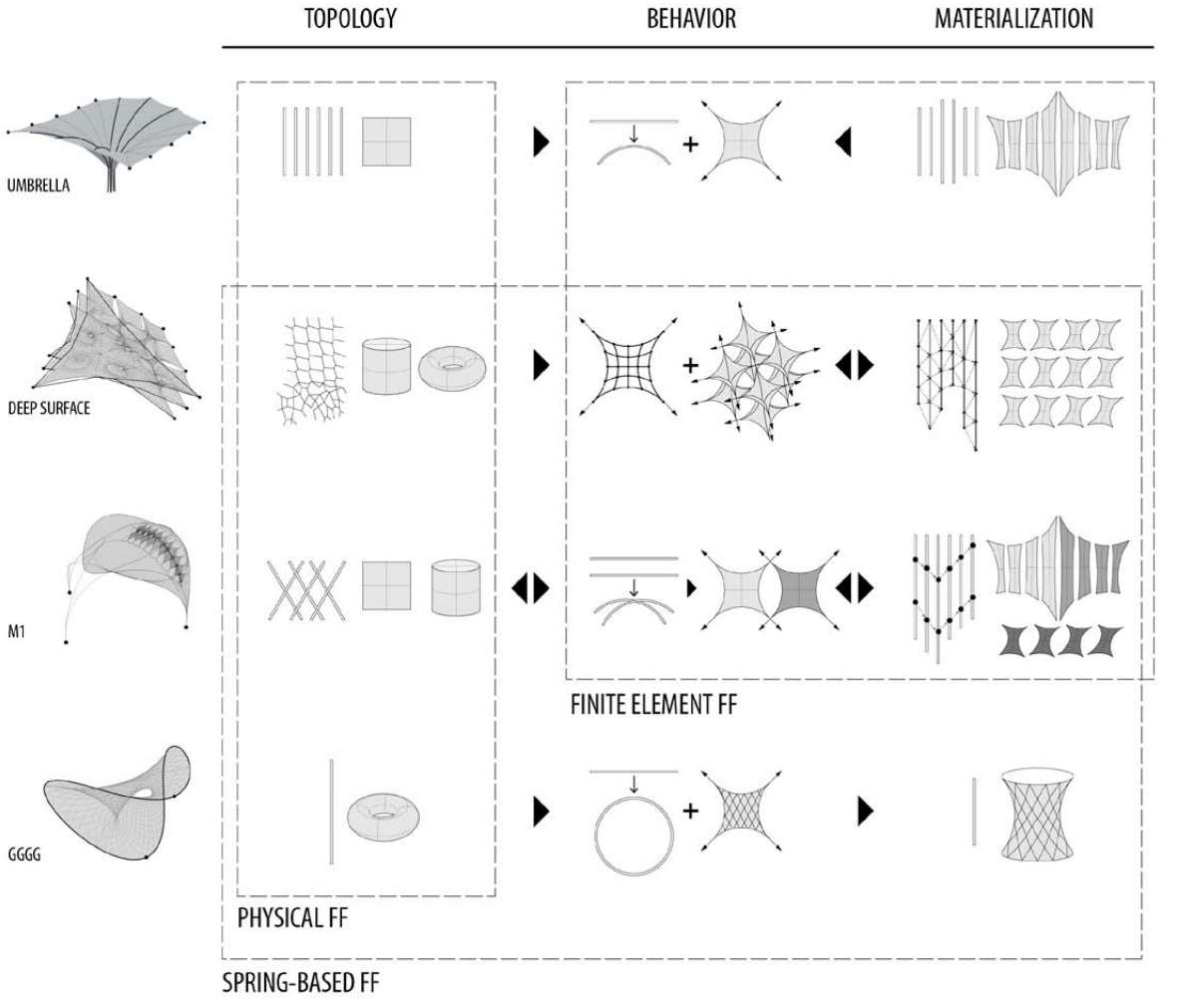
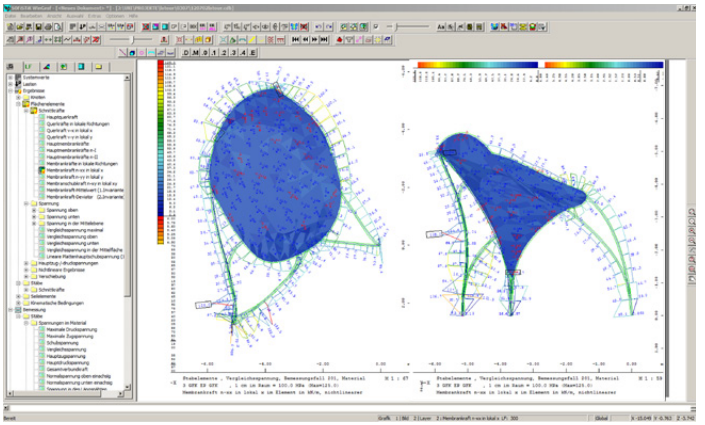
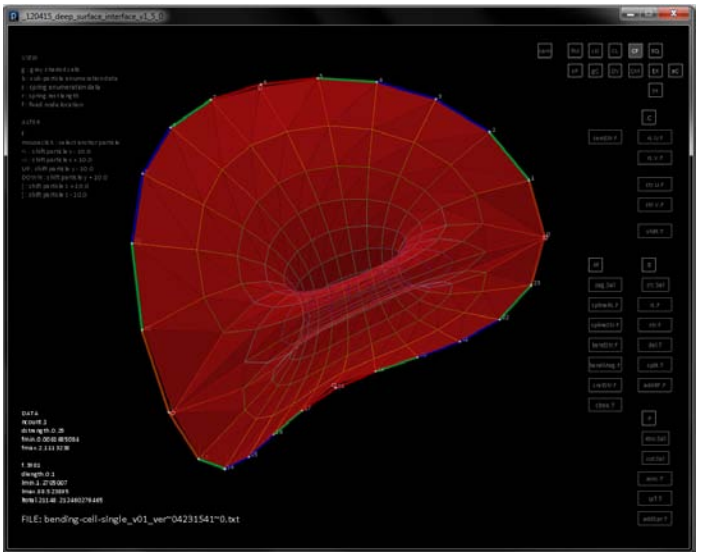


Fig 3.6.2 Diagram showing the relationships between exemplars, modes of design, and critical aspects of textile hybrid systems. (Image: Sean Ahlquist)

Physical form-finding offers the most direct feedback of behaviour through modelling with GFRP rods and textiles. In design scenarios where the rod cross-sections and textile make-up are homogenous, the geometry produced by the behaviour of the physical model is generally scalable. As with any physical modelling effort, the pursuit of variation from a fundamental strategy is exhaustive. A springs-based modelling environment serves to bridge this moment from the single design instance to an examination of a field of possibilities. The modelling environment, in this research, is developed in Processing (Java) implementing generative algorithms for topology creation and vector-based methods for solving behaviours of tension and bending resistance (Ahlquist and Menges 2010). [vi] This mode serves to provide an avenue by which behaviours can be actively modelled and manipulated (Kilian and Ochsendorf 2005).[vii] Yet also as an accessible programming environment, certain learned behaviours, ones that become critical and possibly re-iterated through a specific design series, can be encoded and automatically re-deployed within the environment. With this capability, simple behaviours can quickly grow into increasingly complex assemblies. This particular vehicle for design exploration is built for expediency where the springs use relative values of force between the different behaviours. Bridging to the calculation of specific scaled behaviour and material definition, the finite element analysis considers topology as a fixed input yet explores geometry as a variable result of force and material coordination. Once the topology is set, FEA then offers the possibility of precisely describing the mechanical behaviour, reaching from the simulation of the erection process to the performance under external loads (Lienhard, Alpermann, Gegnagel, and Knippers 2012).[viii] The form-found model furthermore offers the possibility of re-abstracting the geometry by unrolling, or patterning, both beam and membrane elements for production data. Each component of the design process is often a predecessor and an antecedent to the other modes when executing the entirety of the iterative design framework.





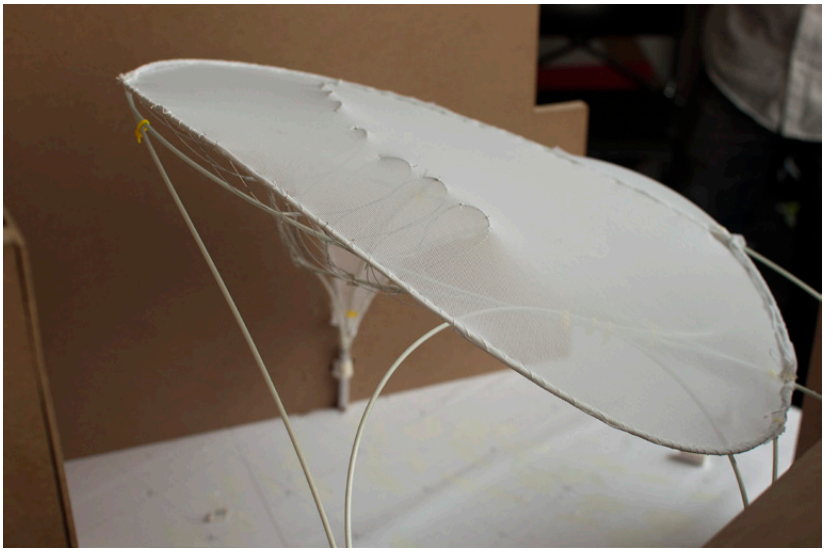


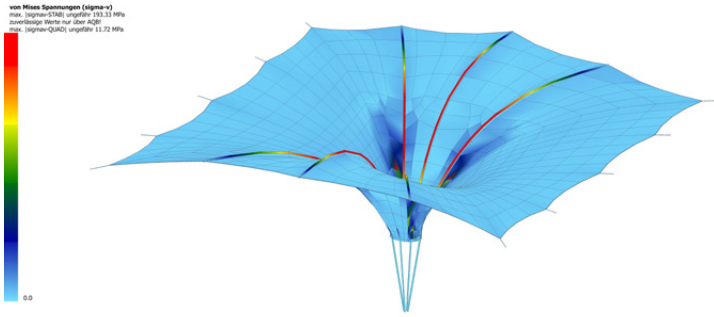
Fig 3.6.3 Examples of the three modes of design: physical form-finding, springs-based form-finding in Processing, and finite element analysis in SOFISTIK, (images Sean Ahlquist and Julian Lienhard)

Exemplars for Differentiated Textile Hybrid Systems
Umbrella Project, Marrakech, Morocco

With a low topological complexity in hybrid system, the form-finding of the bending-active beam elements and pre-stressed membranes may be performed in one combined calculation run. This was exercised by programming of an incremental form-finding routine inside the commercial Finite Element Analysis Software SOFISTIK. Without the necessity to study variations in the number of rod elements, the process was concentrated on developing the method for solving the mutual behaviour for the bending-active elements and tensile surfaces. In particular this enabled the study of multiple solutions to determine how the bending-active beams "float" within the tensile surface. This process was applied to a membrane structure with integrated bending-active beam elements, which was developed and realized through collaboration between the ITKE and the HFT Stuttgart. The project was initially developed through a student workshop as a shading solution for an outdoor plaza space at an architecture school in Marrakech, Morocco. A funnel-like structure was proposed in order to provide shading, an effective clear span within the courtyard space, and straightforward strategy for water evacuation.

A critical feature in the development of the funnel shaped design is the minimization of anchoring forces to the surrounding buildings. Originally the free spans, across the courtyard between buildings, were generated with guying cables resulting in exceedingly high tension loads at the cables' anchoring points. Alternatively, actively bent beams within the membrane surface were introduced, replacing the external guying cables and thereby creating an internally shortcut system which cantilevers freely. Thus, the structural system was effectively altered by introducing a new type of structural behaviour within the membrane system. The final design features six elastically bent GFRP rods each with a length of approx. 7.5m. The rods are pushing out three additional corner points on both free edges of the structure. The funnel shaped membrane has a span of approximately 11m x 11m and eave heights of 5.5m resulting in a membrane surface of approximately 110m² as shown in Fig. 4 (Lienhard and Knippers 2012).[ix]

Positioned in the plane of the membrane the beams may lose stability when snapping through buckling (curvature inversion) is provoked under external loads. Controlling this by adding stiffness to the beam itself is not an option if the beam is to be bent into a significantly curved geometry with sufficient remaining load bearing reserves. A practical solution has been used for several years in the design of the above mentioned camping tents; by attaching the beam eccentric to the surface a significant rise in stiffness can be observed. The effectiveness of such minimal changes to the overall system could be quantified by an FEM study of various sleeving conditions creating eccentricities between membrane and beam elements. Here existing empirical knowledge from the construction of camping tents served as prototype for the design of a large span structure.



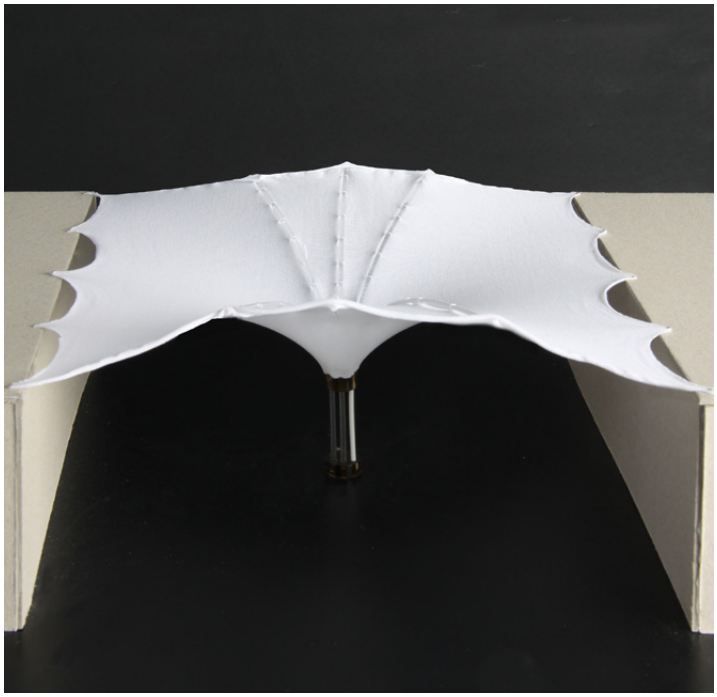


Fig 3.6.4 Three design stages of Marrakech umbrella: physical form-study model, finite element form-finding and analysis model, and finished structure. (Images: Julian-Lienhard)

Deep Surface Experiments

This series of studies develops highly complex topologies via initially simple physically form-found exemplars that are subsequently developed into complex multi-layered arrays through springs-based modelling. This line of research develops the bridge between topology and behaviour, combining the efforts in both physical and computational form-finding. Specifically, these exemplars show the transition from physical studies of a singular topological case to computational exploration of the field conditions where arrays of individual cells become variably interconnected. Working in the computational environment of springs-based modelling allows for exploration of the local and global conditions of both topology and behaviour. Topology is explored thoroughly in the manner by which an individual cell is formed as well as how the interconnection of multiple cells and secondary networks develop into a comprehensive form. Behaviour is resolved in the form-finding of the equilibrium state for the entirety of the interconnected spring force network. Alterations of the spring force properties along with shifts in associations between springs simultaneously adjust the properties and geometry of the overall form.

While serving to advance the prototypical design framework, the material explorations examine textile structures as multi-layer performative systems. In particular, the multi-layer capacity, referred to in this research as a *Deep Surface*, addresses qualities in the differentiation of light transmittance, acoustic diffusion and thermal modulation. This is addressed through cells of a volumetric nature. Mass is introduced into the volumetric cells, ranging from phase change materials to lightweight shredded Polyester fibres, allowing the factors of light, sound and heat to be negotiated simultaneously. While these performative capacities are critical to the research, the decoding and implementation of means for topological articulation and complexity are used as the primary gauge for measuring the fidelity and agility of the design process as a whole.

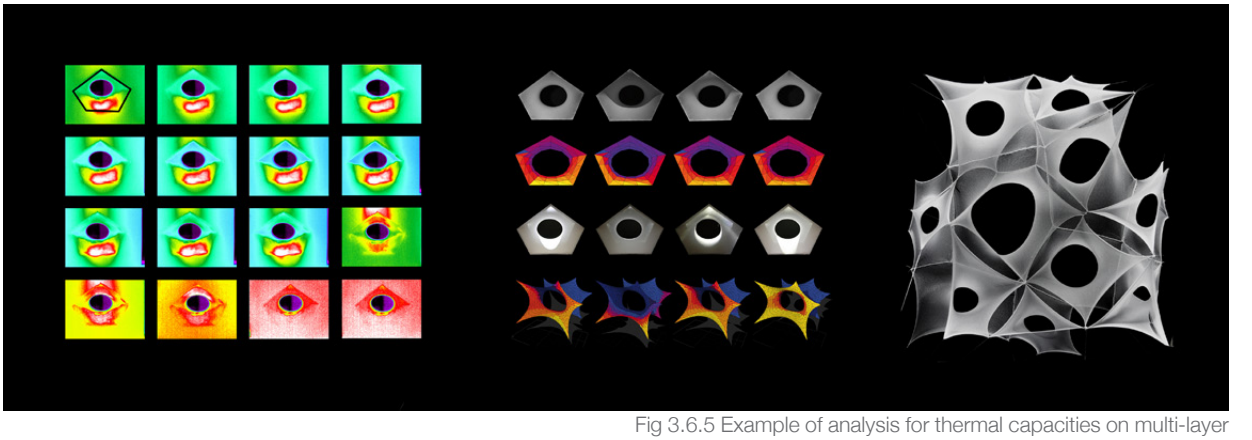
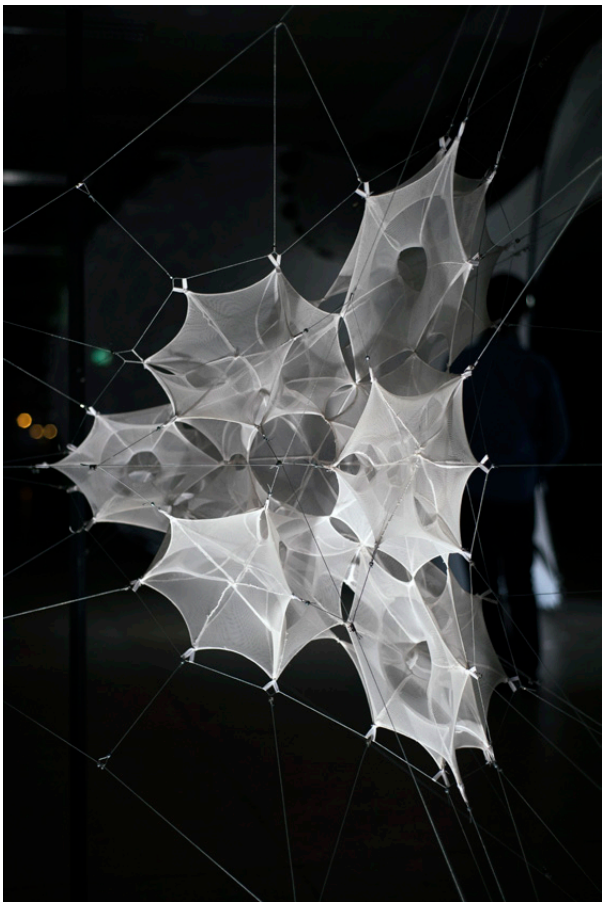
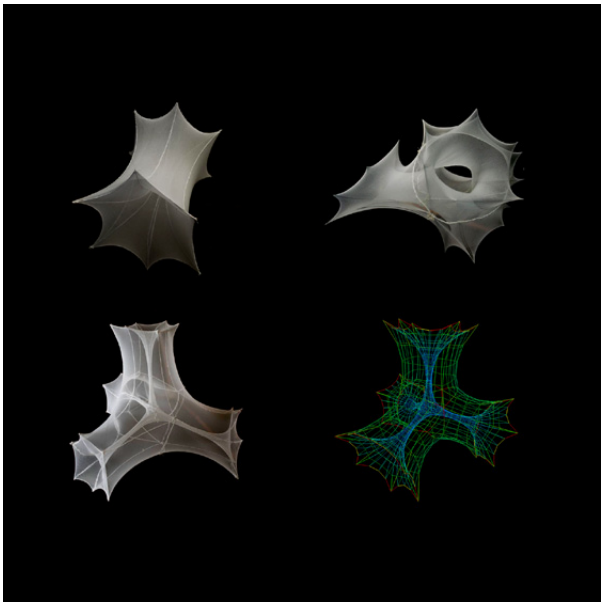


Fig 3.6.5 Example of analysis for thermal capacities on multi-layer Deep Surface textile morphologies, (Image: Sean Ahlquist).

Material has a bi-directional feedback into the springs-based exploration of topology and tensile behaviour. In the management of local topologies, meaning the springs connected at each node, a general indicator of material correlation is invested. The base topology of the springs defines a fundamental distinction between a surface material, such as a textile, and a material constructed of networked linear elements, such as a cable mesh. Primarily, defining a quad-grid, ideally including diagonals to measure the shear condition within each face, registers some correlation with the performance of a continuous surface material. In turn, this method provides the output information of force and geometry for the mapping of cutting templates to be generated. With the degree of intense topological variation in these structures, the force distribution is highly differentiated. At moments, this is managed through a switch in materials, between cable meshes and textile surfaces. An irregular topology can be more easily correlated with a cable mesh as the system can be broken down into its individual spring components and translated 1:1 as individual material element. Within the surfaces, there are significant degrees of differentiation as well. This is managed by the use of elastic textiles that can allow, within their own surface, changes in force directionality and magnitude while still maintaining a purely tensile morphology. The *Deep Surface* exemplars explore these relationships of significant jumps between material types to nuances of force fluctuations within continuous materials in order to develop fully tensile yet highly differentiated material forms. While critical information relating to these capacities is extracted from physical form-finding studies, the embedded properties within the springs-based modelling environment serves as the primary vehicle for exploration. The methods within the springs-based environment have been established to serve a certain level of fidelity through the materialization of the studies shown here and correlation between the both computational and physical descriptions.





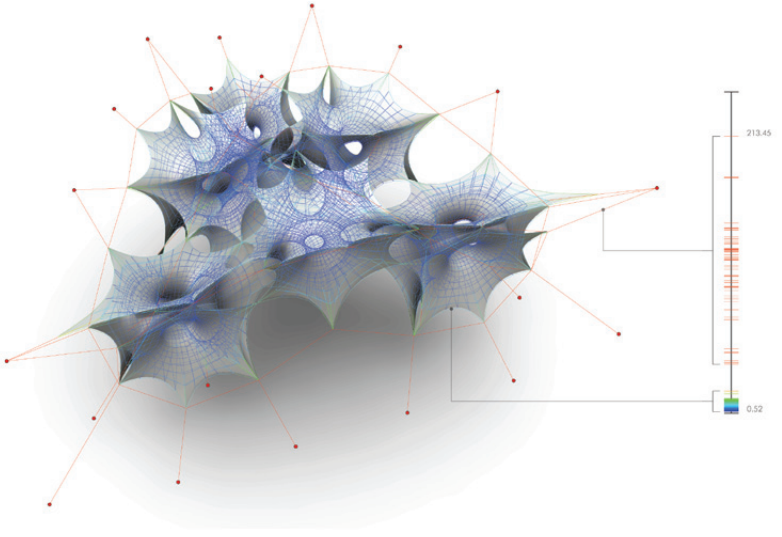
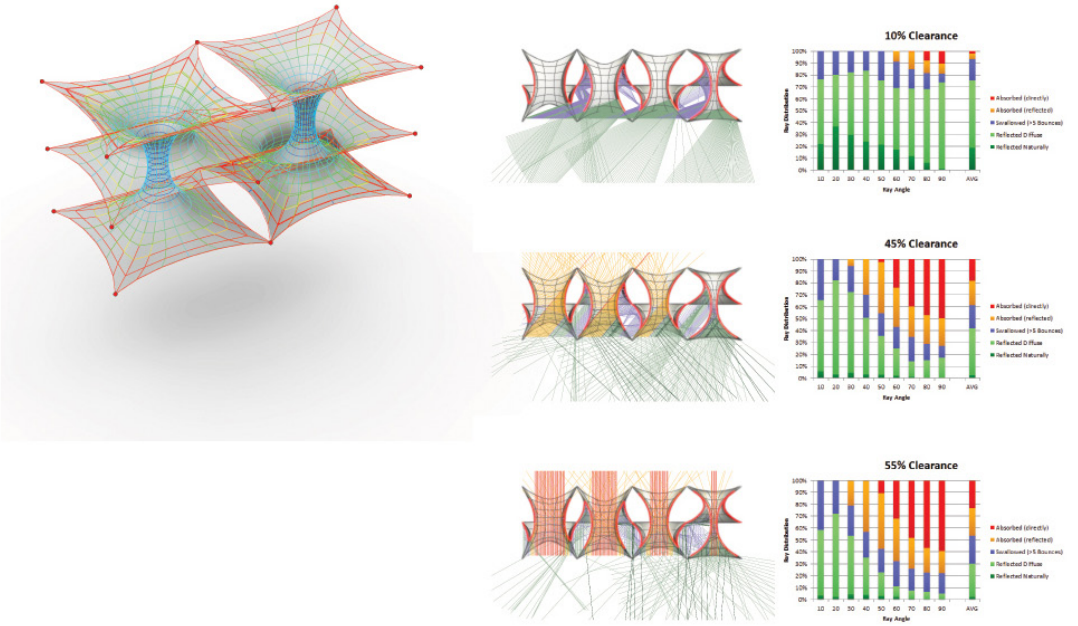
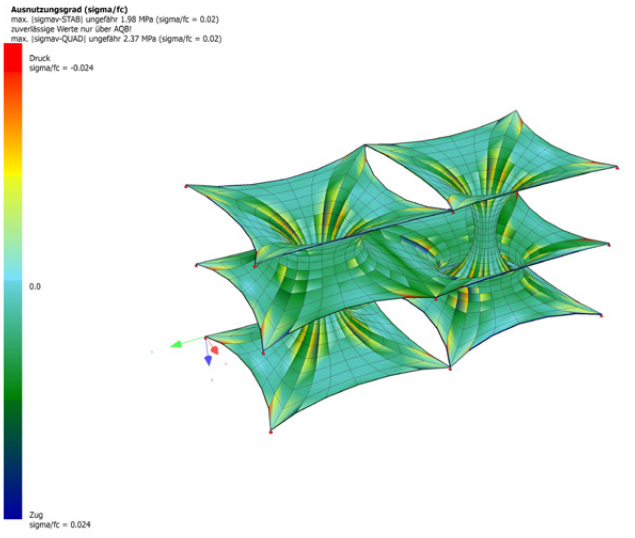


Fig3.6.6 Development of initial complex topology and form of single cell through physical modelling, transformed into multi-cell multi-material array through computational springs-based environment, (Images: Sean Ahlquist).





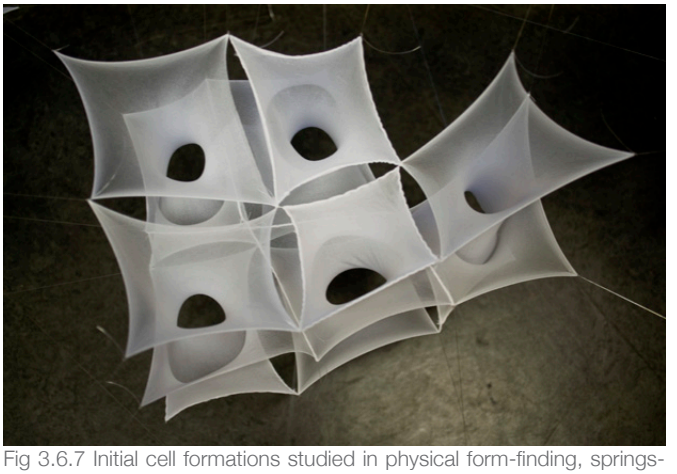
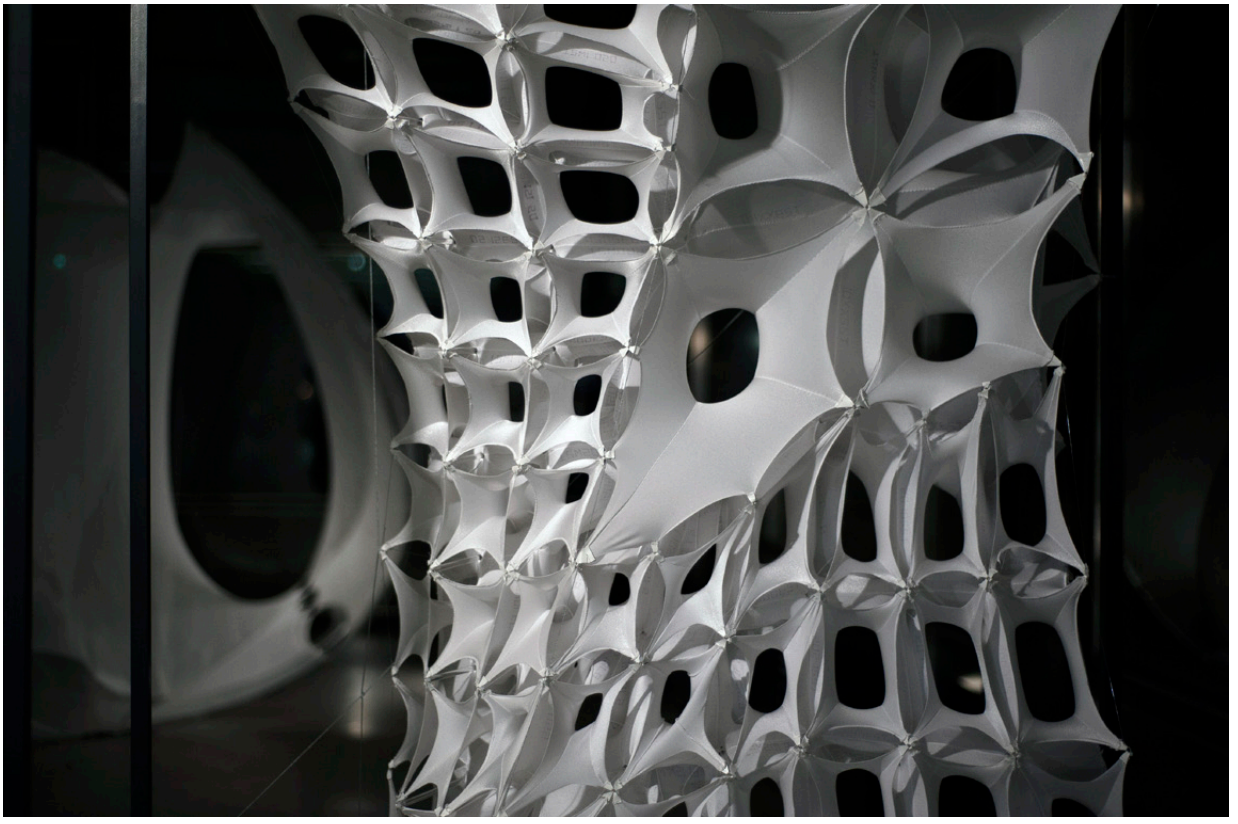


Fig 3.6.7 Initial cell formations studied in physical form-finding, springs-based environment and compared to finite element simulation. The formal logic is tested for acoustic modulation through simplistic ray-tracing method, (Images: Sean Ahlquist).



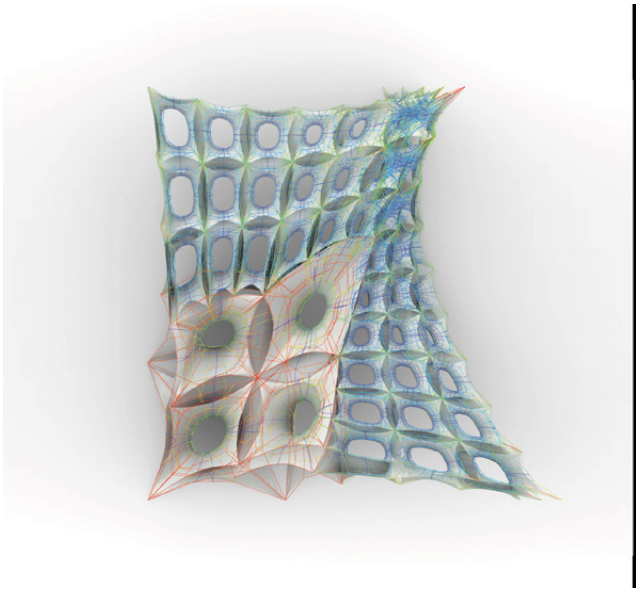
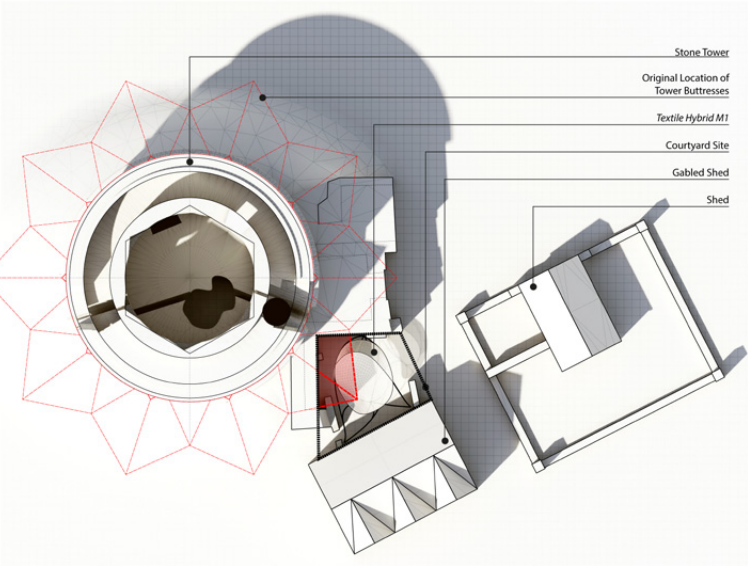


Fig 3.6.8 Comparison between springs-based simulation and resulting physical structure. Fabrication data was translated solely from the springs model, utilizing elastic textiles and minimal cable mesh to manage the force differentiations, (Images: Sean Ahlquist).

M1 Textile Hybrid at La Tour de l'Architecte, Monthoiron, France

The design of this project navigates all aspects of developing complexity in topology, behaviour and materiality, through studies that interleave physical material explorations with springs-based form-finding and finite element analysis. In certain cases, the physical experiments produce an exhaustive model describing the entirety of the structural system. This mode of design was utilized for developing the overall structural strategy. In other cases, the physical studies produce a prototypical singular solution where arrays of multiple interconnected elements were studied computationally. Such was the method for developing a cellular structure as a region within the overall system. In combination, the collective methods serve to develop a highly intricate structure that deals with critical conditions of material specification and contextual constraints.

The primary concern for the design of this project is to minimize the impact on the existing site. The structure is built within the La Tour de l'Architecte complex whose central feature is a tower designed by Leonardo da Vinci and subsequently built in the 1500s in Monthoiron, France. The tower's decrepit state prevents the M1 design from having any impact directly on the tower itself. Thus, the design sits adjacent to the tower and is structured only through three foundations, while being able to span up to eight meters. The structure is comprised of 110 meters of GFRP rods, 45m^2 of membrane material covering an area of approximately 20m^2. In total, the building weighs approximately 60 kilograms, excluding foundations. The ability to span such distances between six and eight metres within minimal material and contextual impact is critical in order to maintain clearance from sensitive ground areas, which contain archaeological material for the tower. In particular, the tower used an external buttressing system to accomplish its height. It is only the foundations of these buttresses that still exist. Avoiding the areas where these foundations lay was pivotal to the design. As well, the structure places priority on exploring differentiation to the degree of the Deep Surface experiments but at a scale akin to the Marrakech Umbrella.



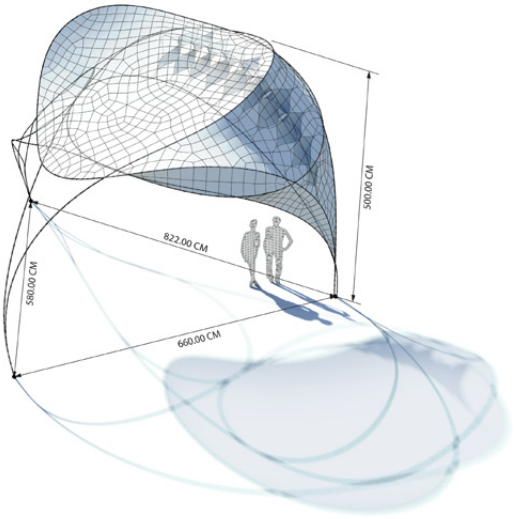
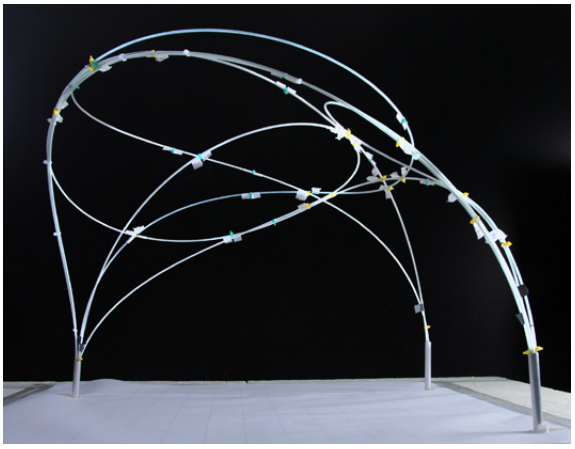


Fig 3.6.9 The cylindrical tower designed by Leonardo da Vinci utilized a series of pyramidal buttresses which no longer exist on the structure. The M1 structure sits adjacent to the tower and spans over one of the projected areas where the foundation of a buttress rests. (Photograph courtesy of Christian Armbruster and La Tour de l'Architecte.)

Having generated the setup for simulating the combined form finding of bending and surface tension for the Marrakech Umbrella project, it became possible to pursue more complex topological arrangements and thereby directly address the functional and formal potentials in combining form- and bending-active structures. As the primary design vehicle for this aspect of the overall system, physical form finding is instituted to determine and articulate both the topology and form of the structure. Where the physical performance of the bending-active system is generally scalable, the physically form-found model serves to outlay the topological description for direct input into the FE-model. As this topology had to be resolved into a mechanical description of geometry and forces, the bending-active nature had to be computed as an initial step before introducing the tensile surfaces. This highly complex topology of interconnected rods is what differs from the Marrakech umbrella and thus introduces an alteration to the methodology in having two-steps for form-finding the combined system. The final result however was like the FE-Model of the Marrakech umbrella a complete mechanical model of the form-found system including all residual and pre-stressing forces. This enabled a further processing of the geometrical data directly through the FE-model, for the unrolling and patterning of the rods and membrane surfaces. Figure 10 shows the different design stages of this process, starting with a physical model to generate the topological input for finite element analysis, as well as the intricate equilibrium of form-active membrane and bending-active rods in a construction stage.

In the Deep Surface experiments using springs-based simulation, the topology for interconnected cells is pre-determined, though many different variations can be studied by iterating the topology generation and form-finding process. For the M1 project, the topology of neighbouring cells cannot be predicted because of the inclusion of bending-active boundary elements that structure the tensile surfaces. It is only once the bending-active boundaries determine geometry that the relationship of where neighbouring cells connect and/or overlap can be determined. Within the springs-based environment, bending resistance is simulated using the vector position method, a robust method using relative values as compared to the vector normal method that can be unitized but slower to compute (Volino 2006; Adrianessens 2008)[x]. Akin to the Deep Surface design generation process, a physical prototype defines the topological scheme where cellular arrays were explored computationally. Like the finite element process, the computational effort involved two stages of first resolving topological description and then introducing the tensile surfaces. Still, the use of physical form finding is critical as both a generator for the topological strategy to spur the design process, as well as a method of measure to compare against the computational results.



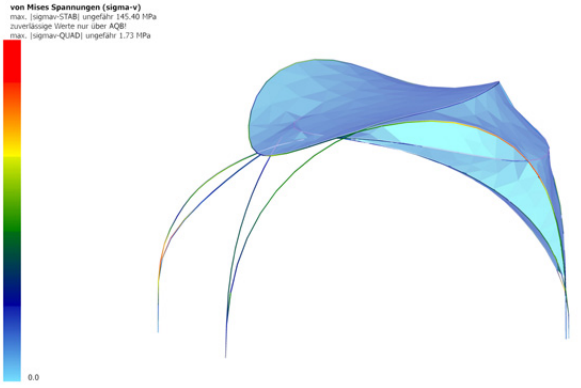
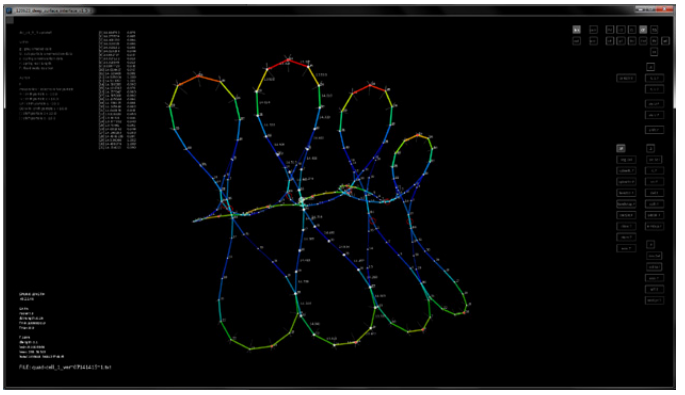
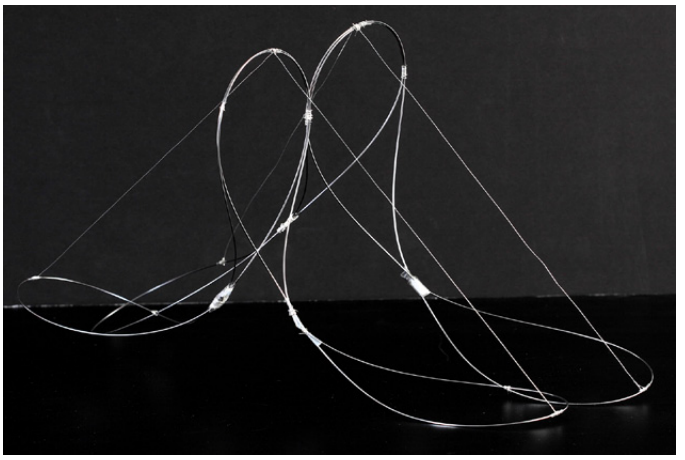


Fig 3.6.10 Various design and building stages of the primary structure: physical and finite element form-finding model as well as erection of the primary form- and bending-active system.





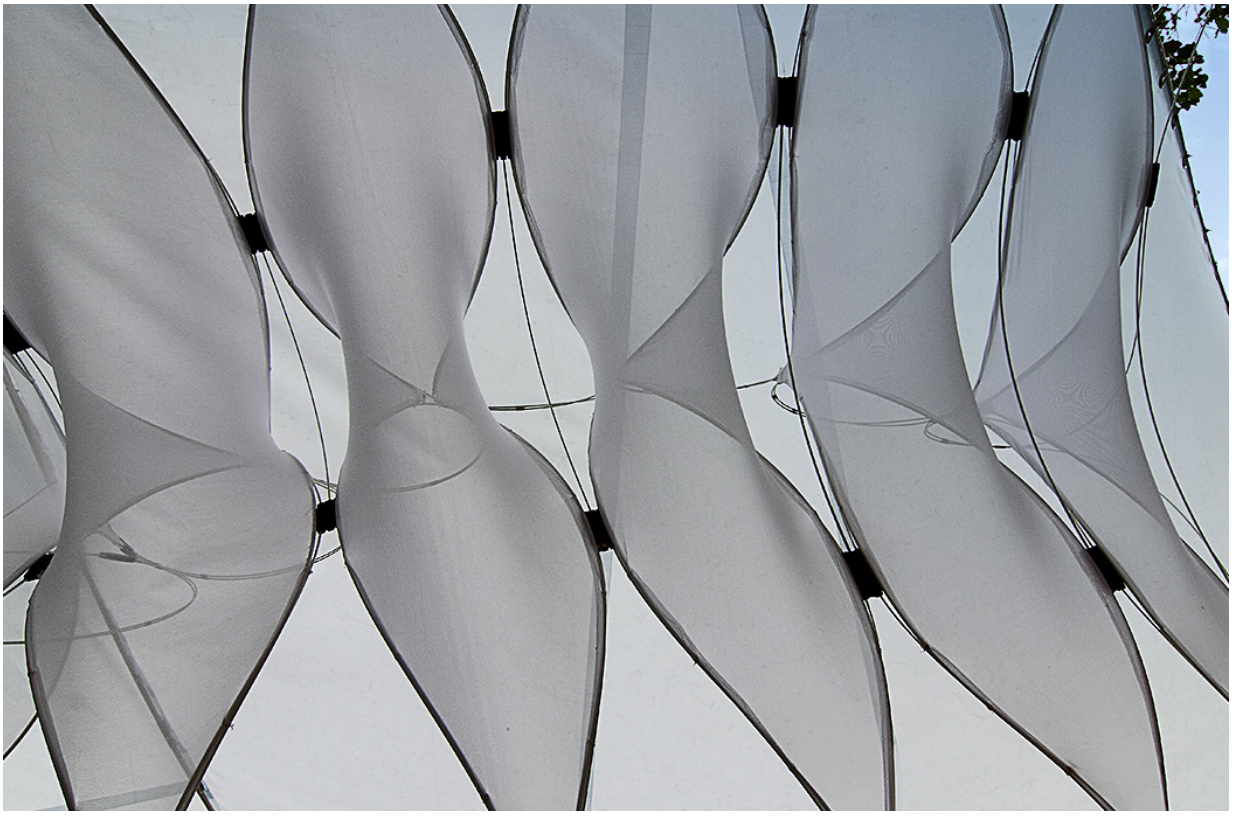


Fig 3.6.11 Development of the internal cell structure from initial physical form-finding studies to more complex simulations in springs-based modelling environment. Constructed cells define varied lighting conditions within the larger continuous structure, (Photograph by Sean Ahlquist.)

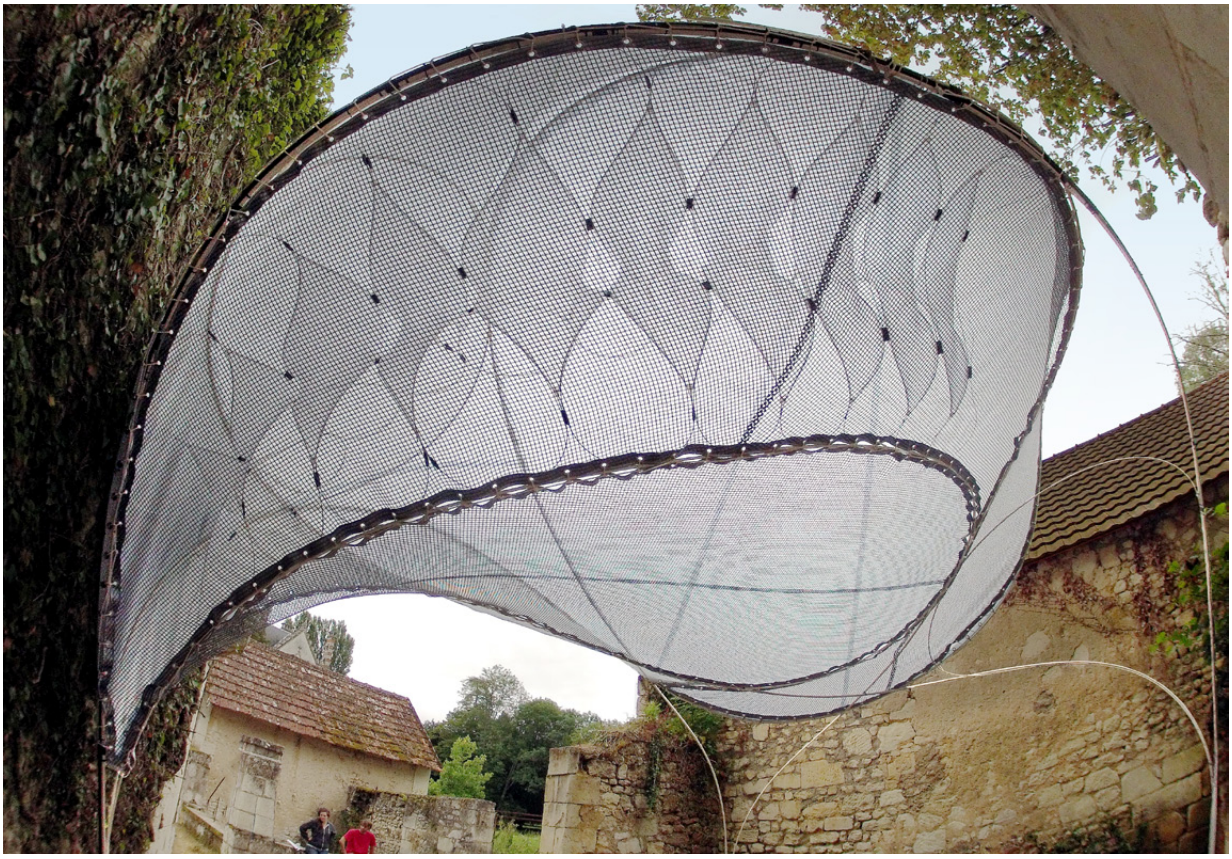
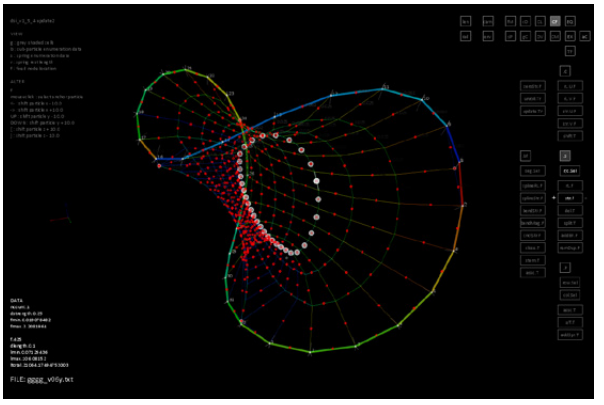


Fig 3.6.12 The Textile Hybrid M1: hybrid structure featuring the integral system of differentiated cells and multi-layer tensile membranes formed with elastically bent GFRP rods, (Photographs by Julian Lienhard.)

Semi-Toroidal Textile Hybrid Installation, ggggallery, Copenhagen, Denmark

This installation explores the potential of instituting differentiation within the textile surface, developing methods that can simultaneously manipulate and resolve the behaviours of tension and bending resistance. Where the M1 studied the implications of critical boundary conditions and structurally dealt with exposure to significant external loads (wind, rain and snow), the gallery installation explores the ability for the structure to be freely placed within the gallery space intending to maximize its volume while touching the surrounding structure with a minimal number of points. To explore such intentions, the springs-based modelling environment is developed further from that in the M1 project so that all force relationships are dealt with collectively. This reflects the process model in which the Marrakech Umbrella project establishes. If the topology is relatively straightforward, then the entirety of the system can be resolved simultaneously, so long as the functionality is programmed into the particular computational environment.

Instituting force as the vehicle for not only form generation but also surface articulation, capabilities for variegating the structure of a textile materially is explored through the use of CNC knitting technologies. Primarily, there is a highly structured hexagonal pattern knitted into the textile that is designed to carry the tensile loads. Secondarily, the field structure of the knit is altered to allow for varying conditions between extensive elasticity at the edges to additional stiffening in the middle. The variations are produced through controlling the regulation or tension in the yarn as the loops are knitted together. The less regulated regions at the edges allow the cylindrical textile to accomplish an approximately 12meter circumference. The middle region of the cylinder has a high degree of regulation in the knit to provide a pre-stressing of the textile to compensate for the minimal stresses that occur in that section of the assembled structure. In controlling these parameters of the textile and knitting process, the entire structure is able to be constructed of only 2 textile elements: a cylinder and a panel.



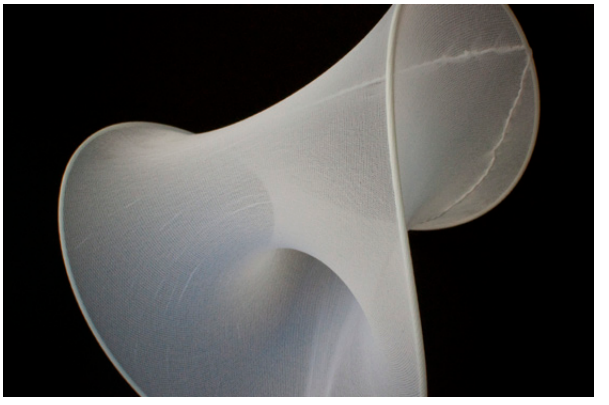
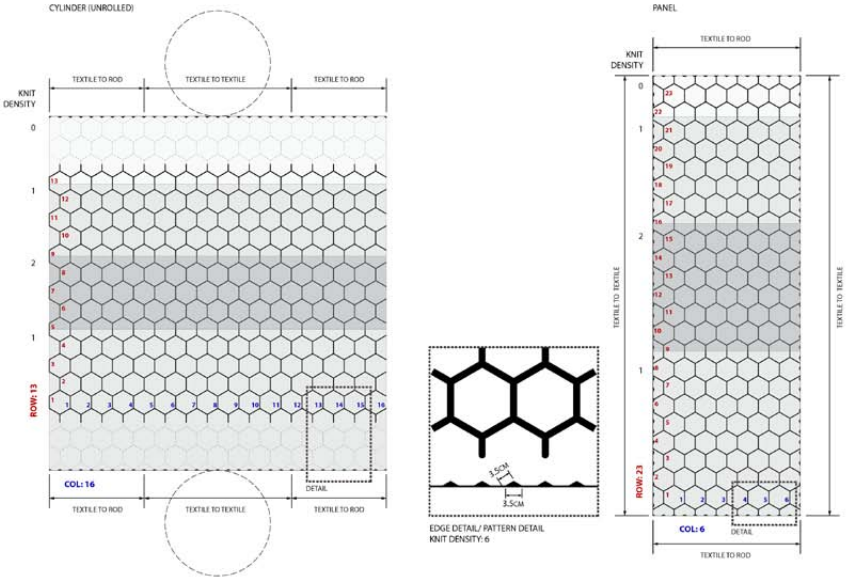


Fig 3.6.13 In controlling these parameters of the textile and knitting process, the entire structure is able to be constructed of only 2 textile elements: a cylinder and a panel.



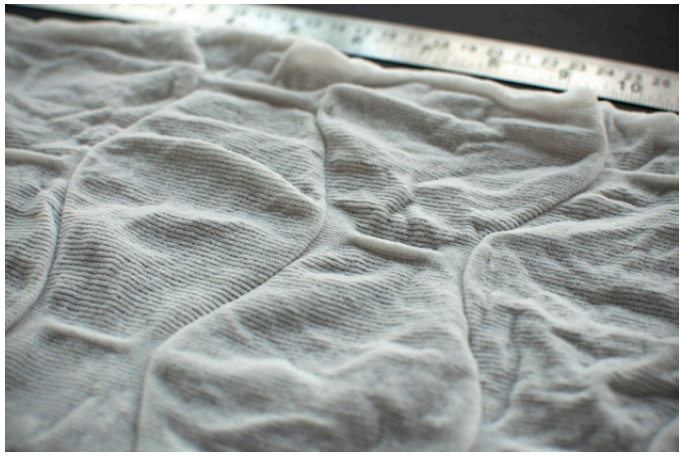


Fig 3.6.14 The data for force and geometry from the springs-based simulation is translated into mappings for variable knit structures. Primarily, the regulation in the knit is varied to induce internal pre-stressed in the textile. Such differentiation offers structural robustness as well as variation in the surface geometry when assembled into the fully force-active structure, (Images: Sean Ahlquist).

Conclusion

The design of textile hybrid systems demands methods that embed fundamental concepts for tension and bending-active behaviours along with ones for specific quantification of material parameters. Yet, the prototype, extracted from the logic of an exemplar, defines generic rules and specific ranges of parameters in order to project a new and larger family of potentials. Upon including material behaviour as a constituent of the prototypical design space, the range of parameters and design functions that a single exemplar infers is considerably narrow. Specifically for textile hybrid systems, the degree of interconnectedness between the tensile surfaces and bending-active elements significantly demarcates a design space from one exemplar to another. What this limitation has imposed upon the understanding of prototyping or the generation of the design space is the stress upon generalizing the methodology and means of design. It becomes the set of procedures and framework of design modes that project the potential design space, rather than any particular exemplar. Where prototyping implicates the advancement of processes, the exemplar itself then serves as a judge of fidelity for such processes. Through the diverse series of projects and explorations described in this paper, a robust framework has been established to support the further experimentation with textile hybrid material systems.

Acknowledgements

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References

i Authors affiliations: Sean Ahlquist, Institute for Computational Design (ICD), University of Stuttgart, Germany and Taubman College of Architecture and Urban Planning, University of Michigan, USA, Julian Lienhard and Jan Knippers,, , Institute for Building Structures and Structural Design (ITKE), University of Stuttgart, Germany, and Achim Menges, Institute for Computational Design (ICD), University of Stuttgart, Germany.

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3.7
Proto-materials: Material Practices in Architecture at Molecular and Cellular Scales

Martyn Dade-Robertson, Meng Zhang, Carolina Figueroa, Luis Hernan, John Beattie, Alexander Lyon, Markus Ryden and Malcolm Welford [i]

Vitruvius suggested in his texts *On Architecture* that architecture is an imitation of nature,[ii] but what happens when architecture becomes nature and we begin, through the design of biological systems, to become architects of nature? Just as the latter part of the twentieth century was transformed through information technologies, it is widely predicted that the twenty-first century world will be radically changed by the emergence of biotechnology. Biological systems exhibit a wide variety of forms and functions, make highly efficient use of energy and other resources and are capable of processes such as programmed self assembly and adaptability which are very difficult or, in some cases, impossible to achieve using more traditional human engineered systems. To this end, Synthetic Biology has been heralded as an important technological and design paradigm, enabling the development of complex material systems.

Synthetic Biology has been the subject of debate in a number of disciplines, including architecture. The possibility of designing material forms through the manipulation of molecular and microscopic scale structures offers a radically different way of thinking about the design process and its possible outcomes. These speculations also raise important epistemological, ethical and practical questions about the role of design in this new field.

While the architectural design discourse around Synthetic Biology is rich, there is a growing gap between speculative practices in architecture and the current practices of Synthetic Biology. As it is currently practiced, Synthetic Biology seeks to conceptualise the design of biological systems through a design framework developed from mechanical and electrical engineering rather than architecture. This paradigm involves understanding biological systems as composed of modular units assembled 'top down' through a hierarchy of abstraction. Architects, on the other hand, view Synthetic Biology in terms of 'bottom up' processes of material self-organisation and emergence. In reality, the design of biological systems is unlikely to be either entirely 'bottom up' or 'top down' and, to close this gap in understanding, it is necessary for architects to move beyond design speculation and to engage in Synthetic Biology as a material practice. A shift in design thinking will need to take place as lab and studio practices are merged to create new sorts of prototypes to experiment with new biological materials and forms.

This paper will develop the theme of Synthetic Biology as a material practice through both a review of our current understanding of Synthetic Biology as a design field, and the current state of the art in terms of architectural design speculations based upon the notion

of a, so called, literal biological paradigm in architecture. It will then focus on the process of biomineralisation and refer to a series of experiments designed to investigate the process of calcium carbonate formation using naturally occurring bacteria. These experiments, which act as pilot studies, investigate how we might combine laboratory and studio practices and how material engagement with, even simple, biological systems might inform and ground design speculations in a material reality.

The Architecture of Synthetic Biology

Synthetic Biology has, until recently, primarily been studied in the fields of molecular and systems biology, computer science and engineering. As a result, most current models of Synthetic Biology are based on an engineering design paradigm that conceptualises the design of biological systems through a hierarchy of abstraction. Critical to this conceptualisation is the notion of standardisation, where biological systems are likened to electronic and computation components. Within this model, proteins and genes are equivalent to physical transistors, biochemical reactions are the equivalent of logic gates, metabolic pathways are the equivalent of hardware modules (e.g. processors), cells are the equivalent of computers and tissue and cell cultures are the equivalent of networks.[iii] Underlying this system is the software of biology: Deoxyribonucleic acid (hereafter DNA). This approach, however, raises important epistemological and practical questions. While the conceptualisation of biological systems as hierarchical, and divided into discreet and interchangeable units, has the effect of taming an otherwise unruly design space, it may also oversimplify processes whose functionality lies in their complexity. In addition, it is important to distinguish between the analogy of hypothetical biological systems, and actual biological systems as they are and as they may be engineered.

In considering an alternative to the engineering design model, a useful reference point is architectural practice. Architects make use of a range of 'mediating artefacts', which enable design at many different levels of abstraction and allow for collaboration across extensive design teams. Whilst the separation of the design process from the material processes of construction has been liberating, however, enabling the design of complex new buildings, it has also been problematic, leading on occasion to unsustainable building practices and an architectural discourse which has, notably in the light of computational methods in design, sometimes led to superficial practices of form creation disconnected from material reality.[iv] At the same time, however, there have also been more 'grounded' developments in architecture, which have continued to investigate the logic of material construction as the genesis for design through direct engagement in material prototypes. Architecture has thrived on this tension between rational abstraction and material reality and this paper suggests that this approach and experience can help to inform the future development of Synthetic Biology. In exploring this proposition, however, we will need to question the very status of design representations as topographical templates or patterns for material articulation. When designing biological systems, there is likely to be a less direct relationship between design representation and material construction as the role of the designer shifts from 'sculptor' to 'cultivator' of materials.

Architecture as Synthetic Biology

While architectural design has often been influenced by the natural world, biotechnology offers the possibility of a *'literal biological paradigm'*.[v] In contrast to biomimicry, where forms

and systems are copied from nature, the literal biological paradigm proposes architectures constructed using biological systems directly. The literal biological paradigm has, for some time, been a focus for architectural theory and speculative design practice [vi] but, to fully understand this work, it is necessary to relate structures and events which are manipulated through Synthetic Biology at microscopic levels, to the creation of material forms at a macroscopic (visible) scale.[vii] As yet, however, we have few practical ways of relating these different scales of material construction. We certainly have no way of easily understanding the implications of designing a building by manipulating its DNA or of entering a design process where it is necessary to produce detail drawings at 1000:1.

There is precedent for design and arts led responses to Synthetic Biology, notably the EPSRC/NSF funded Synthetic Aesthetics project.[viii] However, with the few notable exceptions, referenced above, design speculation on architecture and biology tends not to engage with scientific research but rather to make use of a repertoire of forms and structures that are driven by computation modelling. In so doing, designers simplify the process by which materials and forms are produced in nature by conflating relationships between scales of forms and patterns, see for example Paul Preissner's, *Back to the Future*.[ix] In fully exploring the relationship between architectural practice and Synthetic Biology, there is clearly benefit to be gained from developing an approach that starts with an attempt to give this new literal biological paradigm a material reality.

Conceptual Framework: Towards a Synthetic Shell

To help frame the proposed approach, it is worth considering the case of abalone shells. Shells occupy an iconic status within architecture and have been used as an emblem for scale and proportion as well as providing the basis of many types of building materials. In addition, shell formation is a good example of the complex relationship between biological mechanisms and the construction of inorganic materials through organic processes. An abalone constructs its shell by first forming soft tissues through morphogenesis (the process by which the organism's cells organise into a pattern). The organism doesn't build its shell directly but instead these tissues act like a scaffold and the abalone alters the chemical composition of its outer surface in order to induce calcium in its environment to combine with carbon and crystallize through a process called biomineralisation. Furthermore, by altering the chemical environment through the addition of extra cellular substances, the shell shifts between different crystalline structures from the inner layer of flat plate-like crystals (sometimes referred to as mother of pearl) to the outer layer that is made up of vertical crystals to create an exceptionally strong surface.[x] By controlling this process of mineralisation, the abalone constructs a single material with the properties of a composite material and creates a structure with significant strength with very little expenditure of energy. This is a fascinating process, not least because the status of the shell is ambiguous. Its form and material are products of the interaction with its environment and, although it is not living, it cannot be considered as entirely inorganic. Both biomineralisation and morphogenesis are often studied independently in science but the two processes are rarely studied together and have never been studied together in the context of design.

Biomineralisation

Biomineralisation is the process by which organisms initiate and control physical processes, associated with the crystallization of minerals to produce hard materials, for

example bones, and shells. Biomineralisation is also a by-product of processes in nature such as bacterial activity in soils. Limestone and marble are both iconic building materials and recognizable products of calcium carbonate biomineralisation. This process involves low energy use (compared to the production and maintenance of soft tissue) and has been studied in the context of buildings as a way of creating new 'self healing' materials,[xi] and through design speculations. Examples of the latter are Magnus Larson's proposal to create new sandstone structures through the consolidation of sand dunes, and Rachel Armstrong's proposal to refloat Venice through the building of a protocell induced calcium carbonate reef.[xii]

Aside from the potential applications of biomineralisation, the process itself is worthy of further study, particularly in relation to bacteria induced calcium carbonate production which can be seen as a prototype for processes seen in more complex organisms. In bacterial biomineralisation, the organisms are only indirectly responsible for the crystallisation of calcium carbonate. Rather, calcium carbonate is a product of urease which is a chemical released into the bacteria's environment that alters its alkalinity such that calcium will tend to bind with carbon. In addition, the bacteria produce cellular materials known as extracellular polymeric substances (EPS), which have been shown to control both the morphology and distribution of calcium carbonate crystals. Comparisons have been made between this process and the formation of an abalone shell, described above. This bacterial process, therefore, offers an interesting bridge between comparatively simple biological processes and those found in higher order organisms. As with the bacteria, an oyster does not directly mineralise the calcium carbonate within its cells, but rather alters its chemical environment in phases so that different layers of shell are induced around the organism with varying patterns of crystal distribution and form. The shell is more like a piece of architecture than a part of the organism itself, although the two are dependent on one another.

Experiments in Building Biological Protomaterials

Bacterial biomineralisation has been well studied and provides a context in which relatively simple experiments can yield observable results. In addition, because most Synthetic Biology are conducted using simple bacteria as the basis for genetic manipulation, observing their natural states and processes gives important clues as to how such organisms might be altered by genetic manipulation to produce usable material structures at a larger and, perhaps, architectural scale. The experiments described below also highlight the differences between lab and studio practice and the challenges of marrying scientific objectives with design experimentation. Two sets of experiments were conducted involving bacteria induced mineralisation, both undertaken in collaboration with Northumbria University, linking PhD and Masters students in Architecture with a Researcher in Biochemistry. In both pilot studies the team started with typical growth on agar plates and ultimately extended them by developing scaffolds designed to support the bacteria and expose it to different conditions. The results of testing different bacteria under different chemical and physical conditions led to a wide range of different crystal morphologies and patterns. The key outcome was the demonstration of a process which begins to link the design of macro structures to microscale effects and this helped to foster an understanding of the relationship between biological, chemical and physical constraints on the state space of this type of material construction. The following sections detail both experiments and offer some insights on their analysis and implication for further research.

Experiment 1

The first set of experiments concentrated on evaluating the influence of specific species of bacteria on the distribution and morphology of calcium carbonate crystals. While the basic chemistry of such reactions is well known, the reality of bio-induced mineralisation is more complex and the initial experiment therefore focused on observing the differences in the calcium carbonate crystals induced from two different species of bacteria, i.e. *Bacillus pasteurii* and *Bacillus megaterium*. The two different species of Bacillus were grown on separate nutrient rich plates containing calcium chloride with neural pH. The first plate, hereafter referred to as Experiment 1A, was inoculated with a single colony *Bacillus pasteurii.* The second plate, Experiment 1B, was inoculated with a single colony of *Bacillus megaterium.* Both plates were incubated at identical conditions. A further experiment was also run in parallel as a control, Experiment 1C. This was designed to demonstrate that, by providing a nutrient rich environment without the presence of calcium chloride, no crystals were induced by both bacterial species. Upon completion, samples were cut out of the plates and prepared for observation under electron microscopy by vacuum dried and coated with a thin layer of gold – see Fig. 1.

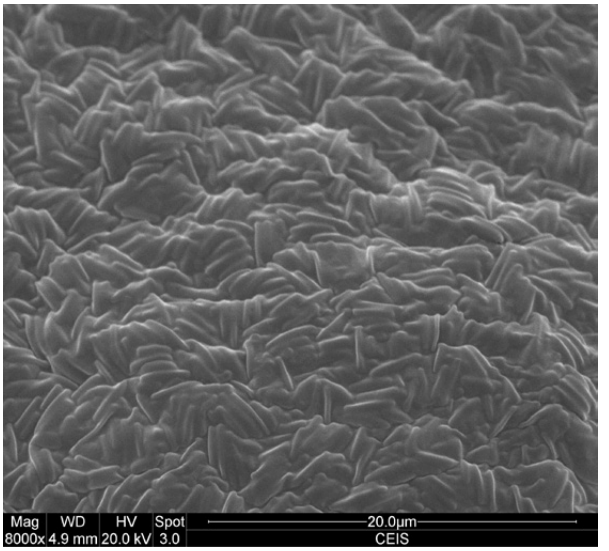


Fig 3.7.1 Electron Microscope image of Bacillus Pasteurii growing in agar without the presence of calcium.

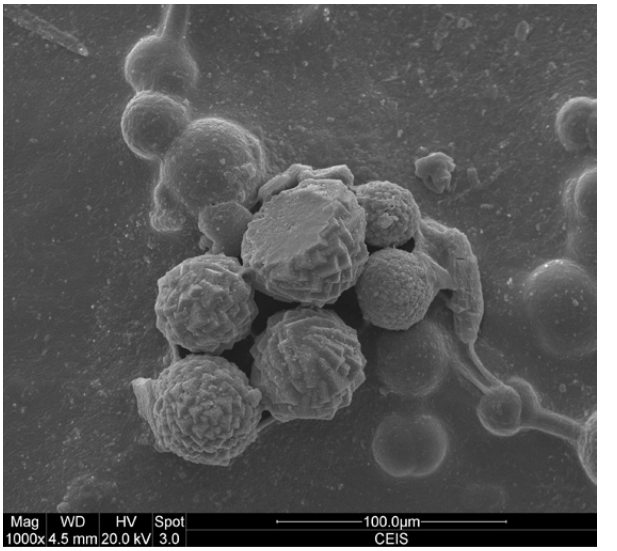


Fig 3.7.2 Electron Microscope image of a cluster of calcium carbonate crystals induced by Bacillus Pesteurii.

Electron microscope images, Fig. 2, from sample Experiment 1C show thriving colonies of bacteria, observed here as long tubular cells, with no sign of crystal formation. This can be contrasted to Fig. 3 showing samples from Experiment 1A, inoculated with *Bacillus pasteurii*, in which can be seen large, apparently multifaceted, spherical calcium carbonate crystals. Fig. 4, which also comes from Experiment 1A, corresponding to the same sample, shows the difference in scale between the bacteria cells and the crystal which are embedded into the broken surface of the crystal.

These crystal forms are unique to calcium carbonate, which has been crystallised in an environment rich in complex organic compounds. A striking feature is the connection between crystals through a network of what seem to be fine filaments. Initial analysis of the filaments reveals that they are not crystalline structures and it contains rich organic

molecules, i.e. polysaccrides and chains of amino acids, although further analysis will need to be carried out to assess their exact nature. The nature and purpose of these filaments is not yet clear however, given their regularity and spatial relationship to the crystals, it seems plausible to suggest that they are related to crystal nucleation and growth.

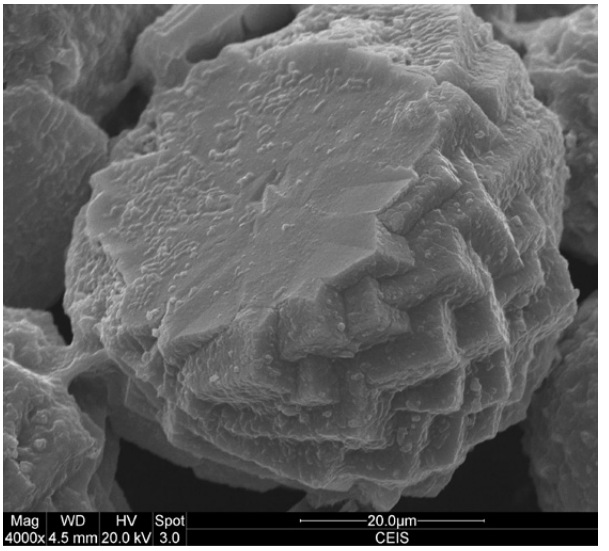


Fig 3.7.3 Electron Microscope image of the surface of a fractured calcium carbonate crystal showing Bacillus Pesteurii bacteria embedded in its surface.

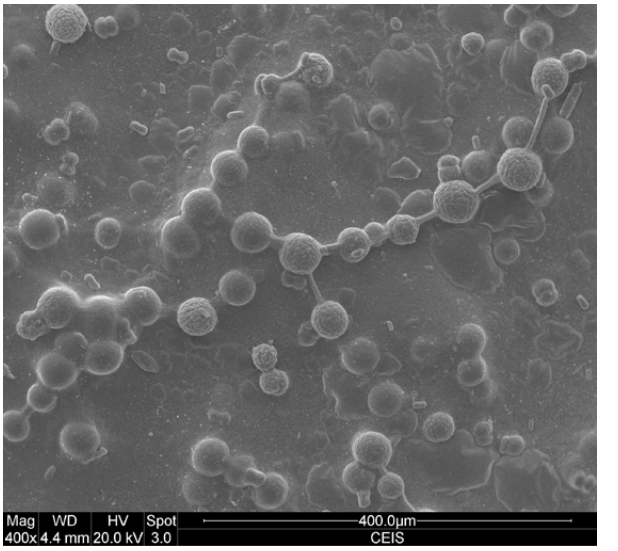


Fig 3.7.4 Electron Microscope image of calcium carbonate crystals connected by a network of filaments made of organic molecules.

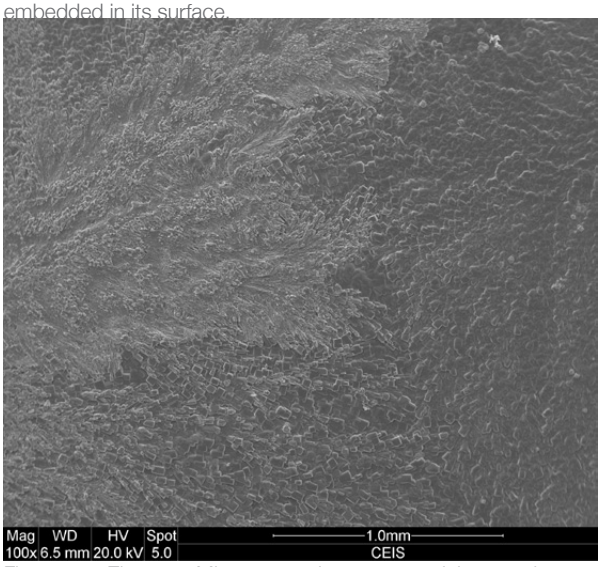


Fig 3.7.5 Electron Microscope image of calcium carbonate crystals induced by Bacillus Megaterium. The image shows the structure of the crystals which appear to flow away from the bacteria colonies.

The extent of the crystallization process in experiment 1A can be observed in Fig. 5. Although crystal formation, which is visible to the naked eye in this sample, is found in higher densities near the bacterial colonies, crystallisation has also been induced across the whole plate. Based on this evidence that the crystals are forming some distance from the bacterial colonies, it may be that this network structure is extending the influence of the bacteria on their environment. While we are unable to make scientifically firm statements at this stage, this relatively simple experiment raises interesting questions, which could be tested further.

The images from Experiment 1B show very different structures, unlike the outcomes from Experiment 1A, Fig. 6 shows that crystals are only found in conjunction with the bacteria colonies and, while the crystals are of similar size, their morphology is plate-like and they are stacked densely through the agar with 'waves of crystals' appearing to follow gradients away from the bacteria colonies. This feature lends support to the idea that the network of filaments found in the first sample are linked to a reaction between the forming crystals and the extra cellular matrix of the bacteria rather than the agar environment. Experiment 1 generated compelling images and clearly demonstrated the importance of different biologically controlled conditions in the formation of calcium carbonate. The protocols followed and the questions asked of the results were well within a scientific mode of enquiry and the experiments, albeit undertaken in a highly speculative mode, could have been conducted by materials scientists.

Reflecting on the results raises questions about the design of objects created using new biologically influenced materials. In considering the relationship between the living invisible organism (in this case the bacteria) and the creation of the visible mineral material, it can be seen that a complex relationship exists between biological, physical and chemical processes. The state space of material creation is not based on the organism alone, but rather on the interaction of many different processes, all of which offer the opportunity for intervention and control. This state space includes factors such as the locations and spread of the bacteria colony, the composition and form of the material substrate, the diffusion of the active chemical agent through the substrate and the interaction between extra cellular materials and non-organic materials. In considering how we might design a system to control the favourable formation of materials, it is therefore important to recognise that genetic manipulation is only one factor in modifying the design's state space. This observation, in itself, challenges the current overriding focus of Synthetic Biology.

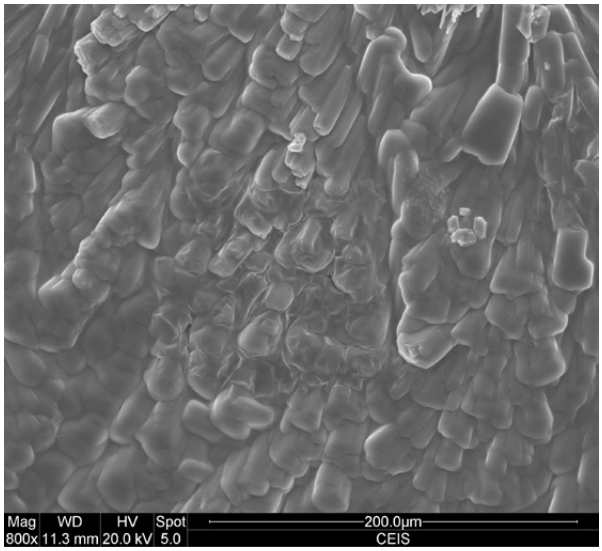


Fig 3.7.6 Close-up detail of calcium carbonate crystals induced by Bacillus Megaterium showing flat, plate-like crystals.

Experiment 2

Experiment 2 was initiated as a student project conducted as part of a Stage 6 (Sixth year of architectural study) design primer. The results of Experiment 1 were presented, as were the physical and resource constraints of working in a laboratory environment. The aim of the short project was to find ways of disturbing or reshaping the process of calcium crystal formation. The research group was not able to modify the organisms themselves so needed to find other ways of altering the state space of material construction and, through a series of experiments, to observe the results and begin to speculate on architectural outcomes based on them.

The students worked on the design of a series of four 'bioreactors' of increasing complexity in terms of the number of variables tested and the deviation from more traditional agar plate type experiments. Bioreactors refer to any engineered device that enables or supports a biologically active environment. Three of the bioreactors involved modifying the conditions of a regular Petri dish, and a fourth was designed to be held inside a bespoke container. In all of the experiments, the emphasis was on controlling the physical conditions in which the crystals grew by manipulating the surface of the agar. Fig. 7 shows the different bioreactors created based on experimental protocols, which gave instructions for the preparation of agar substrate and the locations in which the bacteria were to be inoculated. All experiments were run for a period of four days using both species of bacteria used in the earlier experiments. Upon completion, samples were collected and prepared for further analysis through Electron Microscopy. The aim of the experiments was to observe how crystal distribution and morphology changed from the previous experiments. The experiments were numbered 2A to 2D and, with the exception of Experiment 2C, significant changes were observed. These changes are set out in Fig. 8

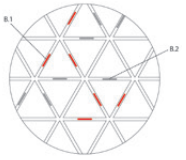
Experiment 2D gave some of the most interesting results as it proposed a three dimensional surface for the bacteria and a protocol which involved pouring agar, rich in nutrients and calcium chloride and inoculated bacterial liquid culture over a series of both slack and taught strings suspended between plastic disks. When the apparatus was dismantled, samples were taken directly off the string and from the areas of agar around the string. In some or these areas, sheets had dried forming connective 'tissues' between the string. It was also found that the bacteria growth and subsequent calcium carbonate deposition was clustered around the strings, suggesting a process of lithification, turning soft 'tissues' into hard structure. It would appear that the presence of the strings controlled the morphological properties of the calcium carbonate deposition. It was also noted that the crystals in this experiment were less well defined and tended to form into fragmented clusters. This experiment provides a first clue as to how an approach might be developed to move us from microscopic bacterial events to structures we can begin to visualise and test.

A. TRIANGULAR LATTIC GRID (PETRI – AGAR)

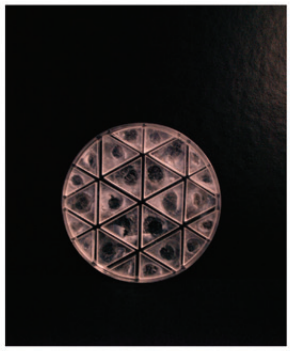
Aim – test the growth and pathway interactions of two or more inoculation sites.

Procedure:

1. UV sterilise Perspex mould and place in petri dish.
2. Pour agar into all interconnected channels in the Perspex mould until a suitable depth is reached without flooding the plate.
3. Inoculate with bacteria at locations marked below:



4. Seal and incubate petri dish.
5. Remove samples from channel convergences for examination.

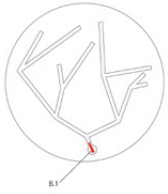


B. BRANCING PATTERN (PETRI – AGAR)

Aim – test whether the growth of calcium carbonate is directional and/or has a range dependant on the mass of available agar.

Procedure:

1. UV sterilise the Perspex mould and place in petri dish.
2. Pour agar into channels of tree network until a suitable depth is reached without flooding the plate.
3. Inoculate with bacteria A at circle location shown below:



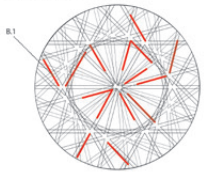
4. Seal and incubate petri dish.
5. Remove samples from branch junctions for examination.

C. LATTICE FRAME (PETRI – AGAR)

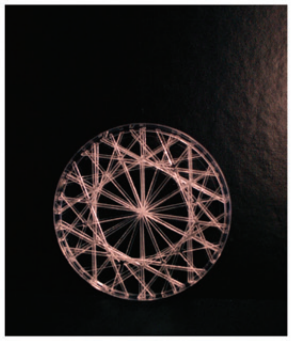
Aim – test the growth of calcium carbonate between layers in a 3D lattice structure.

Procedure:

1. UV sterilise the Perspex lattice structure.
2. Dip lattice structure into agar 5-6 times until coated.
3. Place coated lattice structure into petri dish on top of base layer.
4. Depending on agar pooling inoculate with bacteria at locations similar to those shown below on all lattice levels:



5. Seal and incubate petri dish.
6. Remove frame from petri dish and cut samples with visible growth.

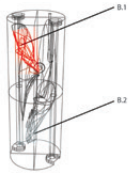


D. WIRE FRAME (CYLINDER JAR – SOLUTION)

Aim – Test the effects of calcification on a web like structure under dynamic forces.

Procedure:

1. UV sterilise jar and web apparatus.
2. Prepare solution and pour into jar (alternatively, dip frame in agar first to coat).
3. Place web like frame into jar.
4. Inoculate with bacteria A and B at locations shown below (on different coloured strings).



6. Incubate.
7. Remove web frame from jar and cut wire(s) with visible growth for examination.

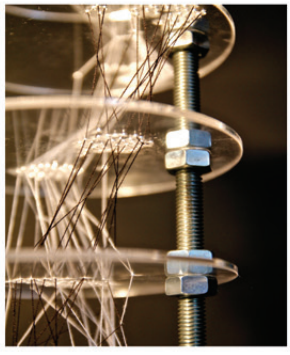


Fig 3.7.7 Diagrams and images to show the four bioreactors and the experimental protocols accompanying them.

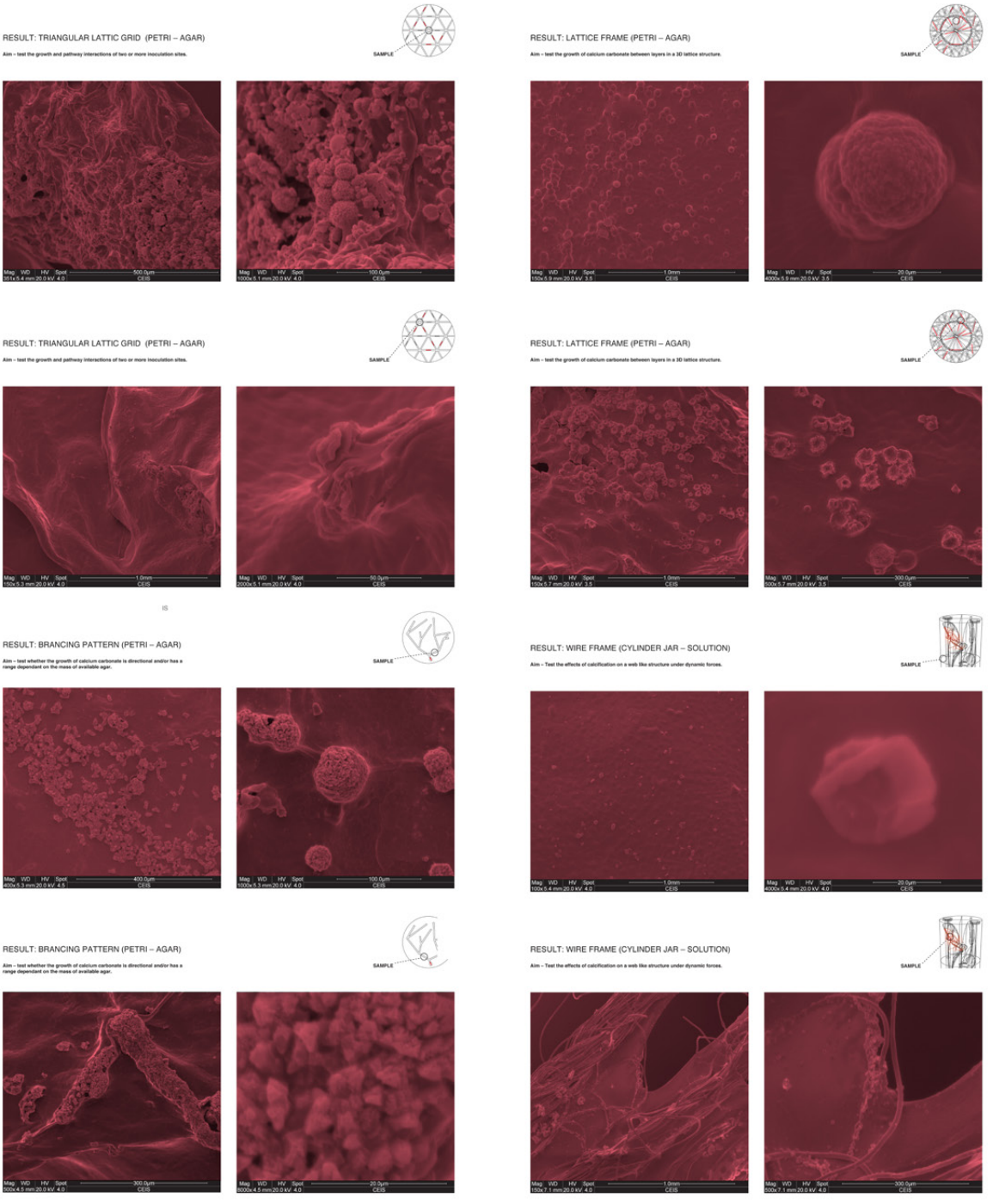


Fig 3.7.8 Images and diagrams of the locations and structures of crystal growth within the bioreactors.

Conclusion

There is clearly the potential for practical applications to flow from such research. For example, taking the earlier illustration of the oyster shell and the production of calcium carbonate as a composite material, we can see that the synthetic engineering of such a material on a larger scale could provide an alternative to traditional cavity wall construction. It is tempting to suggest that such speculation and experimentation should be left to material scientists or that molecular level 'architectures' are more suited to articulation by molecular and micro-biologists. However, this view would miss the potential richness of material engagement with engineered biological systems. Even in the relatively crude experiments detailed above, the notion of 'engineering nature' encourages architects to think in new ways about how the material world is and how it might be shaped. Whilst inert materials are amenable to direct manipulation in the hands of the crafts person, biological systems are subject to indirect control or influence including the manipulation of both the physical and chemical nature of the state space of construction. While this way of thinking about material articulation appears alien to architectural practice, the broader notion of state spaces of influence is not new to architectural discourse. For instance, elements of the built environment are generally understood as being created in the context of a combination of external factors such as political, social and cultural forces, alongside the range of constraints specific to the site. In the same way, the new modes of thinking in relation to material articulation which have been sparked by developments in Synthetic Biology, involve an approach to the architectural object, where form is only possible in the context of the dynamic forces interacting on biological, chemical and mechanical levels.

Consideration of the relationship between the ongoing speculation on the potential impact of engineered biological systems and the realities of Synthetic Biology as it is currently conceptualised, reveals compelling application domains but also a gulf in practices. It seems clear from the existing architectural literature that it is expected that Synthetic Biology will fundamentally change the process of construction from a situation where materials are constructed using a heavily industrialised process—forged through physical and chemical processes or mined from finite mineral resources—to one in which building material or even whole buildings are grown through biologically induced chemical reactions where molecular level parts self-assemble into larger structures. In addition to this compelling possibility, there is the more speculative proposal that buildings may also be semi-living entities, which exhibit life-like characteristics in terms of their adaptable propensity for dynamic change.

However, we must translate these speculations into working hypotheses, understanding that our computational models of biological form constitute significant abstractions when compared to actual biological systems. Whilst it is possible to make broad generalisations about the consilience between molecular scale events and the formation of materials at an architectural scale, we know very little about the complex interrelation of elements across scale which lead to biological morphology. Furthermore, we also need to reconcile our cultural understanding of biological systems with the tectonics of biologically engineered materials i.e. forms that can be evolved to specific needs and tolerances using biological systems. Form may indeed be an emergent property of engineered biological systems, but an aim of Synthetic Biology is to enable design from the top down so that parts will assemble to patterns and tolerances that can be designed for. The challenge for the 'Synthetic Biology Architect' is therefore to tackle two main issues. The first concerns how morphology is evolved through complex interactions across scales. The second concerns the development of appropriate tools and methods of abstraction and representation to enable us to design such systems prior to the actual biological engineering process.

The experimental processes described above give a hint as to how this may be achieved. The bacterial architectures observed and the scaffolds which were designed to shape their constructions give clues as to how we can begin to prototype new types of material assemblage and gain an understanding of the different logics inherent in different scales of material organisation.

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i The authors' affiliations are: Martyn Dade-Robertson, Meng Zhang, Carolina Figueroa, Luis Hernan, John Beattie, Alexander Lyon, Markus Ryden and Malcolm Welford, ArchaID, School of Architecture Planning and Landscape, Newcastle University, Newcastle upon Tyne, UK, except Meng Zhang, Biomolecular and Biomedical Research Centre, Faculty of Health and Life Sciences, Northumbria University, Newcastle upon Tyne UK.

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xii R Armstrong, *Living Architecture: How Synthetic Biology Can Remake Our Cities and Reshape Our Lives* (New York: TED, 2012)

3.8
Prototyping Biomimetic Structures for Architecture

Riccardo La Magna, Steffen Reichert, Tobias Schwinn, Frederic Waimer, Jan Knippers and Achim Menges [i]

Technology has always been a catalyst for design innovation in architecture. One example of technical advancement that still has a profound impact on architectural design today is the introduction of structural analysis in the second half of the 19th century. Since then, almost all architectural structures are based on the paradigm of calculability. This has lead to a certain set of construction typologies that are still predominant today, even though the limitations of calculability no longer exist. Each typology is based on well-defined rules for the development of its geometry and the calculation of internal forces or other functionalities. It has its own boundary conditions and limitations that allow for solutions only within a specific framework. This catalogue of a limited number of structural typologies still has a profound influence on architecture, as it has become so deeply entrenched in design thinking that it still confines our conception of architectural tectonics, even beyond merely structural concerns. The introduction of computational design and digital fabrication offers the technical means to break through these barriers, which raises the question about a rigorous and systematic design strategy that allows the strategic exploration of new systems beyond existing typologies (Knippers 2013).[ii]

Architects and master-builders have been using nature as a source of inspiration long before the terms bionics or biomimetics were introduced, because structures in nature are fundamentally different from any architectural or technical system. Not ruled by the constraints of calculability, they are multi-layered, highly differentiated and finely tuned systems assembled from basic components that make up structures featuring multiple interrelated functions of nearly infinitely diverse articulation. Until now, similar design principles have been used only to a very limited extent in architecture and building construction. While there have been a considerable number of attempts to transfer characteristics from natural to architectural systems in the twentieth century, they were profoundly limited by structural calculability and the dominant constraints of serial production. With the recent advances in design computation, structural simulation and robotic fabrication the boundary between the underlying logics of ‘natural’ and ‘man-made’ structures can be rethought anew.

Given the rapidly changing and fundamentally different, post-industrial technological context of the early twenty-first century, the two case studies discussed in this paper present current research into the structural, architectural, and tectonic opportunities of activating the performative capacities of biological structures within the architectural design domain. The integrative and concurrent investigation of biomimetic design strategies,

advanced digital simulation, and new modes of robotic fabrication converge in the design of novel material systems that are subsequently evaluated with regards to their spatial and structural capacities. The two research pavilions therefore not only demonstrate the capacities of the respective material systems in full-scale but also the new opportunities that can arise from prototyping new means and methods of contemporary architectural production processes.

Case Study 1: Finger-Joint Plate Structure

Biomimetic design methodologies can be categorized by applying either a technological pull or a biological push (Knippers & Speck 2012).[iii] While the former strategy approaches nature looking for answers to technological questions, the latter is a bottom-up and open-ended investigation of biological features, which, when abstracted, has the potential to question existing technical solutions. The biomimetic design process that unfolded in this first case study, the technological pull, started with the specific design question of how to meaningfully explore the ever-expanding possibilities provided by computer numerically controlled (CNC) machinery in timber plate fabrication. The analysis of biological role models then allowed the identification of performative principles that could act as filters in an integrative design and robotic fabrication process. The research aimed at integrating the mechanical features of biological plate structures into architectural design and at successively testing the spatial and structural properties of the newly developed material system in a full-scale prototype. Researchers and students at the University of Stuttgart developed the project in collaboration with biologists and palaeontologists at the Universities of Tubingen and Freiburg, and completed the prototype in the summer of 2011.

Fig 3.8.1 View of the finished research pavilion

Robotic Fabrication of Finger Jointed Timber Plates

Finger joints are a common type of joinery in traditional woodworking and valued for their strong form and force fitting connection without the need for additional fasteners. Traditionally, finger joints require a high degree of artistry as well as intensive manual labour and usually find their application in the field of furniture design (Hoadley 2000).[iv] During the industrialization period, a relatively crude mechanisation of formerly sophisticated manual techniques occurred, and new machinery was developed to fabricate finger joints in a more efficient manner. However, due to the inherent geometric complexity, such machinery and eventually also computer numerical controlled (CNC) routers were generally limited to the production of finger joints at 90-degree angles. The advent of multi-axis CNC machines such as 6- and more axis industrial robots and their associated kinematic freedom, encouraged the development of a new robotic fabrication process as part of this research that makes it now possible to efficiently produce finger joints for connecting wooden plates at various angles (Krieg et al. 2011).[v]

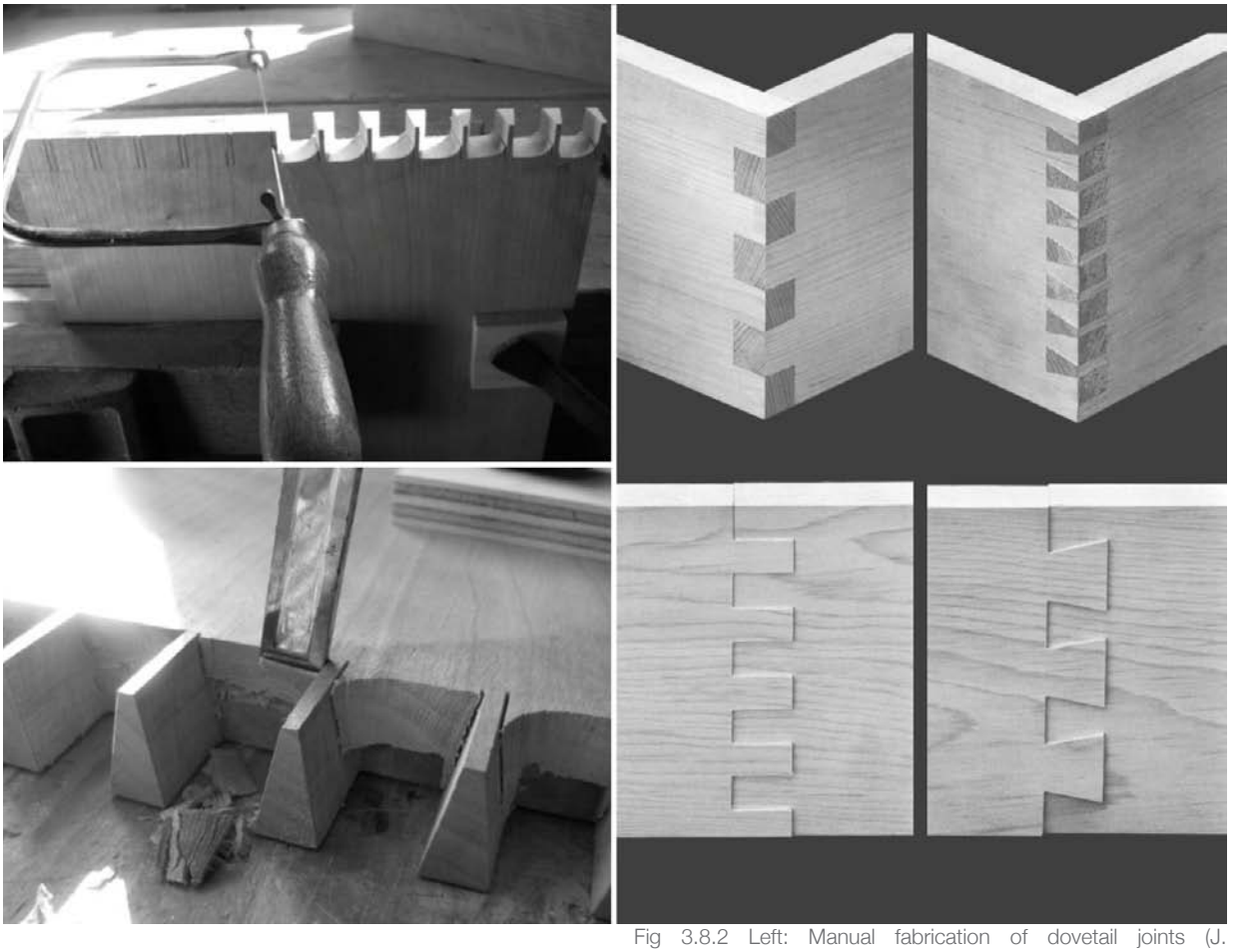

Fig 3.8.2 Left: Manual fabrication of dovetail joints (J. Baumgartner). Right: Finger joints are traditionally used as corner joints to connect planar elements (Encyclopaedia of Wood Joints).

Finger joints are a hinged connection type that performs extremely well under shear forces, however only accommodates limited normal forces and no bending moments. The overall plate arrangement utilized in the presented pavilion design therefore had to be configured in such a way that primarily shear forces occur along the perimeter of the plates and no bending moments. Material tests of different finger joint plate connections have been conducted to verify the joint's strength as well as to acquire empirical data to inform the digital structural analysis model. The biomimetic design methodology then specifically allowed designing a structure that directs shear forces along its finger joint connection. The geometric freedom provided by the 7-axis robotic fabrication process in combination with the capacious connections exclusively made of robotically fabricated finger joints increases the design freedom and even allows the design of non-load optimized structures. The focus was set on the development of a modular structure, which, similar to its biological role model, allows a high degree of adaptability and performance due to the differentiation of its geometric components.

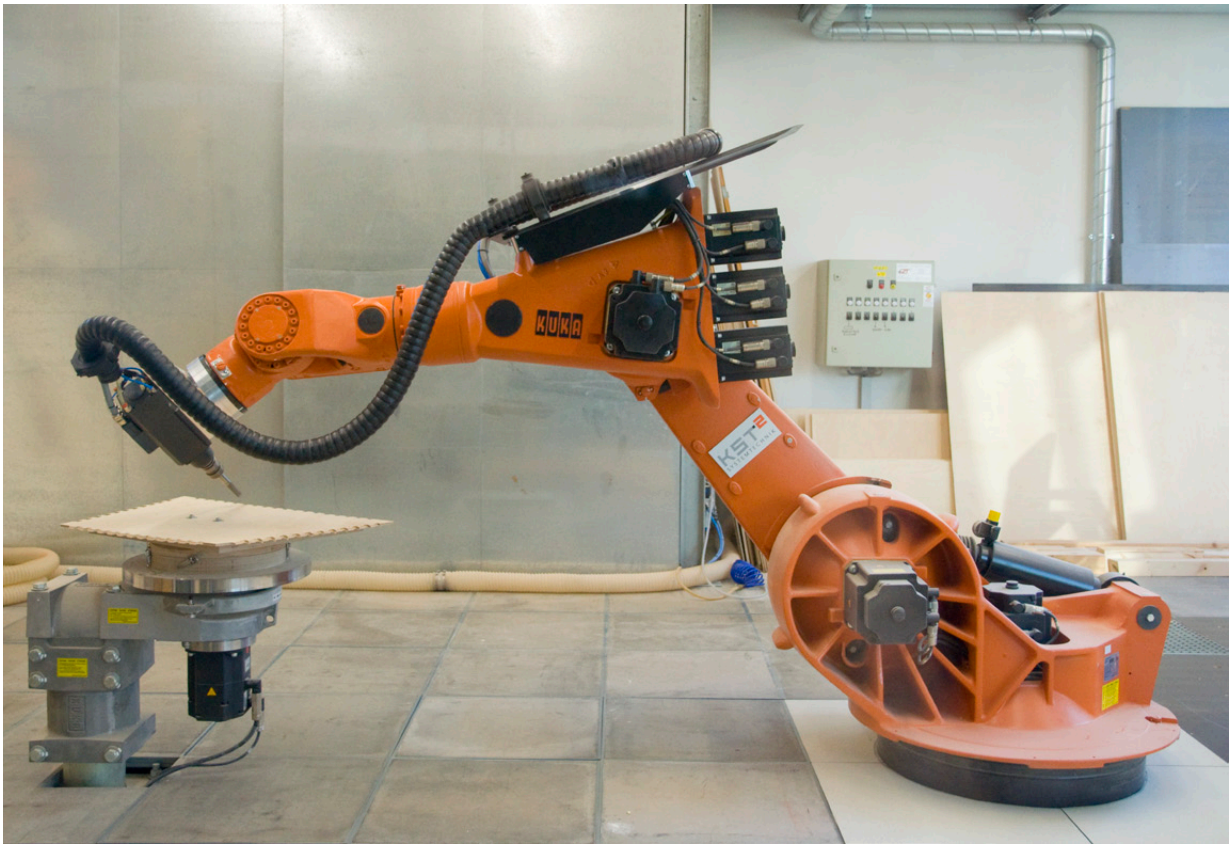

Fig 3.8.3 Seven-axis robotic fabrication facility the University of Stuttgart.

Biomimetic Design Principles and Transfer

During the analysis of biological role models with regards to structural plate behaviour, the morphology of the sand dollar, a subspecies of the sea urchins Echinoidea, became of particular interest and provided the basic morphological principles for the prototype that was successively realised. The shell of the sea urchin is composed of a modular system of polygonal plates joined together at the edges by finger-like calcite protrusions (Seilacher 1979).[vi] The plates of the sand dollar's skeleton are organised following an overall geometric principle according to which a maximum of three plates meet at one point. By following this simple principle, any pure plate structure (i.e. systems composed of just plates and hinges along the edges of connection) will be inherently stable, whereas any variation from this arrangement pattern will result in a deformable and kinematic structure similar to origami (Wester 2002).[vii]

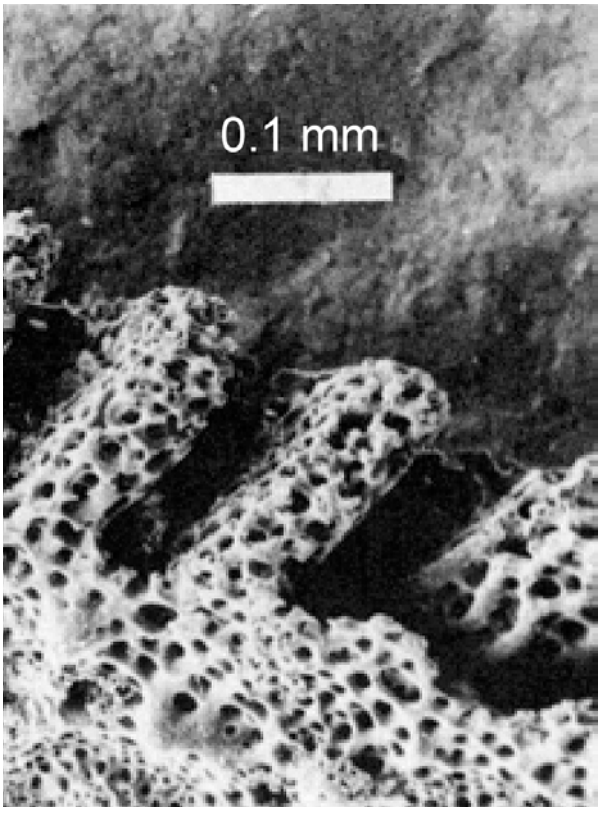

Fig 3.8.4 Microscopic view of a plate edge showing the calcite projections similar to finger joints (Seilacher)

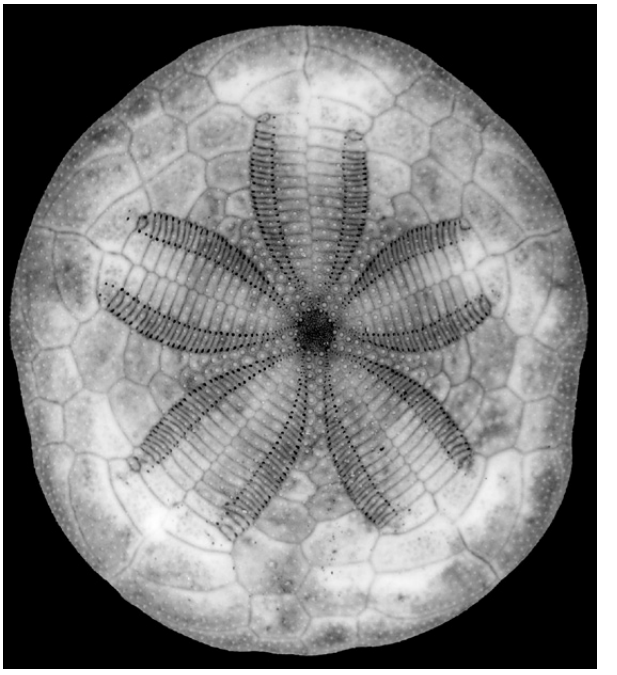

Fig 3.8.5 Plot of the finite-element analysis showing compression and tension forces in the structure.

From a mechanical point of view, thanks to this arrangement the plates are stabilised by resisting internal forces that lie in the plate itself. Each face of a pure plate structure carries plate forces only, i.e. plates must not rely on carrying bending moments and torsion for their own stability. On the other hand, the lines of support enable the transmission of normal and shear forces but no bending moments between the joints. This property allows the sea urchins to grow without interfering with the transfer of stabilising forces, as the direction of growth will be perpendicular to the shear lines, hence perpendicular to the direction of the stabilising shear forces (Knippers et al. 2012).[viii]

The structural morphology of the sand dollar can therefore serve as a role model for modular shell structures of prefabricated components. Finger jointing is introduced as a technological equivalent for the sand dollar's plate joints providing similar structural characteristics. Following the analysis of the sand dollar, the morphology of its plate structure was translated into the design of a material system. Three plate edges always meet together at just one point, enabling the transmission of normal and shear forces but no bending moments between the joints, thus resulting in a bending bearing but yet deformable structure. As the plates are mainly subjected to in-plane forces, the degree of utilization of the material's strength is maximized, guaranteeing an optimal structural configuration.

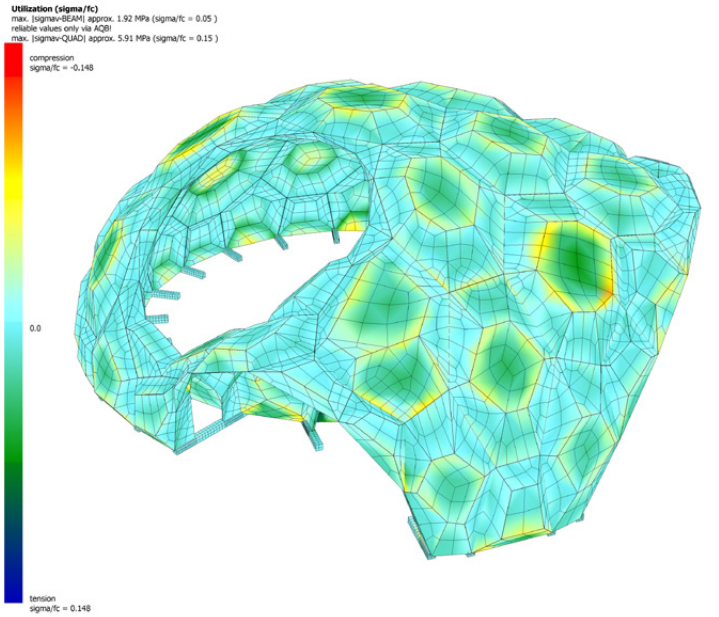

Fig 3.8.6 Plot of the finite-element analysis showing compression and tension forces in the structure.

Besides constructional and organizational principles, hierarchy is also a fundamental property of biological structures. This principle was translated into the built prototype by assembling the plates and cells on a two-tier hierarchical scheme. On the first level, the finger jointed plywood sheets form a cell. On the second hierarchical level, a simple bolt connection joins the cells together, facilitating the assembly and disassembly of the prototype. Due to the arrangement of the bolts in the cells and the material characteristic of plywood and its low stiffness, a transfer of bending moments between the cells could be minimised by creating a hinged connection. Within each hierarchical level only three plates - respectively three edges – meet at one point, therefore assuring bending-free edges for both levels.

Fig 3.8.7 Detail view of the newly developed finger joint connection.

Digital and Robotic Prototyping

The project aims at an integration of the identified biomimetic principles into a custom computational design framework as part of a generative rule set that informs the parametric model, in addition to structural analysis and robotic fabrication (Menges 2011).[ix] Form finding and structural analysis are closely linked, such that the iterative analysis of the complex geometry constitutes a driver of the digital information model. The rules and constraints of the developed robotic fabrication methodology for finger joint plate structures, in turn, inform the local morphology of the case study, i.e. the relation between its building elements, through the fabrication parameters of the specific robotic setup and the specific relation between the work piece and the milling effecter (tool mechanism). By mathematically describing and algorithmically translating this dependency, it can be directly integrated and activated within the computational design framework.

The large amount of unique building elements requires a generative approach to robotic programming that can address the complexity of fabricating finger joints (Bechthold 2010).[x] The aim therefore was to implement a strategy for automating the generation of the robotic machine code directly from the parametric design model, thereby eliminating intermediate software environments (Brell-Cokcan & Braumann 2010).[xi] Specifically, the different tool paths for the fabrication of each plate are a function of the angles between the plate and its neighbouring plates, which, depending on the angle can yield different structural and geometric properties. Taking the specific spindle geometry and the structural integrity of the joint into account, the range of possible plate angles is confined to between approximately 15 to 165 degrees – a constraint that feeds directly back as a fabrication parameter into the generative rule set (Schwinn et al. 2012).[xii]

The sequence of fabrication steps for each plate then consists of, firstly, flank milling the plate's outline with the tool shaft thereby ensuring co-planarity with the adjacent plate; second, mitring a start and end segment of each edge with the tool axis aligned to the bi-sector between the normal vectors of the adjacent plates resulting in the characteristic Y-shaped corner connection detail. Specifically the third and last step in the robotic fabrication sequence, where the plate's edges are indented normal to the adjacent plate's orientation, is critical for the production of accurately shaped, force- and form fitting joints. Custom programmed routines are used to automatically generate these tool paths as ordered point clouds for each edge of each of the case study's 855 individual plates. The Cartesian coordinates of the target points and tool vectors can then be extracted and translated into machine code and ultimately into instructions for the control of the seven-axis industrial robot. In contrast to conventional CAD-CAM workflows where the fabrication model is usually treated as a separate entity, in this custom process the fabrication data model is tightly integrated into the geometry and design model (Menges & Schwinn 2012). [xiii]

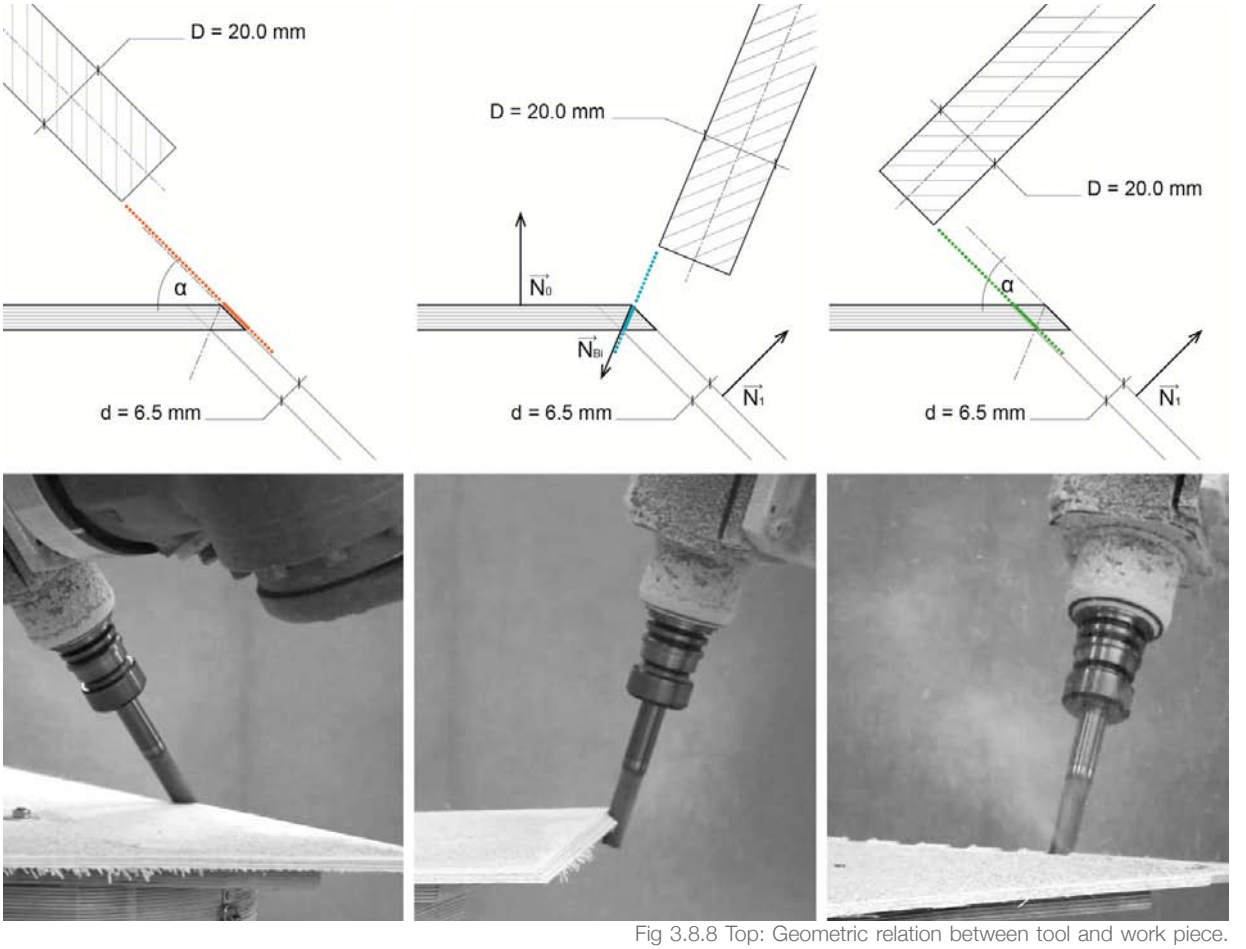

Fig 3.8.8 Top: Geometric relation between tool and work piece. Bottom: Finger joint fabrication steps.

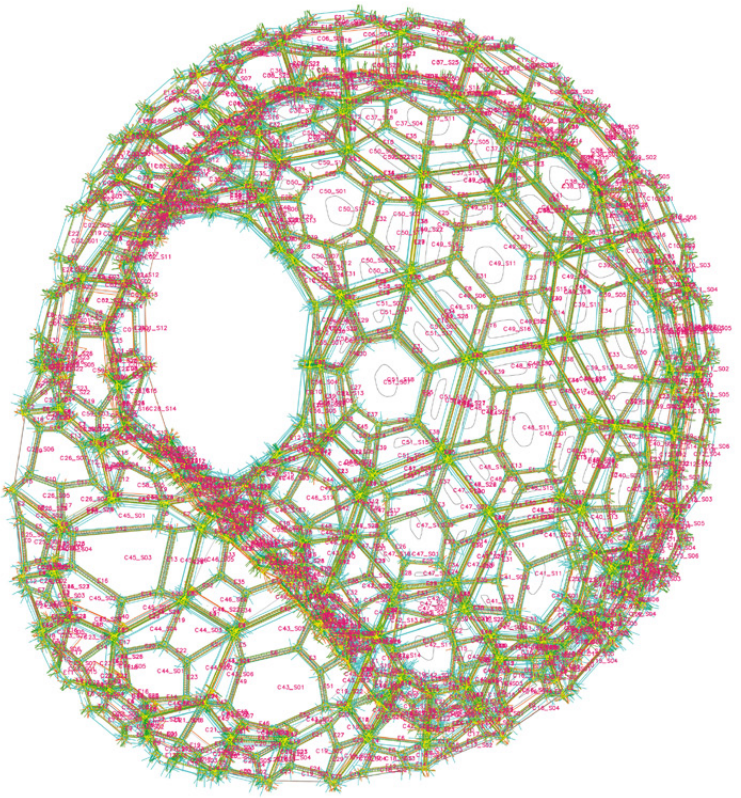

Fig 3.8.9 Fabrication data model of the automatically generated tool paths.

The custom integrative approach to fabrication programming is instrumental for the efficient production of the more than 100,000 individual finger joints. Following the trimming of the plates on the university's robotic fabrication system, the plates were combined into modules and weatherproofed in the controlled environment of the workshop, before being assembled on site.

Result

The finished prototype demonstrates that the integration of biomimetic principles in the design process can open up new performative design approaches. The analysis of biological role models, the identification of their topological and structural principles and their transfer into generative and geometric rules formed the basis for the development of a computational design tool integrating the sea urchin's biomimetic principles, the architectural and structural requirements and the fabrication constraints. Unlike traditional lightweight construction, which can often only be applied to load optimized shapes, these principles can be applied to any custom geometry. The ultra lightweight potential of this approach is evident as the pavilion, despite its considerable size, could be built exclusively out of extremely thin 6.5 mm sheets of plywood and therefore primarily needed anchoring to the ground to resist wind suction loads. Plate action in today's buildings is more or less limited to the resisting of horizontal forces. The research pavilion showed how this principle can be successfully implemented in a complex and expressive spatial system and how it is possible to create an extremely light but at the same time very stiff supporting structure only by the optimal arrangement of its constitutive elements.

Besides, the 3-plate principle indicated new opportunities for the optimization of free-form structures independently of the materiality (Waimer et al. 2013).[xiv] This fundamental principle offers a powerful tool to investigate a wide range of structural morphologies by simple equilibrium assumptions. Finally, the research pavilion offered the opportunity to investigate methods of modular bionic construction using freeform geometry with different geometric characteristics while developing two distinct spatial entities: one large interior area with a porous inner layer and a big opening, facing the public square between the University's buildings, and a smaller space enveloped between the two layers that exhibits the constructive logic of the double layer shell.

Fig 3.8.10 Aerial view of the built full-scale prototype.

Fig 3.8.11 Interior view showing the two main spaces. The double-layer structure responds to both structural and architectural requirements.

Case Study 2: Fibre Composite Structure

The second case study, completed in the fall of 2012, is another example of an interdisciplinary collaboration between architects and engineers of the University of Stuttgart, and biologists of the University of Tubingen. In contrast to the biomimetic design methodology of the technological pull, which was applied in the first case study, this project is characterized by a biological push, that is performative principles of structural morphology of the biological role model's natural fibre composite were abstracted with respect to an architectural application. Transferred to fibre-reinforced composite technology and implemented in a custom robotic filament winding fabrication process this biomimetic design methodology resulted in an ultra lightweight, high-performing structure yielding new architectural opportunities.

Biomimetic Design Principles and Transfer

Natural fibre composites are a common feature among a wide variety of natural systems. Especially the exoskeletons *cuticula* of arthropods, such as the American lobster *homerus americanus*, represent an interesting example since they evolved strong and lightweight structural shells. Differentiation within the material in combination with geometric differentiation allows the biological system to adjust its local properties to integrate different tasks in a functionally graded material using the same material constituents (Fabritius et al. 2011).[xv] The cuticula varies its structural behaviour continuously between anisotropic and isotropic over the whole arthropod's body, which allows the identification and abstraction of very pronounced arrangements: 1, for predicted loads in similar directions, unidirectional fibre arrangements align the material properties to achieve the best strength-weight ratio

Fig 3.8.12 View of the finished research pavilion

(found e.g. along the legs of arthropods); 2, for wide areas with unpredicted forces that can occur in various directions, the cuticula consists of a characteristic helicoidal fibre arrangement. Consequently, the use of fibre composites allows the arthropods to produce a highly adaptable and functionally integrated structure.

In architecture functionality is still mainly achieved through addition of functionally discrete components. The use of fibre composites with its strong bond between the matrix and the fibres allows designing functionally graded materials on a macro-level. Through variation of fibre directions, the integration of different fibre types as well as varying the fibre-matrix ratio or even the matrix constituents, this additive fabrication process allows to specifically design local material properties with the aim of producing functionally integrative, super lightweight structural parts.

The concept of the presented pavilion explores the idea of a robotically fabricated full-scale pavilion as a one-piece fibre composite monocoque that utilizes the presented biomimetic principles within the pavilion's material design. The global design was developed as a continuous and seamless shell with a pentagonal footprint and incorporating three open sides functioning as entrances in addition to two closed sides. Such different architectural features demonstrate the geometric adaptability while the use of different fibre types and fibre arrangements allow a functionally graded material design. The relatively inexpensive glass fibre was used to produce the general enclosure of the pavilion and due to its transparency expresses the overall lightness of the structure.

Areas built with glass fibre utilize the multi-directional fibre orientation similar to the helicoidal arrangement found in the cuticula of arthropods whereas the dark and thicker carbon fibres were arranged directionally for specific reinforcement the overall geometry. Directing the loads from the roof to the ground, the overall material thickness as well as the carbon fibre ratio is increasing and specifically in the lower areas with higher load concentrations the fibres are placed in a unidirectional arrangement similar to the biological system.

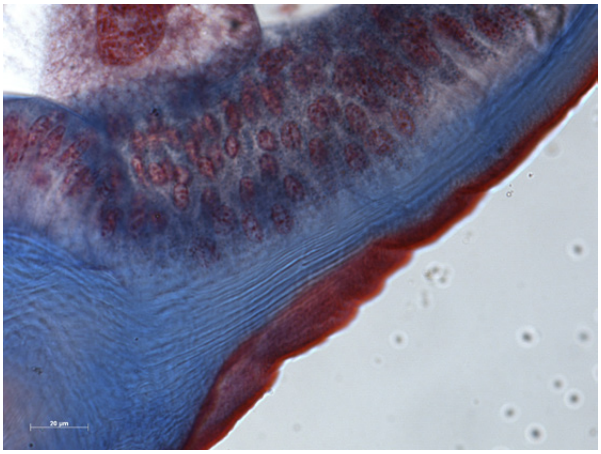

Fig 3.8.13 Microscopic view of the exoskeleton (cuticula) of the American lobster.

FRP Material System

In contrast to metal, glass, timber and other conventional building materials, many fibre-based materials are suitable for moulding and shaping methods that enable the relatively simple production of components with complex shapes. This offers great design freedom but also at the same time risks of improper applications, as in architecture an appropriate building culture with fibre-based materials still isn't widely spread. Traditionally, structures are assembled from a limited number of materials with defined properties. When building with polymers, one of the major challenges is to choose the right solution from the vast range of raw materials and semi-finished products. The selection and control of the material components represent new and demanding responsibilities for architects and engineers (Knippers et al. 2010). [xvi] If, for example, we compare glass and carbon fibres, then we discover that the tensile strengths of the fibres alone are roughly identical. However, the elastic modulus of carbon fibres is much higher compared to glass fibres. Therefore, owing to the limited extensibility of the polymer matrix, the strength of carbon fibre-reinforced polymer is higher than that of glass fibre-reinforced polymer. If the stress-strain curves of these two materials are compared to steel or aluminium the advantages become clear. The strength of the composite component depends on the interaction between fibres and the polymer matrix. A fracture in a laminate is generally caused by cracks in the matrix, which in turn are caused by the maximum admissible strain in the polymer being exceeded. Using a polymer with a high maximum permissible strain therefore increases the strength of the entire composite component.

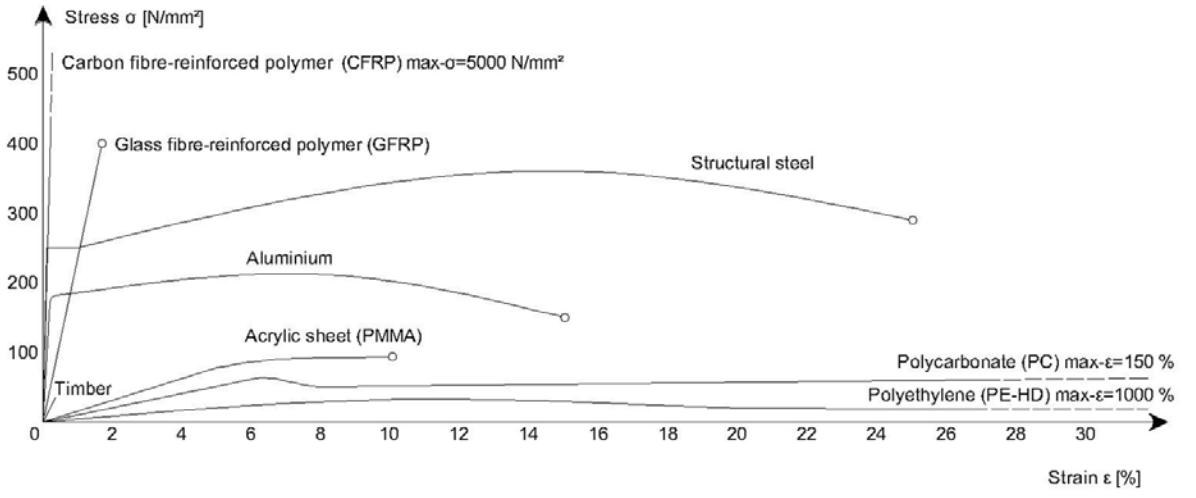

Fig 3.8.14 Stress-strain curves of FRPs and conventional lightweight materials.

The classical winding technique is typically used in the manufacturing of pipes, vessels, tanks, and other rotationally symmetrical hollow components. The advantages of this method are the high level of mechanisation and the exact and high-density fibre arrangement. In composite wrapping, pretensioned rovings are wound around a rotating mandrel. The fibre reinforcement of the laminate is controlled by the rotary speed of the mandrel and the speed of winding fibres. One-off mandrels made from a soluble substance or, for larger series, reusable mandrels made from steel or aluminium are used depending on the batch size and the geometry of the component. To ease de-moulding, mandrels are often slightly conical in shape, or made from folding segments.

During the implementation stage of the case study, the classical filament winding technique was adapted for robotic fabrication. The robotic winding process and the technological setup composed by the resin bath and the effecter were step by step modified and calibrated to guarantee a continuous production. It was crucial to guarantee a constant pretension of the roving and an ideal ratio of fibre to resin. The choice of suitable raw materials of fibre and resin had not only a significant effect on the stiffness and strength properties of the laminate as mentioned before, but also on the reliability of the process. The glass and carbon rovings must have a sufficient tensile strength to prevent the tearing of the fibres in the resin bath and on the effecter. Different resin systems and rovings were investigated by robotically wrapping 1:5 prototypes in the laboratory. The choice of the resin system was dictated by the long manufacturing process, which required a resin with high viscosity and pot life. Additionally, the resin system must have a low cure temperature in order to allow the heat treatment for the given conditions. Parallel to that, unidirectional laminate specimens were wrapped to determine through mechanical tests the material properties, which were subsequently implemented in the FEA model.

Fig 3.8.15 Detail view of fibre lay-up in a 1:5 scale robotic filament-winding prototype

Digital and Physical Prototyping

The design and robotic implementation of biologically inspired, high-performing, and materially efficient fibre-composite systems in architecture require the concurrent and reciprocal integration of the seemingly disparate fields of biology, robotics, material science, engineering, and architecture into one integrative computational design methodology. The mechanical behaviour of glass and carbon fibre composites inform the digital design process through material prototyping, digital simulation, and finite element analysis, which requires the development of custom tools for processing the mechanical response of the fibres in the structural system, along with scripted routines for the evaluation and optimization of the local (material) and global (geometrical) stiffness of the system. Digital simulation of the fibre placement process complemented and extended the initial physical form finding methods by integrating the specific aspects of robotic fabrication into the digital design and fabrication planning process. The biologically, materially and robotically informed digital design and implementation suggests a new methodology of process prototyping that demonstrates how fibre-reinforced composites can be arranged and processed with respect to the specific requirements of architectural design and building construction.

One of the initial goals was set on the fabrication of a seamless, continuously differentiated structure and, consequently, on the development of an appropriate large-scale filament winding process. The mechanical and architectural properties of the laminate are based to a large extent on the interplay between winding support and winding logic. The winding logic or syntax describes the rules and principles of the continuous placement of fibres along a linear framework. In the parametric design workflow, the *syntax* becomes the interface between design, analysis and fabrication through the algorithmic description of the winding sequence: its digital representation then serves as the input for the finite-element (FE) form finding simulation and structural analysis, which, in turn, inform the winding sequence and the number of layers in the laminate. The syntax also serves as input for the parametric generation of the robot tool paths, integrated simulation of the robot kinematics and automated machine code generation. Initial physical models were

used to explore architectural features such as openings, closed surfaces, and the various structural zones, and to verify the custom digital form-finding tools. A central concern in the development of the winding logic was the interaction between the fibres since the quality of the bonding is a function of the pressure between the layers.

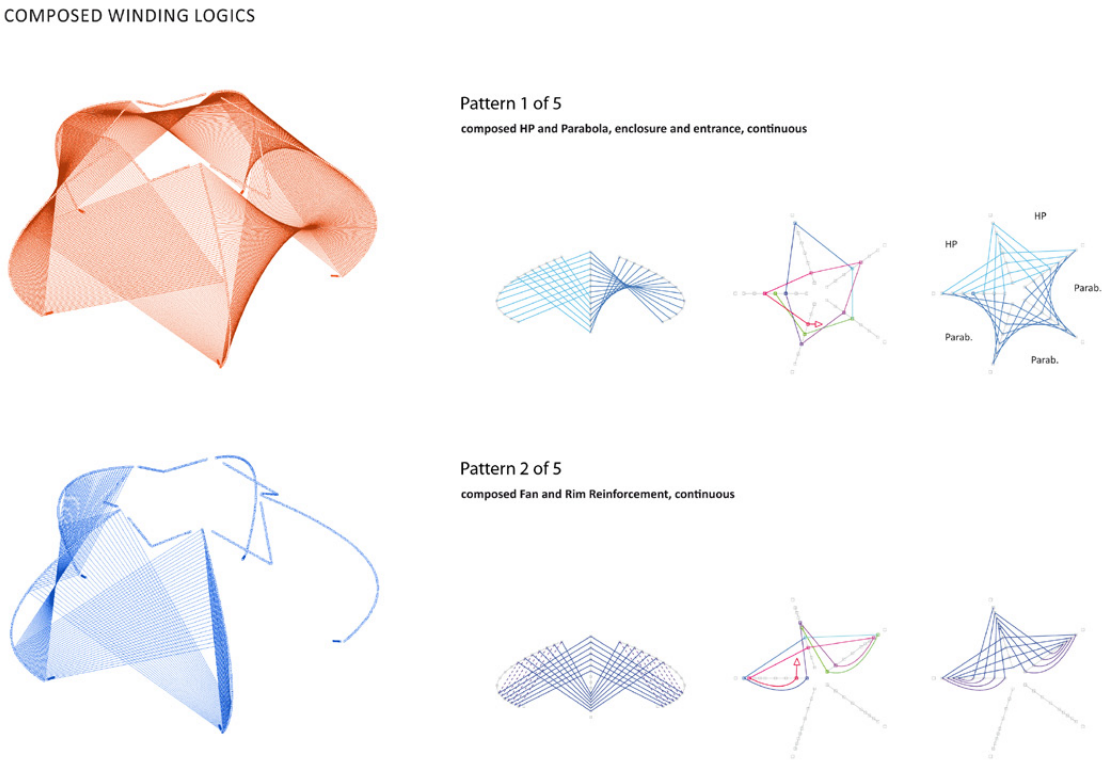

Fig 3.8.16 Diagrammatic representation of the filament winding logic (syntax).

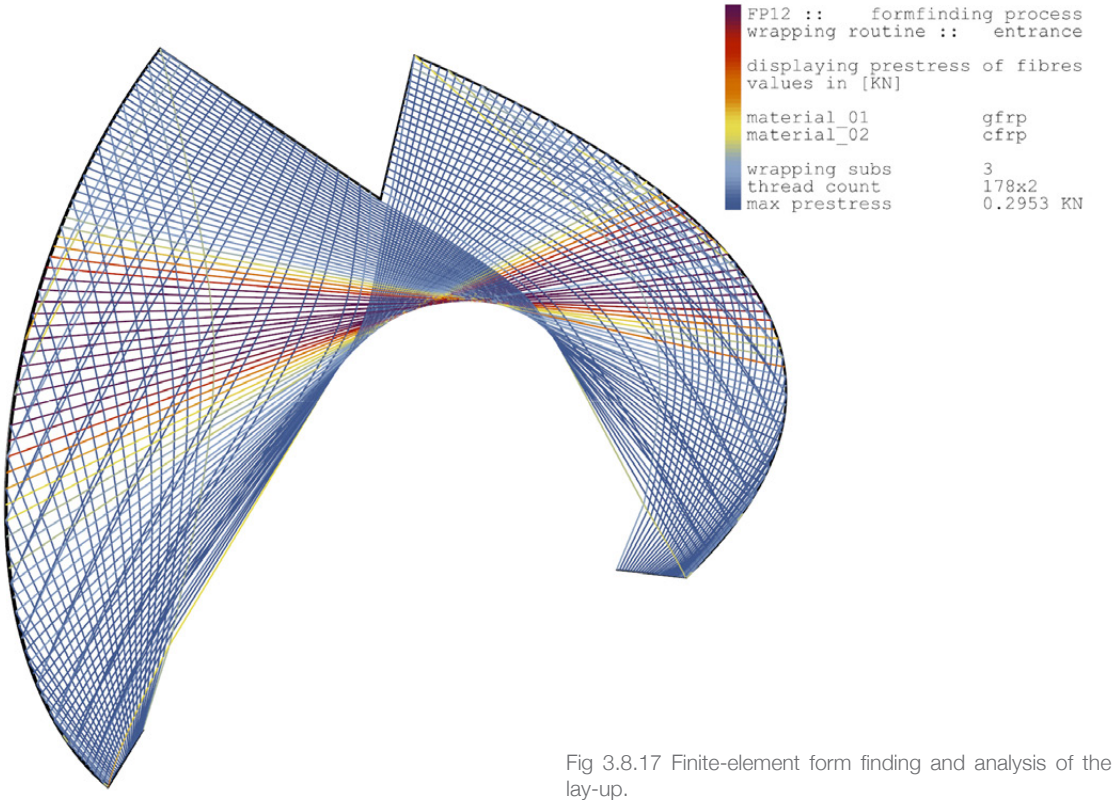

Fig 3.8.17 Finite-element form finding and analysis of the fibre lay-up.

The fabrication of complex geometries produced in FRP typically requires moulds or custom formwork. The materially and time intensive subtractive fabrication of these moulds is usually offset by high production runs. Consequently, an application of FRP in architecture poses the inherent problem that it either requires moulds on an architectural scale or many unique moulds for a potentially single use (Fischer 2012).[xvii] Minimizing the mould requirement was therefore another central concern throughout the project and at the same time became one of its defining features. The requirement was met by prefabricating a linear steel frame as temporary support for the glass and carbon fibres during fabrication. The fibres are spanning between defined anchor points on the frame, which control fibre position and allow for a continuously changing fibre orientation. In the robotic filament winding process the industrial robot continuously lays resin-saturated glass and carbon fibres thereby gradually building up a “mould” as previous layers harden and subsequent layers are placed. This specific setup favours double curved anticlastic surface geometry of negative Gaussian curvature as it naturally produces hyperbolic paraboloid geometry consisting of straight lines.

A dedicated construction tent was set up on site to control the environment for the 3-component resin system and the 7–axis robotic fabrication setup consisting of a 6-axis industrial robot installed on a two-meter high pedestal with a turntable as seventh external axis. The continuous circular movement of the turntable maintained a constant feed of glass and carbon fibre rovings. The fabrication commenced with a series of dry runs to calibrate the machine code, which was directly generated from the parametric design environment. In contrast to the 5 degrees of freedom (DOF) necessary to define tool position and orientation of a rotationally symmetrical tool as in the example of robotic milling of the first case study, this process required the use of the proprietary robotic language in order to control the 7 DOF necessary to fully define tool position and orientation of the filament placement end-effector and the orientation of the turntable.

Fig 3.8.18 Close-up view of the composite structure displaying the directionality of the different layers and the inherent double-curved surface geometry that results from the custom fabrication process

Fig 3.8.19 Robotic fabrication of the full-scale prototype showing glass and carbon fibre layers and the temporary support frame.

Result

The process described in this paper made it possible to produce a structure spanning 8.0 meters in diameter and reaching 3.5 meters in height by continuously winding more than 60 kilometres of fibre rovings. The fibre compound was subsequently tempered in order to achieve sound mechanical properties and to reduce the brittleness of the material. Following the tempering process, the temporary steel frame could be safely disassembled and removed, leaving in place an extremely thin, yet structurally firm shell of just 4mm thickness entirely made of fibre composites.

The confluence of such diverse aspects as structural analysis, simulation technology, material design and robotic fabrication was made possible by the highly integrated framework developed for the current project. The data exchange loop between designers, engineers and fabrication experts enabled the creation of an integral work environment in which a constant feedback flow between the involved disciplines could take place. This highly expands the design possibilities and enhances the final outcome beyond typical top-down approaches.

For instance, the possibility of retrieving in thorough detail fundamental parameters for the assessment of the mechanical response, offered a powerful means to actively design the structural components by drawing fundamental decisions on the thickness of the lay-up and the running direction of the fibres since the very early stages. This complete integration of architectural aspects and mechanical feedback enables the planning and fabrication of highly customised components that completely meet the structural requirements of the project, allowing for an optimisation of shape and geometry along with the local material properties of the element itself. This is evident as the semi-transparent skin of the pavilion weighs less than 320kg despite its considerable size and span, whilst still revealing the system's structural logic through the spatial arrangement of the carbon and glass fibres.

Fig 3.8.20 Aerial view of the built full-scale prototype showing the different structural zones.

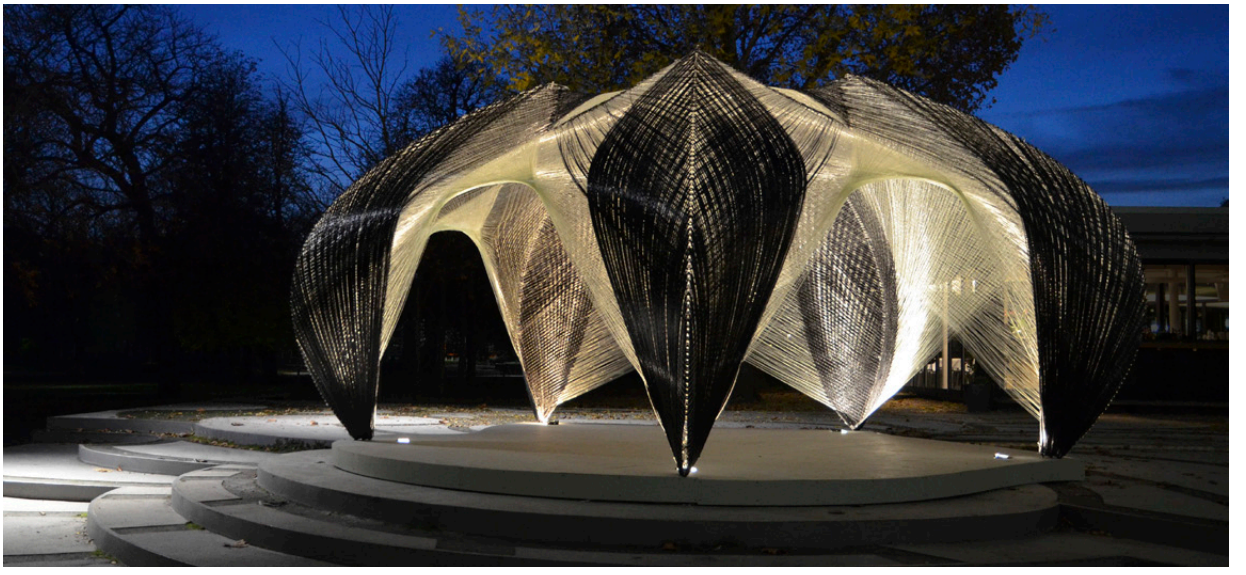

Fig 3.8.21 The lighting accentuates the directionality of the different layers and highlights the different functional zones of the laminate.

Conclusion

In both case studies, the concurrent integration of the biomimetic principles extrapolated from the analysis of a biological role model – the morphology of the sand dollar's plate skeleton in the first case and the lobster's cuticle in the second - and the logics of the newly developed fabrication processes – robotic finger joint cutting and robotic filament winding - within a robust computational design framework enabled a high degree of structural performance and new opportunities in architecture. The synthesis of biology and technology in architecture allows both the exploration of a new repertoire of architectural possibilities and the development of extremely lightweight and materially efficient structures. The research presented above indicates that today, computational design, simulation and digital fabrication processes open up new possibilities for approaching the transfer of design principles from nature to architecture, as the technical requirements for doing so can be met much more convincingly than even a very few years ago. It also shows that new constructional systems provide for novel ways of reconciling structural and architectural demands, offering novel tectonic qualities and spatial experiences while remaining very materially efficient at the same time. All this seems to indicate that the study of biomimetics for architects and engineers is more relevant today than ever before.

Acknowledgements

The biological research presented in the first case study has been conducted in collaboration with the Plant Biomechanics Group in Freiburg (Professor Thomas Speck and Dr. Olga Speck) and the Paleontology of Invertebrates Group (Professor James Nebelsick) at the University of Tubingen. The research has been partly funded through a grant by the European Regional Development Fund administered by the Department for food and regional affairs as part of the "Cluster Forst und Holz" initiative of the state of Baden-Wurttemberg (http://www.rwb-efre.baden-wuerttemberg.de).

The biological research of the second case study has been conducted in collaboration with the Evolutionary Biology of Invertebrates (Prof. Oliver Betz) and the Paleontology of Invertebrates Groups (Professor James Nebelsick) at the University of Tubingen. The project was partly funded by the Competence Network Biomimectics (http://www.kompetenznetz-biomimetik.de).

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3.9
AUTARKI: Coupling a 1:1 Cross Laminated Timber Building Prototype with Parametric Energy Simulation to Investigate Scenarios for Energy Self-Sufficiency

Emanuele Naboni, Jesper Nielsen and Alessandro Maccarini [i]

The research focuses on the investigation of Cross Laminated Timber (CLT) technical configurations that optimise construction processes, while reducing buildings' life cycle impact, operational energy and maximise thermal comfort. To explore such scenarios, a building prototype, named Autarki 1:1 (Greek word for self-sufficient), was built on the campus of the Royal Danish Academy of Fine Arts in Copenhagen. There are various aims of the present research. One of the main aims is to test CLT newly designed details according to the EU targets for 2020, which prescribe that all new buildings consume very little energy (nearly Zero-Energy Building or nZEB). The sub-focus is the investigation of potential for energy saving driven by solely constructive and passive means; therefore, no mechanical or active systems were added to the prototype. To guarantee air changes, an air-to-air recuperative heat exchanger, inspired by studies carried out in the early '90s at the Technical University of Denmark (DTU), was integrated. A second aim is to investigate how, when coupling the use of a prototype and parametric energy simulations it is possible to obtain the most performative design.

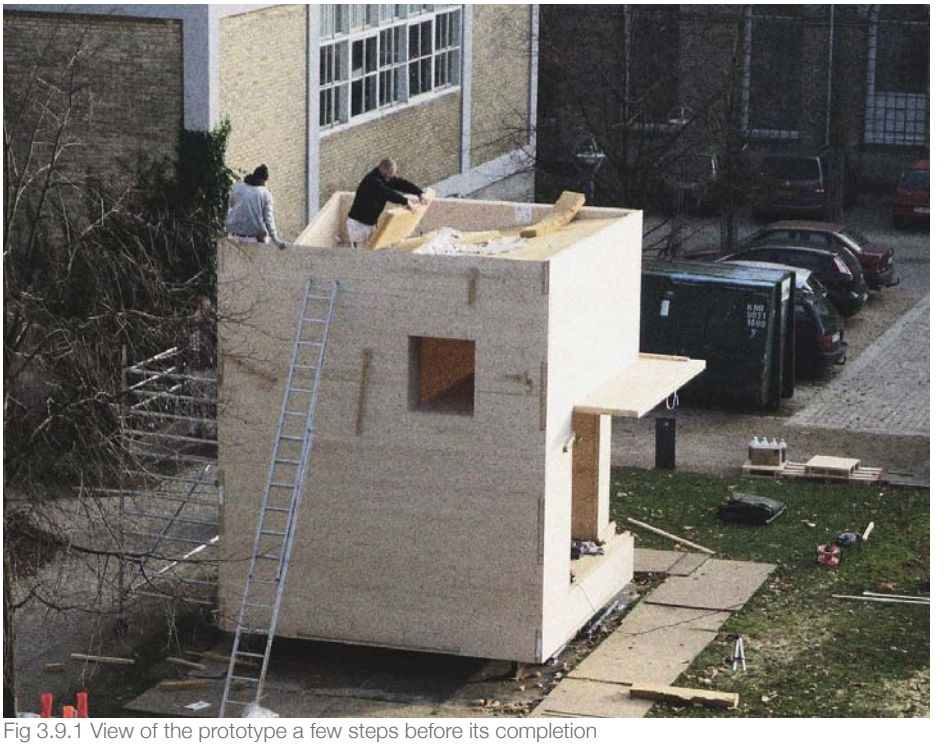

Fig 3.9.1 View of the prototype a few steps before its completion phase. The wood fibre insulation is being placed on the roof.

Autarki's assemblies comply with the Danish energy code BR10. They are composed of a double shell of CLT; inbetween there is insulation made of wooden fibre battens. Thermal bridges are therefore reduced as has been demonstrated by thermal camera analyses conducted on the prototype. Sensors installed on-site have also been recording variables of indoor comfort: inner and outer walls temperatures, air exchange rates and the occupation frequency of users (www.autarki.dk). It was found that CLT allows the control of indoor humidity when the space is densily occupied and its properties contribute to control the indoor radiant temperatures. Additionally collected information was used to investigate the role of the building user in relation to energy consumption and indoor comfort.

Recorded data were functional for the calibration of an energy simulation model that was used to investigate the potential for improvement with regard to the nZEB standard. The energy model was run with 139,968 automatically generated design variations in order to elucidate a ranking of possibilities for small yet effective retrofit adjustments to the prototype and to create a user's manual. The study was conducted using parametric energy simulation using a software shell named JEPlus on a cluster made available by De Monfort Institute in Leicester. The digital modifications of the prototype allowed for the testing of, in only 30 hours of computation, different CLT-based roofs, floors and wall assemblies and finishes. Furthermore, possible configurations of an air-to-air heat exchanger, user profiles and minor architectural modifications were tested. The goal was to understand in detail of how the pavillion performs today and how its performance can be improved by retrofits. The parametric simulation showed clear areas for improvement. In particular, the operation of the building (for example the manual control of ventilation) and the user interaction are the highest impacting factors for achieving a nearly Zero Energy Building.

Fig 3.9.2 View of the interior (credit: Jan Schipull)

Cross laminated timber, energy and comfort

The CLT panels have been used as a construction material during the last twenty years, but recently its application has increased due to its inherent sustainable properties. CLT is an engineered wood product and provides a sustainable alternative to steel and concrete construction. CLT offers renewability, structural stability, storage of carbon during the building's life, good fire resistance, and the possibility for the recycling and reusing of the material. In the Autarki 1:1 pavilion CLT is used both for the inner and the outer structure. At first glance this may seem an unusual approach, because it uses more material than a corresponding construction that uses frames and boards, but on closer inspection the advantages relating to energy and comfort, as well as the architectural possibilities, become apparent.

Given a scenario where building energy consumption is a large share of the world's total use of energy, the use of high-performance materials is a key factor in passive and sustainable design. The prototype is therefore used to test how new configurations of CLT can contribute to the discourse on sustainability. The material is studied in the context of ambitious EU targets to ensure that from 2020 all new buildings show a drastic decrease in energy consumption, making them so-called nearly Zero-Energy Buildings or nZEBs. As a consequence, the Autarki 1:1 prototype implements solely passive design features. The green house effect, the building users and the equipment are the main sources of heating. Natural ventilation provides the necessary cooling.

Fig 3.9.3 Study of the prototype CLT-based components that constitute both the inner and the outer shell of the envelope.

Fig 3.9.4 The assembled prototype model.

The prototype: efficiency through architectural means

The project starts from the assumption that when one considers sustainability strategies, architectural design is generally the most cost-effective means of achieving energy efficiency and comfort. The practice of low-energy design can be broken down into the two (and sometimes competing) areas of architecture and mechanical systems. Architectural design is generally the more cost-effective option: optimising the design can reduce the energy consumption of buildings by as much as 80% (Lechner, 2000).2 Although the percentage formulated by Lechner has not been verified for all climates, it illustrates the huge potential of architectural solutions for reducing energy consumption. The solutions implemented in Autarki are a mix of architectural features, building operations and manual controls. No mechanical or active systems have been used. The following strategies were adopted:

Reducing loads through architectural design. Heating, cooling and lighting loads are reduced through architectural means such as the relationship of the building to the RDA campus, optimisation of form and orientation, maximisation of passive winter solar gains, high-performance envelopes, daylighting, and solar control with shading devices.

Reducing loads by other means. The project also focuses on the use of natural ventilation by extending comfort zone temperatures, exploiting building temperature fluctuations, and by using a monitoring system to highlight additional opportunities for optimising building operations, as well as to educate the building user.

List of possible Strategies	**Implemented Design Features in Autarki 1:1**
Reduce loads and increase comfort by Architectural Design	*Adaptation to Site* *Form (surface area-to-volume ratio)* *Size* *Orientation* *Program* *Envelope Design (Windows to Wall Ratio, Façade Colour and surfaces properties, Insulation, Windows, glazing, exterior and interior shadings)* *Daylight Harvesting* *Construction Materials* *Thermal Mass*
Reduce Loads by other means	*Efficient Lighting* *Efficient Computer* *Extension of Thermal Comfort Zone* *Building Monitoring* *Air-to-air Recuperative Heat Exchanger*
Control, Lighting and HVAC Design	*None*
Alternative Energy Technology	*None*
uRenewable Energy and Active Systems Design	*None*

<< Table 1: Main energy design strategy and features of Autarki

The prototype is situated on a site in the middle of the campus of the School of Architecture in Copenhagen. The building is located at the north side of a court so that solar access is maximised and wind velocity is reduced by the surrounding buildings. Autarki presents a compact shape with a small surface-to-volume ratio of 2.3, curbing heat loss. Compactness was one of the main determinants of shape-space formation. The building has an internal floor area of 9 m^2. The external envelope presents three glazed surfaces, with a window-to-wall ratio of 9%. The openings have been optimised with respect to sunlight, with the main window towards the south yet twisted slightly to the east, as the heat gains in the mornings are important. The southern window is shaded in the summer by a projecting sheet, cantilevered from the inside balcony.

As Copenhagen is in the path of Atlantic low-pressure systems, the city experiences unstable and changing weather patterns in all four seasons, as well as temperatures about 5 degrees higher than average for its latitude (55 degrees North) worldwide, because of the Atlantic Gulf Stream. Significant wind velocities characterise the area, but while those are an issue for pedestrian comfort and they increase building heat losses, they can be utilised for controlled natural ventilation. The use of airflows for natural ventilation purposes was therefore investigated in Autarki through a passive air-to-air heat exchanger.

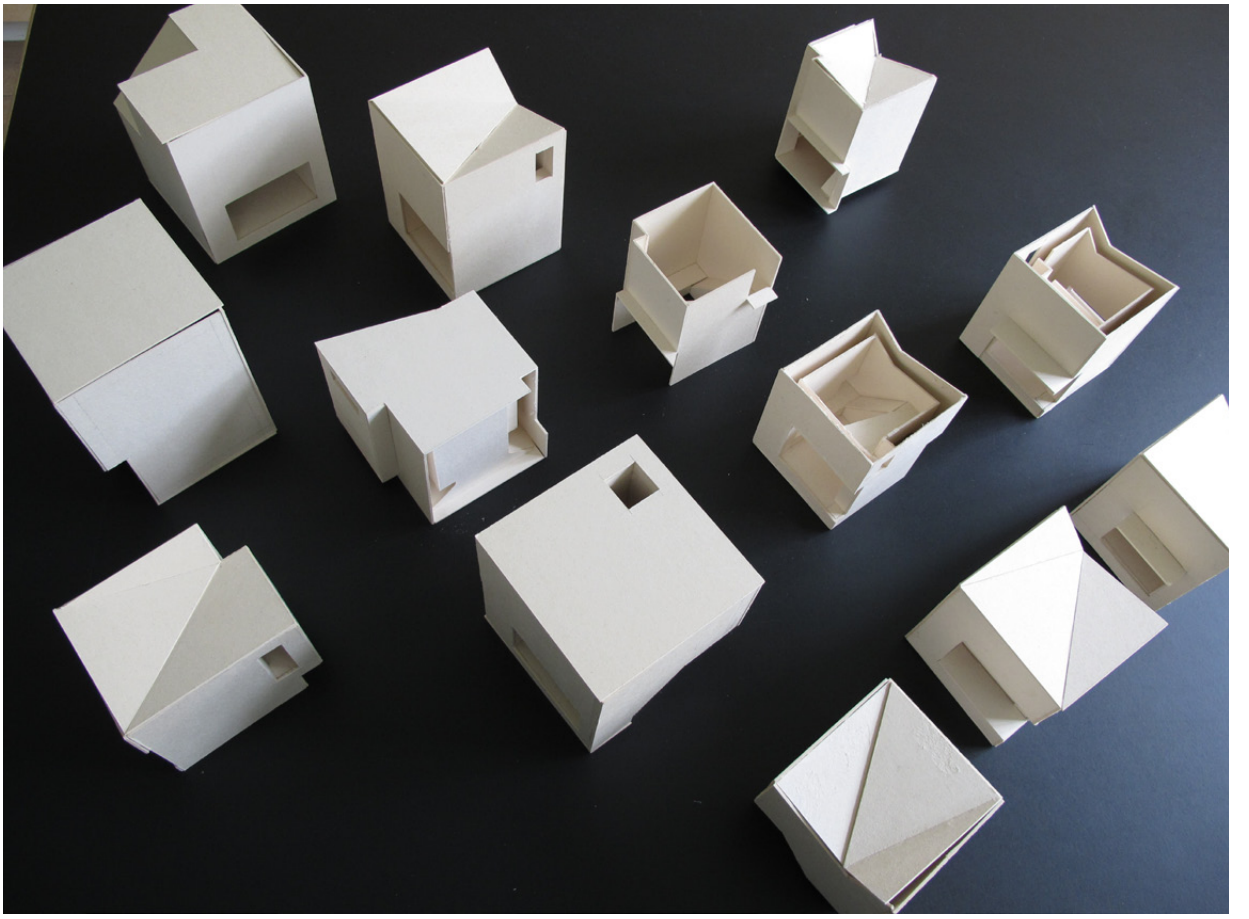

Fig 3.9.5 Some of the models prepared for the shape development. The high compactness is the common denominator of all the proposed schemes.

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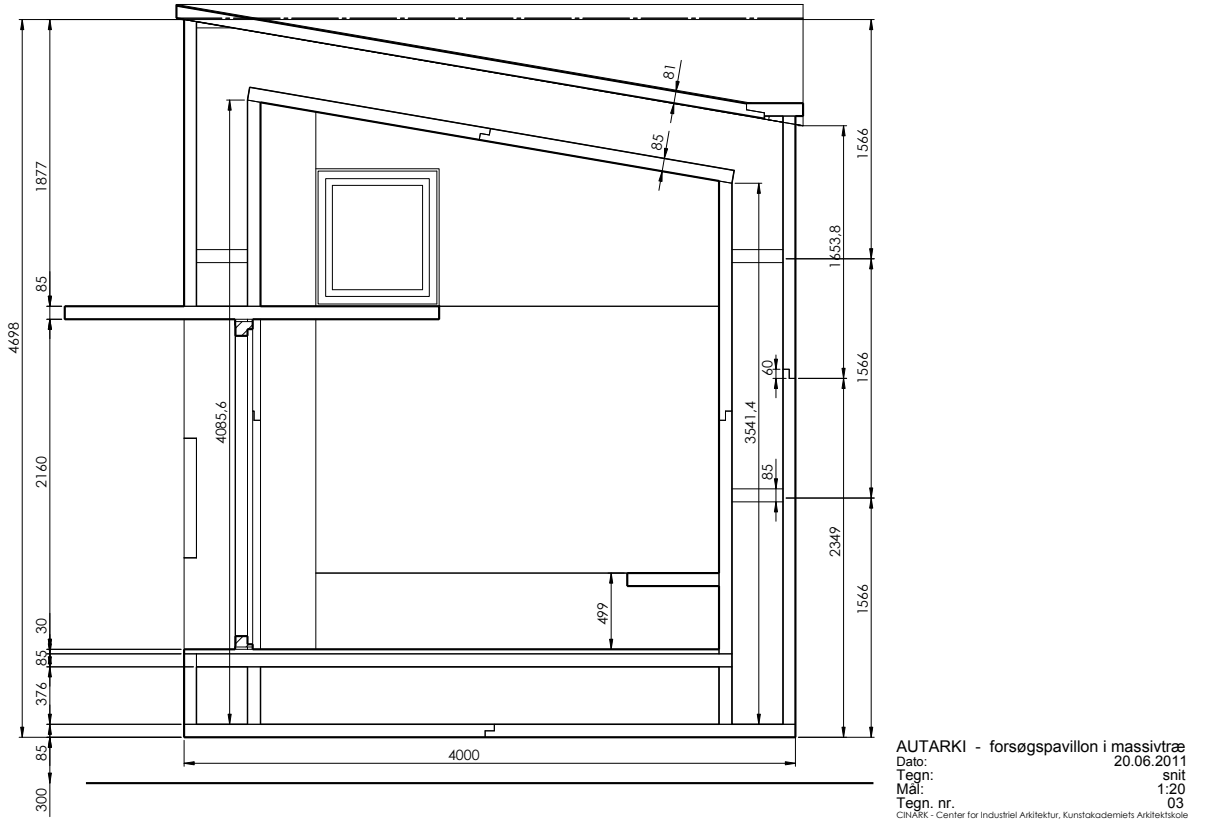

Fig. 6 Section: The main window is facing south and it is shaded by a CLT panel that is extended into the interior space, defining a resting area.

Energy oriented detailing

The used windows feature low-emissivity triple glazing. Air changes are provided using a naturally ventilated air-to-air recuperative heat exchanger. It supplies outdoor air to the building and extracts users' contaminated air utilising wind and thermal buoyancy as the driving forces. The CLT components were delivered pre-cut on site and were assembled using a crane. The prototype was built from the inside out, with the panel layout planned so that the next panel could always be fixed directly to the former. The two shells were constructed in such a way that in principle they are independent of each other. After the inner shell was erected the wood fibre insulation battens were mounted. The building was capped off with the roof plates, which were then covered with tarpaper. Finally, the glazing was delivered and mounted. A thermal insulation of 334 mm made of flexible wood fibres was used in the exteriors walls, roof and floor. The aim was to find a material that would advocate a simple and homogeneous building process and would fit the purpose of recycling. The product has the ability to distribute moisture more evenly than mineral wool so that a vapour barrier was not needed. In addition, wooden fibres have a higher thermal capacity than mineral wool, which gives a more stable indoor climate with fewer temperature fluctuations.

The building envelope presents U-values compliant with the Danish energy standard BR10. The on-site monitoring, performed with an infrared camera, showed how the envelope is well-insulated and does not show significant heat loss. As the images illustrate, surrounding buildings have a much higher rate of heat losses than Autarki.

Assembly	**Material**	**Thicknesses (mm)**	**Thermal Conductivity (W/mK)**
Roof	*Cross laminated timber panel*	*85*	**0.13**
	Flexible wood fibre insulation board	*334*	*0.0039*
	Cross laminated timber panel	*85*	*0.13*
	Bitumen coating	*3*	*0.17*
			U=0.1 W/m2K
Floor	*Mastic asphalt*	*30*	*0.7*
	Cross laminated timber panel	*85*	*0.13*
	Flexible wood fibre insulation board	*334*	*0.038*
	Cross laminated timber panel	*85*	*0.13*
			U=0.09 W/m2K
Walls	*Cross laminated timber panel*	*85*	*0.13*
	Flexible wood fibre insulation board	*334*	*0.038*
	Cross laminated timber panel	*85*	*0.13*
			U=0.1 W/m2K
Door (south)			U=0.79 W/m2K
Window (south)			U=0.68 W/m2K
Window (west)			U=0.91 W/m2K
Window (east)			U=0.89 W/m2K

Table 2: Envelope thermal properties

Fig 3.9.7 The inner wall made of CLT.

Fig 3.9.9 Wood fiber insulation is being placed on the floor.

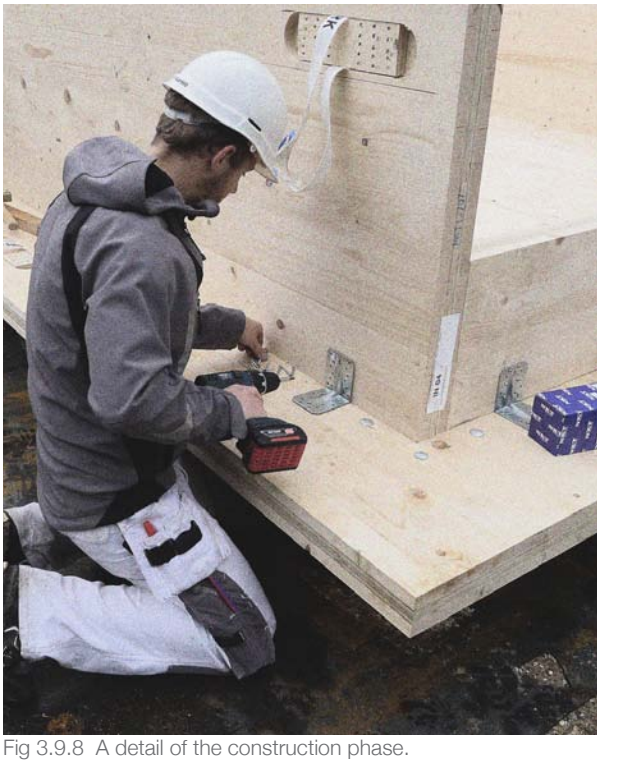

Fig 3.9.8 A detail of the construction phase.

Fig 3.9.10 The outer CLT shell is being installed. Insulation is included and protected.

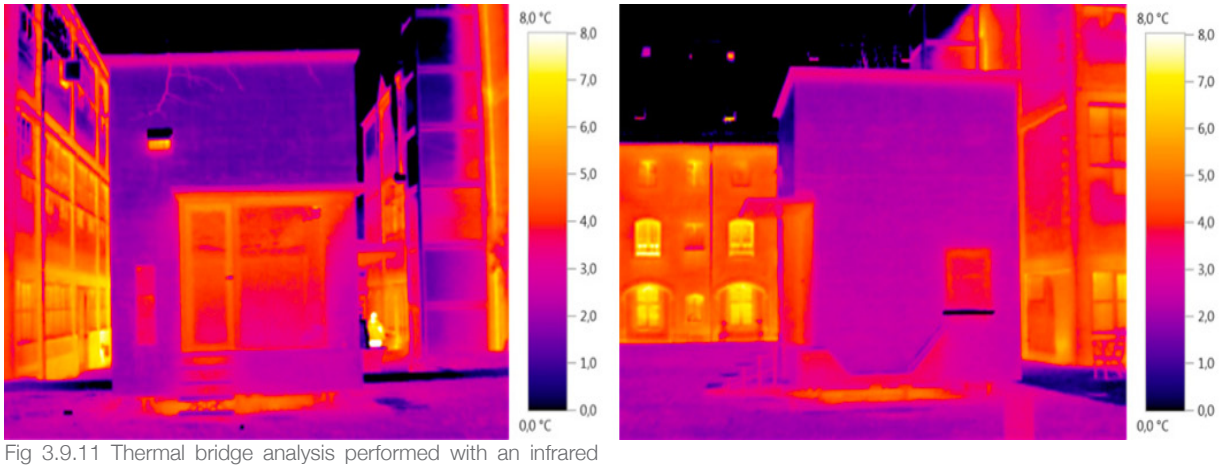

Fig 3.9.11 Thermal bridge analysis performed with an infrared camera. Surrounding buildings have a much higher rate of heat loss (credit: Jan Schipull)

Extended Thermal zone by natural ventilation

For Autarki the user is the key to energy performance. To achieve the desired energy targets an active occupant is necessary. Active occupants that are in tune with their surroundings tolerate a wider range of 'comfortable' conditions. They are willing and able to modify their building to maintain their necessary comfort levels. The concept of "extended comfort zone" is implemented as an efficient strategy for reducing the energy loads and this is achieved by natural ventilation means. Research conducted at UC Berkeley has shown that occupants of naturally ventilated buildings are comfortable with a wider range of temperatures than occupants of sealed air-conditioned buildings. Naturally ventilated buildings allow for a comfort temperature of 26°C in summer compared to 23°C used in an HVAC design and a temperature of 18°C in winter. For a building located in Denmark, an extended comfort zone means that most of the cooling demand can be met by using natural ventilation opposed to air conditioning. Starting from these assumptions, the relation between the users' experiences and the air-to-air recuperative heat exchanger operation was one of the most important investigations conducted on the project.

The aforementioned heat exchanger is driven solely by natural convection. Cool air from outside is drawn from the top part of the south façade (where the pressure is often higher due to the prevailing wind) into the top of the exchanger, where it is led through a series of thin-walled aluminium tubes. Upon exiting the tubes the air continues to the bottom of the room, where it leaves the device at floor level. This airflow is countered by the movement of warm interior air that flows along the aluminium tubes in the opposite direction, delivering its energy to the incoming air. The whole system takes its energy from the differences in height, temperature and pressure of the two airflows. In this research particular attention was given to estimate the impact of the heat exchanger. The role of the users in relation to a possible manual control of the heat exchanger was studied.

Fig 3.9.12 The naturally ventilated air-to-air heat exchanger. Polycarbonate is used to show the mechanism. (credit: Jan Schipull)

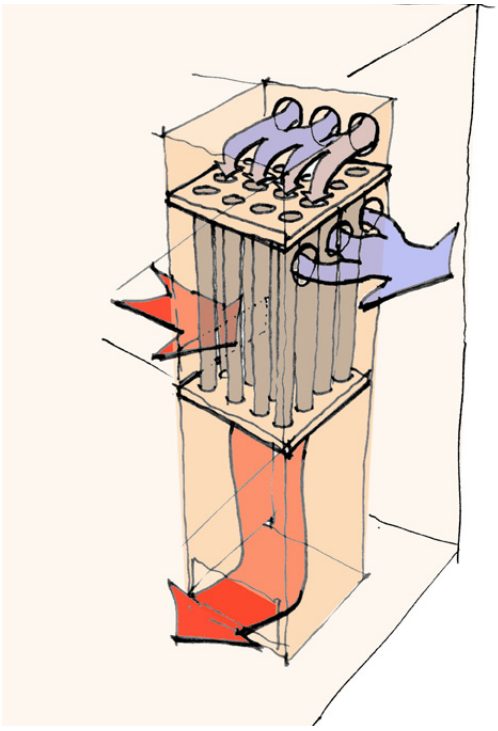

Fig 3.9.13 Diagram of the naturally ventilated air-to air heat exchanger operations.

On-site monitoring

One of the main features of this research refers to the real-time analysis of the thermal performance of Autarki. All data recorded by loggers is displayed in 5 minute intervals on a dedicated website (www.autarki.dk). Starting from the 21st of September 2012, on-site monitoring was performed following the installation of nine data loggers of temperature (air and surfaces), relative humidity, light intensity and air velocity. The data gathered from this monitoring made it possible to verify the quality of the design assumptions. The data analysis shows that, if unused, the temperature in the pavilion could fall to approximately 5 °C in December and January. When people enter the building a long time is required to increase the indoor temperature. The measurements revealed that the combination of solar gains, users, and computers could bring the indoor condition to thermal neutrality (and therefore thermal comfort) on cold winter days. The data reveals that the air-to-air heat exchanger is one of the main causes of poor comfort since it allows cold air to flow into the building without any user interaction and control. While the heat exchanger is quite functional in early autumn, as soon as the temperature drops to 12 °C it performs poorly. The research therefore investigated whether or not the integration of an active user role into the building energy profile has a potential impact.

The digital prototype

Upon discovery that the building did not perform as planned, an energy model was created with the purpose to analyse which factors were reducing building performance and how low-cost improvements can enhance energy and indoor comfort performance in keeping with the nZEB target. The model enabled a better understanding of how comfort and ideal energy consumption are distributed throughout the year, which combination of options use the least energy, and what alternatives - both physical and behavioural - will be most effective for reducing project energy use. An energy model of Autarki was created with EnergyPlus (a whole building simulation program) and subsequently calibrated with the recorded data. The difference between the recorded and simulated indoor temperatures was considered to be within an acceptable range (+/- 1.6°C). The direct measuring of outdoor temperature, solar radiation, wind velocity and directions was important for the accurate calibration of the simulation model. The standard weather data file of Copenhagen was modified accordingly.

After calibration of the model, the simulation showed a total number of 1,457 hours of discomfort throughout the year. The ideal heating and cooling energy demands for maintaining a temperature of 20-26°C during hours of occupation (09:00-19:00) result in a total annual energy consumption of 98.6 kWh/m2. 95% of this hypothetical energy usage relates to heating and this is mainly related to the fact that the air-to-air heat exchanger is not properly controlled. Winter in Denmark is generally very cold and temperatures can dip below freezing (typically to –5°C during the day and –12°C during the night). The heat exchanger performs poorly when the outdoor temperature is below 10°C, even though its effectiveness in spring, summer and early autumn has been demonstrated. Thus, further investigation was directed at exploring the effectiveness of the heat exchanger and its optimal operationalisation. The results of these parametric studies are described in the next chapter.

Parametric studies

A parametric simulation was conducted in order to quantify the impact of various design variables on the performance of the Autarki prototype. Only architectural and constructive design variables were studied because the aim is to achieve energy consumption levels of an nZEB, without involving mechanical systems. While in first instance the design team pursued a conventional design by generating a code-compliant energy model, several design solutions were automatically generated in the parametric studies starting from the built prototype energy model. It should be clear that the investigation of a large number of design alternatives is critical to finding successful designs options.

Starting from a selection of 11 design variables, the parameterisation involved 139,869 different design alternatives. To overcome the computational time issue, simulations ran on a 256-cores cluster made available by the Institute of Energy and Sustainable Development, De Montfort University in Leicester. The parametric model was run using jEplus. This software is designed to assist building researchers to prepare and execute parametric runs with EnergyPlus. The total computational time was 30 hours. A series of low-cost modifications of the existing prototype were explored. The variables are explained in Table 3.

Variables tested	**Number**	Selected Parameters
Building Connection To The Ground	*2*	*Standing on the ground plate or suspendid*
Wall Insulation Thicknesses	*3*	*0.334m, 0.384m, 0.434m*
Floor Insulation Thicknesses	*3*	*0.334m, 0.384m, 0.434m*
Roof Insulation Thicknesses	*3*	*0.334m, 0.384m, 0.434m*
Main Window Overhand Depth	*4*	*0m, 0.55m, 1.1m, 1.65m*
Natural Ventilation Schedules (Natural Heat Exchanger Control)	*4*	*Always on, Always off, summer on, 9-17 on*
Concrete Thermal Mass Thicknesses	*3*	*0m, 0.05m, 0.1m*
Number Of Users (daytime)	*3*	*1,2,3 persons*
Computer And Lighting Internal Gains	*3*	*30W, 125W, 220W*
Colour Facade	*2*	*Black, White,*
Heat Exchanger Internal Insulation Thicknesses	*3*	*0m, 0.05m, 0.1m*
Total Of Simulated Design Alternatives	*139,968*	

Table 3: Description of the simulated parametric variables

Modification of the prototype to achieve the nZEB targets

The parametric simulation results are summarised in a scatter plot. 139,968 design alternatives are shown according to their heating and cooling needs. The graph highlights the current design of the prototype, and the most performative solutions (minimum ideal energy need). The actual energy demand to maintain indoor comfort is 98.6 kWh/m2, whereas by using the optimal design solution we can improve the building performance by 92.8%, achieving an annual demand of 7.05 kWh/m2. A deeper analysis of the results defined the route towards the achievement of a nearly Zero-Energy Building.

The road toward self-sufficiency relies on the following factors:

- A key factor is related to natural ventilation. As is, the air-to-air heat exchanger does not have any mechanical or manual control system, therefore there is a constant air exchange with outside. The heat recovered in winter is insufficient to maintain acceptable comfort levels. The parametric study showed how a manual system that allows the user to open and close the heat exchanger (depending on specific occupancy and weather scenarios) would reduce the energy demand to 18.8 kWh/m^2.

- As explained above, occupancy schedule plays an important role in passive design. Internal gains provided by people help to warm up the indoor air temperature. With an average occupancy of three people, Autarki decreases its total energy consumption to 10.6 kWh/m^2.

- The actual prototype is detached from the ground, so part of the heat loss happens through the floor. Its placement on the ground will lead to a surface to volume ratio of 1.9 resulting in a total energy demand of 9.7 kWh/m^2.

- Autarki presents a small amount of thermal mass. Mastic asphalt was chosen in order to provide thermal mass, but adding a dense concrete layer of 10 cm in the floor assembly makes it possible to achieve further energy savings. The modification results in energy saving equal to 0.6 kWh/m^2.

- The exterior surface of the prototype is white. Light colours have low solar absorption coefficients as they reflect most of the solar radiation. Painting the façade black would reduce the energy consumption to 8.8 kWh/m^2.

- The extension of the overhang from 1.1 m to 1.65 m has a positive annual effect on the prototype and it brings the energy needs down to 8.5 kWh/m^2.

The modifications explained above are not invasive, require minimum effort, and represent low-cost modifications of the prototype. Such modifications give rise to a final energy consumption value of 8.5 kWh/m2. There are other strategies to improve performance, but those require major modifications of the prototype. For instance, adding insulation (for example an extra 10 cm) would result in saving an additional 1.45 kWh/m2. However, this would result in thick walls and a higher embodied energy in the construction. Such a major modification and others like it are not viable solutions to reducing energy consumption of Autarki.

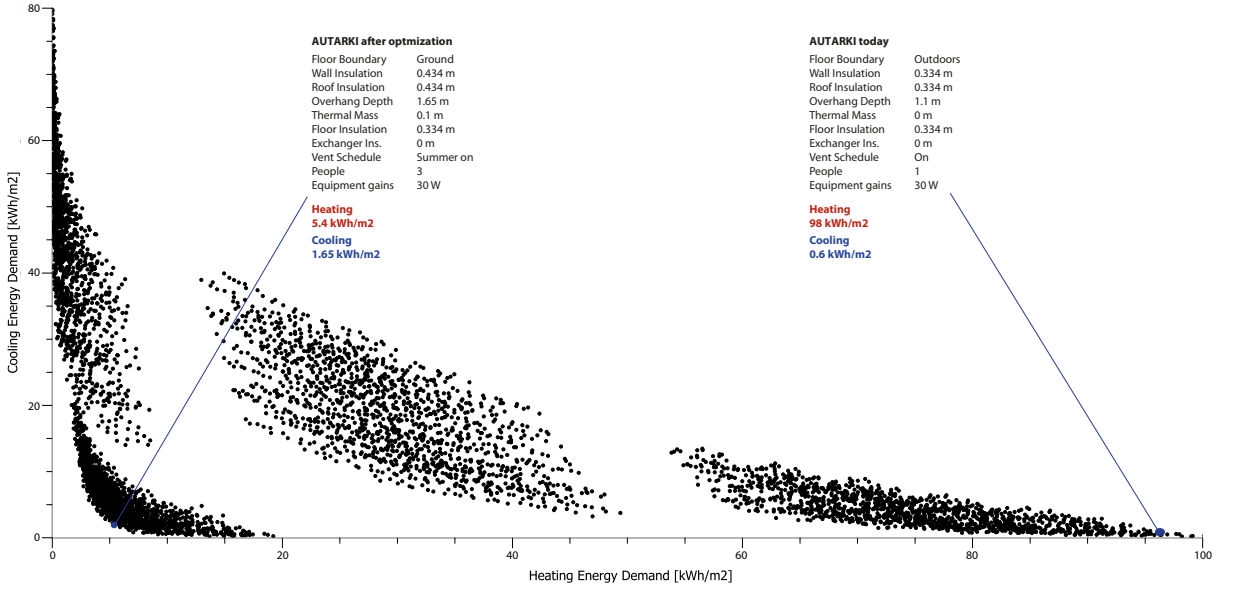

Fig 3.9.14 Scatter Plot of the energy simulation parametric study. Heating and cooling demands of the 139,869 simulated design scenarios are compared.

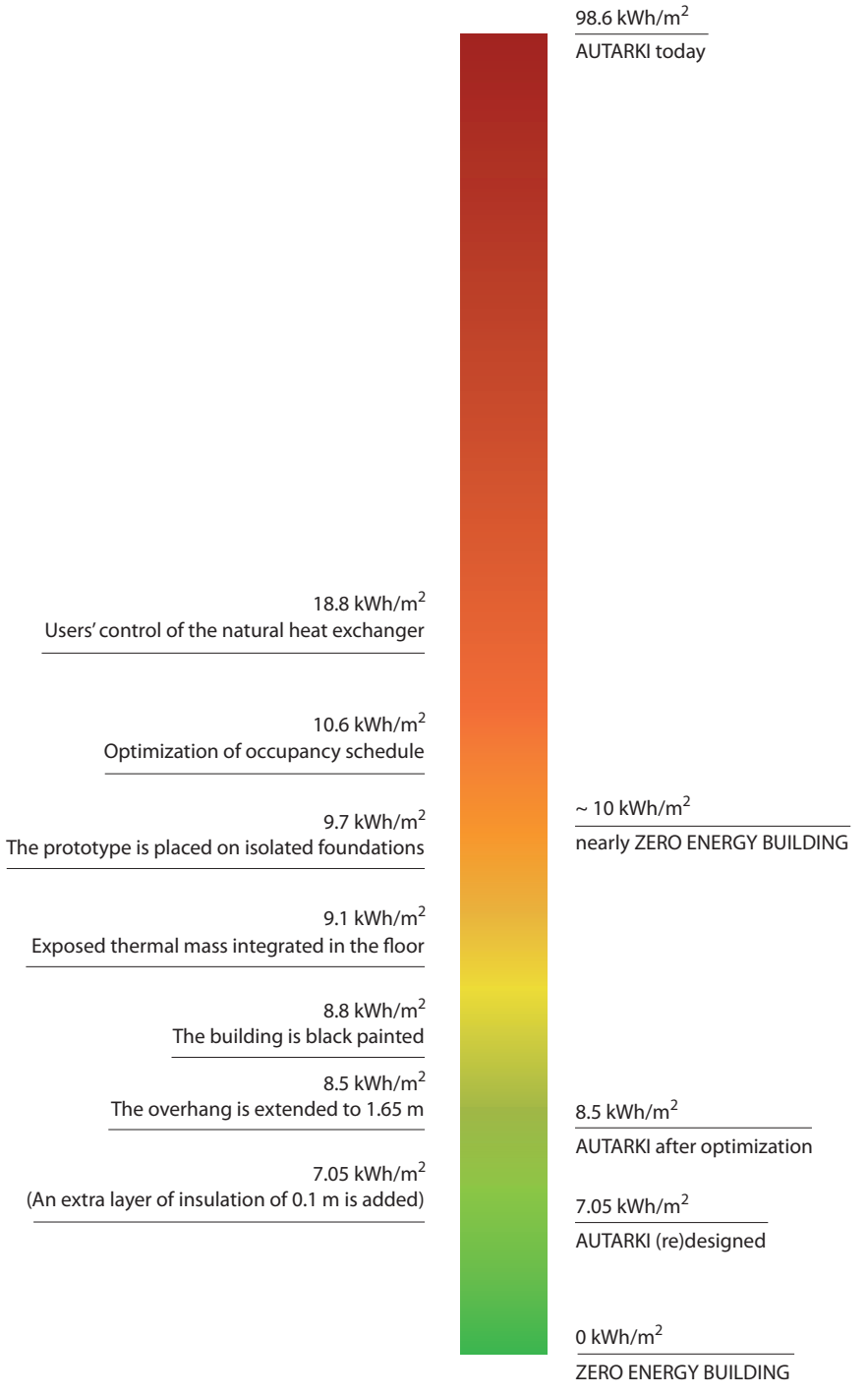

Fig 3.9.15 The path toward a nearly Zero Energy Building is described through a few adjustments of the prototype.

Conclusion

In conclusion, the use of the prototype and the simulations have demonstrated a vast range of energy- and comfort-effective configurations based on Cross Laminated Timber. While the prototype provides information on tangible building performance unobtainable from virtual models, the simulation allowed an in-depth analysis, determining the best configurations and thus informing directions for further tests. Parametric studies yield a wider range of solutions and contribute to maximum energy savings, aiding to achieve the performances suggested by nZEB targets. This approach enhances the process of discovering and promoting technological innovation. The building user, specifically, plays an important part in Autarki energy performance: their control of the heat exchanger according to their desired comfort is key. While frequently a transient occupier of the space has no vested interest in energy efficiency, a permanent user has a big interest in personal health and well-being. Thus, the key concept in Autarki 1:1 is the union of the two systems - energy and health - so that the building operates as an ecosystem supporting global issues (for example carbon reduction) and personal matters (for example health).

The occupants' behaviour has a big impact, particularly in situations where users can control the internal climate of a building. The goal of Autarki 1:1 is to educate occupants on their role in achieving energy savings fine-tuned to the characteristics of the building. The real-time visualisation is a determining factor in improving the interaction between users and the prototype, enabling the users to directly observe the effects of their behaviour. Finally, the prototype was central to the discourse between students, researchers and professors making it an excellent tool for sharing and building knowledge.

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i Emanuele Naboni, Associate Professor, Alessandro Maccarini, Assistant Researcher, Jesper Nielsen Associate Professor, at the Institute of Architectural Technology Royal Danish Academy of Fine Arts, School of Architecture, Copenhagen, Denmark,

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TECTONICS AND TECHNOLOGY TRANSFER

4
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4 TECTONICS AND TECHNOLOGY TRANSFER

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4.1
Building with Beesley

Chantelle Niblock [i]

This paper investigates the impact Making Architecture has on student experience using the Protocell Mesh project as an educational model example. The project was integrated into the early stage of a Diploma in Architecture design studio. Fifteen students from the design studio participated in the exercise. Observations, reflective student feedback and a retrospective interview with the architect Philip Beesley have been used to examine the relationship between making and learning. The research identifies with Beesley's understanding:

> *"Making Architecture may be considered a conscious endeavour to imagine and investigate the physical and psychological aspects of human experience" (2005).*

This paper will seek to identify the issues surrounding empirical teaching methods, within the discipline of architecture, from an intellectual and social perspective.

Teaching Methodology

Architecture is a real-world design activity defined by social, cultural and technological situations. It currently embraces open-source communities, particularly in the realm of digital design and learning. These international communities are complimented by a growth of local digital fabrication laboratories (some of which are based on the Fab Lab concept popularised by Neil Gershenfeld at MIT) intended for small-scale fabrication to help build inexpensively. The impact of open-source learning and digital fabrications upon the development of architectural education is unknown.

The University of Nottingham has invested in the advancement of digital fabrication and workshop facilitates including the Wolfson Prototyping Hall to support design invention, experimentation and research through Making Architecture. The University of Nottingham is an academic partner within the Living Architecture: Hylozoic Partnership Development Program, a SSHRC-funded project led by Waterloo Architecture, This research program included collaborating on design, fabrication, and building of the Protocell Mesh installation in the Prototyping Architecture Exhibition, 2012-13. The work was designed through the collaboration of Philip Beesley of Waterloo Architecture, Nottingham Architecture researchers, and the studio of Philip Beesley Architect Inc. (PBAI) led by Jonathan Tyrrell in Toronto, Canada Acrylic components were laser cut by the University of Nottingham,

aluminium components were laser cut by F.C. Laser in Derbyshire, and thousands of chevron-shaped components were assembled by students from the studio unit called Urban Manufacturing: The Process of Making co-led by Dr Chantelle Niblock and Tom Osborne at the University of Nottingham. The installation was later dissembled and reassembled at The Building Centre in London as part of the second stage of the Prototyping Architecture Exhibition.

The author performed multiple roles throughout the project, which included studio tutor, participant, collaborative researcher, and project manager. The roles related to each stage in the project. During the early design stage the role was primarily as a researcher; initiated during a planned research visit hosted by PBAI in Toronto, August 2012. The visit provided great insight into to PBAI's multi-disciplinary working method and collaborative expertise. The direct experience, observations, and personal discussions focused on developing the first generation part-prototypes and were instrumental in obtaining a mutual design and research understanding of the Protocell Mesh project.

Parallel prototype iterations were constructed in Nottingham during the summer 2012 as part of an Engineering Research Placement conducted by Kaplan Pirgon, supervised by Chantelle Niblock. Kaplan investigated material specification, fabrication techniques (such as water-jet cutting), and 1:1 scale part-prototyping; his research directly informed the method of fabrication and assembly of the final Protocell Mesh installation in Nottingham.
The next stage involved integrating the project with a studio teaching programme and securing a local fabricator for the aluminium pieces. The building of Protocell Mesh event was planned for the duration of six days, this included a weekend. The acrylic pieces were cut at the University of Nottingham in advance, however a delay in securing a new university supplier meant that the local fabricators could not deliver on-site until the last minute. During fabrication and assembly stage the author's role was a hybrid of participant, research observer, studio tutor, and project manager. This included observation of the students' performance and how they interacted and participated in the production system, whilst securing deliveries, equipment, and materials.

After production of the Protocell Mesh installation and Prototyping Architecture Exhibition in Nottingham the author's role reverted back to solely being a studio tutor, encouraging reflective critique of the experience when Building with Beesley throughout development of student studio projects.

Conventionally, architecture is taught in a design studio environment. Often the tutor develops a personal approach to developing expertise in novice designers, drawing from their own problem-solving experience. The group involved in Building with Beesley included 13 Diploma Level (RIBA Part 2) and two Master Level Architecture students. The student group were exposed to many practical skills related to design, construction, and on-site management. They participated in health and safety training and contributed to a larger team working towards the opening of Prototyping Architecture Exhibition in Nottingham. The Protocell Mesh project enlightened students with a more kinesthetic method of learning, similar to a field trip. This taught experience-based techniques to students. The intention being that in learning by making, the students appreciate the rationale of component assembly and understand material limitations gaining confidence through application of these skills in their own studio projects. The integrated learning methodology for the studio unit can be summarised as follows:

Background: a seminar session introduced examples of work by Philip Beesley Architect Inc. Students discussed his ideas and how they were represented through two-dimensional drawing.

Fabrication: smaller student groups (2-3 people) laser cut thousands of acrylic pieces using the on-campus workshop. A small student group visited the local fabricator (F.C. Laser) to understand the process of cutting aluminium sheets.

Health and Safety Training: all students obtained free Personal Protection Equipment (PPE) and a small group participated in stepladder training.

Classroom component-assembly: a brand new seminar room was transformed into an off-site assembly room to convert components into small sub-assemblies.

On-site full assembly: sub-assemblis were combined and assembled in Wolfson Prototyping Hall. This space was shared with a number of student groups who were constructing other exhibits for the Prototyping Architecture Exhibition.

Lecture: on completion of the installation Beesley consolidated the project with an overview of his work and reflected on the Protocell Mesh installation.

Studio feedback: during studio tutorials students were asked to reflect on their experience and apply learned thinking strategies to the studio design project.

Assessment: a small percentage equated to the student's final assessment for their first Semester 30 credit studio module.

The Protocell Mesh Project

The Protocell Mesh installation embodies the idea of Living Architecture. Personally this idea goes beyond the Protocell chemistry. In simplified terms the installation is never static; it gently wriggles as the viewer walks through and whether intentional or not he or she interacts. Psychologically, the installation evokes emotive responses: recognition, memory, and pride in those who have constructed it. It portrays elegance, fragility, robust beauty, and a complexity, which cause some to be wary.

Fig 4.1.1 Protocell Mesh completed in Nottingham

Taking inspiration form the work of Samuel Beckett the next section of the paper takes the form of a discourse with Philip Beesley. Hopefully when presented at the Prototyping Architecture conference, this will not sound like Waiting for Godot, voice by just one actor.

Chantelle Niblock: *From where did the inspiration for the design of the Protocell Mesh installation arise?*

Philip Beesley: *The Protocell Mesh project is motivated by several parallel ideas with the common thread of designing near-living systems. The pursuit of life-like qualities by artists has a background of thousands of years of history. However, there are some ways of working that seem new, making a project of working with literally living things seem much closer to reality. Some examples could be the new information offered by the Genome project, self-renewing chemical metabolisms offered by synthetic biologists, learning and adaptive environments offered by computation, and the ability to craft highly resilient, complex structures through digital fabrication. Those examples encourage me to attempt to integrate multiple systems and to orchestrate active, responsive mechanisms within architectural building fabrics. I have been especially encouraged by the examples of brilliant colleagues working in chemistry, structures, and computation, and by writers working ahead of technology in fictional projections. I am impressed by people who can work both in precise material research and in poetics. People such as the futurist Rachel Armstrong and the fashion designer Iris Van Herpen are particular inspirations. Their examples have encouraged me to work on buildings that have circulation systems, kin to the way natural blood and lymph work within a natural bodies, and that have responsive textile skins, kin to the way pleated fabrics in a dress can drape in vivid ways over a human body.*

Carbon-Capture

CN: *At the Nottingham and London exhibitions I was asked to quantify the Protocell carbon-capture filter array. Some observers showed intrigue, comparing the amounts of carbon dioxide produced during the process of manufacture to the amount processed into inert calcium carbonate by the filter array. How would you respond to this comparison?*

PB: *The question of carbon dioxide produced in the process of manufacturing compared to the amount processed in inert calcium carbonate is entirely appropriate if we are judging this work as architecture integrated within its environment. To be clear, the carbon effluent of this prototype in its current form is vastly larger than the carbon it fixes. However that answer will be distorted if we use it to directly judge this first-generation prototype, because no attempt has been made to optimize the performance of the system. Instead, the question is more effectively one of potential: could buildings perform effectively using this kind of strategy, and might their net energy and resource be positive in their impact? Our work at this point is to establish potential. The prototype is a model that suggests potential functions. Much more work needs to be done before the system is ready for functional performance testing.*

Fig 4.1.2 Protocell Carbon-Capture array

Prototyping

The translation process from an abstract two-dimensional drawing to concrete representation of the Protocell Mesh was dependent on the smallest detail such as variation in machine speed, material properties and micro-millimetre accuracy. Great care was required, for example in material specification and translating metric to imperial tolerance. In Toronto PBAI's studio inhabits an abandoned transformer factory; it is the magical stage set for the in-house design experience, fabrication experimentation, and 1:1 scale assembly. In contrast, the Protocell Mesh was out-sourced, for instance drawing files were shared, iterative tests made across the North Atlantic Ocean and it was part-fabricated and assembled in Nottingham.

The teaching exercise did not involve the students in pre-assembly design. Similar to the studio working method in Toronto, students were instrumental in last minute design decisions collaborating with Beesley and Tyrrell on-site. In terms of architectural embodiment this process enabled students to visually and physically experience the personification of familiar laser cutting 2D techniques used to create a complex 3D flexible hyperbolic grid-shell mesh. The activity related to design and was an experimental process that challenged the neat boundaries of design authorship.

CN: *In terms of the structure and the material behaviour of the Protocell Mesh, do you feel that the prototype was successful?*

PB: *In the projects that I and my collaborators do, I tend to focus on both success and failure. We developed Protocell Mesh with our collaborators at the school of architecture at Nottingham, and worked up to the last moments before opening the exhibition, refining details and adjusting jointing systems, and we set up a new filter system that we hadn't seen working at this scale before. The prototype aluminium meshwork system that we developed together with the school showed tremendous promise for its sheer strength and its tolerance for wide distortions. The glasswork 'reticulum' of lightweight valves and filters showed strong calcium-carbonate precipitate formations, directly demonstrating carbon capture operating. In those ways, I'd say the work was a resounding success. On the other hand, the jointing systems took quite a bit of wrestling and even a bit of blood in the laborious hand-work of their assembly. Next generation for this system will be much more refined, concentrating on making things 'finger-friendly' and faster to assembly.*

Fig 4.1.3 Aluminium hand-work

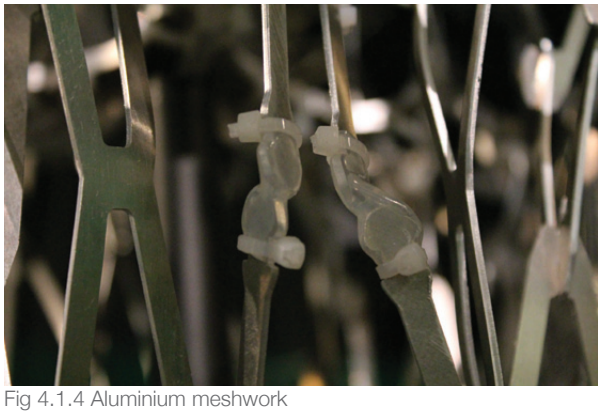

Fig 4.1.4 Aluminium meshwork

Likewise, the amount of carbonate precipitation that continued after the first chemicals were inserted was very slight, and so we could say the system has only very limited performance when we judge it as a large-scale industrial process capable of contributing to the environment. We would adjust the filter details to encourage more active air exchange in next versions of this work, and we're looking for more effective chemical formulas. These kinds of results speak directly to the nature of iterative prototyping. So long as we learn from them and make adjustments in the next generations of prototyping, we can say that the initial stages are working quite well. However, their limited performance mean that the work is in its early stages of development, and doesn't qualify for near-market release.

Working as a Team

Making the Protocell Mesh prototype was a situated learning experience that evoked intellectual debate. The participant students described skills learnt from the experience as an understanding of complex assembly and team production/management skills. The students said they were motivated by the anticipation of 'seeing', team spirit, project calibre, and responsibility. The reward was simply the delight of 'making' which they described as assembling to create the final installation; validation a newly learned expertise.

Fig 4.1.5 Off-site seminar room assembly

Students were concerned by workload and how this related to assessment. The project was assessed in terms of how students engaged with the experience and were able to extrapolate the newly acquired skills into their studio project. The identifiably skills included rationalisation of component assembly in construction, investigating design by making, and performance in a team. During the assembly process students were emplaced, they became experts of assembly and together they developed an efficient production team. When asked to describe their experience all responses were positive and most students commented that it was a new practical experience and an engaging learning experience.

Early morning, 13th October - the second day of build, we received a last minute delivery of a large number of laser cut aluminium components. With restricted time, unaware of aluminium behaviour when combined as a meshwork, Beesley encouraged the students to "embrace being a machine, understand your small bodily movements and look for ways to build, as part of a team". Moments of 'situated cognition' emerged when intelligent behaviour such as self-organisation came out of the interplay between minds, body and working environment. Decisions were based on an understanding of material behaviour and physical (bodily) constraints.

CN: *Personally, I found immense value in the project and was honoured to participate from a pedagogical stance. The experience has highlighted the idea of Authorship and Co-operative labour in making architecture. A project aim was to translate practical and critical exchanges into educational models to foster innovative and creative thinking skills for new generations of students (Beesley, 2011. SSHRC Partnership Development Grant). In Nottingham I observed a small community bound together through the integrity of the idea. In making the Protocell Mesh, students were provided with skills beyond the material and it is hoped that they adopted alternative thinking strategies. How would you develop this type of exchange into future educational models for architectural students?*

PB: *The exchanges between researchers and student communities are a really satisfying part of the project for us, and it seems to suggest a renewed interest in the potency of collective design and fabrication. I have no interest in creating one singular universal system in this. Rather, I think the tribal, fragmentary architectures that can result have tremendous resiliency and fertility. Perhaps collaborative group work would have been taken for granted if we were speaking during the Russian revolution of 1917, or during the height of the Aquarian age in the late 1960's, or indeed in a barn-raising in a rural community during a past century. Today, however, my own experience is one of being surrounded by acutely separate individuals, and the experience of liberally shared commonly built work is quite rare. The collective actions offered by this work do seem valuable.*

It might sound like a too-simple homily to say that it is valuable to work together. However when we ask students to share impressions of their experience of completing the designs and building these installations, I consistently hear about how satisfying the collective experience is. Some dimensions of that seem obvious: there are hundreds of thousands of tiny pieces, and it would make for mind-numbing labour if we only approached those as mechanical piece-work. By inventing cooperative ways to process the myriad of mechanical actions, the group seems to cohere and develop extremely interesting collective personalities.

This translates quite directly into a shared experience of the public dimensions of the architecture. The group builds the filtering veils and hyperbolic vault-works that quite literally form the enclosing architecture all around them. A striking kind of emplacement results, rooted in shared experience. This directly invites an educational model based on collective action and collaborative design.

Fig 4.1.6 On-site lily assembly in the Prototyping Hall, Nottingham

Beesley's work shows that art, architecture and craft can be totally cerebral. Individuation does not need the direct contact of the human hand. Knowledge, skill and invention, however, are essential in the creative process – the ideas go beyond this realm and become physically immersive. (Stacey, 2010).

Imagination and Prototyping

Most students felt that the experience had an impact on how they imagine complex three-dimensional spaces. Prior to the Protocell Mesh installation one student "couldn't imagine how a structure could be partially 'alive'." Another commented, "it has helped me to see beyond static forms". The experience also had an impact on how students thought about drawing in relation to construction. They began to question how designs could be manufactured. One student commented that "it was really interesting to see how the plans and elevations of the installation looked compared to the end product ...when building the mesh as instructions I couldn't imagine how it would look until it was resolved at the very last stages." Imagination is a cognitive process and engages with augmented physical reality of making.

CN: *I am interested to know more about the role of imagination in your work. Frederick Kiesler described man, caught in the net of his imagination (Kiesler, 1949) and looked to other media such as poetry, model making, and surrealist painting as ways to materialise ideas. This made me think of Karl Popper's theory of Falsification - described as the truths that architects seek to be temporal and belonging to specific design context dependent on the situation (Popper, 1963). Using the Protocell Mesh as an example how would you describe the interaction between your imagination and the physical prototyping during the iterative design process?*

PB: *Your comment about Kiesler is tantalizing, and I have the sense that he distrusted his own human consciousness because of the way it seems to be bound by its own projections. I am also attracted to Popper's quite practical outlook on philosophy—I am struck by his suggestion that ideas do not need to be justified; instead, they need to be criticized and worked with in quite practical ways, defining their value by involvement rather than by absolute standards. Perhaps my own work is similar in its methods to both of these ideas. We've developed a working method that tends to use corruption and failure as motivating increments. If we make a new arrangement through casting and digital printing, we'll tend to play with it aggressively until it breaks, and then will fabricate it again with some adjustment to its details, playing and taking it to the limit of breaking again.*

I think this kind of cycle, rooted in material performance, can reveal far more richness in a design than one that focuses only on the most refined simulation possible. In the case of the studio method however, the pursuit is not just one of seeking the greatest durability and resistance to failure. In most of our design work we're looking for reactive, resonant qualities, where things are brought as close as possible to their points of potential collapse. Those kinds of states tend to be ones where things act in potent, 'live' ways, amplifying vibrations and echoing from the perturbations they receive from their surroundings.

There are many examples of this kind of approach that can be seen in the Protocell Mesh project. For example, we developed an aluminium chevron-meshwork that makes up the hyperbolic waffle-forms of the overarching scaffold structure, progressively thinning and voiding out the elements in order to bring them into a state of extremely lightweight, ductile performance. Their ability to handle forces shows some interesting qualities. By working like a lace-work net, forces tend to be shed and transferred from part to part. Each part is extremely weak when considered in isolation, but the deflection and shifting of forces allows these quite delicate elements to handle formidable forces in composite. Similarly, the mylar frond-works of the carbon-capture filter system have deeply fissured extensions that tend to twitch and tremble. This can be justified by the way the filters tend to harvest surrounding forces, creating a diffusive action. On the other hand, the emotional quality of this trembling, similar to the way the aluminium waffle undulates and deflects when it is disturbed, might be acknowledged as well. Emotional, ambivalent handling of the work during its development helps guide the shaping of these details. Perhaps Kiesler's use of poetry and painting to disrupt his preconceived designs, and the way Popper encouraged practical criticism to reveal the quality of his ideas, is similar. In the case of our work, we're trying to find potent qualities of fragility and resilience.

Provocation for Future Architecture

With high-end fabrication, prototyping resources and opportunities for cross-disciplinary international collaboration we are drawn to question what architecture is, or will be in the future. How will educators prepare the next generation of architects for this borderless intellectual design exchange? The Protocell Mesh project was an exercise beyond practical skills and enabled students to engage in international collaboration, and to mentally simulate three-dimensional space and complex geometries. Students were able to extrapolate the experience and develop architectural topics such as layering, component design, responsive and immersive architecture, and ways of representing architecture.

PB: *The curriculum also invites inquiries into the nature of public space today. What geometries, and what spatial forms can fulfil public experience in our new century? The slightly drifting, labyrinthine spaces that these meshwork and filter systems make might seem far from proudly framed public chambers, but they do offer tangible gathering spaces amidst their multiple hollows and creases. If we could develop this further, we'd work with open-source design models and cycles of simulation, fabrication and testing. I think this approach could readily build up fertile libraries of shape-grammars capable of working at multiple scales that reach from personal clothing to urban scales.*

Conclusion

This paper investigated the impact of Making Architecture on the experiences of our students. The Protocell Mesh project, design by Philip Beesley Architect Inc., and made by a group of students in the University of Nottingham was used as an example teaching method. The intent of the project was to provoke investigation as to what architecture is or will be and how to explore the impact of this teaching method on student experience.

Programmatically this type of teaching method is difficult to integrate within a teaching semester. Issues such as assessment and workload are required to fit within the remit of a studio design project. The exercise proved extremely effective and was often referenced in studio tutorials. Students were challenged on their preconceived perceptions of 'living architecture' and how they perceived types of space. The students developed team spirit, an understanding of material properties, and strategic thinking skills that could be applied in studio projects. The project was constrained by many aspects that included, budget, training, access to facilities, and student concerns regarding assessment.

Re-addressing Beesley's understanding of Making Architecture - how do educators in the discipline of architecture encourage students to engage with making architecture, imagining and investigating the physical and psychological aspects of human experience. The discussion of relationship between imagination and physical prototyping is of huge intrigue. The most rewarding – to see students develop confidence in their conscious imaginations and investigate these through drawing and making.

Fig 4.1.7 The Protocell, all complete and ready for the opening of the Prototyping Hall, and Prototyping Architecture, Nottingham

Acknowledgement

The author wishes to thank Philip Beesley for participating in the interview and agreeing to this discourse being published. Thanks are extended to the student group for their valuable feedback, which contributed to this paper.

References

i Chantelle Niblock, MArch, PhD, is Course Director of MArch Technology and Lecturer in Architecture at The University of Nottingham since 2010. She is co-convenor of a Diploma Studio [RIBA Part 2] in Digital Architecture and Fabrication, which focuses on developing design methodologies and innovative facade design. She is a member of the Architecture & Tectonics Research Group [ATRG] at The University of Nottingham.

ii Philip Beesley, Orgone Reef, Design Through Making: Architectural Design, 2005, vol.75, pp. 46–53.

iii Kaplan Pirgon successfully completed the Engineering Research Placement, summer 2012, which provided a unique opportunity to sample first-hand, the life of a researcher.

iv Weekend activities were classed as voluntary participation and therefore could not be used as a form of assessment.

v However unlike some of Philip Beesley's installation Protocell was not animated by proximity senses and nitinol wire a conscious decision agreed between PBAI and ATRG to focus of the prototyping of the aluminium structure and animation by other passive means.

vi The reflective e-mail interview was conducted 17 January 2013.

vii Estragon and Vladimir are the principle characters from Samuel Beckett's Waiting for Godot, Faber, 1956.

viii The author in a contemporaneous set of field notes recorded this comment by Philip Beesley and the feedback of the students.

ix Michael Stacey, From Flat Stock to Three-Dimensional Immersion, in Philip Beesley (ed.) Kinetic Architectures and Geotextile Installations. Riverside Architectural Press, 2010, pp. 59-64.

x Frederick Kiesler, Pseudo – Functionalism in Modern Architecture. Partisan Review, 1949.

xi Karl Popper, Conjectures and Refutations: The Growth of Scientific Knowledge (2 ed.). London: Routledge, 2002.

4.2
TRADA Pavilion - Searching for Innovation and Elegance in Complex Forms Supported by Physical and Software Prototyping

Stephen Melville, John Harding and Harri Lewis [i]

In late 2011, the Timber Research and Development Association (TRADA) commissioned Ramboll Computational Design (RCD) to design, analyse, fabricate and construct a pavilion to be a showcase for inventive use of timber and a working trade fair stand for the *Timber EXPO 2012*. A re-useable thin-shell structure optimised for the often conflicting drivers of structural efficiency, cost of fabrication and ease of erection was created. A single design team rarely have the opportunity to manage and take responsibility for a project from concept to construction so it was seen as an opportunity to apply and demonstrate the advantages of digital design tools. This paper describes the processes and methodologies utilised by the RCD team including the important role physical prototyping made towards the success of the project.

The underlying shape of the structure was designed using an in-house form-finding application to develop structures optimised to resist their self-weight efficiently via in-plane forces. The balance of control between the software and the designer is discussed and the rationale behind the chosen constraints that led to the final form is explained. The complex surface created by the software would have been difficult and expensive to replicate exactly so it was 'discretised' into planar faces. The process from an initial triangulation to the development of bespoke software, to create the three-valent mesh that was ultimately used, is described, future uses suggested and recommendations regarding the use of bespoke digital tools in design are made. The structure used simple hinges to connect adjacent panels. The geometry of the panels and the overall form restrains the panels – which allowed the same connection detail to be used throughout the structure - drastically reducing costs and manufacturing complexity. The development of the connection detail and production of a parametric model to automate the positioning of hinges, numbering and nesting are described.

Three prototypes were created – an early paper model, an accurate 1:10 scale model and a full scale 'leg'. The prototypes addressed many of the design team's concerns, including but not limited to overall stability, aesthetic, ease of construction and fabrication processes. Details of the manufacture and implications of the prototypes are included, recommendations for future projects and the value of such prototyping is discussed. Despite the innovative and irregular form, unnecessary complexity was avoided by considering all phases of development at the earliest stage. Two prototypes an accurate 1:10 scale model and a full scale 'leg' formed part of the Prototyping Architecture exhibition.

Introduction and Brief

The history of the pavilion in Architecture is that of innovation and the expression of creative freedom and many have incorporated a high level of technical research and design exploration that belie their small size. In late 2011, having seen Ramboll Computational Design's (RCD) experimental foyer structure, see Fig. 1, TRADA commissioned the team to design, structurally analyse, help fabricate and build an enclosure for their stand *at the Timber Expo 2012*. The brief was to create a practical demonstration of how simple timber elements can produce innovative and elegant structural forms. TRADA hoped to fire the imagination of the public and encourage new ideas about what could be achieved with timber. The RCD team resolved to extend that brief to show how digital design techniques could be used to simplify the construction of complex forms by automating menial tasks and allowing the use of simple timber elements, with inexpensive fabrication techniques and without complex joints.

Fig 4.2.1 RCD's experiment foyer structure

The brief also stipulated that the pavilion must be simple and quick to construct and to be demountable once the show was complete. Only two days were available on-site prior to the show opening and only one day after to demount. A tight budget was imposed by TRADA and minimal material wastage was highlighted as a priority. The plan dimensions and height were dictated by the size of the plot within the conference hall, six metres by eight metres and a maximum height of four metres. Although the plan dimensions and height were set, it was also important to ensure that there was sufficient room inside the pavilion for an information desk, a literature stand plus ample space for staff and public to move around freely. It was seen as a very open brief, especially for a team of engineers. The response was a funicular shell structure with a central funnel and four legs in birch plywood, see Fig. 2, drawing on previous work with digital form finding by the RCD team. The shape was not explicitly determined but allowed to form an optimal surface from imposed boundary conditions in response to the self-weight of the structure. By adopting this approach the shell was extremely efficient and could be constructed from thin timber elements. The form finding process is described in Form Development.

The surface itself was discretised into a mesh where three flat faces meet at every vertex (known as a three-valent planar mesh), an arrangement rarely seen in the construction industry but prevalent within nature. The technique used to achieve this is described in Surface Discretisation. This reduced the number of connections required, performed better structurally in comparison with a triangulated mesh and lent a unique visual quality to the shell. Physical prototyping supported the innovations and was an indivisible part of the design process, starting with a paper 1:10 scale model of an approximate form, then a thin ply scale model of the final design then finally a full scale test leg. Without the assurance provided by the prototypes, delivery of the structure may not have been possible.

Fig 4.2.2 The completed pavilion at the Timber Expo 2012

Form Development

The complex, curvaceous and highly structurally efficient forms of Frei Otto and Heinz Isler have often inspired the RCD team. These structures were designed using intricate scale models where a range of materials such as chains or fabric were hung with varying boundary conditions, see Fig. 3. With little or no bending resistance the material hangs in pure tension and the form they find in equilibrium can be flipped to produce a structure, which works in pure compression. These methods produced slender structures capable of spanning long distances.

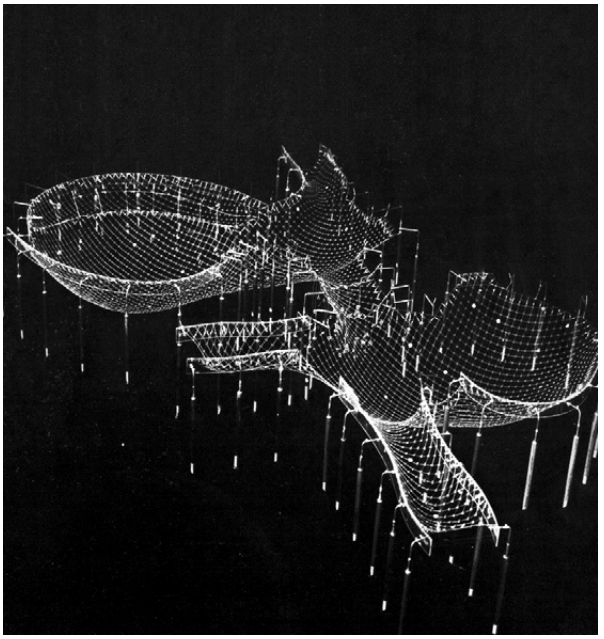

Fig 4.2.3 Form finding model for Frei Otto's Mannheim gridshell

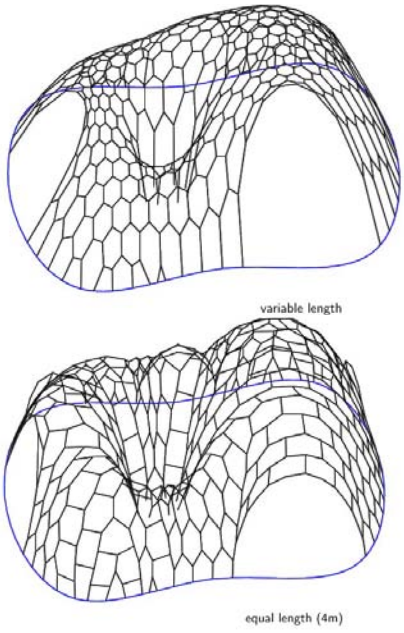

Fig 4.2.4 Experiment combining form-finding with equal length members

The design team created the software using the Processing[ii] libraries for creating Java applications. For this project the method was evolved to include 'dynamic mass'[iii]. This involves updating the mass of each node for each iteration of the simulation, in response to the extension of the connected springs, therefore improving the validity of the resultant form. The software is fully interactive and the design team experimented with various boundary conditions to find a form that fitted within the site constraints and could work as an interesting focal point to the exhibition. An early experiment was to further adapt the software by setting the natural length of 'spring' edge member equal to the average length of all the edge members. With a high enough spring stiffness this produced a mesh with members of approximately identical length, see Fig. 4. Whilst this was an interesting experiment, it was felt that with the ease of fabrication of timber of varying lengths this method did not actually offer any considerable benefits. It has been suggested that for other materials this may not be the case and the system was shelved for future reference.

In contrast to the grid-shell structural typology of the foyer sculpture, the team decided at this stage they would widen their experience and aim to produce a shell structure. This decision meant that the previously used connection details and rationalisation techniques would not be suitable - in effect forcing them to innovate and develop new methods. The challenges and solutions that arose as a result of this decision are discussed later.

The brief defined a maximum height of 4m. This and a desire for a maximized useable floor area led to the four legged and central funnel form that is seen. As form found shapes cannot be directly manipulated (without affecting the structural efficiency) the designer must play a role similar to a puppeteer – tweaking and adding boundary constraints as they see fit. An initial design made up of four legs on the perimeter highlighted one of the challenges this method can generate - the lower the angle of the legs the more inhibited the space becomes, however if this angle is increased by increasing the mass of the digital fabric the maximum height is quickly exceeded. The solution was a central funnel form, which pulled this maximum height down whilst maintaining a high angle for the legs, see Fig. 5. The output of the form finding process was a high-resolution mesh of triangles to be used as a base surface from which to develop a buildable structure, see Fig. 7.

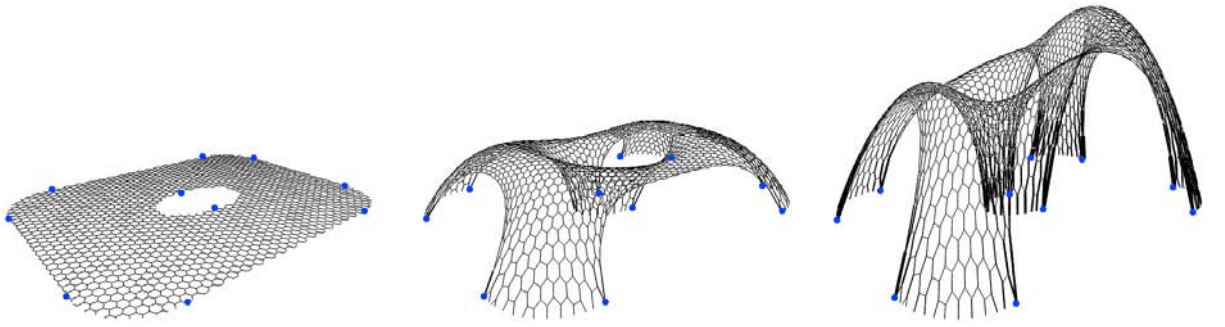

Fig 4.2.5 Form finding sequence for final design

Surface Discretisation

Having decided upon the form and shell typology the next stage was to investigate how to discretise the surface into panels. Sheets of timber can be bent or milled to create curved surfaces however this would have been prohibitively expensive, as each panel would have required a unique jig or be highly wasteful of material. The challenge was therefore to divide the surface into completely flat or *planar* panels. The initial solution was to work with triangular panels. A plane can be defined by three points therefore a triangle must always be planar. Fig. 6 shows a preliminary design using this method.

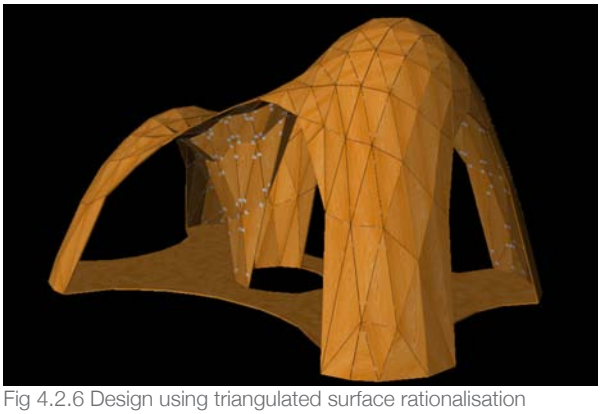

Fig 4.2.6 Design using triangulated surface rationalisation

Although the result was an interesting form, there were a number of concerns about this solution. Firstly, it was felt that triangulated surfaces were too common and would not offer a significantly new aesthetic for the structure. Triangulated meshes also have lines of edge continuity throughout the surface and it was predicted that these would allow the shell to fold as it deforms and therefore require stiff connections to resist this action. Finally, as one move beyond triangles to many-sided shapes there is no guarantee that the shape will be planar – in fact, for a freeform shape, it is highly unlikely they will be. The challenge to solve this was one relished within the team and they saw the opportunity to implement a new algorithm to extend their suite of custom tools for future projects.

In their research of various methods for producing a planar mesh the team came across the work of Cutler and Whiting, whose paper *Constrained Planar Re-meshing for Architecture*[iv] adapted a technique called *Variational Shape Approximation*[v] for use in the building industry. The technique had not been previously applied to a structure larger than a desk, which appealed to the team. The algorithm takes a high-resolution mesh as an input and from this a user-defined number of seed triangles are chosen on the mesh at random. The remaining triangles are then grouped into clusters around each of these 'seeds' in relation to metrics such as distance or difference in triangle face direction. Once all of the triangles in the mesh have been assigned to a cluster, the triangle closest to the centre of the cluster is defined as the new seed and the process repeats. This process is repeated iteratively; until the clusters are evenly spaced over the mesh, see Fig. 7.

At this stage a plane is created at the centre of each cluster. These planes are then intersected with all neighbouring planes and each intersection line becomes an edge of the planar face. Corrections are then made if the neighbouring topology of the clusters is not the same as the planar mesh. This system creates what is known as a three-valent mesh. This means exactly three faces and edges are attached to each vertex. This is advantageous both structurally and geometrically – continuous fold lines are broken and fewer panels have to fit together at a single point.

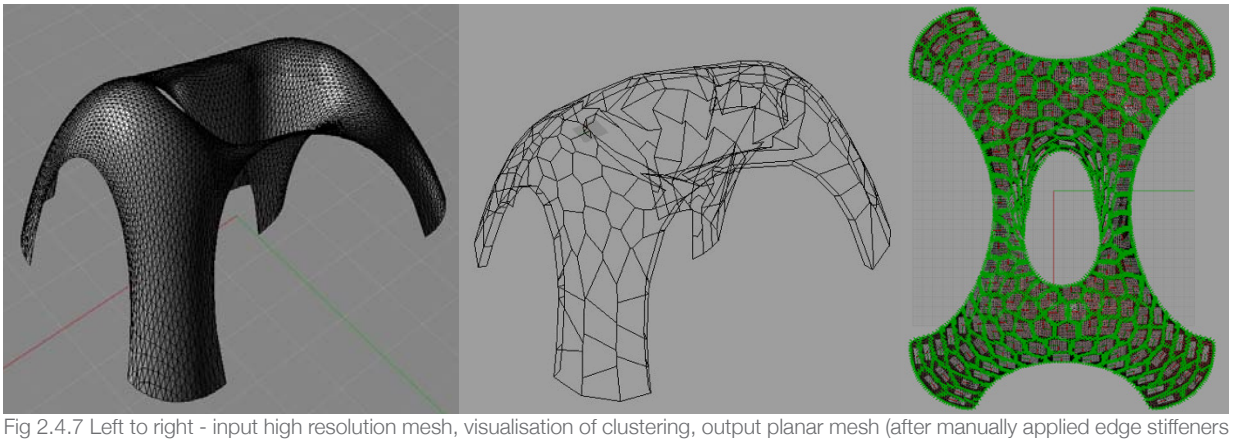

Fig 2.4.7 Left to right - input high resolution mesh, visualisation of clustering, output planar mesh (after manually applied edge stiffeners were included)clustering, output planar mesh (after manually applied edge stiffeners were included)

The appearance of the mesh is irregular but ultimately related to the curvature of the surface. In areas of positive Gaussian curvature such as the dome-like areas at the top of the structure the panels are convex. In areas that are close to cylindrical or have approximated zero Gaussian curvature, such as the legs, the panels are generally rectangular. Finally, in areas of negative curvature such as the funnel we see the interesting concave bow-tie shapes, see Fig. 8.

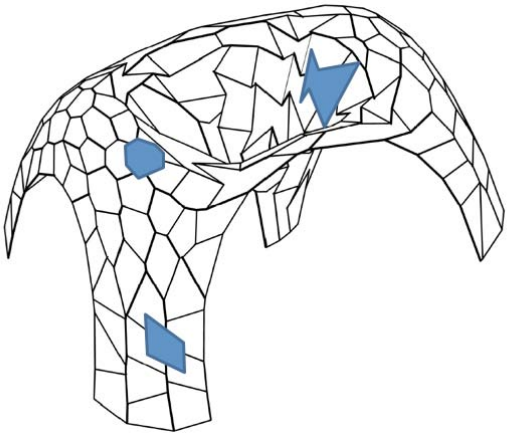

Fig 2.4.8 Panel shapes reflecting the underlying curvature of the surface

To implement the algorithm the team chose to use Rhino [vi] a 3D surface-modelling program, which with the addition of parametric plug-in Grasshopper [vii] has become ubiquitous within the computational design community. Grasshopper allows users to create visual networks of components to create a parametric model. Whilst this basic functionality is appropriate for the majority of users the complexity of the algorithm meant the RCD team had to move beyond this and develop their own custom components.

Previously, (and for the form-finding software) the RCD team have created lightweight standalone programs rather than plug-ins to existing software; however they found there are a number of advantages of working within the Rhino environment. Firstly, they can utilise all of the functions and data structures available in the software. A good example of this was when they needed to check whether a curve was self-intersecting - rather than having to write and test a series of geometrical algorithms they could simply call an existing robust function, which returned a detailed output of the existence, position and nature of all the intersections. This saved a huge amount of time and its utilisation is recommended wherever possible. In addition to this, once a component has been created, it is easy for other users to implement it without any detailed knowledge of how it works – they can simple drag and drop it into their existing parametric model.

Despite these timesaving advantages there are a number of limitations and negative aspects to working within Rhino. Meshes (linked collections of vertices and faces) in Rhino are strictly limited to only three or four sided faces. The team knew the output of the re-meshing would be made up of faces with a wide range of edge numbers and so they had to write and implement their own mesh data structure. This was a time consuming process but it was written to be re-usable for future projects.

The algorithm was successfully implemented however it was not completely robust. Problems arose when the adjacency of the clusters did not match the adjacency of the planar faces. This can be fixed by switching which clusters should be intersected to create the edges of the planar faces. However, it was found that to program a robust algorithm that worked for every possible self intersecting situation would have been inefficient for the project timescale. A more practical solution was to automate corrections for the most common situations and then manually fix any errors. The form chosen for the structure turned out to be a particularly challenging one to discretise – free edges, holes and a range of Gaussian curvatures all added to the complexity for the algorithm.

Connections

As with all timber structure, the connection design was an integral part of the debate on how the funicular surface could be constructed. The joints between panels of the timber shell must transfer in-plane loads resulting from the self-weight and restrain the panels against the rotation of adjacent panels. They are also needed to transfer out-of-plane shear at the interface between panels. The triangular and three-valent panel configurations were evaluated and each required the joints to provide different levels of restraint. The triangulated configuration required partial moment continuity whereas three-valent arrangement provides geometric constraint to rotation of adjacent panels and hence a simple pinned mechanism could suffice. In Fig. 9 it can be seen that unless there is a rigid connection along the edge the triangular node can be progressively collapsed. With the three-valent node - the opposite face of any edge of will resist any rotation and therefore resist collapse. This appealed to the structural engineering background of much of the design team, as it was understood that this would lead to lighter and less obtrusive details. This structural behaviour was confirmed globally with scale and full-size models, see Physical Prototyping.

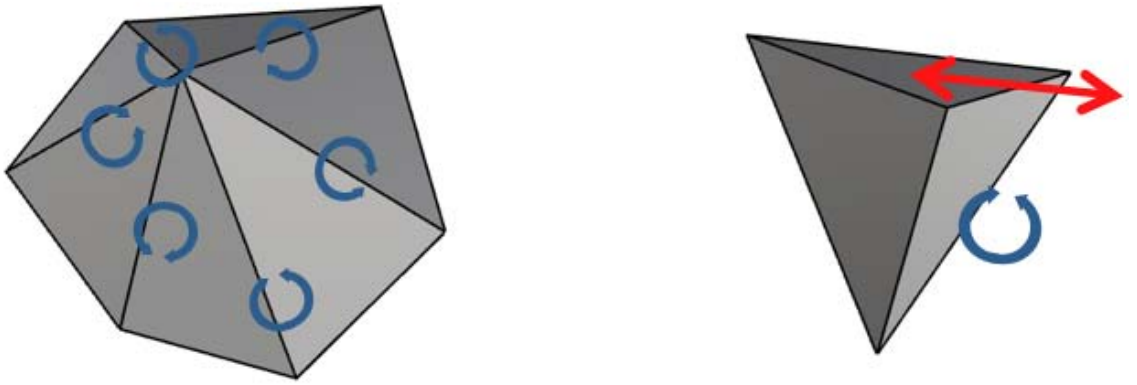

Fig 4.2.9 Comparison to show how the three-valent node locks the surface even without rotational restraint on edges

In addition to technical considerations the client's brief called for an easily demountable structure this meant neither glued joints nor screwed connections were possible solutions. Another significant challenge was that the angles between panels throughout the structure are irregular and every angle is unique. Creating a unique connection detail for each angle would have been time consuming and undoubtedly expensive throughout design, fabrication and erection. Also, unless copies were made of each (that would have been potentially very wasteful), there would have been no recourse in the event of a missing or broken detail during the short build time.

After sketching and brainstorming came the realisation that the combination of different angles being required but no rotational resistance were complimentary – a system allowed to rotate could fit any angle. In order to express this concept as clearly and as 'honestly' as possible it was ultimately decided to use common steel hinges and flush Allen head bolts within a rebate into the timber face, see Fig. 10. These satisfied all of the technical and practical constraints extremely well and the design team were attracted to the concept that they were creating a complex structure with only the 'ingredients' for a simple door – flat sheets of timber, bolts and hinges.

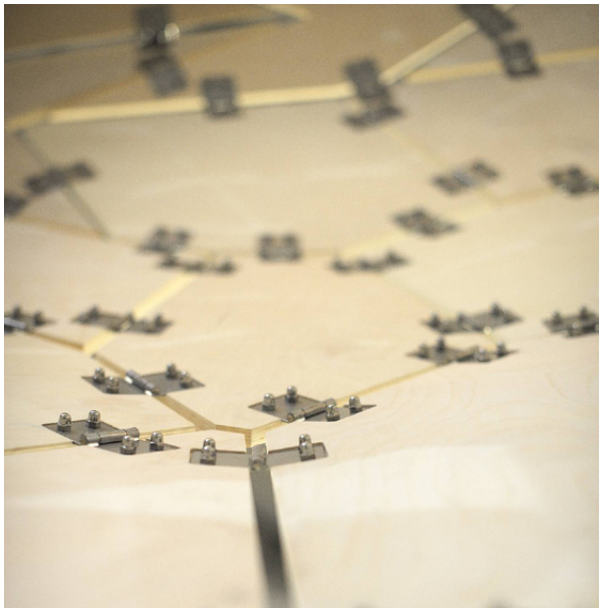

Fig 4.2.10 Hinge connection detail

Parametric detailing

Once the form, discretisation and connection design was complete, the next stage was to detail and prepare for fabrication. As the team wanted to showcase the use of digital design techniques throughout the delivery of a project this was seen as a perfect opportunity to automate what would otherwise have been a laborious process. As can be seen in Fig. 10, there is a small gap between adjacent panels; this was created for a number of reasons. Firstly, as many pieces must fit together in a highly constrained system a tolerance between panels provides room for error during fabrication and construction. In addition to this, a shadow gap was seen as aesthetically preferable to highlight the interesting shapes of the panels. Finally, as the team only had access to 3-axis CNC machining, the edges of each panel could not be cut at an angle – therefore as the angle between two panels varies a gap must be included stop intersection between adjacent panels

The calculation and modelling of this offset, a hinge rebate, a panel reference number and bolt positions were automated by creating a parametric model using the Grasshopper platform (see Fig. 1) and the edge curves of the three-valent mesh as an input. Once the detailed 3d model had been created, each individual panel was translated onto a horizontal plane and, using a 3rd party plug-in called RhinoNest [viii] arranged in an optimal position onto standard plywood sheet sizes to minimise material wastage. Finally, this information was exported in the .dxf file format and sent to the fabricators. This method of parametric detailing is highly recommended for the delivery of such projects.

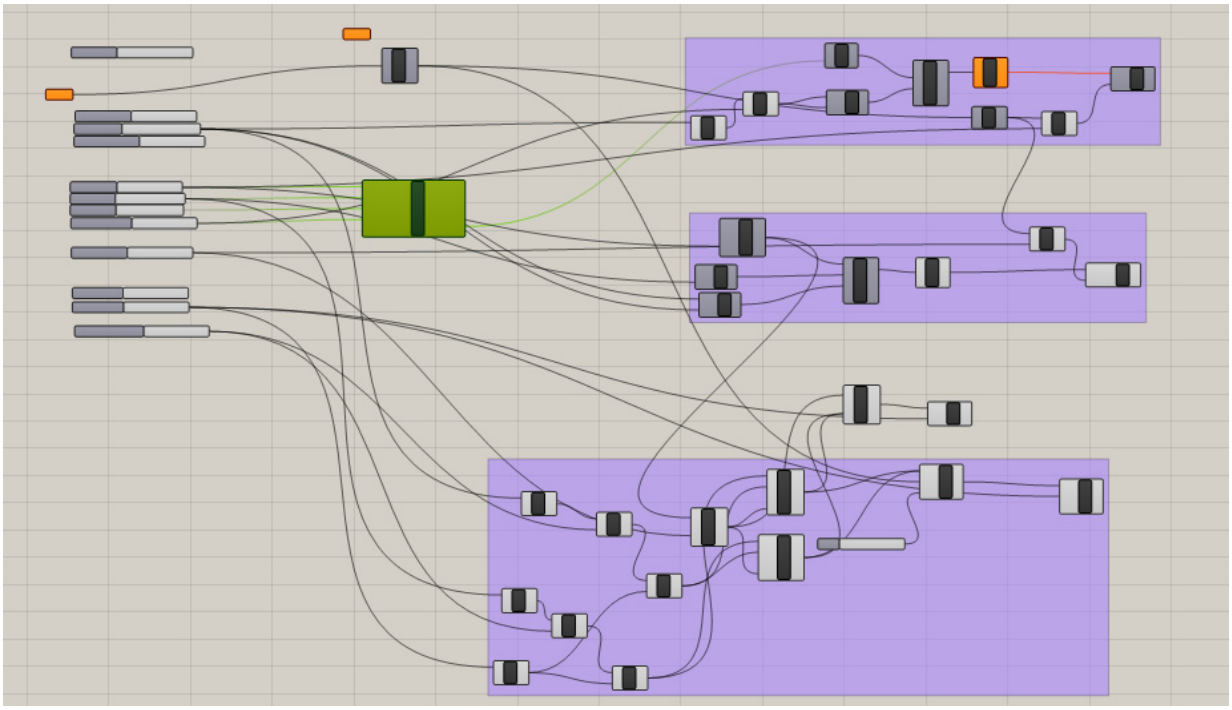

Fig 4.2.11 Overview of a the connections in a parametric model

Physical Prototyping

Three prototypes were created at different junctures in the design development. Firstly, an early paper model to test the overall massing and 'look' of the form and give an early indication of the critical modes of failure. This is a common approach for structural engineers and gives the designer an opportunity to physically push the structure and observe its deflected form. Following the paper model, and after the decision had been made to use a three-valent mesh, a 1:10 scale thin ply model was built. This was necessary in order to test the theory that the double curved nature of the form and the three-valent mesh gave the pinned jointed panels adequate mutual restraint against rotation. The model was very successful in this respect and also gave a valuable morale boost for the team - it was the first time the team could see how the pavilion would appear in real life and gain a sense of the internal space. It also served to help visually plan the construction sequence and formed a focal point in meetings and internal technical reviews.

The last, and possibly most important, prototype was a full-scale leg constructed at Ramboll UK's head office, see Fig. 13. The driving force behind this model was to finally confirm the structural performance of the full system and connections, with material inconsistencies, joint slip, and other problems, rather than the idealised scale or finite element models that had been used up to this point. Also it was understood that although the mesh should lock itself into a rigid structure, it was not expected that this behaviour would be exhibited at the free edges. To support these areas, a line of edge stiffeners fixed at 90 degrees to any edge panels were installed. Once fully connected, the structure was observed to be extremely robust.

Fig 4.2.12: 1:10 thin ply scale model

Fig 4.2.13 Full scale prototype of single leg of the structure

In addition to the structural feedback, the team were conscious that when it came to erect the structure no heavy lifting equipment and a limited amount of scaffolding would be available. The structure was also to be built by the design team who were relatively inexperienced in actual construction. The prototype leg therefore gave a valuable understanding of the weight of the elements, how difficult they were to handle (especially once several had been hinged together) and how the predicted tolerances translated into the real world. This information meant the team could effectively plan and predict their time on-site. The same fabricators and machines were used which meant that any issues in the fabrication and transfer of information could be ironed out before full production.

One of TRADA's guiding principles was that the pavilion should embody the natural beauty of timber and hence the team were determined that it should be fabricated as cleanly and neatly as possible and that any finish applied to the plywood enhanced rather than detract from its appearance. The panels also had to be fire protected, which could leave some staining. After viewing the whole test leg it was felt that the natural pale appearance of the plywood was the most attractive and that a darker wood stain would give a sense of oppression within the space. The staining from the applied fire protection was felt to be minimal and could be left without further treatment. The full-scale leg prototype proved extremely valuable in alleviating any concerns and it gave the team confidence to proceed. It also gave the Ramboll UK staff that were not intimately involved in the project an early insight into the project and instilled a sense of support throughout the company.

Conclusion

Without physical prototyping many of the fundamental questions with regard to global structural stability and the behaviour of the joints would not have been resolved until the final construction by which time it would have been too late to effect any changes. As a result of the testing the final construction of the pavilion went smoothly and in some ways it was easier than expected – the shell nature of the structure meant it was able to cantilever further than expected, thus removing the expected requirement for temporary propping.

Despite being a functioning exhibition stand the pavilion is, in itself, another prototype. The RCD team are currently exploring how the concepts and techniques used in the design of the structure could be applied to different materials and forms. Free-form glasshouses, meeting room pods and internal armature for large-scale sculpture are some research avenues currently being explored.

In this paper the development of the design has been presented sequentially, however, as part of each decision, how it would later affect downstream activities was considered and investigated and as a result the journey was far less linear. Despite the unusual form that was created it could be argued that the design team resisted frivolousness throughout – the curved surface was a direct response to the self-weight and the functional space required; and the irregular panels were created to fit within the available budget, fabrication capabilities and structural performance required. It is hoped the software created to design and deliver the pavilion has been used to create simplicity and elegance in the physical form rather than creating unnecessary complexity.

It could be argued that the designer takes a back seat in such projects. They are not explicitly defining the form and the requested number of panels and metric are the only effect they can have on the final shape of each panel. This relationship is especially interesting if, as was the case with the TRADA pavilion, the designer of the structure was also the designer of the software. The decisions made when designing an algorithm are no more or less conscious than explicit design - the reasoning behind the choices are what validates them. As mentioned, some of the algorithms were not completely robust, however concepts can be proven without producing a flawless product – this is the essence of prototyping and recommended if software development is to be carried out in parallel with design. Efficiency and robustness are to be fine-tuned in both physical and software products at a later stage.

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References

i Stephen Melville, John Harding and Harri Lewis helped set up Ramboll Computational Design in 2010 after a number of years researching and developing digital design tools for the built environment.

Stephen Melville BEng MSc DIC MIStructE FRSA, leads the Ramboll Computational Design Team which is dedicated to the research and application of digital tools for building and masterplan design. Stephen writes a weekly blog for Building Design and is a member of the Bristol Urban Design Forum and RIBA education panel. He is also a part time tutor at the Oxford Brookes School of Architecture and has also tutored or lectured at TU Delft, Texas, Copenhagen, Bristol and Cardiff Universities.

John Harding BSc BA MSc is a current doctoral candidate in computational design at The University of Bath. His research is in parametric modelling, multi-objective optimisation and the application of complex systems theory in the design process. Recent advances in computing modelling and analysis have involved rethinking the relationship between architect and engineer, particularly at the concept design stage. His practical application of computational design theory to real world projects has led John to collaborate with various architectural practices during his research.

Harri Lewis MEng MPhil, enjoys collaborating with architects and artists to help them develop innovative structures. He completed his MPhil degree at the University of Bath as part of their Digital Architectonics program where he developed a number of interactive software applications to help designers create elegant forms with embedded structural logic. Since returning to Ramboll he has combined this with his structural engineering background to help deliver a number of intricate projects.

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v Variational Shape Approximation (http://hal.inria.fr/docs/00/07/06/32/PDF/RR-5371.pdf)

vi Rhino 3D software

vii Grasshopper software

viii Rhinonest software

4.3
The Evolution of Shell Lace

Mike Tonkin Tonkin Liu and Ed Clark [i]

The Origin of Shell Lace

Shell Lace is a single surface structural technique inspired by the evolution of seashells and the ancient art of tailoring. The exploration has been made possible through the contemporary production techniques of computer-aided design and fabrication. The experiments have made the most of currently available technology but they have also utilised an iterative hands on approach. Shell Lace as a technique learns from both the ancient and most modern. The biomimetic investigations over the past three years have been an ongoing collaboration between Tonkin Liu and Arup.

Fig 4.3.1 Shi Ling Bridge Model
[Shi Ling Bridge 1_Mike Tonkin]

Seashells

500 million years of evolutionary development undertaken by molluscs have given us an array of highly refined shell forms, tested against structural parameters to offer protection using the minimum thickness of material. There are over 20,000 known species of mollusc making it the second most diverse phylum. The preservation of shell structures through fossilization gives us an insight into past species. Two of the classes of mollusc demonstrate the characteristics that have informed our structural investigations, bivalves and gastropods. Bivalves such as oysters have pairs of opposing domed shell forms. The distinct characteristics of the orders and species within the class are displayed through different shell shapes, curvature, corrugation and surface patterning. Gastropods have a spiralling form into which the creature can retreat in time of attack. The formal characteristics of the species in this class are determined by the differing whorls of the spiral forms. In many cases mathematic formulae can be derived to define the geometries.

Shells are produced in layers of calcium carbonate accreted by the mollusc's mantle. It can be a slow, energy intensive process, so these sea creatures must develop their protective shells using the minimum material possible. Although seashells immersed in water do not respond to gravity in the same way as land creatures they have developed in an environment of three-dimensional pressure. They are also subject to currents and potential impacts so it is no surprise to find that a seashell out of water is often very difficult to break. The practice wished to draw inspiration from the way in which three-dimensional curvature, corrugation of the surface and distortion of the curving form lock in strength and allow for incredibly thin structures. The question was how to bring the three-dimensional principles of shells into the gravity bound world of architecture in a way that was achievable economically with contemporary fabrication techniques.

Fig 4.3.2 Giant Clam – Bivalve
[Giant Clam, Bivalve, Tridacna Squamosa_H Landshoff]

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Tailoring

The art of the tailor has for centuries taken flat sheets and cut them in particular ways so that they can effectively cover the three-dimensional human body. Tailors will cut flat sheet fabric into a shape which, when offered up to a neighbouring piece will define a volume. On a suit the production of the shoulder is a good example, it needs to be stiff to support the fabric arm below. This is done by bringing together three precisely cut pieces making a breast panel, back panel and arm that join as they curve over the shoulder to create a form that could not be made from a single sheet. The tailor is also concerned with the ability of the fabric to curve and how far the material can be twisted along any given axis before it creases. To avoid the local distortion the tailor uses cuts and darts. As well as being unsightly to the tailor's eye, creases would result in a weakened surface. The method of making a cut to pull in a curving surface or adding a dart to fill a gap when the fabric has gone beyond its limit allows the tailor to reduce the overall use of material.

The intention was to make flat sheets that would have their own strength, essentially a suit that could hold itself up. Using another sheet material instead of fabric could add thickness to increase rigidity but this will also add material weight and cost. The design team needed to take advantage of the intrinsic strength of the curved seam in order to use a much thinner, lighter material. This was done by adding undulation, through the joining of sheets in a corrugated form that travelled along the surface. In many cases the corrugations can describe structural forms, some inspired by shells, to add depth to ridges, domes, arches, beams and columns.

The design team also needed to prevent the failure of the material through creasing, taking the material beyond its elastic limits. The thickness needed to be reduced enough to allow maximum lightness whilst still curving smoothly without creases. Only where the profile of a surface can be correctly controlled can the join be accurately made with an adjoining piece. Only with accurate joins can forces be transferred between the different structural surfaces combining their strength.

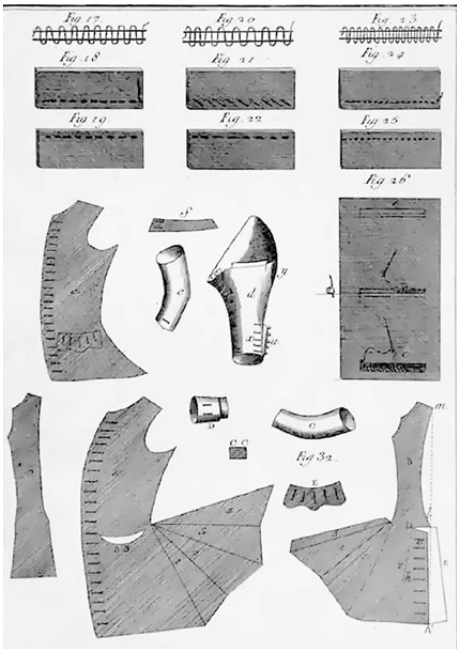

Fig 4.3.3 Cutting pattern for tailoring c. 1760
[Tailored Cutting Pattern 2 1760]

Lace

The production of traditional lace is akin to the action of the spider spinning a web. A lace-maker uses structural principles to ensure the continuity of the material plane whilst using aesthetic judgements to create graphic pattern. The lace elements of a garment are rarely given structurally challenging tasks requiring durability or rigidity. One unique case is the Elizabethan ruff where the lace is given a sinusoidal flow of fabric to provide structural depth. This allows an extremely light material to project outwards from the wearer's neck to great effect.

Like lace, Shell Lace seeks to achieve lightness. Less like a spider spinning and more like a caterpillar eating a leaf, leaving only the veiny threads that keep it rigid. Shell Lace is a reductive process whereas Lace is an additive one. Structurally, as long as the surface retains its rigidity, the majority of the material is required near to the seam joins where local compression and tension forces translate. The removal of material also reduces self-load. Numerous small cuts into the surface effectively turn the flat sheet material into lace.

A plain sheet does not readily display its curving form. The design team were also interested in how the breaking of the surface could catch light and articulate curvature. Aesthetically, the perforation of the Shell Lace also demonstrates the delicate thinness of the material and casts dappled shadows of its own form.

Fig 4.3.4 Lace detail
[Honiton Lace Poppy & Bryony Design, John Hopper]

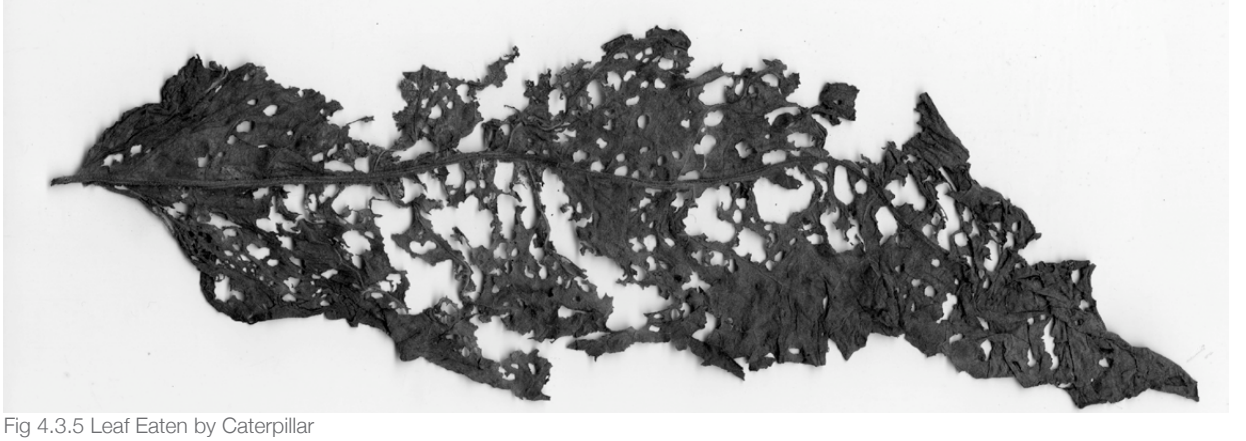

Fig 4.3.5 Leaf Eaten by Caterpillar
[Leaf Eaten By Caterpillar_Mike Tonkin]

Fabricating Shell Lace - Bexhill Shelter

Developing Shell Forms

The development of the Shell Lace structural technique was precipitated by our participation in the competition to design a series of beachfront shelters for Bexhill-on-Sea. Our architectural concept was for a form inspired by the arching, rolling waves, the light bubbly froth and the sheltering, enveloping form of a seashell. The practice composed a vaulted form to provide shelter from the wind and rain, fabricated from a thin, lightweight and durable material such as aluminium and perforated with frothy holes to allow sea views while taking cover from the weather. The twisting, contorted series of arches, curving walls and part spirals drew inspiration from the spaces created inside and outside of shells. Our aim was to take the inherently strong forms of nature and use them to our advantage.

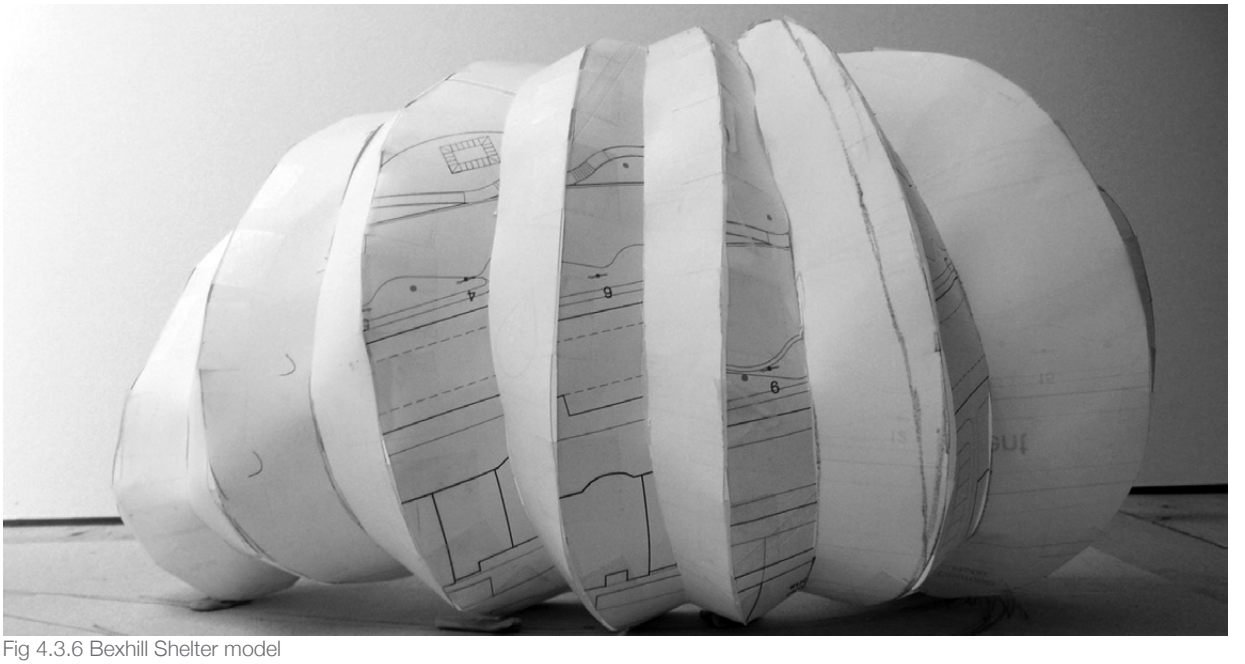

Fig 4.3.6 Bexhill Shelter model
[Bexhill Pavilion Ply Model 2_Tonkin Liu]

Modelling and Tailoring

Our first exploration of how to gain the strength of three-dimensional curvature came from hands on experiments with plasticine and paper. Our intent was to make a shell-like form with minimal material thickness. The major advantage plasticine is the ability to demonstrate simple structural viability. If a particular arrangement does not stand up in plasticine at the scale of the hand then it is likely that it will be structurally weak in any material at a larger scale. Having proven the basic principles with plasticine, the design team sought to replicate the shelter design in paper, a scaled representation of sheet aluminium. Having made a bowing arching shell from multiple pieces of overlapping paper the design team had achieved the overall form the design team wanted but there was an evident problem, the shell form wanted to flex, as there was no local stiffening. Our solution was to add a triangular rib of plasticine to the rear of the arching form that provided stiffness but added dead load. Removing the plasticine rib, the design team traced the outlines of its surfaces. The design team then remade each of the surfaces in paper to create a hollow version of the rib that attached to the back of the curving form of the shell. The design team were

able to remove the original surface and the two new rib surfaces became the new form. This process was repeated until the entire surface of the shell had been recreated as a series of ribs, producing a stiff single surface structure with three-dimensional curvature, built from strangely shaped flat sheets. Unlike origami, the form was not folded. Each piece was a specifically cut sheet that when joined with the next could only become one particular form. Each edge of each cut sheet was a specific length matched in turn with another edge on a specific neighbouring sheet. The joined sheets made a unique form of a precise, non-deformable shape. The design team had tailored the shelter.

Fig 4.3.7 Bexhill Pavilion Plasticine 1
[Bexhill Pavilion Plasticine 1_Tonkin Liu]

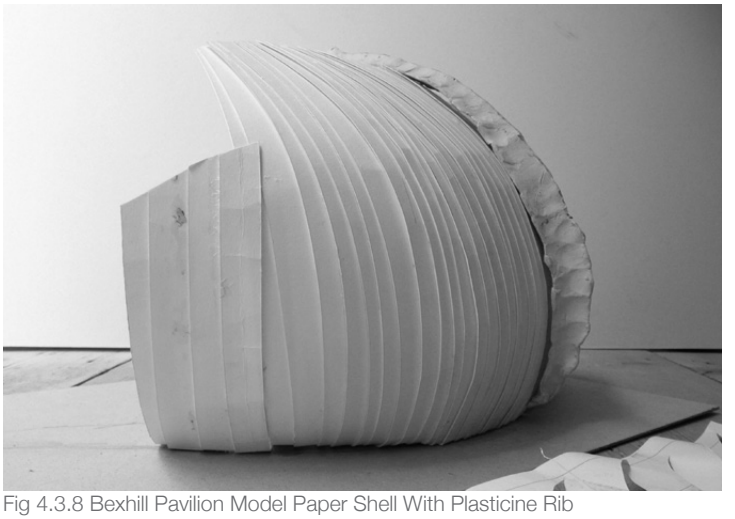

Fig 4.3.8 Bexhill Pavilion Model Paper Shell With Plasticine Rib
[Bexhill Pavilion Model Paper Corrugated_Tonkin Liu]

Digital Models and Making Lace

The lessons learnt from nature and from traditional techniques were underpinned with our recent experience of contemporary construction techniques. In tandem with our physical modelling explorations the design team were using digital modelling to study undulating surfaces in more detail. Through the development of the seafront shelter 3D model the design team refined an iterative process of modelling and analysis that the design team have continued to refine on more recent projects. The early digital model went through many iterations testing various properties such as the curvature of the arches, the depth of the corrugation and the distortion of the curves of the arch in plan that lock in strength. These early versions were produced in parallel with the plasticine and paper models and assessed by the engineering team through collaborative working sessions.

Once the design team got to a point where the whole team was satisfied with the product of the process, Arup's analytical modelling software was introduced. The team found the graphic stress diagrams that mark the problematic areas to be the most useful for refining geometry between iterations. Adjustments were made and an iterative process between architect and engineer was undertaken, enabling particular fabrication and joining considerations to be developed. Using software to map the forces acting in each part of the structure the team were able to mimic lace by finding and removing material where it was not structurally required. The design team were able to create a pattern of perforated holes that would allow views through the finished structure and reduce the overall weight of material. Using a small-scale laser cutter the design team built a model prototype of the shelter, employing 0.8mm micro-ply to replicate aluminium. Each of the unrolled pieces of micro-ply was arranged in a nested group on the laser bed. Once cut and glued together the whole team was surprised by the fluid form, rigidity and lightness of the structure.

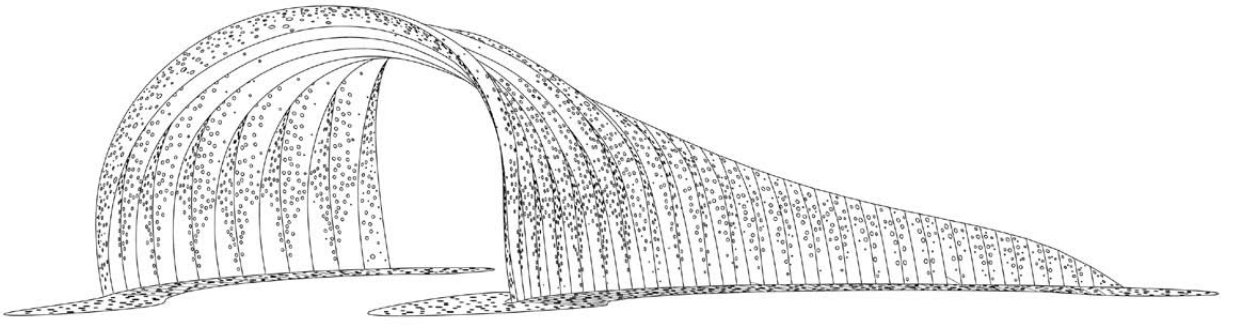

Fig 4.3.9 Bexhill Pavilion Perspective
[Bexhill Pavilion Perspective_Tonkin Liu]

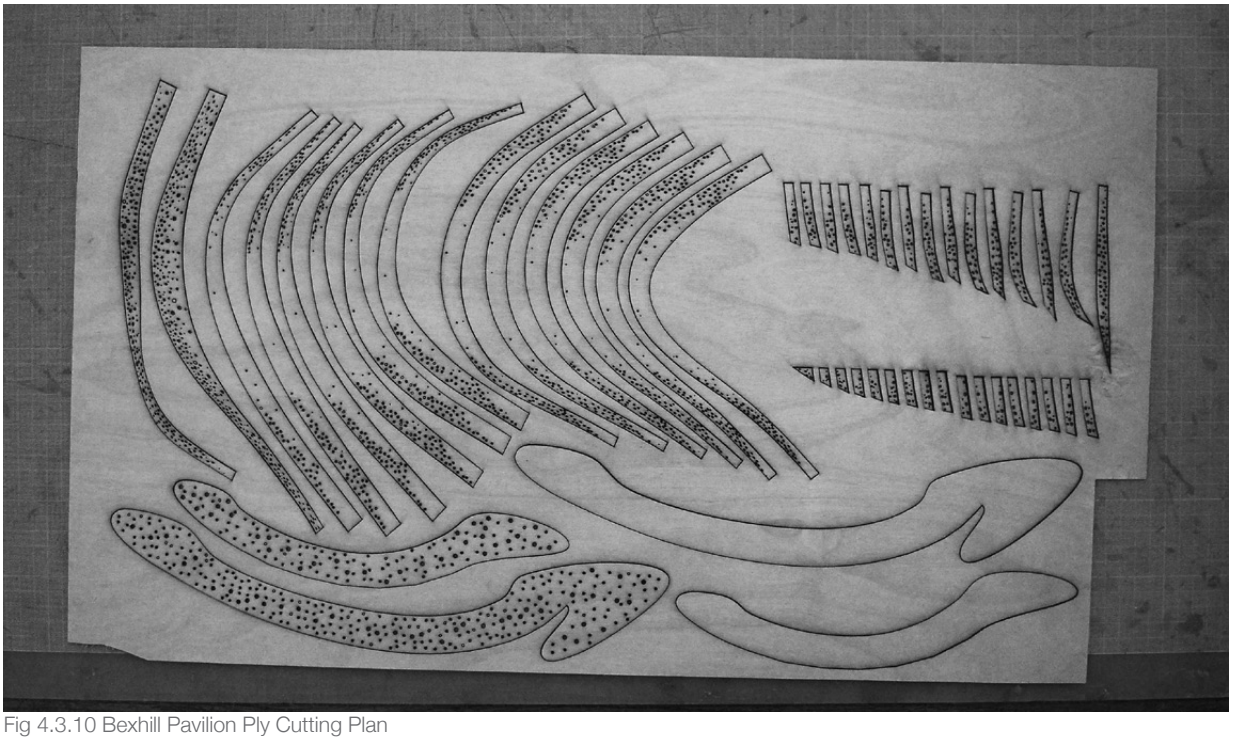

Fig 4.3.10 Bexhill Pavilion Ply Cutting Plan
[Bexhill Pavilion Ply Cutting Plan_Tonkin Liu]

Fig 4.3.11 Bexhill Pavilion Ply Model 1
[Bexhill Pavilion Ply Model 1_Tonkin Liu]

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Shell Lace Evolves – Vault, Beam and Arch

Lisbon Bridge – Beam Structure

The success of the locked in stiffness of the sinusoidal corrugation over the vaulted shelter suggested the potential of the system for other applications. The principle of adding undulation could theoretically apply to other structural forms. The design team set out to explore a series of new design briefs with varied architectural solutions, in each case trying to determine new design parameters for Shell Lace and test its capabilities. A competition for a bridge in Lisbon provided an opportunity to explore another Shell Lace typology. The design team saw each ridge of the Bexhill Shelter as a bridge. By taking the two adjacent surfaces of a ridge and closing their remaining edges with a third surface, the design team found that the design team could create a Shell Lace torsion beam. The design team designed three curving, arching torsion beams connected with compression plates, each establishing a distinct route for walking, running or cycling. The analysed digital model confirmed that the 40-metre span could be achieved with steel 8mm thick steel plate.

The terraced arrangement of the routes created interaction around a shared view of the setting sun. The weathering steel plate structure was covered in photovoltaic cells and the curved plan form was twisted away from the motorway axis and towards the sun. The bridge surfaces were perforated to reduce material weight while adding a decorative pattern artwork that cast a sunray pattern onto the ground in daylight and glowed from within at night.

Fig 4.3.12 Cadogan Cafe Detail
[Cadogan Cafe Detail_Tonkin Liu]

Fig 4.3.13 Lisbon Bridge Ply Model 4
[Lisbon Bridge Ply Model 4_Tonkin Liu]

Fig 4.3.14 Lisbon Bridge Ply Model 5
[Lisbon Bridge Ply Model 5_Tonkin Liu]

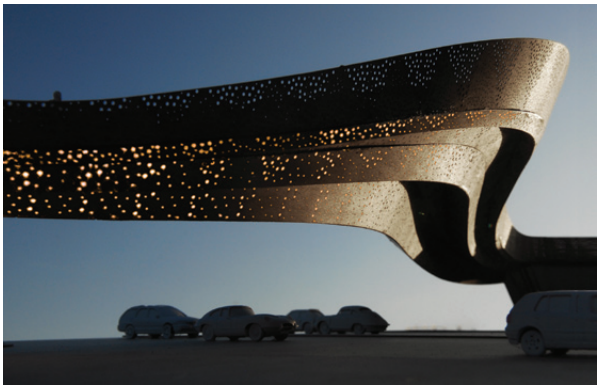

Fig 4.3.15 Lisbon Bridge Ply Model 2
[Lisbon Bridge Ply Model 2_Tonkin Liu]

Regent Street – Column Structure

In our third experiment the design team wanted to explore a Shell Lace column that branched out into arches. The opportunity to explore this tree-like form was afforded by the RIBA Regents Street Windows project. The design team were given a small budget to occupy the window of a clothing shop with something that was applicable to its location, in this case a tailored structure. The design team chose paper as the sheet material, partly for budget reasons but more importantly because a technique that offers strength through its form was best demonstrated by a material that was not perceived to have any inherent strength in itself.

Two major problems were overcome in the production of the Regent Street structure. Firstly, the design team had to overcome the problem of the flexible columns. The seam paths in the column could not wave too much as they had to transfer loads along their length, so instead they spiralled round each leg. Small paper test models demonstrated that the hollow columns could crush in on themselves if the seam joints were able to slip past one another. The design team devised a series of castellated tabs along each edge with an inverse version along the corresponding adjoining surface. The result was an interlocking set of surfaces that became difficult to deform once the column forms were complete. In addition to devising strong permanent longitudinal joints the design team also had to consider temporary joints across the surfaces that would allow the structure to be assembled in small sections and joined together quickly later. The reason was that the shop window could only be accessed via an opening far narrower than the proposed structure. The design team utilised an over-lapping scarf joint borrowed from a Japanese temple that allowed forces to pass across each joined piece as though they were one surface.

The three-column composition was designed in nine separate sections, each tested in the digital model to confirm that it would fit. Very large paper sheets were sourced and then laser cut. The pieces were prefabricated in a modelling workshop using temporary formwork and jigs as necessary. The lightness of the finished piece was in strong contrast to the heavy rusticated stone of the sweep of Regents Street.

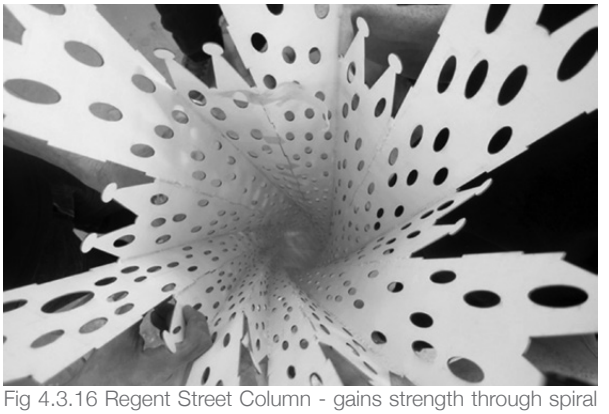

Fig 4.3.16 Regent Street Column - gains strength through spiral form
[Regent Street Column_Tonkin Liu]

Fig 4.3.17 A tailored structure in the window of a tailor
[Regent Street Photograph 1_Mike Tonkin]

Kaohsiung – Column Structure

The competition for the Kaohsiung Ferry Terminal gave us the opportunity to take the same basic column/arch structure and test it in a large-scale project, hopefully proving its applicability as a large primary structure. The Shell Lace structure became a conceptual forest that was set on an island-like building, enclosing a huge open space, through which passengers pass as they go to and from the boats. A large-spanning steel Shell Lace structure was covered in an ETFE (ethylene tetraflouroethylene) membrane roof. The membrane cut down light levels by 50% and the structure by a further 70% to make a semi-conditioned hall surrounded by a shaded cloister. Non-travellers, who could rise up to the level of the ferry deck to watch their relatives arrive and depart, occupied the outer edge of the structure. The canopy of the tree structure filled the interior with a gentle dappled light while the hollow legs provided a passage for rainwater and sustainable air-handling equipment. The task of increased scale had not diminished the potential; conversely it had proved Shell Lace's suitability for large span transport structures. This strengthened our ambition to find a suitable project where the design team could fabricate a Shell Lace structure for the first time.

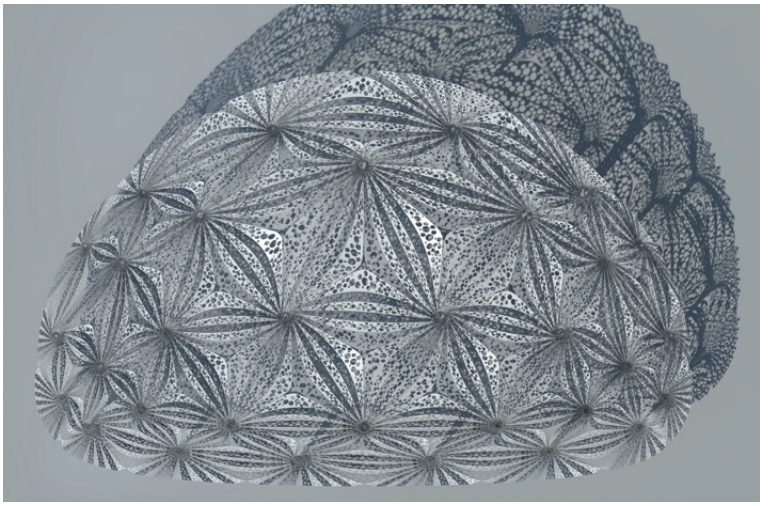

Fig 4.3.18 Kaohsiung Roof Plan- large Shell Lace roof plan-scale
[Kaohsiung Roof Plan_Tonkin Liu]

Fig 4.3.19 Kaohsiung Ferry Terminal
[Kaohsiung External View_Tonkin Liu]

Rain Bow Gate – Column Structure

In January 2011 the design team won a design competition for a landmark artwork in Burnley, Lancashire, which was an ideal opportunity to build a large scale, permanent Shell Lace structure. The industrial heritage of Burnley left behind a legacy of high-tech industry including laser and water jet cutting, so this was a perfect place to develop a metal Shell Lace. Inspired by the weather that had made Burnley such an influential mill town, the bow-shaped viaduct near the site and the sculpture's status as a gateway to a new district, the design team designed a seven metre three way spanning gate with a central covered area studded with prisms. When the sun comes out in Burnley the moment is celebrated with numerous rainbows cast onto the ground under the shadow of the sculpture.

The structure, fabricated from shot blasted stainless steel, comprises seven separate prefabricated components that were designed to travel on a three-metre wide truck bed. The plywood formers used for the welding, blasting and transportation were also used as profile guides for the joining of the sheets. The individual flat components that went into making the three main arches ranged from 12 to 15 meters long and were made from butt and full-fill welds laser cut sheets. Their size and proportional flexibility allowed them to rest in the formers in much the same way as the paper prototypes had done. The edges of the sheets were stitch welded together and the sections of the sculpture were bolted together on site. The sculpture did not gain its full strength until the components of the surface had been fully joined together. Burnley Council engineers were concerned that the 3mm steel appeared to be too thin, however Arup undertook additional calculations to prove that the structure could withstand a considerable number of revellers on its upper surface.

Fig. 4.3.20 Steel components transported on formwork
[Rain Bow Gate Delivery 2_Neil Charlton]

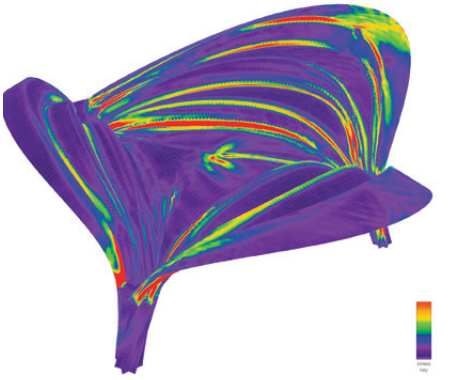

Fig 4.3.21 Rain Bow Gate stress diagram
[Rain Bow Gate Stress Diagram_Arup]

Fig 4.3.22 Rain Bow Gate
[Rain Bow Gate Night_James Moran]

Relief Shelter – Vault Structure

One major benefit to the Shell Lace manufacturing process is material efficiency. Using thin sheets and cutting away material results in significant reductions in weight for the structure, however the benefits of such an approach are less tangible in some applications than others. For instance, with a larger scale steel structure, where the curving surfaces are themselves constructed by joining smaller standard sizes of plate, wastage is limited to a few small corners of steel. In a paper scale model, a single ribbon-like piece might be cut on a diagonal of a large sheet, leaving the rest useless. Likewise, the sections removed by perforation may be recycled afterwards but this is not an efficient process.

A relief shelter brief allowed us to explore the way in which a single piece of shell lace could not only form all the necessary surfaces of a structure when repeated, but also tessellate perfectly on a cut sheet. The design team designed a geometry that could be rolled out on a continuous sheet using a die cutter, which when assembled could make a vaulted building as long as required. The design team imagined a scenario where the cutting pattern information could be sent to a disaster location for local machinery to produce thousands of shelters as fast as cardboard boxes. The design team also began to develop a quick, low-tech joint fixing system based on the zip cable tie.

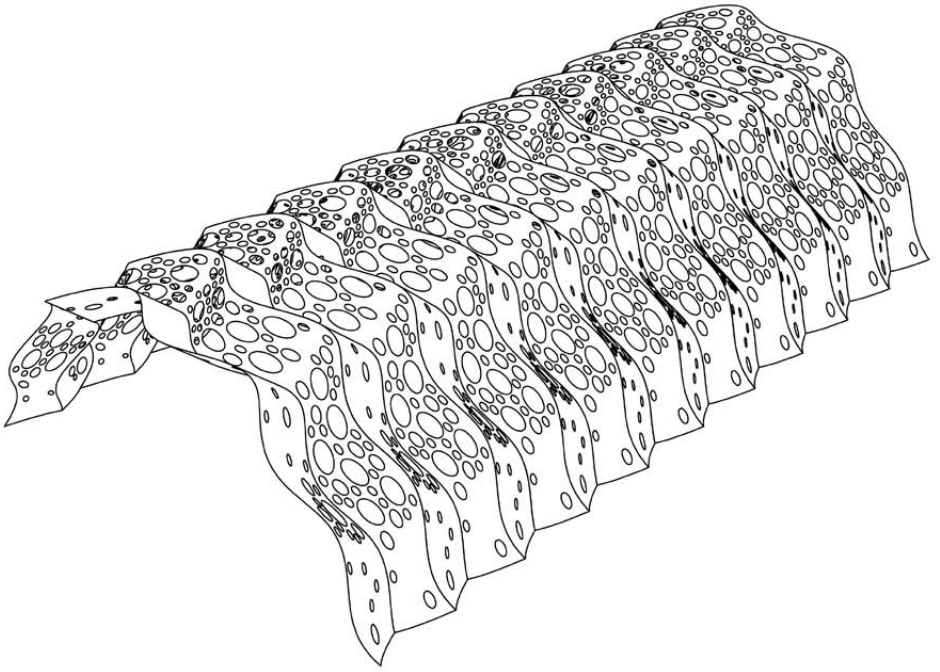

Fig 4.3.23 Relief Shelter Vault -repeated tessellating pieces form continuous roof structure
[Relief Shelter Vault_Tonkin Liu]

Shi Ling Bridge – Beam Structure

In their new London headquarters Arup curated an exhibition entitled 60 years of Bridge Design to showcase past achievements. Tonkin Liu were asked to collaborate on a hypothetical proposal for a cycling and pedestrian bridge for the Shi Ling Stone Forest in China. The bridge design further developed the torsion beam structure. The proposal used three interconnected torsion beams coming from three bridge entry points whose inner facets transformed from beams below bridge deck level into hollow arching trusses that became the main spanning element. The three trusses then descended through the deck near mid span to make an amalgamated nine-sided spiral column. A two-meter long model of the bridge was produced in thick paper. The Shell Lace bridge proposals became the stimulus for a symposium at Arup, which included the Evolutional Ecologist Eleanor Michel from the Zoology Department of the Natural History Museum. In the same year the model was given central place at the *Royal Academy Summer Exhibition* and received a prize from the exhibition sponsors Lend Lease.

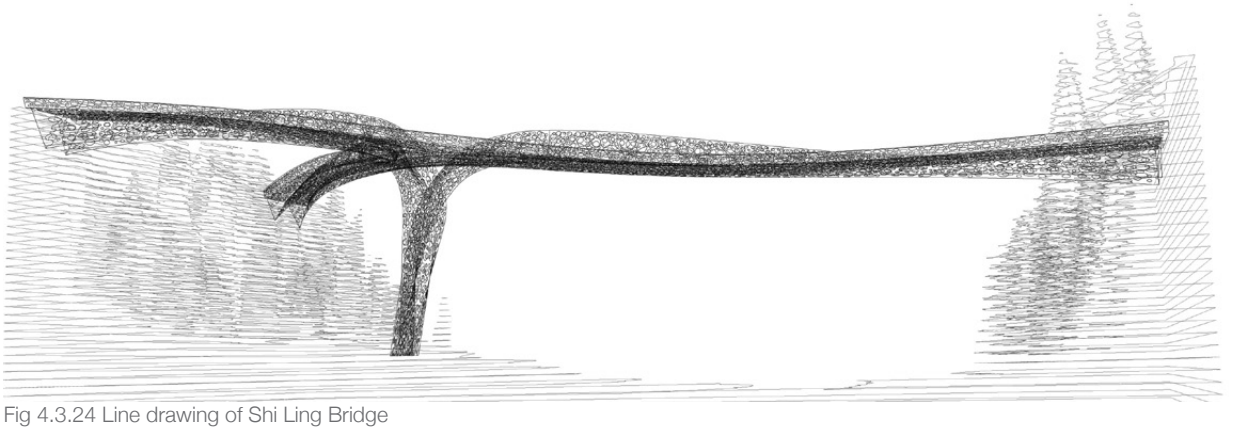

Fig 4.3.24 Line drawing of Shi Ling Bridge
[Shi Ling Bridge Perspective_Tonkin Liu]

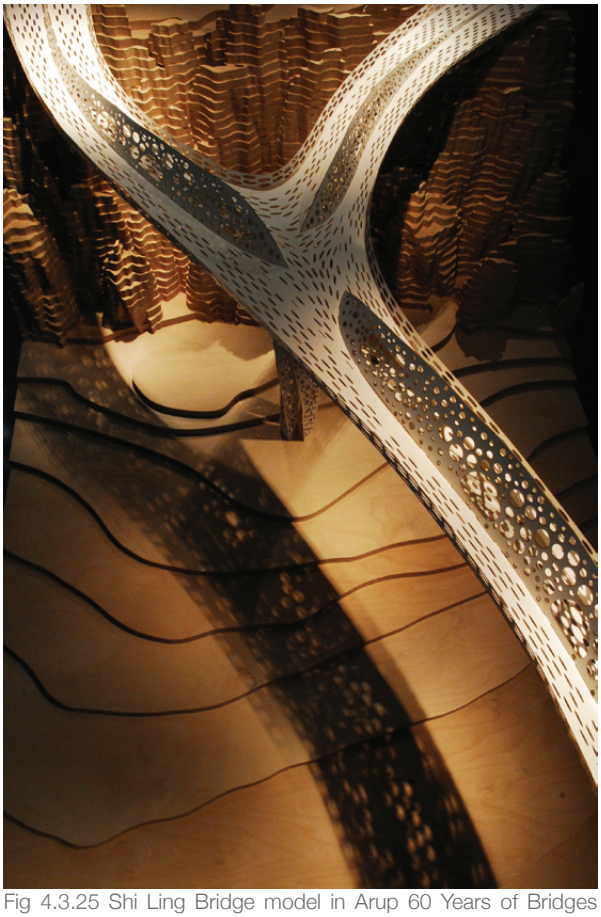

Fig 4.3.25 Shi Ling Bridge model in Arup 60 Years of Bridges exhibition
[Shi Ling Bridge 3_Mike Tonkin]

Fig 4.3.26 Shi Ling Bridge model in Royal Academy Summer Exhibition, 2011
[Shi Ling Bridge Royal Academy_Andrew Putler]

Bluewater - Column Structure

Lend Lease invited Tonkin Liu to develop designs for an extension to Bluewater Shopping Centre. The proposals developed further the column structures that had been investigated in earlier tree prototypes but concentrated the design development on the production of duplicated elements within the structure that would potentially reduce costs, speed up production and allow the use of common formers. A diagonal grid plan formation allowed triangular bays featuring two leaf-like configurations to be replicated across the atrium space. Each of these shapes was in turn made by the addition of two halves that also had rotation symmetry. The whole roof surface was produced by just eight common pieces that accounted on their own for less than five percent of the total area but could be repeated to make the whole.

Although the formers could be reused, the perforation of the cut pieces would not need to be the same, allowing the surface to respond to local environmental or structural conditions. For the first time also the digital model used parametric tools to control the overall form so that once the input criteria had been established various models could be tested. The software was also used to control the perforation of the surface according to local parameters and the exact shape of the perforation so that it would follow more closely the forces travelling through the surface

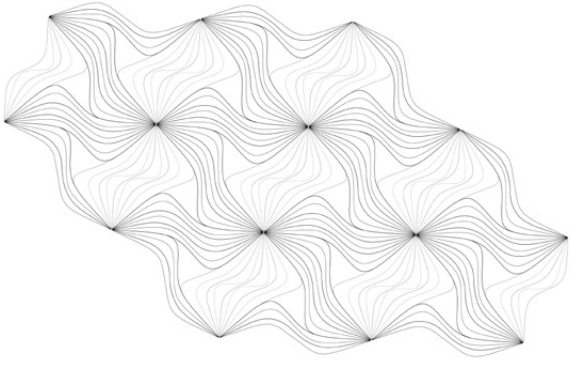

Fig 4.3.27 Bluewater roof surface group 1
[Bluewater Roof Plan 2_Tonkin Liu]

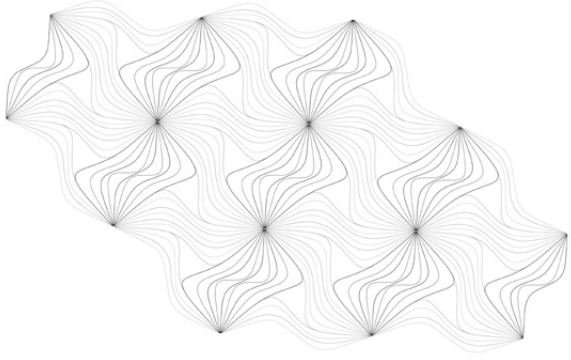

Fig 4.3.28 Bluewater roof surface group 2
[Bluewater Roof Plan 3_Tonkin Liu]

Conclusion

The evolving Shell Lace process has established a technique that is more than a sum of its parts. It is a holistic and flexible approach that allows a great deal of architectural expression, as well as responsiveness to site, structural and environmental demands. Each project is a species, evolved to pursue a particular series of investigations. In each case the Shell Lace family tree can expand and develop further.

Key areas of continued study are the application of Shell Lace to different structural typologies, creating stiff hybrids for specific tasks, the development of the fixing details to aid assembly and the exploration of ways in which the cutting and building process can be made even more efficient, through repetition, customization and tessellation. The strange beauty of the built forms is reminiscent of its natural inspiration and the perforations can get even more responsive through the development of parametric tools that will allow climatic and structural conditions to dictate the pattern. The design team are keen to explore the pioneering technique at different scales and the design team are currently searching for a project that will give us the opportunity to build a timber Shell Lace pavilion.

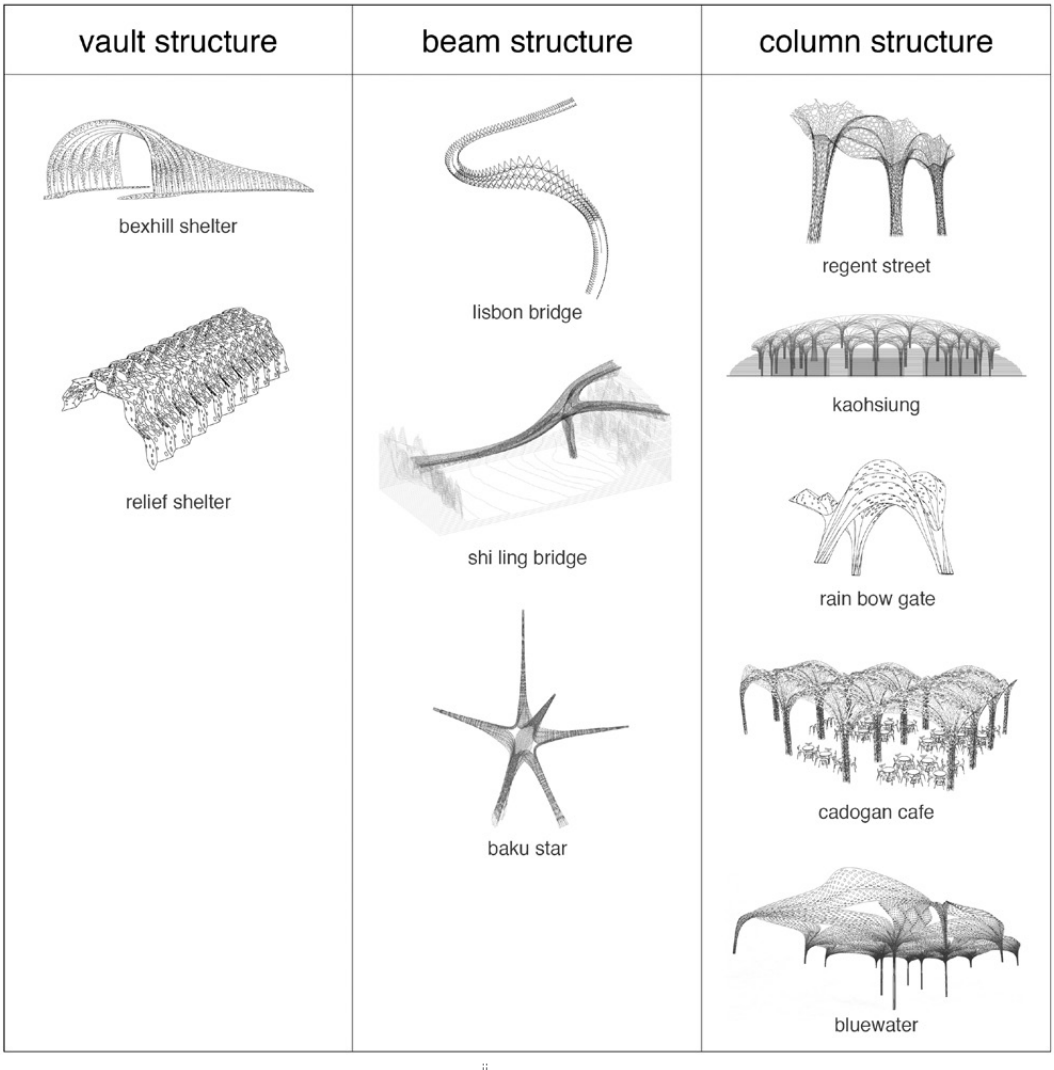

Fig 4.3.28 Evolution of shell lace structural typologies [ii]
[Shell Lace Structural Typologies_Tonkin Liu]

References

i Mike Tonkin, of Tonkin Liu Architects, graduated in Architecture at the Royal Collage of Art, London, then qualified as an architect in 1989, after studying at Leeds Polytechnic School of Architecture and Bath Technical College. Mike has taught and lectured at numerous schools of architecture in England and the Far East, and he currently teaches at the University of Bath. He lectures on a number of subjects including world vernacular architecture, using the experience and photographs taken from his extensive travels.
www.tonkinliu.co.uk

ii Image credits: Fig.1, 5, 17, 25 ©Mike Tonkin, Fig. 2 ©H Landshoff, Fig. 4 ©John Hopper, Fig. 6-16, 18-19, 23-24, 27-28 © Tonkin Liu, Fig. 20 © Neil Charlton, Fig. 21 ©Arup, Fig. 22 ©James Moran, Fig. 26 ©Andrew Putler.

4.4
Low-Cost Prototyping of Comfortable and Healthy Homes in Tanzania

Emanuele Naboni, Rasmus Bruun, Konstantin Ikonomides, Lorenz von Seidlein and Jakob Knudsen [i]

This interdisciplinary research project aims to develop prototypes for healthy homes in Tanzania. The region has a hot, humid climate and is malaria endemic. Malaria remains a major health problem, with several hundred million people becoming infected in sub-Saharan Africa each year, an estimated 0.7-1.2 million cases of which end in death.[ii] A prototype based on local construction techniques was built in order to understand the role of architecture in separating the disease vector, i.e. the mosquito, from the residents while providing the proper thermal comfort. Anthropology, building physics, architecture, medicine and epidemiology are all contributing factors in the development of the design domains.

Fig 4.4.1 The prototype, before modification

The prototype design was inspired by a study of rural houses in two Asian (Thailand, Philippines) and two African countries (The Gambia, Tanzania) over a 12-month period. [iii] The data suggest that typical African homes, such as mud-huts, do not provide the necessary thermal comfort that makes people likely to use bednets to protect against malaria. Conversely, the typical hut in Asia is elevated, well-ventilated and provides a more comfortable indoor climate, making people more tolerant to the use of bednets. Based on these findings and the understanding of local building styles and user preferences, the authors describe a series of design experiments conducted on the prototype that can enhance comfort whilst at the same time reduce health risks.

The study data were used to design a simple, low-cost, and locally-built building prototype. The prototype was constructed with typical techniques and materials and was modified incorporating both emerging trends in Tanzania (for example corrugated iron roof) and design features derived from Asian houses (for example elevated floors and larger windows). The effect of modifications of the prototype was measured with a number of installed sensors. Members of the local community used traditional building methods to construct and modify the prototype roof, walls, and foundations in eight different ways. The recorded thermal performances were used in order to calibrate a digital thermal model. The latter was functional in the exploration of how form, construction techniques and material interact with climate and building occupants. The simulation focused on predicting comfort conditions during the hot season and specifically around 21:00 when people go to bed and decide whether or not to use a bednet.

The digital thermal model illustrated the potential of four additional design scenarios, which would have been difficult and costly to implement. Buildings in Thailand, where malaria is more successfully controlled than in Africa, provided ideas for the virtual design alterations. The use of a butterfly roof and bamboo panels resulted in comfort indices close to thermal neutrality. There are two main results of the research. Firstly, the prototype proved that local construction in Tanzania is not effective and that it is possible to improve indoor comfort of existing and newly built houses through minimal design modifications. A more comfortable indoor climate will hopefully result in an increased usage of bednets and a consequent reduction of exposure to mosquitos. Secondly, the potential of coupling physical and digital prototypes has been successfully demonstrated. The two prototypes, when combined, are a powerful element of engagement of the local community with the multidisciplinary design team, the involved researchers and the larger malaria community.

Background

Early nomadic shelters including caves, animal skin tents and igloos were used for protection against the elements (wind, rain, snow and sunlight).[iv] These structures also provided some defence against predators and storage facilities for a few important possessions. These early buildings were temporary and the proximity to a water source was of prime importance. For the hunters and gatherers, shelter was essential for survival. Health and comfort were likely of minor importance.

As civilization evolved, housing became more permanent and the attention to wellbeing increased. Unlike in industrialised countries where piped-in water, indoor toilets and sewage systems are the norm, in many low-income countries these facilities are often not available.

Waterborne enteric diseases, preventable by the supply of safe water, hand washing and appropriate sanitation, continue to be a major disease burden in poor countries. Vector-borne diseases such as malaria, filariasis, leishmaniasis and dengue fever continue to cause illness and death in these settings. People living in tropical regions where these infections are endemic have adapted their housing structures in different ways to prevent entry of disease vectors. The more affluent segments of society protect their houses through structural barriers, including concrete walls and floors, screened or glass windows and sealed eaves. This building strategy is effective in limiting the entry of pests but also prevents airflow and ventilation leading to the need for indoor fans and air-conditioning, which may be available to a small elite but, are too expensive for the larger majority of the population.

Fig 4.4.2 A bednet setup in a typical Thai bamboo hut. The two thermo-anemometers measure airflow inside and outside the net.

Fig 4.4.3a, b, c. The wattle structure of an unfinished mud house in Tanzania. The wall is being filled up with mud from a whole dug next to the building site.

A different approach is used in traditional tropical Asian housing. Instead of heavy and costly constructions that limit the entry of pests, as well as ventilation, low cost Asian homes are light and open. These homes use other techniques to deter pest invasion whilst enhancing ventilation. Huts are raised above the ground to reduce the entry of mosquitoes, ants and fleas, increase airflow, and protect against flooding. Secondly, houses are built of porous materials such as bamboo lattice or wooden planks to allow cooling by air flow. Attacks from insects are prevented by the use of bednets tucked into tightly woven straw mats laid on the floor and used as beds. Bednets were used in Asia long before large donor and aid agencies started promoting them and they continue to be popular.

On the African continent where the incidence of a vector borne disease like malaria is higher than in Asia[v], low-cost housing evolved in a different direction than in Asia.[v] Walls in African huts tend to be constructed of mud or brick with few if any windows. Airflow in such houses is minimal. Thick walls and minimal airflow may be appropriate in dry desert climates where the coolness of the night, is retained in the walls only to warm up slowly during the day and in turn release heat during the night. But in large regions of sub-Saharan Africa, such as Tanzania, where it is hot during the night and even hotter during the day, mud huts with minimal ventilation do not enhance comfort. Although donors and aid agencies have been aggressively promoting the use of bednets in Africa, the results have frequently been disappointing.[vi] The use of bednets tends to drop off within months of the distribution of nets.[vii] The most frequently cited reason why sub-Saharan Africans are reluctant to use bednets is the discomfort associated with their use.[viii] The little ventilation that can be detected in a mud hut is reduced by half inside a bednet.[ix]

Poor housing allowing mosquito entry has been identified as a risk factor for malaria for more than two decades.[x] A series of studies has demonstrated that open eaves in particular are a critical risk factor for insect entry into African huts.[xi] This observation is best explained by the attraction of mosquitoes to human odours that leave the house through the eaves. Mosquitoes following the plume of human scent enter through the eaves and find their blood meal. Recognising this structural vulnerability of huts Lindsay and co-workers recommended that eaves be closed and they showed that screening of houses substantially reduces the number of mosquitoes inside the house.[xii] The ultimate aim is to seal these mud huts in hot humid settings to prevent the entry of mosquitoes.[xiii]

The unintended consequences

Measures to reduce contact between mosquitoes and human hosts such as the sealing of eaves, screening of windows and even the use of bednets may have unintended negative outcomes. Each of these interventions has structural consequences for the indoor space, which may be overlooked or thought to be insignificant. During the hot season each of these interventions adds to the effects of an already uncomfortable indoor climate. People living in African mud huts have to decide whether they prefer the discomfort caused by a bednet or the mosquito nuisance. Once mosquito densities drop mosquito nets are often no longer used in spite of persistent low levels of disease transmission.

Sealing the eaves may have larger and wider reaching negative consequences. As shown by the use of the prototype, air entry through eaves is critical for airflow and air turn-over. Having reduced airflow in a mud hut, the indoor climate can become so uncomfortable during the hotter months that the residents prefer to sleep outdoors.

Fig 4.4.4 Fishnets have been used for thousands of years to protect against insect bites. Who can object to using mosquito nets for fishing?

Thus, hermetically sealing homes to prevent the entry of mosquitoes has unintended negative consequences and alternative approaches need to be considered.

The thermal behaviour of existing rural houses in Tanzania

We studied traditional mud huts in Tanzania, a malaria-endemic sub-Saharan African country. Indoor temperatures are highly uncomfortable during the hot season, increasing to above 40°C during the day. If any windows were present they tended to be small. Where eaves were open they were the major source of air exchange. The evolution of huts in Asia suggests alternative approaches. If eaves are closed in mud huts the reduction in airflow has to be compensated with large windows on opposing sides of the room. Screening and bednets attenuate airflow but reduce the exposure to mosquitoes. Ignoring the discomfort created by interventions against vectors is short-sighted since such interventions will not be sustainable.

Rural houses in Tanzania

Rural sub-Saharan African architecture is like all architecture in steady transformation. There is a range of building styles seen throughout Africa but variation within a single village tends to be rather limited. There exists a wide range of influences on the design of homes among which the availability of new building materials ranks high, but social and economic factors continue to play a major role. Buildings in rural Africa tend to be

short-lived and need to be replaced or renovated regularly. These constant changes may suggest opportunities to introduce changes in the design of rural homes. Traditional house construction tends to be a highly cooperative venture which involves the whole community. The helpful neighbours expect in return support when it's time to rebuild his house. The skill required to get the building to stand should not be underestimated and is handed down from one generation to the next. The traditional building materials available in Africa are stone, mud or clay, timber and plants such as bamboo, reeds, grass and banana leaves. Today, concrete and corrugate iron sheets are increasingly popular building materials

Asian homes differ in building materials and construction from African buildings. While tropical Asian buildings provide a comfortable human environment in hot and humid climates this is not necessarily the case for African homes. In contrast to the open Asian structures described above, rural sub-Saharan African homes have not evolved to optimise the thermal comfort zone. There is little if any emphasis on ventilation in rural sub-Saharan African homes consequently airflow is minimal and usually not planned. Many homes have no ceiling and the gaps between the top end of the wall and the roof (eaves) allow some minimal airflow especially if there is an open door or window. Indeed airflow is not necessarily considered a positive force instead it is rather associated with the movement of mosquitoes and other insects and hence prevented. This situation is frequently aggravated by smoky fires, which are employed to repel mosquitoes. In a sweltering hot, humid night there remains little choice but find some coolness outside the home.

Prototype House Construction

To get a better understanding of how structural changes can improve comfort the authors built a prototype in the Tanga region of Tanzania. The climate is tropical and the hot season is from the 1st of January to the 1st of May. The experimental house was built in a flat area with surrounding open spaces. There was a tall tree approximately three meters from the house, which provided shade at midday. The surface area of the experimental house was 3 x 2.5 meters and its height was 2.5 meters at the highest point. There was one door and one small window (0.25 x 0.35 m). Inside the room there was a bed. The critical structural elements of the prototype were modified in a series of experiments. The effect of these modifications was measured using a range of sensors. Data loggers were fixed at 1 m and 1.5 m above the floor, both indoor as well as outdoors in order to record air temperature and relative humidity. A thermo-anemometer located in the sleeping area recorded the air speed. A second anemometer was installed outside the house.

Fig 4.4.5 The unmodified prototype

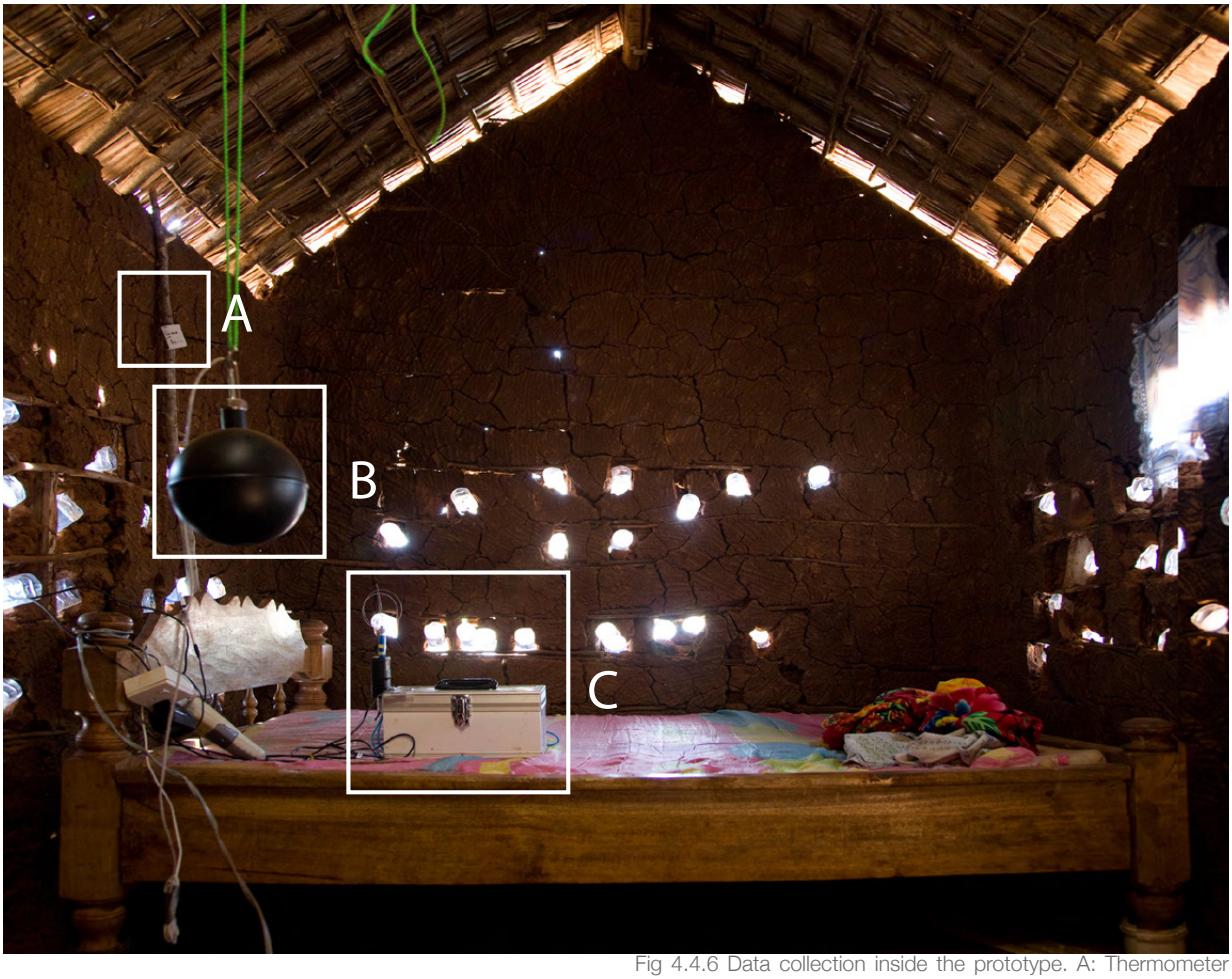

Fig 4.4.6 Data collection inside the prototype. A: Thermometer and hygrometer, B: Thermal radiation sensor, C: Anemometer.

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The prototype was built of typical material of the region. Walls were constructed from mud, a versatile and strong material used in large parts of Africa. Thatch was used for roofs since it was the most frequently used roofing material in the region. The model was then changed in various versions. For instance, the effect of corrugated iron sheets was studied since it had increasingly replaced thatch as roofing material. Corrugated iron sheets are considerably more expensive than thatch. As aerial photographs in most parts of Africa show, large numbers of thatched roofs have been replaced with corrugated iron roofs, which are impermeable to rain and pests, they do not burn and they have a longer life expectancy compared to thatch.

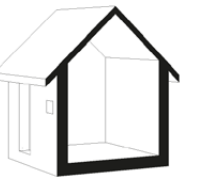
The roof, walls, and the foundation of the experimental house were modified in eight different ways illustrated in the figures below. In the unmodified version the experimental hut had a thatched roof, which was replaced with corrugated iron sheets (Modification 2-8), and was further modified by increasing the gap between the top-end of the wall and the roof (Modification 2-4). The walls where modified to increase ventilation. Additional openings were inserted into the walls of the experimental house (Modification 4 and 5). Finally, to increase the airflow under the building and to minimise radiation heat from the ground the building was elevated 0.5 m above the ground.

Fig 4.4.7 Aerial view of a village in Tanzania. The new corrugated iron sheets have a high albedo effect.

Fig 4.4.8a, b, c, d. On-site modifications of the prototype.

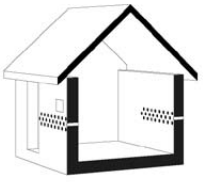
Climatic experiments on mud house in Tanzania:

On-site and digital modifications



Unmodified
Roof : Thached
Walls: Mud
Floor: Ground
Gaps: 100 mm Wall/roof

On-Site Modifications

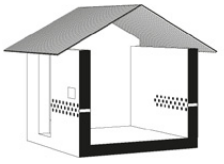


Modification 1
Roof : Thached
Walls: Mud
Floor: Ground
Gaps: A)100 mm wall/roof
B) 60 mm Wall

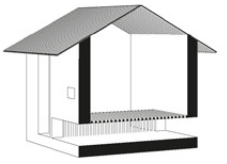
Modification 2
Roof : Corrugated iron sheet
Walls: Mud
Floor: Ground
Gaps: -

Modification 3
Roof : Corrugated iron sheet
Walls: Mud
Floor: Ground
Gaps: 450 mm wall/roof

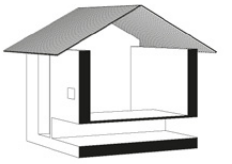
Modification 4
Roof : Corrugated iron sheet
Walls: Mud
Floor: Ground
Gaps: L,450mm
R, 800 mm Wall/roof



Modification 5
Roof : Corrugated iron sheet
Walls: Mud
Floor: Ground
Gaps: A)100 mm wall/roof
B) 60 mm Wall



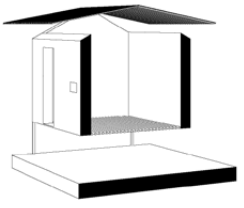
Modification 6
Roof : Corrugated iron sheet
Walls: Mud
Floor: Elevated 500 mm
plastic carpet
Gaps: -



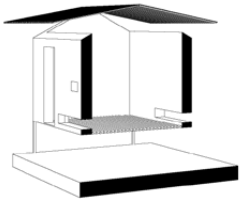
Modification 7
Roof : Corrugated iron sheet
Walls: Mud
Floor: Elevated 500 mm
plastic carpet
Gaps: -

Modification 8
Roof : Corrugated iron sheet
Walls: Mud
Floor: Elevated 500 mm
plastic carpet
Gaps: A) 100 mm wall/roof
B) 350 mm wall/floor

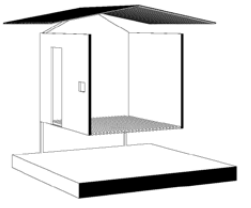
Digital Modifications



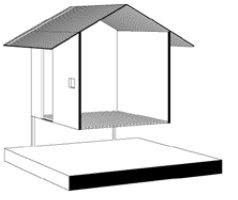
Experimental Model A
Roof : Corrugated iron sheet
Walls: Mud
Floor: Elevated 500 mm
Transparent
Gaps: -



Experimental Model B
Roof : Corrugated iron sheet
Walls: Mud
Floor: Elevated 500 mm
Transparent
Gaps: 350 mm wall/floor



Experimental Model C
Roof : Corrugated iron sheet
Walls: Bamboo
Floor: Elevated 500 mm
Transparent
Gaps: --



Experimental Model D
Roof : Corrugated iron sheet
Walls: Bamboo
Floor: Elevated 500 mm
Transparent
Gaps: -

Fig 4.4.9 Local workers were engaged in the work

The Digital Modifications of the Prototype

To understand how changes to construction and form can improve indoor comfort, and to explore more scenarios without having to modifying the prototype, a series of additional digital thermal models were created with EnergyPlus, a dynamic energy and thermal simulation tool. In addition, to predict airflows in more detail, more analyses were conducted with the use of Computational Fluid Dynamic Simulation (CFD) techniques. The major benefit of a simulation model is that, once it is calibrated to real data, it predicts the performance of several design scenarios that would otherwise take significant time to be built and measured, adding significant cost to the limited budget of the experiment. The digital prototype was modelled by taking various components and their physical properties into account and subjecting the hypothetical structure to the dynamic regime of occupant-related heat gains, external solar loads, outside air temperatures, and wind velocity. Thus, all the fundamental sources of heat loss and heat gain of the house could be considered and the resulting internal conditions evaluated.

The process allowed us to understand the details of thermal behaviour of the eight on-site-modified houses and to compare them to the four additional digital models. The digital modifications include two mud houses and two bamboo houses, inspired in their features by buildings in Thailand and the Philippines where malaria is more successfully controlled than in Africa. The study period was a typical week in February and the sleeping and pre-sleeping hours during the evening were the focus of the analysis, as they are considered critical for disease vector control measures.

A weather file, containing data on local weather conditions including, temperature, relative humidity and airflow during the period of analysis was created with data collected by a weather station. The model was calibrated by minimising the discrepancies between reality and simulation by adjusting simulation variables such as Discharge Coefficients, which relates to the effectiveness of openings to facilitate airflow. After calibration, the difference between the recorded and simulated indoor temperatures was considered to be within an acceptable margin. Simulation output such as indoor air temperature, radiant temperatures, humidity, heat gain and heat loss, and a comfort index, called Predicted Mean Vote (PMV) were used in order to analyse the relationship between construction, design variations and occupants' comfort levels.

The effect of design variations on air temperature

The most important design feature for indoor air and surface temperature is the building envelope. This is due to the different thermal mass properties of materials. While bamboo constructions have little thermal mass, mud strongly stabilises internal temperatures and therefore provides a reduction in extreme temperature swings between inside and the outdoors. As a consequence, the mud house had a lower temperature during the day when the building was unoccupied, but a higher temperature at sleeping time. The bamboo digital prototype responded to temperature changes more rapidly; while daytime was warmer, night time was cooler. Bamboo is therefore appropriate for rooms that need to cool down such as those used for sleeping.

Simulated operative temperatures

Week of study: 13-18 Febuary

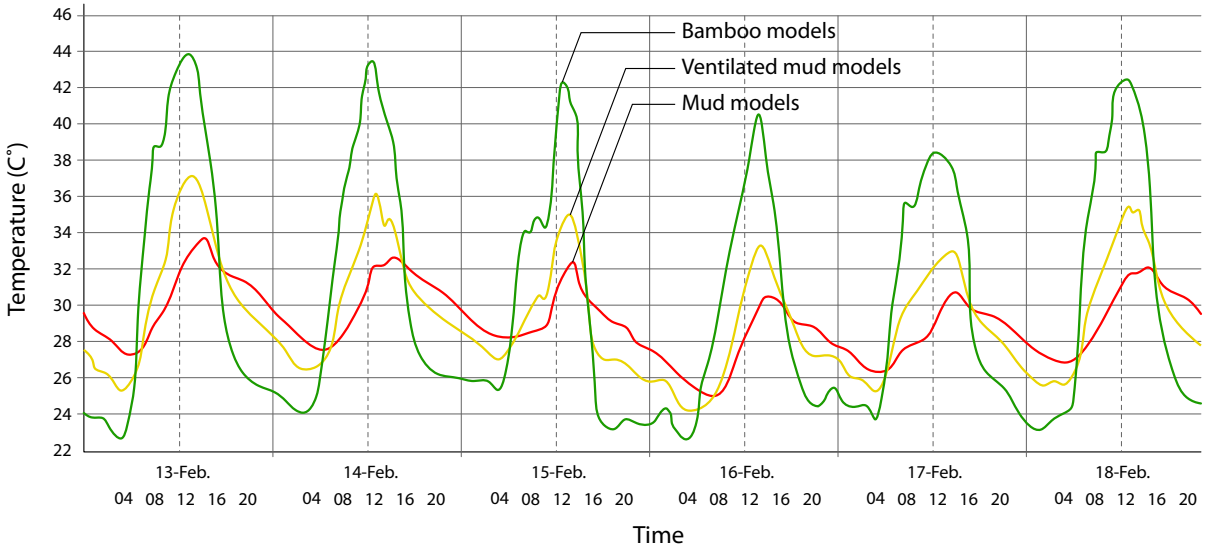


Fig 4.4.10 Operational Temperature Diagram

Geometry to deal with Solar Radiation

The digital prototype was only (virtually) occupied at night when the indoor temperature was influenced by the heat collected during the day. Unwanted heat from solar radiation entered the prototype by radiation through holes or cavities or via conduction through the opaque elements of the building fabric, which heated up the outer surface and increased the heat flow. The best way of dealing with solar radiation is to prevent it from reaching the buildings' surfaces. It is easiest to control solar radiation on the equator-facing facade. The solar analysis showed that the east and west facades are much more difficult to shade due to high-intensity low-level solar radiation in the early mornings and late afternoons.

Independently from the orientation it is recommended that houses in Tanzania have shading devices such as roof overhangs, shading fins and light colours. Surroundings should be dominated by tall trees that provide shade. It is also often possible to shape the building in such a way that some parts of it are self-shading. Any shading element or self-shading principle should be implemented without obstructing possible air flows.

Materials to control heat gains and losses

The research team investigated the factors that impact temperature changes in the different design solutions. Temperature variations are the result of the balance between heat gains and losses. Also analysing how different types of walls, floors and roofs impacted on temperature.

Walls. Bamboo, due to its low mass and permeability, dissipates some of the internal heat to outside. Bamboo may not be a suitable material for a building located in Tanzania that is occupied during the day, but it may be ideal for sleeping areas. In contrast, mud walls store heat during the day and discharge it at night, which may have a negative impact on the occupant's comfort.

Roofs. The experiment showed the benefit of a butterfly roof. Despite the fact that a butterfly roof with widely open eaves provides optimal air exchange, it can expose the inside to direct sunlight, and as such a shading system would be essential for comfort. If, in addition, security is considered (e.g., from animals), a double roof system could be considered. This kind of system uses a ventilated air gap between an upper exposed roof and a lower protected roof. The air carries much of the solar gain from the upper leaf away before it can pass to the lower leaf. At night, the prototypes with corrugated iron roofs cooled faster than those with thatched roofs. During the day, corrugated iron roofs reach very high heat levels, potentially requiring a ceiling to reduce radiant heat for buildings that are occupied in the mornings and the afternoons. It should be noted that roof ventilation strategies have more impact on temperature than does the roof material.

Floor. Floors are frequently made of earth. The analysis of thermal exchanges of the floor suggests that the direct contact of the indoor space with exposed ground is an effective strategy. The earth indeed has a stable temperature throughout the year, and which is consistently lower than both the outdoor and indoor air temperature. Using the earth as a component of the comfort is defined as "earth-tempering".

Natural Ventilation

Natural ventilation influences the heat gain or loss of a room, depending on the difference of internal and external temperature. During the hot daytime when outdoor temperature is higher than indoor temperature, a controlled reduction in the rate of ventilation may reduce heat gains. At night, when outdoor temperatures are below those inside the room, an increase in ventilation rates lowers the internal temperature and discharges the heat stored in heavy materials such as mud walls.

The prototypes' ventilation was initially modelled with EnergyPlus in order to measure air exchange rates and airflow in and out of the openings. The bamboo-constructed prototypes, due to their air permeability, guarantee an adequate air exchange. In mud houses with thatched roofs, the insertion of small wall cavities is critical to ensure the required minimum airflow rate for any given occupant.

The output of EnergyPlus was used to input a Computational Fluid Dynamic Simulation. This shows the role of the butterfly roof, which allows more airflow and thus a more efficient cooling of the sleeping area. Butterfly roofs seem to promote both cross-ventilation and convection currents due to temperature differences within the space. Therefore, in some of the proposed models, a stack effect was used as the primary means of inducing natural ventilation and removing excess heat from spaces.

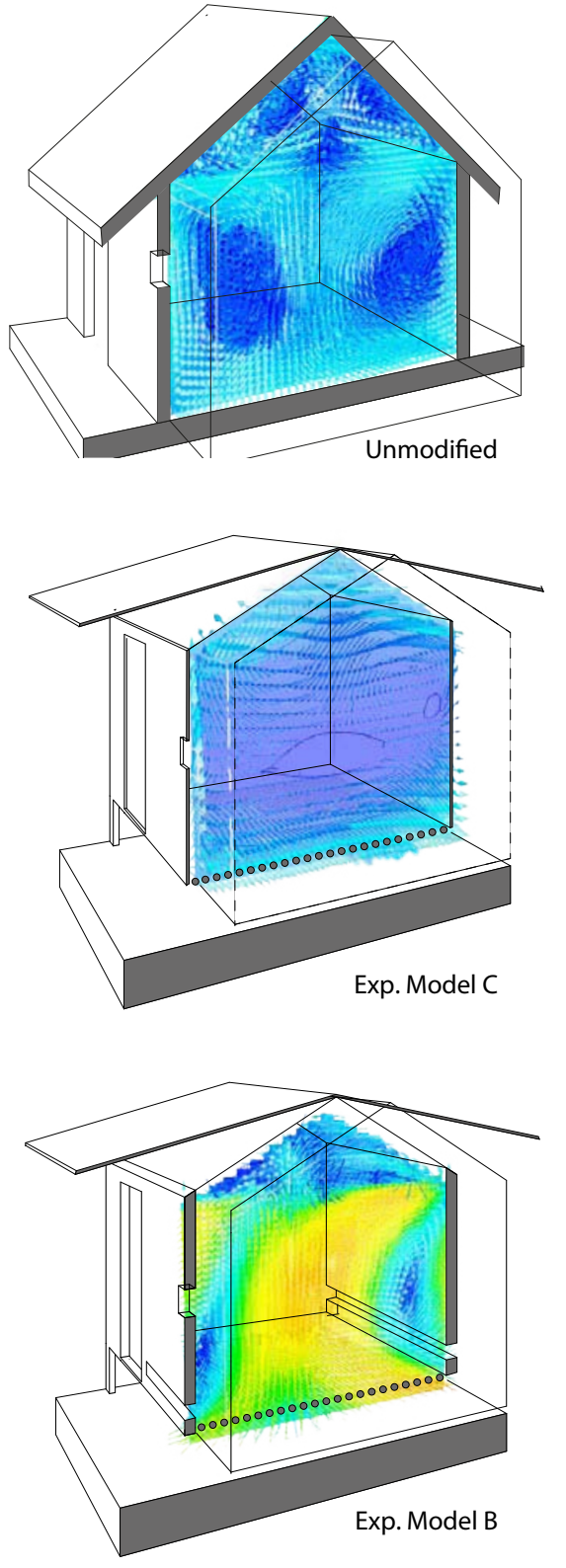


Fig 4.4.11 Computational Fluid Dynamic Simulations showing airflow in three different models

Design the Comfort with Architecture

The digital model takes into account the environment surrounding the building, the shading patterns and the properties of on-site materials. The prototype was simulated with a time step of 10 minutes providing information about the main *environmental factors* (Operative Temperature, Relative Humidity, Air Movement). The latter were compared to *physiological factors* (Metabolic Rate, Clothing Level), in order to determine the comfort level with an index named Predicted Mean Vote (PMV), which refers to a thermal scale of the comfort of occupants that runs from Cold (-3) to Hot (+3).

All the modifications of the experimental house determine changes in the occupants' quality of living. If a modification of the basic design resulted in a desired thermal condition and comfort, this was considered a step in the right direction - providing a clear validation mechanism by which one can objectively judge subsequent design decisions. Bamboo houses offer the greatest level of comfort during the night, while during the day mud houses may provide more comfortable conditions. The intended purpose and thus the occupational pattern of the houses should decide the building materials.

The digital bamboo prototypes had a comfort index close to thermal neutrality. The low heat storage capacity (low inertia) of bamboo results in rapid cooling after sunset. Houses with mud walls are experienced as warm to hot compared to the comfortable neutral. In between "slightly warm" and "warm" there are houses with both an elevated floor and a butterfly roof.

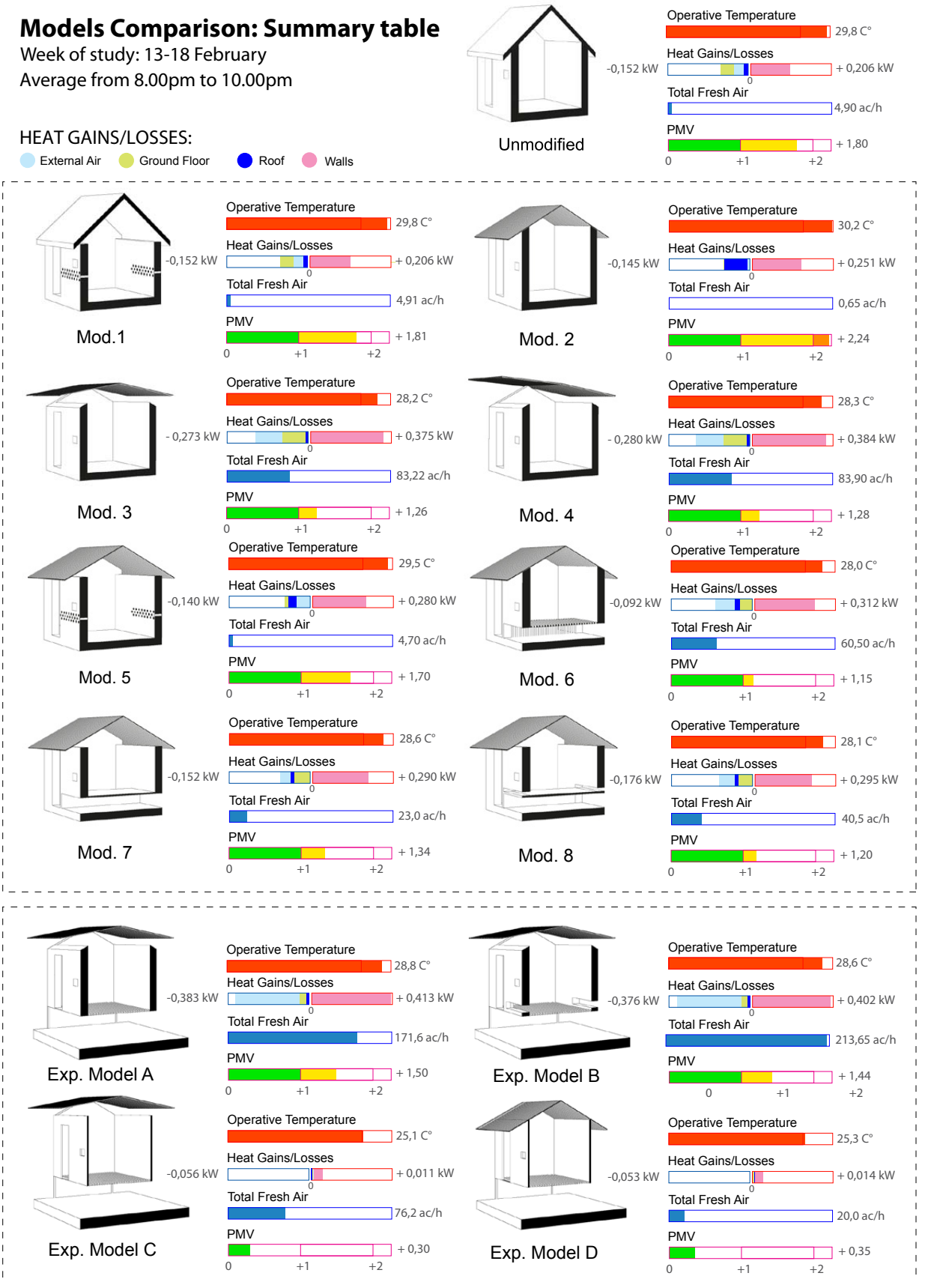


Fig 4.4.12 Summary table of the prototypes performance

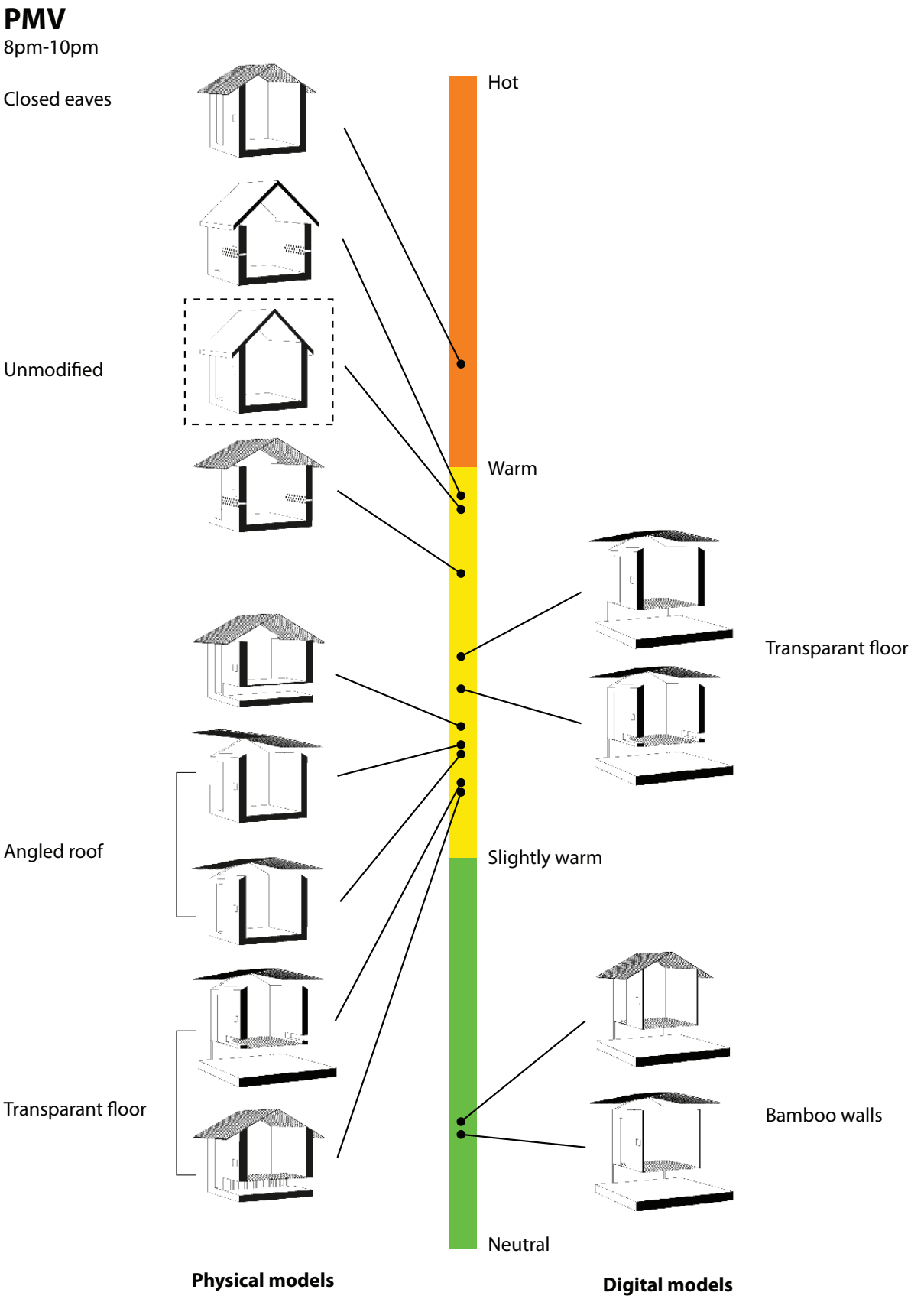


Fig 4.4.13 Summary Comfort Diagram showing the Predicted Mean Vote (PMV) at times of high mosquito concentration

Conclusions

Summary charts suggest that it is possible to improve the indoor comfort of the prototype by using the combination of a real (i.e., physically constructed) and a virtual thermal model. Specifically, the use of an open butterfly roof and bamboo panels result in comfort indices close to thermal neutrality, which represents a comfortable condition. A more comfortable house will provide a more promising setting for the use of bednets and may result in health benefits.

The two main objectives explored with the use of a prototype were to find ways to reduce unwanted daily heat gains and to generate cooling. The collected data showed that the three main sources of heat gain in summer are direct solar radiation, high outside air temperatures during the day and internal gains from occupancy at nights. The simplest way to deal with internal loads is to remove them. One approach would be to create thermal zones that are only used at night and zones that are better suited for use during daytime.

The tested models cannot cover all the approaches that could potentially lead to increased thermal comfort. The aim was not to find the optimal solution but to show how with few variations, comfort can be manipulated. Based on the prototype presented above the authors suggest taking some of the climatic principles from the Asian architecture and adapt it to traditional African building techniques. The authors current research plan includes the construction of a number of physical prototypes in Africa in order to test not only the climatic performance but also all the other factors involved in building constructions; acceptability, price, durability, security, etcetera.

Acknowledgments

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i Affiliations of the authors: Emanuele Naboni Associate Professor, Institute of Architectural Technology, The Royal Danish Academy of Fine Arts, School of Architecture. Denmark, Rasmus Bruun Research Assistants, The Royal Danish Academy of Fine Arts, School of Architecture, Denmark, Konstantin Ikonomides Research Scientist, Menzies School of Health Research, Australia, Lorenz von Seidlein and Jakob Knudsen Associate Professor, Department Two, The Royal Danish Academy of Fine Arts, School of Architecture, Denmark.

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4.5
A Short History of Building Fabric and Architecture

Ron Fitch [i]

Energy prices are certainly going to continue to rise for the foreseeable future. There is an ever increasing demand for building envelopes to provide higher thermal insulation values, combined with more effective methods to control solar gain and further reduce heat loss by providing better air-tightness. One option to achieving improved envelope performance is to increase the thickness of walls and roofs to allow for the addition of extra insulation. Another possibility is to design 'double façades' where a controlled intermediate zone between the external skin and the interior wall can be used to control the movement of air, often by mechanical means. Any construction that increases the overall wall thickness of a façade will inevitably be in conflict with a developer's main aim, which is to maximize the internal letable floor space of a building, although some argue this is an outdated paradigm. This is particularly important in cities such as London where internal floor space can be let at rents as high as £55 per square foot, at 2013 values.

This paper analyses the development of façade systems from the early lightweight and modular construction methods of the twentieth century to some of the latest technology in use today. A modular façade system QbissAir will be used as an example to demonstrate how the science of thermodynamics can be used to produce a highly insulated product with low G-values and minimum air leakage, whilst maintaining a minimal wall thickness.

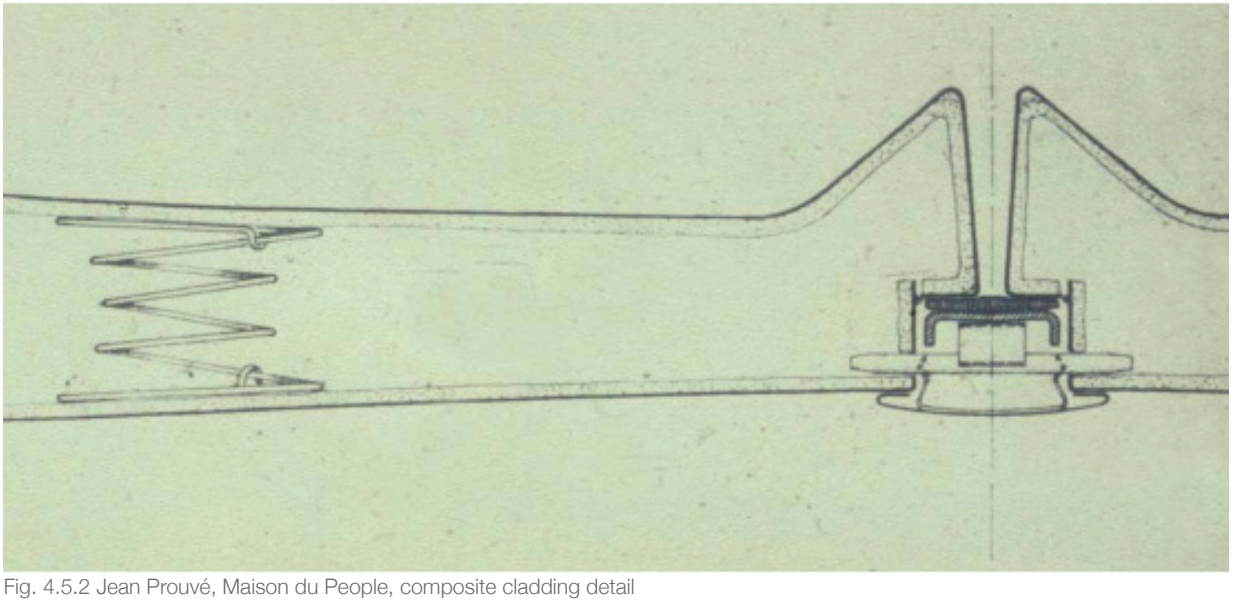
Reflection

Many new materials and processes now used in the construction industry originated from developments between the two World Wars, with the technological uptake accelerated by Second World War. The need for new and innovative methods of manufacturing structures and buildings, which could be factory produced in large volumes ready for fast site assembly was critical to the war effort. One of the first examples of innovative technology was the Mosquito bomber, developed during the Second World War, which was built from balsa wood and plywood, which together, created a strong composite lightweight structure.

Fig 4.5.1. De Havilland Mosquito

New methods of folding metal such as roll forming were beginning to be introduced for commercial purposes by the 1950`s. New glass production methods were developed by Alistair Pilkington in St Helens, England, between 1953 & 1957 which resulted in Drawn glass being replaced by Float glass which offered much higher optical qualities as well as increased production volumes and much greater affordability. The Float process is probably the best example of a non-military advance in technology as the idea of floating molten glass on molten tin has no military antecedence.

Using simple press brakes, a remarkable early example of a metal panel facade was designed by Jean Prouvé for the Maison du People in Clichy near Paris, 1934. Prouvé designed one of the first metal composite panels but still managed to incorporate an elegant recessed joint with a very simple weathering gasket. The panel was not in compression as is the standard approach today, but in tension and held apart by springs.



≤≤ Fig. 4.5.2 Jean Prouvé, Maison du People, composite cladding detail

One of the most interesting features of the panel is that the core is a void with a natural fill of air, mostly nitrogen and oxygen. It would be reasonable to assume that long before any thermal regulations, no one understood that air is an excellent insulator, providing it is controlled. The use of air as an insulator will be discussed later in this paper.

Due to the enormous effect the gulf wars of 1967 and 1973 had on the world price of oil, new regulations for minimum levels of thermal insulation were introduced for buildings.

These new thermal regulations combined with a growing demand for buildings with larger clear internal volumes led the demand for the 'supersheds' which ranged from the Renault Parts Centre in Swindon to Stanstead Airport, both designed by Foster Associates. This trend for highly efficient engineered buildings became known as "high tech" and culminated in some projects, which were known as the 'superbuildings' such as Lloyds of London by Richard Rogers and Partners. The Beaubourg in Paris by Piano and Rogers] and the HKSB in Hong Kong, architects Foster Associates. All of these buildings were designed with metal and glass facades but are more appropriately identified by their attention to detail, and in particular the way the different components and elements are articulated and connected together. If fact, the joints became one of the central features of their concept. This can be seen from the following quotation by Peter Rice, the inventive structural engineer from Team 3 at Arup, who was a key figure in the façade design of many iconic buildings of that time. "The key to this was the joint. The dominant memory [of the Sydney Opera House] was the importance of detail. The building was carefully detailed down to every joint. Beaubourg too, was big, enormous really, but the joint became the central element of the design, making the joint the central essence of the solution." Peter Rice, 1935 -1992

Current Trends

Arising form both architectural demands and building regulations, the cladding industry is currently undergoing a period of refocusing, in order to respond to the demands of contemporary building envelopes. Until a few years ago, the majority of buildings were designed with orthogonal facades and there was a clear distinction between different building elements such as glazing and metal panels systems. This gave the architect the opportunity to work with a specialist manufacturer from each discipline and develop the façade by integrating these different elements. Today's architecture makes the selection of appropriate materials and the integration of different construction elements more difficult. The current trend for buildings that have a less rigid, more organic form increases the demands placed upon the products chosen to clad the envelope.

Some of the main changes that contemporary façade manufacturers have to consider are:

Ever increasing thermal performance
Non-orthogonal building envelopes
Larger modular formats
More seamless envelopes and joints
Unitised facades.

A good example a project whether there is not distinction between the façade and the roof is the Gateshead Music Centre by Foster and Partners.

Fig. 4.5.3 Gateshead Music Centre, architect Foster and Partners, 2004.

Compare this to one of Fosters' earlier projects, the Renault Centre in Swindon, 1982.

Fig. 4.5.4 Renault Centre, Swindon, architect Foster Associates

On Renault, the clear toughened glazing and the insulated cladding system were both stand-alone elements coming together at only two vertical interfaces. The Sainsbury Centre, 1977, within the University of East Anglia campus, also by Foster Associates, was one of the first building envelopes to be designed as a series of interchangeable modules. Insulated metal panels, windows and louvers were all designed with the same edge profile that fitted into the aluminium carrier frame in the same manner. It was also one of the first buildings to use pre-fabricated "ladder" gaskets.

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Fig 4.5.5. Sainsbury Centre for Contemporary Arts, University of East Anglia, architect, Foster Associates

The dimensions of the modular grid based on a 1800mm x 1200mm module would be considered small by current standards for such a large building. Today, the trend is to create larger grids with fewer joints has made material manufacturers increase the sizes of their products with aluminium now being available up to 2 meters wide and double glazing units being produced up to 3300mm x 8000mm.

Even though Gateshead Music Centre is constructed using [mainly] the same two materials as Renault, metal and glass, interfaces between the elements occur all over the envelope in different geometric conditions. This is a much more demanding challenge for both the architect and the manufacturer[s] of envelope systems. Current building products have to respond to the trend for a less structured elevational treatment as well as conforming to higher performance criteria in terms of fire risk, acoustics and the ever-increasing demands of the Part L building regulations, BREEAM, LEED and other low energy standards.

Connections

The key to a successful interface detail is the joint. Not only does the joint have to provide a robust and weather-tight connection, it should be aesthetically elegant and often has to provide additional functions such as an access point for the replacement of individual modules or guide rail connections for external access equipment. Within the technology of metal cladding, many large 'sheds' use composite cladding panels, which rely on a 'top hat' cover profile for the vertical joint to provide a weatherproof connection between the panels. The horizontal joints are typically a 'male/female' stacking joint. For glazing, traditional pressure plate and cap joints for curtain wall connections are now considered slightly out of date and are being replaced by slimmer recessed joints wherever cost permit.

For buildings where more a elegant construction is desired, a slimmer recessed connection usually provides a more appropriate architectural tectonic. Joint connections also vary according to architectural style, for example Grimshaw Architects who often leave the fixings within a joint on exposed, whereas practices such as Foster and Partners usually conceal any fixings to provide a more seamless aesthetic.

Complex geometric building forms are made possible by 3D computer modelling, which is now being successfully integrated with manufacturing technology. Key complex points in the design where three-dimensional interfaces are required can be produced in the factory using Additive manufacturing methods leaving site connections to be simple two dimensional joints.

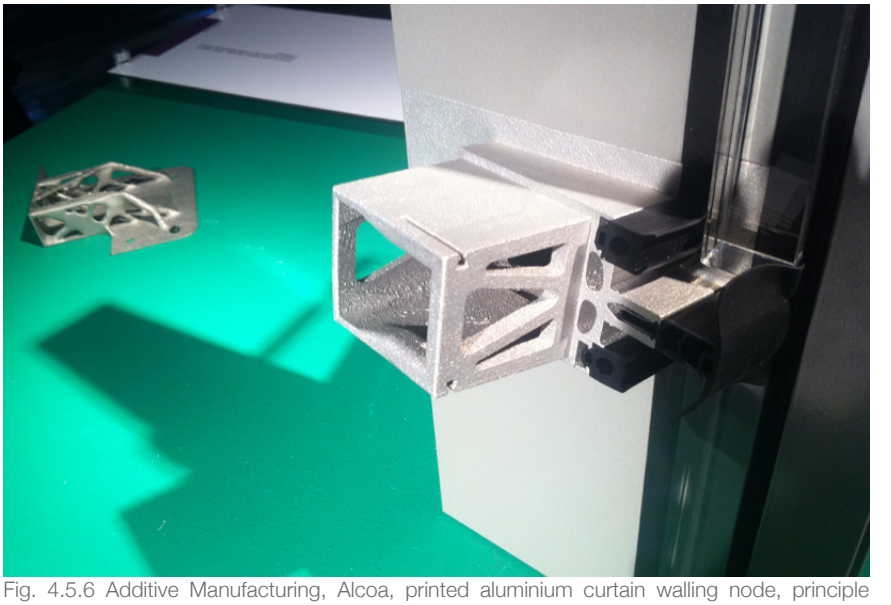

Fig. 4.5.6 Additive Manufacturing, Alcoa, printed aluminium curtain walling node, principle researcher Holger Strauss of the ConstructionLab, Detmold

Selecting a Suitable Metal Cladding System

Beyond profiled metal sheet cladding, there are two generic types of metal façade options available:

Composite Panels

Rainscreen Panels

Each has a role in forming the building envelopes of contemporary architecture.

Composite panels

During the 1970s & 80s composite panels were the most efficient and commonly used method to clad buildings in metal, but by the 1990s they were mostly confined to building for industrial use commonly known as “large sheds”. One of the main reasons for this change was the more aesthetically pleasing joints which rainscreens could provide, normally recessed rather than surfaced mounted profiles or caps which was the standard solution offered by most of the large composite panel manufacturers. Composite panels did offer one great advantage that they were a low u-value ‘one-wall solution’ and by default, their self-spanning capability greatly decreases the number of fixings and penetrations required which minimises cold bridging and potential water ingress problems. Today, recessed and flush jointing details are available for some metal composite systems, which provide aesthetics comparable with the standard recessed joints of structural glazing systems and are suitable for use in both industrial and office developments.

Rainscreens

As an approach to cladding architecture rainscreens were originally introduced in the 80’s as an overcladding solution for existing building stock. This technique was pioneered in Norway and Canada. A rainscreen forms only the outer skin of the total wall construction. It requires an inner wall, which provides most of the thermal, air infiltration, sound performance and the second stage of weathering. As the generic design for a rainscreen means the outer skin has to be positioned outside the ventilated cavity and ‘standoff’ the main structure, the number of structural supports back to the inner wall should be taken into account when accessing the number of cold bridges and potential for water ingress. A ventilated cavity is required between the two walls, which means there is a considerable total wall thickness requirement to meet current U value regulations. The sectional dimension of a rainscreen solution including the inner wall and cavity designed to suit current thermal regulations can be 400mm or more. This is a major factor that should be taken into account when considering a façade solution as developers are always looking to maximise the internal volume. Increased wall thickness to conform to thermal requirements is often in direct conflict with the demand to maximize internal letable floor space.

Unitised Facades

To speed up construction and improve the delivered quality unitised façade systems are increasingly being specified. Unitised façade can be metal or glass or a combination of a wide selection of materials. They have the advantage of being assembled in factory conditions, which should ensure a high standard of quality control and a high quality of finish. They normally reduce the installation time considerably and as they are usually installed from inside the building, they eliminate the necessity for external access equipment. Unitised assemblies are not appropriate for all buildings. A high degree of repetition and consistency in the facade design is a good guide to ensure a unitised system will provide an economical choice.

Fig 4.5.7. A unitised curtain-waling element being installed

Latest Developments

Some of the latest developments of façade technology include the development of materials based on biomimetics such as the honeycomb structures in beehives and the honeycomb structure of bones, when examined microscopically, to maximise the performance of many building products. Metal foams replicate the internal structure of bones and have commercial uses in the construction and automobile industries as well as medical practice. For example the metal foam can be used to fill hollow tubes to give them additional structural and mechanical strength. Aluminium and plastic honeycomb cores can be inserted between lightweight metal skins to produce exceptionally flat panels, which can be used as lightweight walls as well as “walk on” surfaces.

Another good example of products being developed using biomimetics is a new silicone based adhesive tape thah has been developed and can be in the same manner as ‘scotch tape’ but has no glue to achieve bonding. The tape was developed by Professor Stanislaw Gorb at University of Kiel in Germany. He studied the green dog beetle to investigate how the tiny creature could walk upside down whilst carrying a weight 30 times its own body weight.

Fig 4.5.8. Green dog beetle – has amazing traction

The secret behind this ability to walk up side down was found at an atomic level, microscopic pads on the end of the creature's hair on the bottom of its feet, which could even establish an adhesion on the underside of smooth surfaces such as glass. This mechanism has been successfully reproduced synthetically and is currently being scaled up for volume manufacture by a leading German chemical company. It has great potential use in construction, automotive, medical and many other fields.

Energy and Environmental Issues

The requirement for buildings to provide acceptable BREEAM, LEED and EER [energy efficient ratings] performance levels means the carbon offset of materials during their manufacture and in use phase will have a major effect on which materials will be selected to provide thermal performance. By 2018, proposed legislative changes will call for minimum energy standards for buildings and make it unlawful to let residential or commercial properties with an EPC [energy performance certificate] rating of F or G, the two lowest grades of energy efficiency. Many of the insulants which currently provide thermal insulation are hydrocarbons so the need to provide highly insulated buildings is offset by the requirement to use environmentally friendly materials produced by environmentally efficient manufacturing methods.

GULt

Energy efficiency is not limited to achieving low U-values; it is also about achieving low G values and providing comfortable internal lighting levels. A carefully balanced solution between the three criteria should be achieved to produce a satisfactory internal environment for the building users, whilst as the same time minimize energy costs.

The three main criteria that should be considered are:

The thermal performance	the U-value
The solar gain	the G-value
The light transmission	the Lt-value

The U-value is a measure of heat loss in a building and forms the basis of any energy or carbon reduction. A low U-value usually indicates a high level of insulation. The G-value measures the degree to which glazing blocks heat from sunlight and is expressed in a number between 0 and 1. The lower the G-value, the less heat is transmitted. The Lt-value indicates the amount of visible light which is transferred through glazing. A high Lt-value is desirable to maximize daylight but should be balanced against excessive solar gain.

Solar Gain [G-value]

U-value regulations are now well established and understood in the UK but G-values are relatively new to many UK specifiers and organisations. Solar gain is of particular importance in the northern hemisphere where the sun is often in a low trajectory. Although solar gain is often simplified as being beneficial in the winter, studies undertaken Faber Maunsell on behalf of BRE demonstrate the reality is more complex. Solar gain and light transmission are interdependent to a certain degree. Visible light, which can be seen and perceived by humans, is a very small part of the full electromagnetic spectrum, approximately only 3% of this spectrum. The sun emits slightly more infrared than visible light, 52% to 48% respectively. Visible light is absorbed and emitted by electrons in atoms moving from one energy level to another and lies between the infrared and the ultraviolet wavelengths in the electromagnetic spectrum. Electromagnetic radiation [EMR] in the visible light region consists of quanta (called photons) between the invisible infrared with longer wavelengths and invisible ultraviolet with shorter wavelengths. Above the range of visible light, ultraviolet light becomes invisible to humans mostly because it is absorbed by the tissues of the eye.

At the lower end of the visible light spectrum, EMR becomes invisible to humans because its photons no longer have enough individual energy to cause a lasting molecular change, a change in conformation, in the human retina. The aim for any energy efficient glazed façade system should be to minimise the Solar gain, 700-2500nm infrared radiation, whilst transmitting as much visible light as possible, 400-700nm. This will help to create a constant and comfortable interior temperature within the building, whilst minimising the need for artificial light.

External shading

Static and solar activated external brie soleil have often been used to combat the glare and solar gain experienced by many buildings but it is often an expensive solution which has some disadvantages such as detailing the support frames back to the main building structure which often penetrates and cold bridges the insulated façade zone. Active solar shades also have energy and maintenance costs which add to the buildings in use overheads as well as restricting the light transmission as well as the external view from the inside of the building. Projects with a high percentage of glazing, solar gain and glare can cause interior overheating problems which often require energy driven cooling systems to maintain a comfortable internal working temperature.

The use of Thermodynamics

An alternative solution to external methods of solar control for glazed facades is to use thermodynamically designed multi-glass units where the glass layers are treated with low emissivity coatings to minimise solar gain. Coatings within multi glass units can be used to reduce solar gain and glare and if designed in coordination with the thermal and light transmission requirements, can eliminate the requirement for external brie soleil. Light transmission levels through glazing need to be coordinated with the requirements for interior lighting levels. Principally the aim is to eliminate long wave radiation which carries infrared energy which whilst maximising short wave radiation which carries visible light.

Internal light levels [lux]

In the USA, day lighting is a well-proven and accepted part of building envelope design. The guidelines they use are based on an external luminance at ground level of 5000 lux, which is equivalent to an overcast cloudy day. For an internal space to feel largely lit, the average daylight factor should be 5% or more. [CIBSE LG10: an average daylight factor of 5% or more will ensure that an interior looks substantially day lit]. This equates to a light level of 250 lux. On first site this may appear to be low but if this level is uniformly achieved from a large proportion of the external wall compared to a smaller more concentrated area such as a window, it will normally satisfy the requirements of the British Standard BS 8206-2:2008.

This standard highlights the three ways that the provision of glazing contributes to the quality of an internal space:

View - amenity

The enhancement of the overall appearance of interiors using direct sunlight and diffused daylight

The use of daylight for visual tasks.

Today the main challenge is to design buildings that will achieve efficient energy management, balanced by the requirement to ensure adequate daylight. Only by a carefully calculated study of the required internal lighting levels that must be coordinated with solar gain variation can an energy efficient solution be established.

Light transmission is often calculated after the façade has been designed to meet the required U value. This means the area of transparent glazing is already established and the light transmission is limited to the area set out for the transparent glazing. This usually results in a high proportion of visible and non-visible light transmitting through a small area, which will result in solar gain and probably glare. A more balance option would be to increase the glazing area of the wall to allow the maximum area of short wave visible light [380 – 780 nm] possible and eliminate the non-visible light that carries long wave infrared wave energy that is the main cause of solar gain by engineering the thermodynamics of the multi-glazed units. Designers of energy efficient facades need to consider all three critical factors at the outset instead of designing the façade to meet the required U value and then trying to fit in the required G and Lt-values. In addition to creating a more energy efficient façade, fully glazed facades are almost always considered high on most architects 'most wanted' list.

QbissAir

An inventive methods of controlling the thermal, solar gain and light values is QbissAir, a unitised façade system by Trimo Dd., a Slovenian based façade manufacturer. This glazed façade system is designed to offer exceptional GULt performance within a very slim façade zone without the need for any solid insulants. The system was engineered to utilize the thermodynamics of convection, conduction and radiation within a series of chambers that reflect infra-red radiation and minimizes conduction between solid materials. Heat transmittance is limited by low thermal conductivity gas within a calculated volumetric space.

QbissAir is a range of clear, translucent and opaque modules of identical thickness, 133mm, which can be installed from inside the building. A QbissAir glazed facade can achieve a U-value of 0.35w/m2 k and a G value of 0.1 at an overall thickness of 133mm.

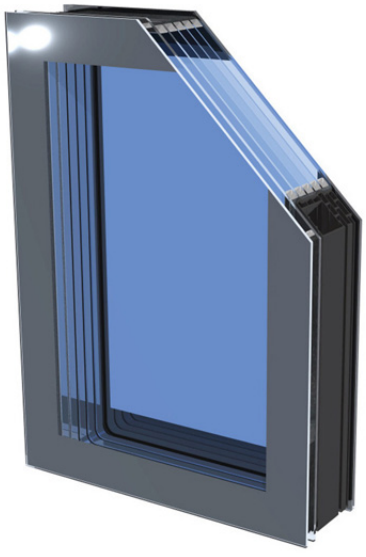

Fig 4.5.9. Example QbissAir glazed module

When QbissAir was originally conceived as a high performance façade system, every type of potential insulant was investigated and analysed. It soon became clear that carbon dioxide [CO2] had a thermal conductivity comparable with most of the urethane-based insulants but none of the fire, toxicity or environmental issues.

For example the thermal conductivity [K-value] of:
Polyisocyanurate is from 0.021 > 0.036
Carbon dioxide is 0.014 [at 0°C]

The problem was how to control and use the CO2 in a façade system. By using thermodynamics, the development team engineered a solution of internal chambers that reflect radiation, minimize conduction and limit heat transmission. Metal foil chambers are used for opaque modules and low E coated glass is used for clear modules, which also contain various amounts of inert low conductive gases such as argon.

Conclusion

To create an energy efficient building, a careful study should be undertaken and analysed for each new project; to identify the criteria for the U-value, G-value and the light transmission and a balanced solution should be established to suit the building's performance requirements. Each elevation should be evaluated separately as they will each be subject to different levels of climatic conditions and therefore a bespoke solution for each elevation may be required. In future, simply adding thicker insulants to walls will not be satisfactory. Not only does this encroach on the internal space, add to embodied energy but it makes detailing around items such as windows and doors more difficult. To satisfy the future demands for high performance facades which are both aesthetically pleasing as well as efficient in use, façade manufactures will have to incorporate holistic scientific analytical solutions into their products rather than simply making facades thicker to provide higher levels of thermal performance.

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Peter Rice - reference including page number please Ron
Professor Michael Stacey, Prototyping Architecture, The Building Centre Trust, 2013, Nemotex II

4.6
Prototyping Architecture - Hurlingham Club Evolutionary Prototypes, Survival of the Fittest Ideas

Tim Lucas [i]

This is a story of a shared journey in designing and making between people in two firms; a structural engineering practice, Price & Myers based in London and a manufacture based contractor, Commercial Systems International (CSI) based in Hull. Over the past decade both parties have developed a shared interest in being able to realise interesting and exciting projects in an affordable way through collaborating on the design, manufacture and installation of a series of prefabricated buildings and more recently an 80m long sculpture. These projects share a common theme of using CNC cut plywood and OSB to build complex volumetric forms. The recently completed plywood roof for the new outdoor swimming pool pavilion at the Hurlingham Club in London is a good example of this work and is the main project described in this paper.

Fig 4.6.1 The new Outdoor Swimming Pool Pavilion at the Hurlingham Club, London, designed by David Morley Architects, timber engineering Price & Myers with CSI.

Project to project evolution

Our ideas in CNC based construction have evolved through a number of projects. Each project is a prototype for the next, building on established concepts and methods, whilst trying new and extended ones in the context of a proven working frame work. This evolution of ideas and techniques happens in the office, on the factory floor and on site. Like evolution, better ways of say modelling and drawing emerge together with improved techniques for cutting and assembling plywood parts to replace the way things were done earlier on a project or on a previous project. The Hurlingham Club Pavilion is very much a product of this evolutionary process through several projects. Two earlier projects; a Banstand at the De La Warr Pavilion in Bexhill that Price & Myers designed with Niall McLaughlin Architects and a large roof extension to a former textile mill in Bradford designed with David Morley Architects and built in collaboration with CSI are effectively ancestors to the pavilion's roof.

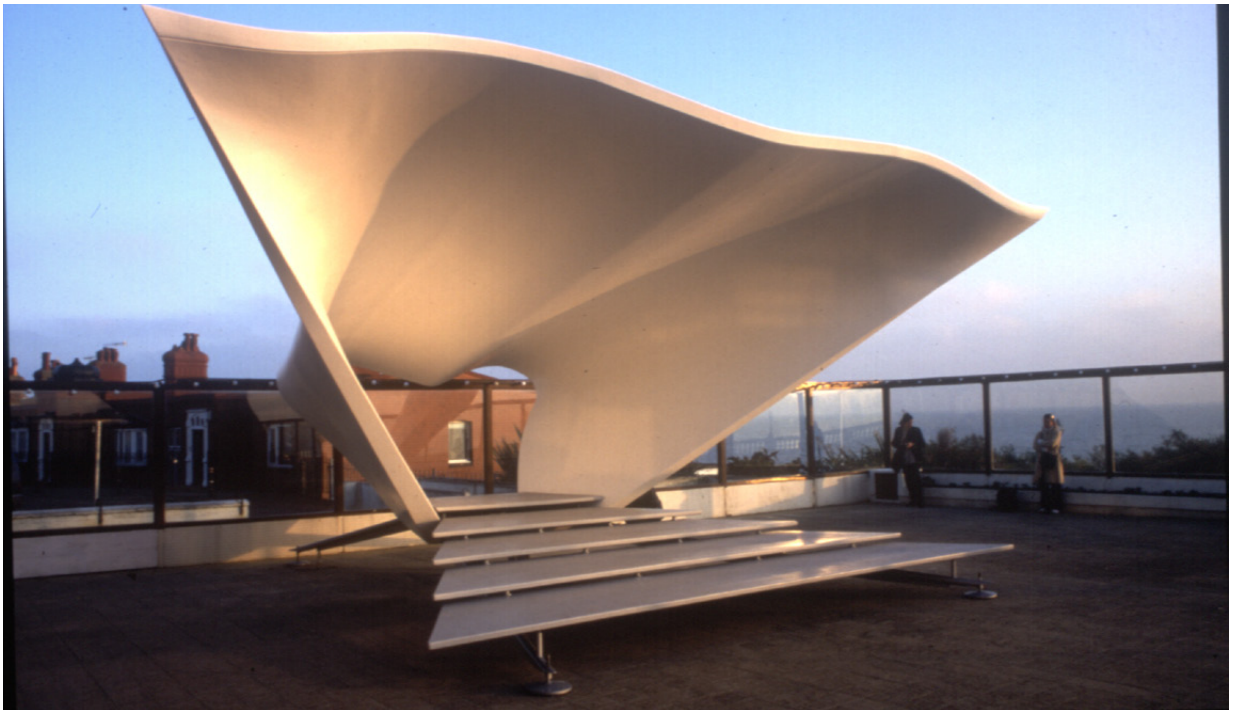

Fig 4.6.2 Bandstand at the De La Warr Pavilion in Bexhill, Price & Myers designed with Niall McLaughlin Architects.

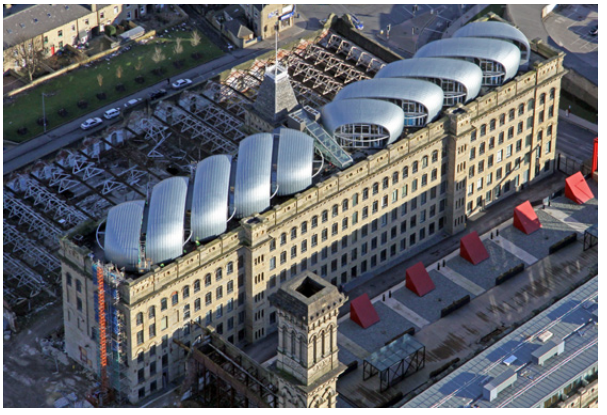

Fig 4.6.3-4 Aerial views of the roof top pavilions designed by David Morley Architects as part of the regeneration of the listed form textile mill in Bradford, Lister Mills.

The ancestors

The original inspiration for this chain of evolution was a plywood dinosaur skeleton toy. The skeleton is an abstract but simple set of flat ribs cut into a sheet of plywood. The fun is in creating the three dimensional shape of a dinosaur skeleton from these parts. The model is crafted by the carefully planned distribution of shaped two dimensional parts that are notched to interlock with other parts; providing support to each other and together making a structural three dimensional skeleton in the shape of a dinosaur.

Price & Myers first used this concept in the construction of a canopy for a bandstand at the De La Warr pavilion in 2001. The complex and varying curved form of the canopy can be rationalised by cutting it into a series of shaped plywood ribs that can be clad in thin plywood sheets. Price & Myers pioneered a process of drawing the exact shape of each rib to give to the joiner who made it the exact shape of each bit needed to make the overall shape. The project was very much hand made and analogue in its execution. Drawings at 1:5 scale were produced, each rib set against a grid. The grid was transferred onto the plywood by a line of marker pens spaced along a stick. The curves were hand drawn over this grid and cut out with a jigsaw. The project proved that bespoke and unusual forms can be simply made. Fundamental to it are the processes of sectioning 3D models to produce 2D rib profiles along with cutting and assembling these parts into the overall form. Improved methods for doing this have been at the heart of the overall evolution from project to project.

Fig 4.6.5 The Bandstand at the De La Warr Pavilion, Niall McLaughlin Architects and engineers Price & Myers, completed in 2001

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Industrialising the Process

In 2006 Price & Myers won a competition with David Morley Architects for a new roof extension to a redundant textile mill in Bradford. The scheme was made up of curving pod structures that enclose two storey penthouse flats. A shape for the building emerged that was inspired by a plaid of yarn and informed by the grid of the building and the views from it. The shape, a series of repeating skewed and curved vault was difficult and expensive to manufacture in conventional building systems like standing seam metal roof cladding. An idea emerged to build the roof like the plywood dinosaur and De La Warr Pavilion bandstand, albeit on a much larger scale. The bandstand is 8m wide, the roof extension to Lister Mills is 100m long so the same hand crafted approach that was used on the bandstand would have to be industrialised to make it feasible.

At this time Price & Myers came together with CSI, to build on the design concept of interlocking plywood parts. The scale of the project meant that cutting and assembling these had to be something that could be quickly and efficiently carried out by people in a factory setting rather than a joiner's workshop. The key techniques of producing profiles and cutting them evolved. Rather than printed drawings and hand cutting, CAD drawings went directly to CNC routers to cut the profiles. Assembly was also critical and was the subject of virtual prototyping with CSI – by modelling jigs intended to assemble the units on, it was realised that the same result could be attained by learning from the dinosaur and slotting parts together. More appropriate software than used for the bandstand allowed us to coordinate notches between parts so that one would marry to another with no need for complex jointing. The CNC router gave us the opportunity to machine profiles complete with their notches and reference numbers on an industrial scale.

Other production techniques were pioneered, principally the pre production of large modules that balanced transportation and site assembly logistics, the resulting 100m long plywood building and steel frame building proved that these ideas could be applied to a large and complex project as well as a small bespoke one like the bandstand.

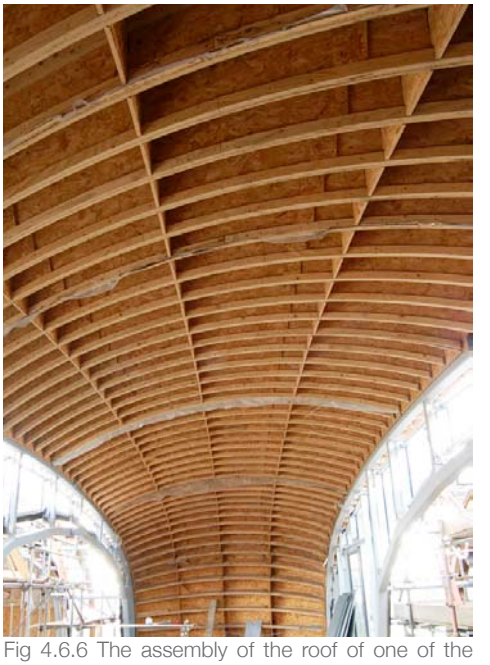

Fig 4.6.6 The assembly of the roof of one of the Lister Mills Rooftop Pavilions.

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Background to the Hurlingham Club Project

In 2010, David Morley Architects asked Price & Myers together with CSI to propose a scheme for building the roof of a project they had at the Hurlingham Club. They were interested to know if Price & Myers could develop something in line with our previous project with them at Lister Mills. An existing structure for the roof using profile cut Kerto beams and rafters had already been proposed for the building by another engineer, and the project was well into its detailed design stage. As part of a value engineering exercise Price & Myers were asked to propose an alternative that could be manufactured off site and be installed in large prefabricated units. The building is a single storey changing pavilion for an outdoor swimming pool. It has a tapering wedge shaped plan with rounded ends. In section, the roof has curved ridges and valleys running across the plan which create curving skewed roof surfaces. As the tapering building becomes thinner in plan, the roof curves become tighter and more pronounced.

The overall form was made up of skewed surfaces that can be formed in CNC cut plywood units in a similar way to the Lister Mills project. The significant difference from Lister Mills however was the lack of repetition of geometry. Each roof unit would be a unique shape. Our proposal was to build the roof as a series of three dimensional plywood cassettes with structural skins on the top and bottom of the units to effectively create a hollow structural slab of timber. When assembled, the uniquely shaped cassettes form the tapering and curve roof form. Whilst some aspects were new, the proposed manufacturing method using CNC cut plywood and OSB panels was strongly linked to Lister Mills as was the in-depth understanding of prefabrication techniques and volumetric installation methods acquired through that project.

Fig 4.6.7 Assembly of the Rooftop Pavilions for Lister Mills

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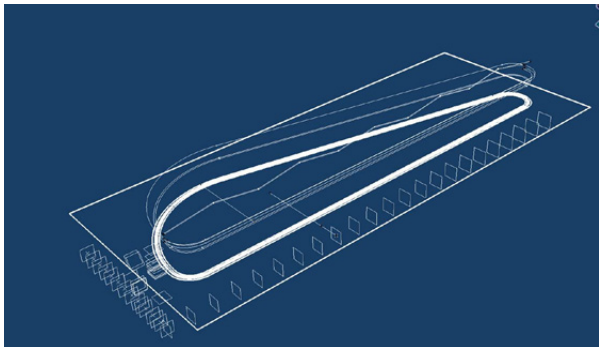
Design catch up

Joining the design team late in the day meant that Price & Myers had to develop our concept to work with architectural and structural design principles that had already been fixed. These included the positions of supports for the structure, the overall geometry and other aspects such as the cladding choice and method of roof ventilation. The working method of using CNC cut plywood parts relies on us providing a fabricator like CSI with complete cutting & assembly plans. Every single piece of plywood or timber in the structure requires a CAD drawing to feed to the CNC router. Each part must be coordinated to others around it so they fit together.

Price & Myers approach to deal the variable geometry was to design a parametric cassette that incorporated the required features of the roof such as structural skins and ribs, ventilation slots and structural support points. The initial design focus was on this parametric cassette and it was treated as a virtual prototype where the required features were built in the model. Once the design of this parametric unit had been developed in detail, the unit could be instantiated across the roof, picking up new parameters for its required size and shape to suit the roof geometry at specific points in the building.

Script based modelling process

Modelling the roof cassette so that it could change shape, after Price & Myers had established construction details in the virtual prototype cassette raised productivity issues. To speed up the production of fabrication information, the parametric cassette modelling was automated using a number of inter related scripts to produce the geometry. These scripts remodelled the surface geometry of each instantiation to suit the position in the building. The script modelled specific features such as internal stiffening ribs, with the required number of ribs being adjusted to suit the cassette size. Relating the depth of each cassette on the overall span optimised structural performance. Other factors in the geometry such as considering if the cassette was a ridge or valley unit, or right of left handed were built into the scripted modelling. In this way it was possible to instantiate each cassette relatively quickly, and produce the CNC cutting drawings for the several hundred unique parts in each cassette in an automated way. As each part is made exactly as it is drawn, its shape must be generated from the 3D model with no manual drawing. There are in the order of 13,000 parts in the roof so manual drawing would not be possible within the time and cost constraints of the project. Human intervention was limited to making sure that the right number of part profiles had been generated rather than deciding what shape the parts needed to be.



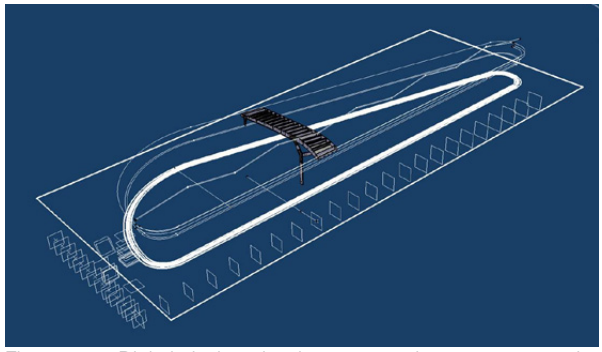
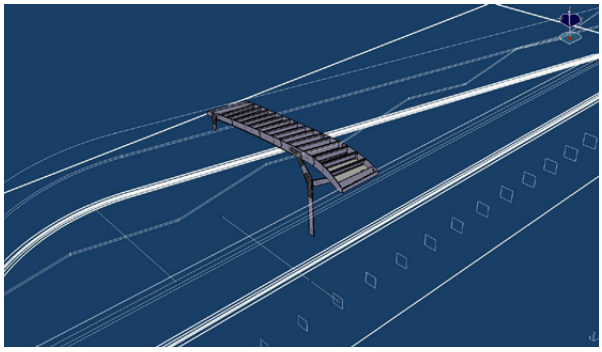
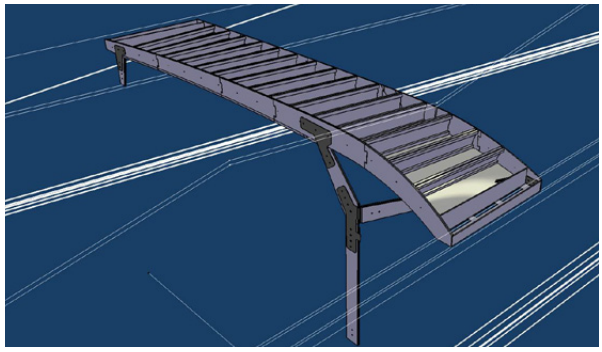
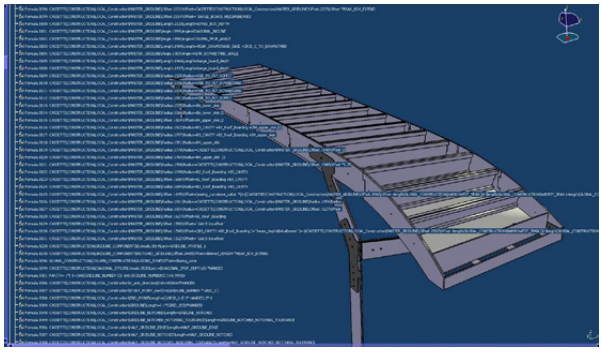


Fig 4.6.8-9 Digital design development of the geometry of the timber roof cassette for the Hurlingham Club Pavilion







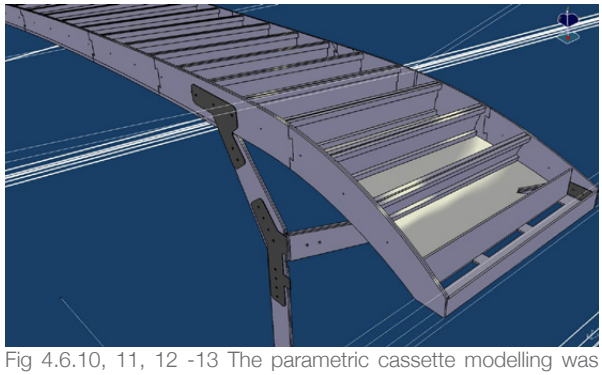


Fig 4.6.10, 11, 12 -13 The parametric cassette modelling was automated using a number of inter related scripts to produce the geometry.

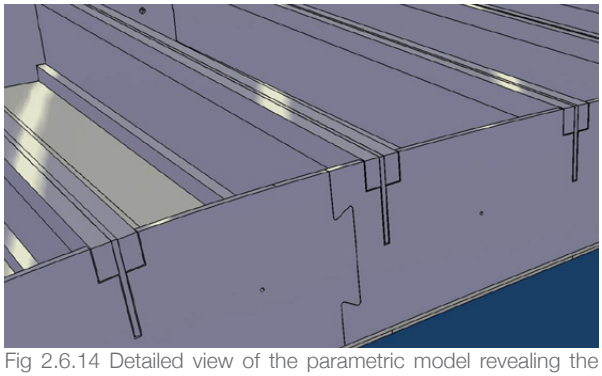


Fig 2.6.14 Detailed view of the parametric model revealing the individual timber components of the cassette

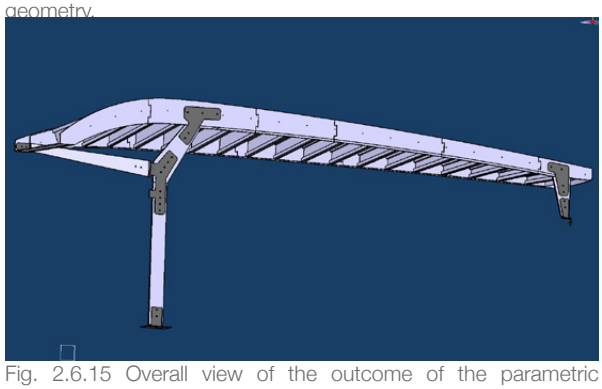


Fig. 2.6.15 Overall view of the outcome of the parametric modelling of a Hurlingham Pavilion timber roof cassette

Assembly & Production prototype.

Price & Myers and CSI decided that the production process from material processing through to final assembly should be prototyped in a desire to minimise the opportunity for human error and maximise the efficiency in the use of material from the parent plywood panels. The design team decided to make several full-scale samples as prototypes to both prove the envisioned manufacturing process, and help establish a full understanding of tolerances and material behaviours which could be fed back into the model for final mass production. This work culminated in the production of a full-scale prototype of the largest cassette. The CNC cut plywood production process produces relatively small parts, which are limited in size by the overall dimensions of a sheet of plywood. The process must include practical and rapid ways to accurately assemble parts into the overall roof form. There are two issues to consider; the assembly of cut units into sub components such as edge ribs, cross ribs or skin panels and the assembly of these parts into an 8m long and 2.25m wide roof cassette.

Fig 2.6.16 1:1 Prototype of the Hurlingham timber roof cassette being assembled by CSI in its works in Hull, note the use of an adjustable geometry steel jig.

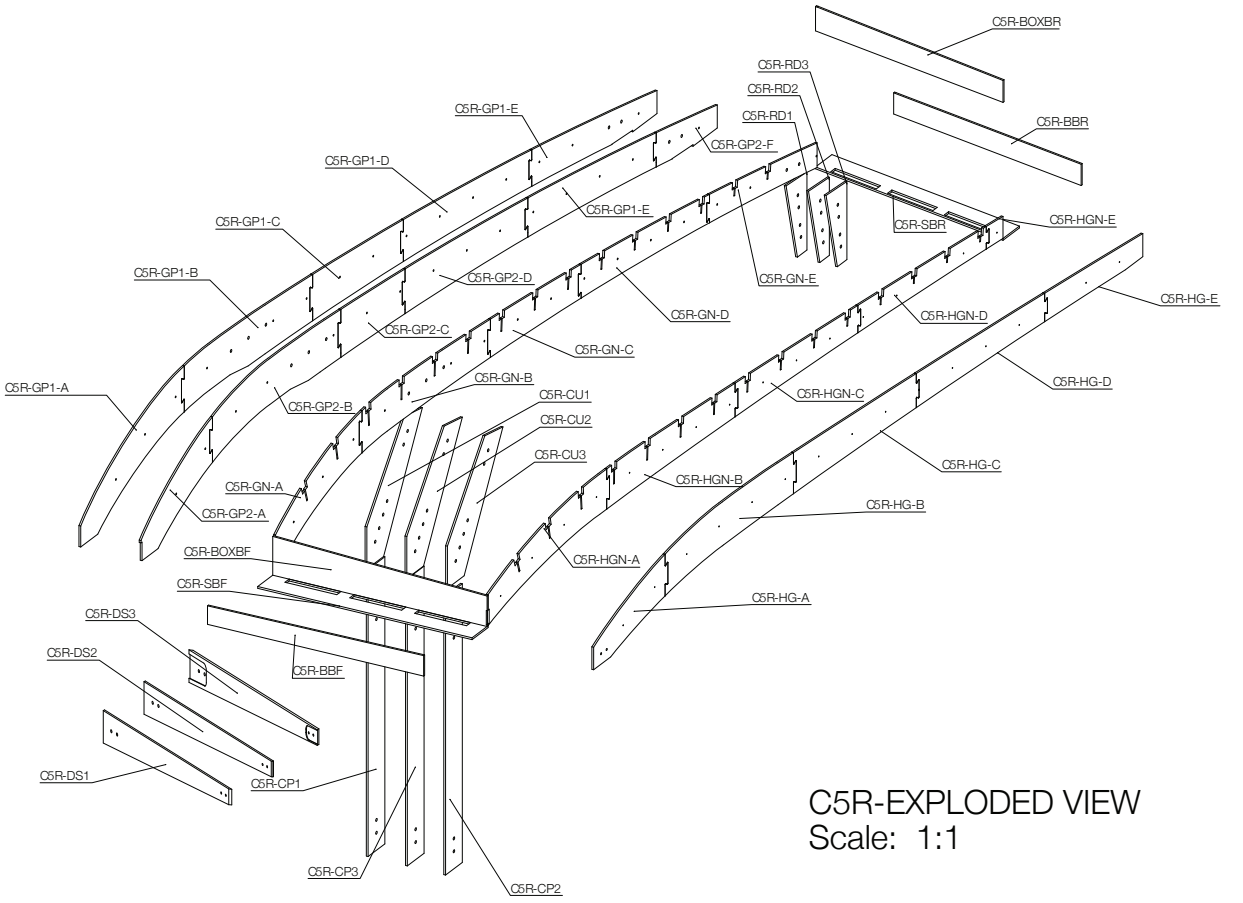


Fig 2.6.17 The timber components of the roof cassette, exploded drawing at 1:1

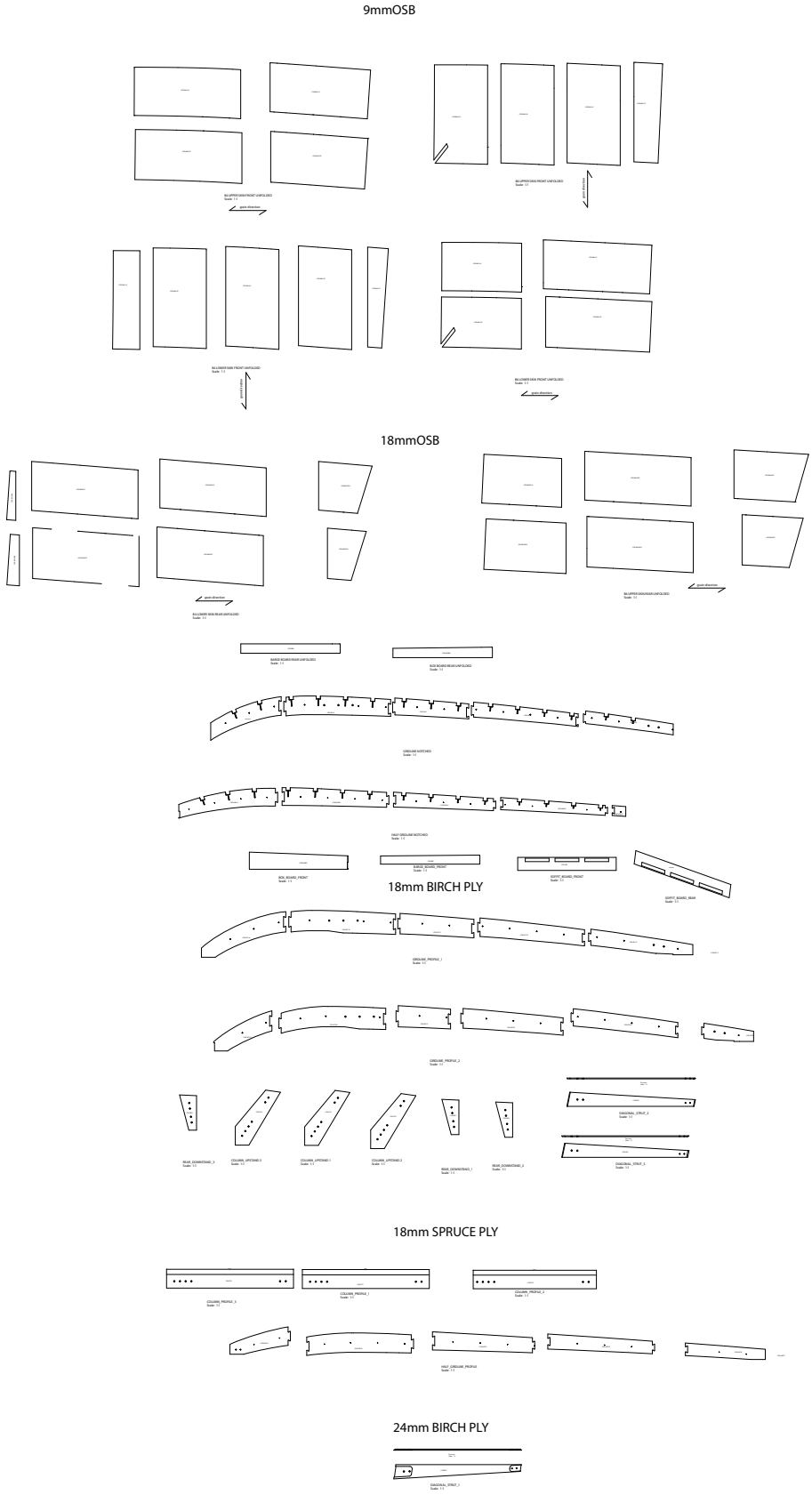


Fig 2.6.18 The cutting templates

Assembling sub components from individual CNC cut profiles needs to be done quickly and accurately. The ability to make bespoke cut paths on the CNC machines means that features that aid and speed up assembly such as dovetail joints can be almost freely cut into the panels. The joints can be made tight enough and self securing so that they can be knocked together using hammers to create sub assemblies of parts that are larger than a single sheet of plywood. Further coordination between parts helps assembly. A series of slots in one part can act as both a more secure structural joint and a positioning jig for other parts in the unit.

The Hurlingham club roof modules span up to 8m and are only capable of doing this when they have been fully built. To enable accurate and rapid production of the unit, Price & Myers developed an adjustable assembly jig with CSI that enabled each unique module to be assembled in a well supported condition. When the structural top and bottom skins of the roof were finally fixed on to the internal ribs, the unit was de-propped, and gravity effectively turned on.

Fig 4.6.19 Detail of the Hurlingham timber roof cassette prototype in an adjustable steel jig

Fig 4.6.20 The steel adjustable assembly jig made certain that each unique module could to be assembled in a well-supported condition.

Visual prototyping

A key aspect of our design of the roof structure was that as much as practical, the CNC cut plywood parts should be exposed and un-clad. In areas such as columns and struts, this was particularly important since, to clad these items would create a visually bulky structure. The close tolerance of CNC manufacturing enabled the results to be reliant on the exposed cut profiles being visual. To prove this approach to designing the exposed elements, the team produced a visual prototype of the principle node that connects adjacent roof cassettes, raking struts and a supporting column together. This unit proved that by using high strength birch plywood an exposed structural joint could be produced that looked nice and worked well from a structural and assembly perspective.

Fig 4.6.21 Timber roof cassette modules waiting to be craned into place

Fig 4.6.22 Craning a timber roof cassette module into place

Economy of materials

All of these projects share a theme of making the most of materials. The upper and lower surfaces of the Hurlingham Club pavilion are there to hold insulation in and provide a substrate for the outer zinc and inner plywood cladding. Usually a roof deck like this sits on a structure of joists and beams, in structural terms it provides a diaphragm to allow horizontal shear loads to be transferred but it does little to help the joists work more efficiently. With careful and jointing of skins and ribs, the skins can become a key part of the structure and eliminate the need for a separate set of supporting beams and joists. This creates economy in the use of materials by having less dead weight to support, the surface skins are at the most effective place to resist bending moments, as sheet material, they are simple to form into curved skewed sheets. Like the aluminium surface of an aeroplane wing, they become a stressed skin that both acts as structure and cladding. Bespoke ribs between the upper and lower surfaces define the skeleton for the skins to sit on. Each has a unique shape that fits in with the others around it to make a skeletal inner structure that follows the straight lines inherent in the skewed surface.

Fig 4.6.23 Assembling the roof of the Hurlingham Club Pavilion is almost completed.

Concluding thoughts

The principle goal that Price & Myers have in practice is to help design elegant simple architecture and sculpture with good architects, artists, contractors and clients. How things are made and built is fundamental to this elegant simplicity. Design decisions on methods of construction that are often passed down to others in the construction chain away from the core design team. This does not always yield the best results. The design approach outlined here together when combined with a close relationship with open minded contractors such as CSI has proved that bespoke construction projects can be realised economically and elegantly.

Our projects that use CNC cut plywood and other materials directly link us to the manufacturing and building process. In fact Price & Myers find ourselves having a strong influence on the method of making and therefore the exact look of a building or detail. In the past the designers of most buildings were artisan craftsmen who new how to design and build in timber stone for example. The skill in their craft created high quality buildings. Tightly fitting together buildings. Price & Myers can see a trend where as designers, teams like ours work in close collaboration with fabricators and have a strong influence of construction details of our projects, to the extent where the team effectively add a lot of the skilled work ourselves via the link between our CAD programmes and computer controlled CNC cutters.

The craftsman's ability to cut and shape a tight joint in masonry or timber is mirrored by our ability to design joints that are cut to exact tolerances and assembled as a pre made kit of fully dimensionally coordinated components. With this approach, designers working with good contractors can become artisan designers making use of technology to create highly refined objects from simple base components. Price & Myers are finding that our approach is gaining momentum and that with manufactures such as CSI our teams are able to economically bring complex & bespoke structures, complete with finishes, into tectonic reality.

Fig 4.6.24-25 The completed roof structure of the Hurlingham Club Pavilion.

Fig 4.6.26 The new Outdoor Swimming Pool Pavilion at the Hurlingham Club, London.[ii]

References

i Tim Lucas is a structural engineer. He joined Price & Myers after graduating from Leeds University in 1996 and became a partner there in 2007. He founded Price & Myers' Geometrics group in 2001. His work includes unique and iconic buildings, bridges and sculptures. He enjoys creating exciting structures that are simple to make and build. He and his team make use of advances in computer modelling and manufacturing technology to create buildable structures. This is underpinned with a sound knowledge of engineering theory, principles of geometry and the nature of materials.

ii Image Credits: Fig.1-19 and 26 © Price & Myers, Fig. 20 and 23-25 © Tim Lucas, Fig. 21and 22 © Ian Fussell.

4.7
Digital Design and Fabrication of Carbon Fibre Beam Prototypes with Stress/Deflection Analysis Driven Envelope Morphology

Dirk Krolikowski and Davide Costa [i]

The Paper discusses use and transfer of existing material technologies from the automotive and aviation industry and implementation thereof in a prototypic trial assembly for structural static, dynamic and architectural validation. The prototype is a beam component part of a proposal for an assembly of an entry structure of a high specification development in the UK. The composite carbon fibre beam component provides all necessary milled stainless steel connection fittings within its carcass for further component interfaces like façade and column connections, resulting in a highly integral solution. Structurally it is classified as a monocoque that supports loads via its external stressed skin, as opposed to a frame or truss which carries shear through the section itself.

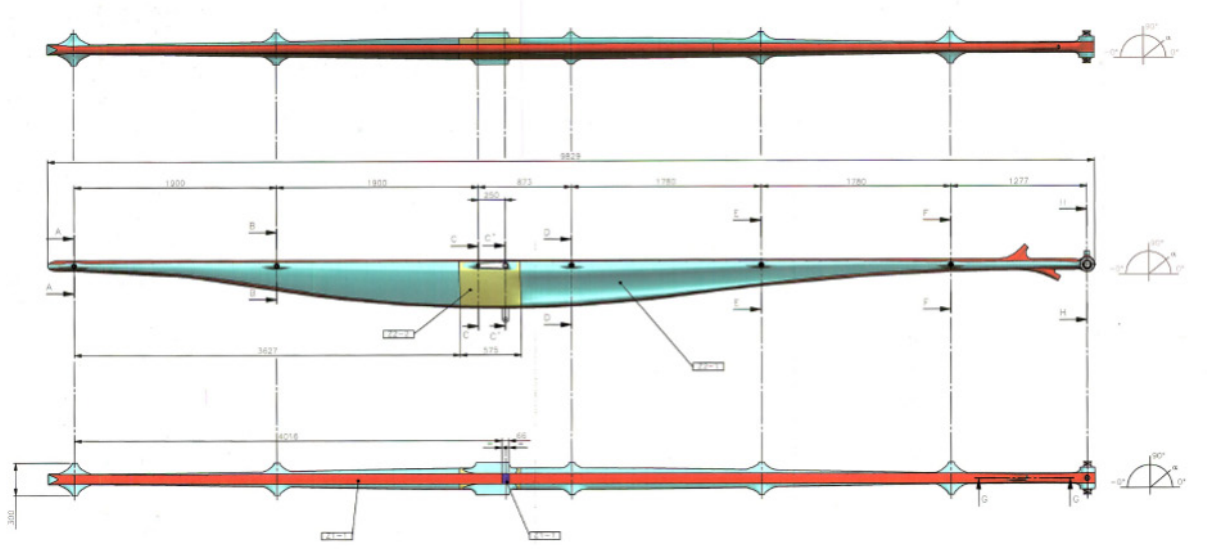


Fig 4.7.1 Composite carbon fibre beam component – the morphology of the component reflects connection requirements as well as defection and stress analysis

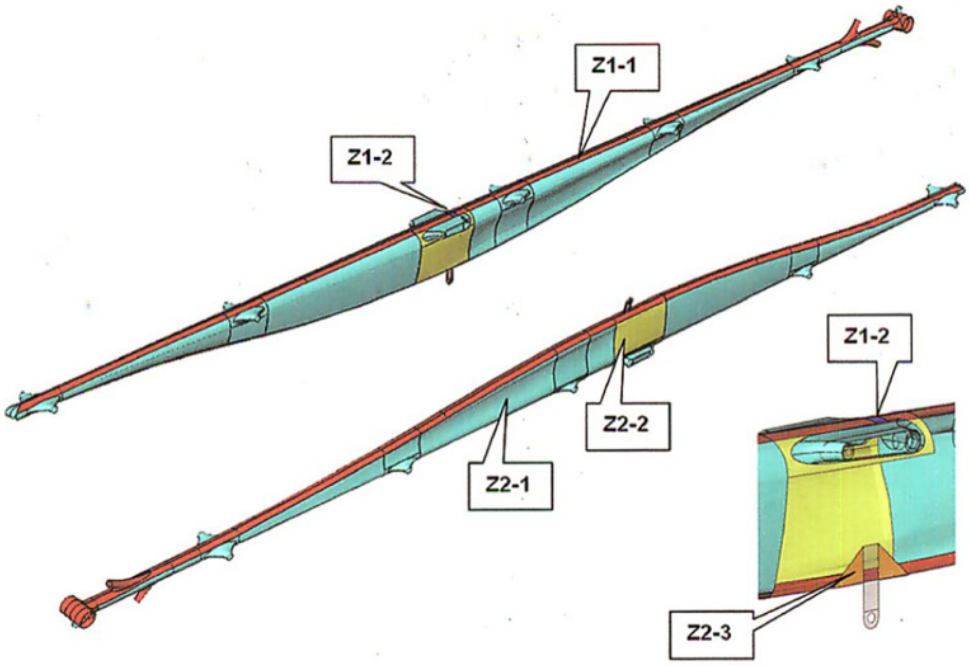


Fig 4.7.2 Composite carbon fibre beam component - carcass branches out to form connections, inspired by biomimetic strategies for highest functional integration and shape optimization

The material technology

The employed material technology for the prototyped integral Carbon fibre beams is transferred from the high-end automotive industry where it is commonly used in the formula one racing class. It is applied in the manufacture of racing car monocoques, body shell sections, wings down to gearbox casings and suspension parts. The use of CFRPs (Carbon Fibre Reinforced Polymer) is also common in the aeronautical industry where it is increasingly replacing traditional methods of construction. With the 787 Dreamliner Boeing make extensive use of composite material for airframe construction to a revolutionary degree for commercial aviation. The airframe constitutes to almost 50 percent of CFRD or other composites realising significant weight savings in comparison to conventional aluminium designs, capitalizing on CFRP's weight, corrosion resistance and fatigue properties. Carbon fibre monocoques are about 3 times lighter and 4 times stiffer than conventional construction a method of fabrication that results in a superior rigidity to weight ratio. Specialist manufacturers where engaged through out design to production to provide the design team with the necessary knowledge and insight into fabrication methods and access to specialist tools like large size autoclaves (D=2.5M L=12.0M) for the 10metre beam components. Cure cycle conditions are 980mbar vacuum at approximately 21°C with heat up to 120°C for 16hours. These parameters vary component specific due to the exothermal effects of resin curing where thick laminated zones occur. The chosen resin has a relative high glass transition temperature providing a good safety factor for the given maximum service temperature.

The main material for the beam body is a ±45° biaxial fabric from a family of fibres that guarantee minimal deformation due to their stiffness. The fact that the weaving patterns of the chosen fabric are very course has been validated as architecturally advantageous. CFRP material technology is not very common in the building industry. Particular issues in achieving appropriate fire ratings have limited the use of fibre composites in the industry generally. However, the development of refined fire engineering techniques have made a application in instances possible, justified by sophisticated analysis and strategies.

The Digital Workflow

The aim was to sculpture the morphology of the component to reflect connection requirements as well as defection and stress analysis, resulting in a differentiated sectional composite beam geometry. Along its section the geometry responds to in plane forces and mitigates against secondary forces caused by flexural deformation. This leads to a form that legibly reflects the forces it carries and responds in a highly material efficient way. At the same time all connection fittings were to be embedded within the actual carcass to achieve the highest degree of structural and functional integration. This includes shape manipulations where the carcass branches out to form a connection, inspired by biomimetic strategies for highest functional integration and shape optimization. The digital workflow incorporated several generations of Rhino 3D models, which underwent an iterative and sophisticated finite element analysis to understand and incorporate geometry requirements as well as to meet structural performance criteria. Rhinoceros models were driving the final CAD/CAM manufacturing process. The digitally prototyped beam carcass provided machining data for a CNC-milled moulding process to arrive at a female mould, which was used for final production.

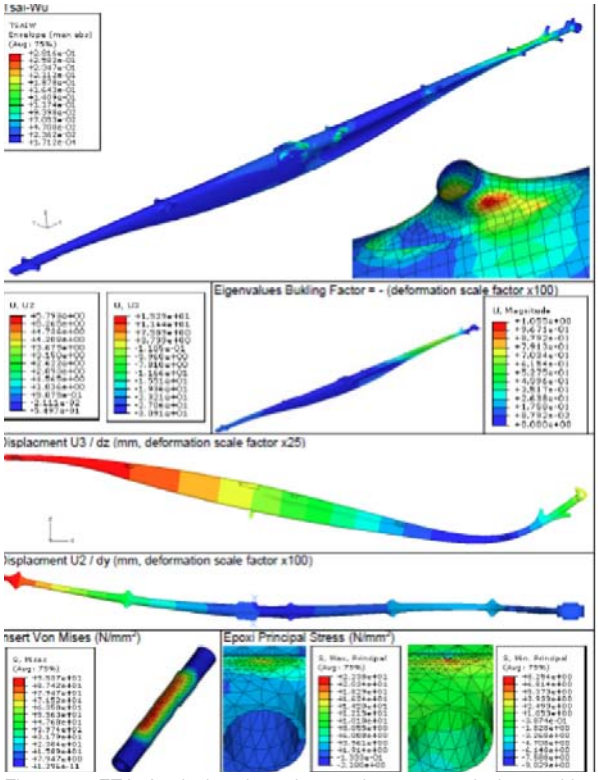


Fig 4.7.3 FEA Analysis- defection and stress analysis resulting in differentiated sectional composite beam geometry. Along its section the geometry responds to in plane forces and mitigates against secondary forces caused by flexural deformation.

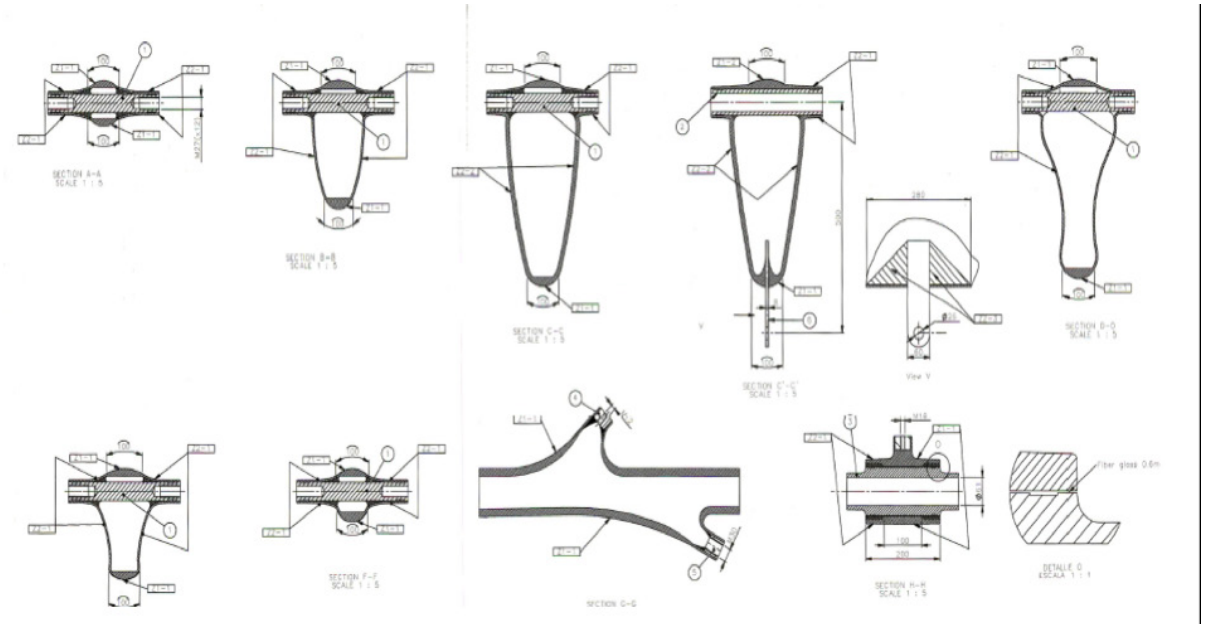


Fig 4.7.4 Integral carbon fibre beam carcass with differentiated geometry cross section

The software methods for structural analysis varied through out the different stages and was based on the laminate theory applied to a finite element model. In general static linear analysis has proven to be sufficient during Preliminary design as only small displacements were expected. In case of the detection of geometrical non-linear effects the analysis type was to be switched to non-linear. In addition a modal analysis and buckling analysis for natural frequency determination has been carried out for about 400 load cases. The aligned carbon fibres of extreme rigidity minimize creep effects, which consequently have been neglected for analysis. Optimized material fibre directions for fabrication were direct output of the complex analysis process.

Fig 4.7.5 a. Carcass front with steel fittings and branching connection geometry, b. Carbon fibre weaving pattern

Fig 4.7.6 One of many prototypes of the carbon fibre beam carcass

Prototype Tests

The performance of the component was tested in a series of trial assemblies and proved validity of design assumptions like serviceability and its linear behaviour. The test rig consisted of one beam component with column supports and lateral restraints. During testing loads were applied incremental with the use of 10mm steel plates. Deflections and strain were continuously monitored via a computerised gage system confirming that torsional rotations under load are minimal. Mayor aspects of the architectural validation process were the employed weaving and arrangement methods of the carbon fibre textiles for which several variations were prototyped and tested. Fig. 7 illustrates a load test of a beam component to test anticipated deflections and buckling behaviour of the 10M component with a self weight of approximately 70kg. This research proves the potential of transfer of existing material technologies and manufacturing processes from other disciplines for the building industry, driven by prototypic test assemblies.

Fig 4.7.7 The performance of the component was tested in a series of trial assemblies and proved validity of design assumptions.2

Acknowledgments

Architect: Rogers Stirk Harbour+Partners
Partner in Charge: Amo Kalsi
Concept Engineering Consultant: Expedition Engineering
Manufacturer/specialist and engineering:
Strain Engineering /Bellapart/Nexus Technologies/Mira Technologica

References

i Davide Costa is an architect and Associate at Rogers Stirk Harbour + Partners, projects include The Berkeley Hotel Canopy, Termal 5, Haethrow Airport and Monte Carlo Sporting D'Hivers. Dirk Krolikowski RIBA Dipl.Ing. (Dist) is architect and Associate at Rogers Stirk Harbour + Partners, projects include The Berkeley Hotel Canopy,The Leadenhall Building and One Hyde Park. He is also a Lecturer in Innovative Technology and Design at The Bartlett University College London.

ii Image credis: © Bellapart/Nexus Technologies/Mira Technologica/ Strain Engineering

4.8
Keynote: Third Generation Light Weight Vehicle Architecture

Mark White [i]

Keynote: **Mark White** is Chief Technical Specialist, Jaguar Land Rover [JLR], where he is responsible for all Body Engineering, System Strategy, and Research and Advanced Projects at JLR, with focus on design and development of new body structures, including new platform development and light weight vehicle (LWV) development. He has worked for JLR for over 25 years having graduated from The Coventry University with an Honours Degree in Automotive Design. The Range Rover 2013 is the third generation of lightweight body architecture Mark White has researched, designed and developed with his team at JLR and industrial collaborators, in particular the UK aluminium industry.

Fig 4.8.1 The Range Rover 2013 is the third generation of lightweight body architecture

PERFORMATIVE

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PANEL CHAIR: MICHAEL STACEY

5 PERFORMATIVE

5.1 Keynote: Bricolage / Bricoleur
5.2 De-Fabricating Protoarchitecture
5.3 HubPod: A Prototypypical Design System for Acoustically Diffused Enclosures
5.4 Soundforms
5.5 Soft Kinetic Prototypes for Adaptive Architecture
5.6 Keynote: Prototyping for Extimacy: Emerging Design Methods

5.1
Keynote: Bricolage / Bricoleur

Frank Barkow

Frank Barkow studied architecture at Montana State University and the Harvard GSD. He is Professor at the Royal College of Art in London and has recently taught at the EPFL in Lausanne, Harvard GSD, and University of Wisconsin in conjunction with his firm winning the Marcus Prize for Architecture. In 1993 Frank Barkow and Regine Leibinger founded their practice in Berlin. Their interdisciplinary, discursive attitude allows their work to expand and respond to advancing knowledge and technology. Recent projects include a gatehouse and factory-campus event space in Stuttgart Germany and the TRUTEC Office Building in Seoul. Current research projects have focused on digital laser cutting; infra light concrete, facade systems, space-frames, and ceramic elements. Current projects in Berlin include a high rise near the main train station for CA Immo Developments. Barkow Leibinger's research work was shown recently at the 4th Marrakech Biennale and was included in the 11th Architecture Biennale, Venice, Arsenale Show. It was shown at the Architectural Association in London and 032c Gallery in Berlin in conjunction with the publication of the catalogue An Atlas of Fabrication. Their work is in the permanent collections of MoMA, New York where it is currently on display, the Heinz Architecture Center, Pittsburgh, and the Deutsches Architektur Museum, Frankfurt.

Revolutions of Choice

Revolutions of choice signifies architectural opportunity as driven by the rise of digital capabilities and competences but also something more essential: an architect's longing for the agility, authority, and ability to predict and control the very nature of architectural making arising from our imagination. We began to ask ourselves how can we better mediate between the tools we use and how they might inform an architectural outcome? Perhaps symptomatic of our restless generation is an oscillation between practice, research, and the academic studio. In doing so an experimental thread unites these areas of endeavor further mediating between the speculative and practical emphasizing discovery that can be measured, judged, and eventually be made useful. Some of this is a critical resistance to the status quo of the building cultures we find ourselves in but the following examples speak more accurately to the profundity of ideation and the handling of materials as a mutually intertwined activity.

Design follows technology. Identifying and harnessing new technologies coupled with curiosity and imagination reinvigorates a process of making and invention. This orientation empowers architects to become our own best experts in assessing technology and developing innovative applications to achieve design goals. This challenges the standard building catalogue where architectural elements can be developed within the practice instead of relying on manufacturer's products. This is an inclusive and comprehensive expertise, which intersects design with sustainability, economics, materiality, and time-management where we are in a position for best determining an outcome.

Our practice has been transformed significantly in the last fifteen years where digital and analogue processes have been integrated through all project phases from initial speculative experimental research to conclusive building projects. Designing assembly, as a material issue, is the most characteristic aspect of this shift. Developing an understanding of how tools shape materials that constitute surfaces, form, and space marks a production path and workflow that reverses how we worked previously at the outset of our practice. Our competence in digital technology has evolved from being initially and exclusively limited to its use as a drawing tool to its now expanded role where digital is a guidance system for tooling materials. Locating an expansive network of fabrication partners, tools, and testing sites has been essential to supporting this research. Much of our recent work has been supported by access to emerging technologies outside of traditional architectural boundaries such as the automobile and machine tool industries to cite two current examples.

With this expanded role of digital processes in our practice, we have developed a workflow that links initial research to final realization of a building. Three focus areas locate how this work develops and evolves in a research-based practice.

Off-Cuts

We start by setting up a research area of experimental prototyping that is specific to a material and a digitally controlled tooling technique. This initial step tests materials against a machine to develop a range of possibilities for transforming the material independent from a particular utility, purpose, or economic constraint. This produces a body of work or archive that is architectural latent, scale-less, (other than it's own physical size) and open-

ended to how it might be applied. The archive is constantly being added to or edited if a better method is discovered along the way. Material is tectonically transformed by a tooling action (bending, cutting, stacking, casting, etc) and typically involves a serial logic of repetition and differentiation allowing individual material components to aggregate and join to one and other to form larger and more complex systems. Tools are understood and explored precisely in terms of their capabilities and limitations to transform a material.

Often this work begins with student interns who are asked to investigate a particular CNC or digital machine and learn its capacities including what type of action it is capable of and on what materials, the speed of production, and economic consequences, etc. After gaining this knowledge, we begin to speculate and design work-pieces or "off-cuts" that test the limits of the machine. In other words, this is the search for an architectural prototype that emerges from the control and constraints of a technical system. These off-cuts are catalogued in inter-office manuals, our website, and more formal catalogues such as the *An Atlas of Fabrication, AA Publications*,[ii] available to all designers throughout the practice.

Scripting software offers another degree of digital exploration and control, initially applied to generate abstract patterns incorporating both repetition and differentiation, now used to solve complex geometric construction problems. This know-how, often brought to the practice by student interns, flattens an inter-practice hierarchy where student/ architects take lead roles on project development that in the past they would merely support. This is an essential part of the academic studios that we teach within the context of the practice. These internships, with accessibility to technology and professional consulting, make for compelling supplements to traditional academic training where academic work (far removed from practice and industry) is complimented by architectural apprenticeships where the reality of ideation and production can exists as simultaneous and overlapping activities.

The identification of fabrication partners offers us direct access to a range of industrial machines to conduct our research. One of our initial partners, Trumpf GmbH is a leading machine-tool manufacturer in Stuttgart who introduced lasers to the cutting of sheet metal in the 70's. Their large and expanding line of machines helped set up our initial archive of "off-cuts." While architectural applications of their machines is a minor portion of their market the possibilities are enormous and this relatively new initiative is well under way. Another significant partner is Holzbau Almann a fabricator more directly involved in construction who has the capacity to digitally cut laminated structural timber and assemble these components on-site, a process which was utilized for our Stuttgart Cantina project.

In order to maintain this research area as a vital source for architectural applications it requires an initial autonomy. This autonomy enables an experimental approach where the possibility of success (or failure) is independent from ongoing project deadlines, budgets, codes, or other forms of restraint that would hinder a more inquisitive approach. This cannot be underestimated and is especially critical in the context of a German building culture that is highly regulated and controlled. This is achieved in our practice by a rotating team of students and architects designated to work on research projects as they develop. Research also takes place in an academic setting when a fabrication partner and/or technique is

introduced to explore design in relationship to a specific technology. At the Harvard GSD, we teamed with Chris Bangle of BMW and used his concept car GINA (a kinetic/ elastic concept for a car body and interior) as a way to re-think American suburban housing with an emphasis on sustainability and production. At the EPFL in Lausanne we teamed with structural engineer Mike Schlaich to explore Infra-light concrete as a sustainable self-insulated concrete that can now be poured with digitally produced formwork that can be mass customized.

Digitally fabricated components are assuming a larger and more comprehensive role in our buildings. When a building project begins, the research work is activated (as appropriate) from the archive (or developed for a specific ongoing project) where it becomes a possible candidate to use on the project. A single building project might employ one or more research projects that might be applied as built-ins, cladding, facades, or even primary structural systems. At this stage experimental research is more thoroughly tested to better understand its appropriateness and adjustability to solve building systems at this application level. Modeling here occurs at scales of 1:50 up to 1:1. At this stage we determine if we can use the same fabrication partner from the research phase for construction or if we need to change. This stage of research is still developmental and inconclusive.

One to One

The one to one construction mock-up, historically in use for some time now to pre-determine a building's appearance, scale, color etc., has evolved to where aesthetic effect is understood more comprehensively in direct relationship to physical performance (weather, structural robustness, sustainability and tectonic physicality), its viability, and how it can be made in relationship to its economic and time-managed buildability through digital means. The digital mock-up offers slight changes to be made easily allowing a more refined understanding of comparable choice.

The one to one prototype is a hinge between initial design research and building execution and is used both as a mock-up for client approval (as mentioned above) and also for architectural installation and exhibitions. Depicting nothing more than itself, the one to one architectural installation offers an intermediate test between experimental research and final building. The installation is a format that offers a public forum that helps direct internal experimental speculation where materials and tooling techniques can be tested technically and experientially as viewers engage and occupy it physically and spatially. Contrasting a fragment of an incomplete whole (mock-ups) the installation offers a complete autonomous architectural proposition in full effect.

The exhibition/ installation and mock-up are also instrumental in offering an alternative to the enduring and troubling gap between representation (historically models and drawings) and building. With digital software acting as a guidance system for tools rather than merely producing visual representations, we use one to one scale constructs to extend the current limits of the architect's imagination and engagement with the building process. We refute the tendency toward representing architecture virtually or digitally as a superior alternative to the physical prototype and maintain a commitment that the experience of material, effect, and haptic workability cannot be adequately simulated. A material's atmospheric effect as situated on-site is unpredictable. Light, weather, and movement are just some of the

many conditions that no digital simulation can perfectly predict as a physical architectural outcome. Because of this, the one to one is an instrument that we front-load into the design process so that it can be more effective as a design tool within the whole process rather than remain exclusively as a final check before construction.

The digitally fabricated one to one also sets up new solutions for off-site assembly processes with all of the advantages of pre-fabrication and its ability to accelerate building schedules, reduce waste and improve quality, accuracy, and precision. A digitally fabricated building component can be assembled off-site as a larger but still transportable element that is then assembled on-site and "just-in-time" with other systems, speeding up construction and requiring a much smaller on-site staging area. Digitally coordinated assembly processes can then manage the aggregation of complex pre-fabricated components arriving on site to couple with other large components eliminating the necessity of tooling materials on-site sequentially, one at a time, to construct a building. This thinking happens throughout the design and building process, both off-site and on-site where fabricators and architects work collaboratively to plan both the fabrication of construction components and also anticipate how these components are combined and assembled on-site with all of the other like or unlike systems that make up a building. Again, considerations relating to fabrication, assembly and site coordination are front-loaded and digitally integrated into design processes.

References

i Frank Barkow, Director of Barkow Leibinger, in 1993 he and Regine Leibinger founded their practice in Berlin.

ii An Atlas of Fabrication: Barkow Leibinger, Architectural Association Publications, London, 2009

5.2
De-Fabricating Protoarchitecture

Bob Sheil [i]

> *"Tools provide possibilities, from these possibilities we discover advantages, advantages become a convenience, and convenience can too easily become a convention. There are alternatives: rather than supporting just the more efficient execution of conventional tasks, tools can encourage new ways of thinking. The creative use of a tool should include opportunities for the designer to embed his own design logic within that tool. Such customisation should be recognised as a key aspect of design creativity."*
>
> Robert Aish[ii]

This paper has developed from a short article that first appeared in the *Material Computation* issue of Architectural Design in February 2012. It came about through an invitation by the publisher to pose a counterpoint to the issue's overarching themes, and was framed at that time as piece entitled *Distinguishing between the Drawn and the Made.* Rather than construct a deliberately opposing critique of the work described in the issue, the aim of the article was to reflect on a series of underlying issues associated with building things from digital data, a discipline many in the construction industry are still grappling to master. Robert Aish, someone who is a master of this technology is the author of the quote above. Apart from his pedigree as a graduate of Industrial Design at the Royal College of Art, where he studied under David Pye, his PhD in Human Computer Interaction from the University of Essex, his career as a senior engineering software developer with Arup, Rucaps, Intergraph, Bentley, and now Autodesk, and his role as a consultant for many of the world leading practices and universities, it is his early experience in the shipyards of Gdansk where he managed information generation for the fabrication and assembly of hull components that strike me as a formative reference behind these remarks. It is such underlying knowledge and tacit experience in the physical and tactile that forms the basis of this paper and the work it refers to.

Fig 5.2.1 Manufacturing Protoarchitecture 1: In the foreground, early components of the '55/02' shelter by sixteen*(makers) in collaboration with Stahlbogen GmbH. In the background components of more everyday fabrications by Stahlbogen. For the former, precise assembly of the digital model was not a project objective, for the latter, it is a quality upon which the business depends. Material: Steel

Fig 5.2.2 NW Projection: 55/02 Kielder 07.03.10 1643 hrs: Partial scan of shelter 55/02 at Cock Stoor, Kielder Forest and Water Park, Northunberland, UK. 3D survey carried out by ScanLAB Projects.

Set within the context of design and fabrication tooling of ever increasing definition and adaptability, the ideas this paper shall explore are:

- The status of the dynamic and adaptable digital design model in relation to the physical results that are built from it;
- The status of the resulting physical assembly as an architectural prototype, and:
- The difference between the drawn and the made.

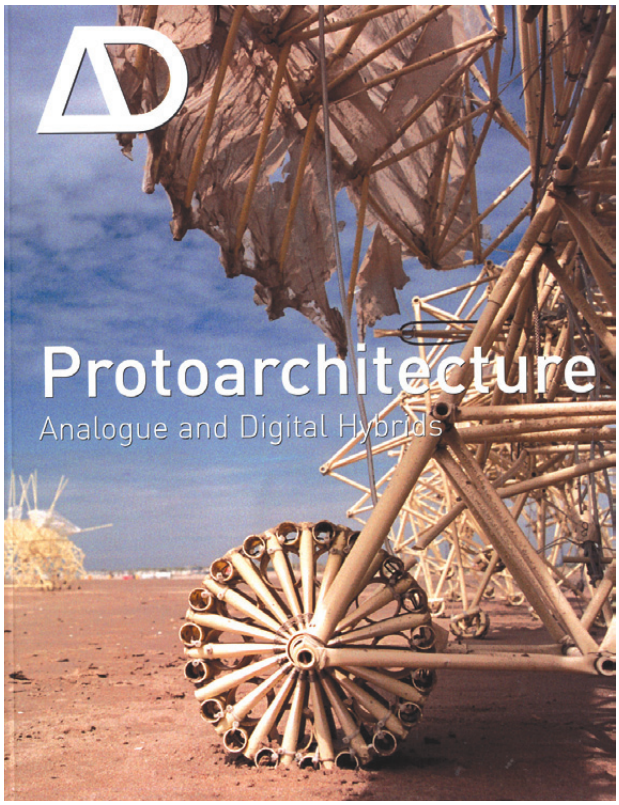

Fig 5.2.3 Protoarchitecture: Analogue and Digital Hybrids

This paper also draws upon and refers to the publication '*Protoarchitecture: Analogue and Digital Hybrids*' (Wiley July 2008)[iii], and a forthcoming title *'High Definition: Negotiating Zero Tolerance'* (Wiley January 2014)[iv], currently in development. Each of these publications seek to examine parallel and immediate developments both in practice and research that present new challenges to established methodologies in design and fabrication. The former title explores the beginnings of a recent period in architectural history (circa 2000-2007) where a significant and growing proportion of experimental design was not exclusively colonised by computational processes or computational theory. The rose tinted glasses of the computational age were slipping off, and a hybrid world, dense with the feedback of unpredictable, inconsistent, and unexpected results was readdressed as a defining ingredient in making architecture.

The term *Protoarchitecture* has been adopted to reflect work that is part real, part ideal, part resolved, and part in progress. It also recognises propositions that are prompted by a compatible interest in analogue and digital techniques and thus parallel constructs of the physical and the virtual. *Protoarchitecture* captures work that does not conform to type, is exceptional, experimental, and transgresses habitual practice in representation with that of making. Examples of work argued in this context include amongst others that by the Founder of the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba, Professor Mark West[v], the products and environment of 'La Machine' in Nantes led by Pierre Orefice and Francois Delaroziere[vi], 'Strandbeests' by Theo Jansen[vii], 'Prosthetic Mythologies' by Kate Davies and Emmanuel Vercruysse of Liquidfactory, and 'Robotic Membranes' by Mette Ramsguard Thompson of the Centre for Information Technology in Architecture (CITA) at the Royal Academy of Fine Arts Copenhagen. Each of the presented works not only portrayed an alternative and critical approach to practice, but an alternative and critical role for the designer as an active participant in the work's production.

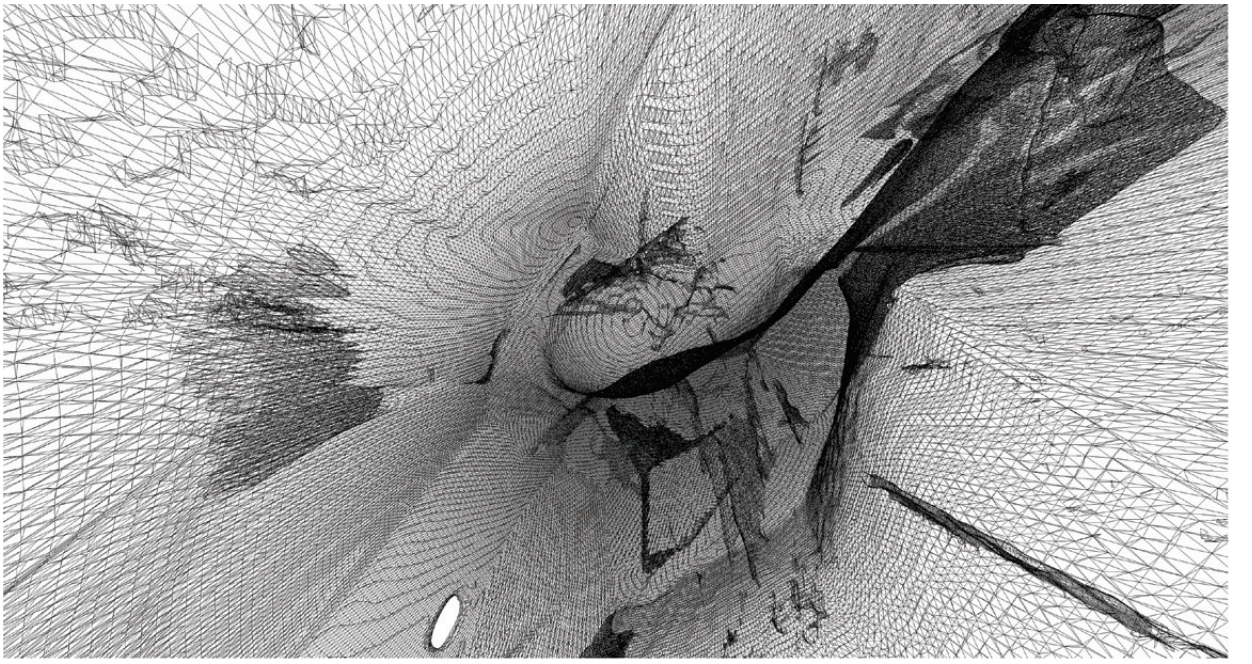

Fig 5.3.4 Subverting the Lidar Landscape by Matt Shaw (Bartlett School of Architecture MArch Unit 23, 2007-09). The point cloud image of a speculative building component is captured from a 3D laser scanner. Material defects and unseen anomalies are detected by the scanner and appear in the point cloud as digital noise. We have yet to fully understand the behaviour of real materials in digital space. Materials: Polymers, grease, hardwood, gelatin and steel

Six years on, *High Definition: Negotiating Zero Tolerance*, 2014, is exploring subsequent developments in design tooling and practice. Central to this forthcoming publication is an examination of Light Detection and Ranging Technology (LIDAR)[viii] in architecture; Presently capable of capturing distances up to 6000m in radius (or more if launched from airborne positions) and generating 3D point clouds to an accuracy of less than 1mm, such tools offer unprecedented accuracy for the development and interrogation of design strategies before, during and post production[ix]. With its roots in the automotive production industry, and applications in crime forensics, mining and marine engineering, mechanical verification,

medicine and landscape, the use of 3D scanning instrumentation in architectural design opens up entirely new avenues of understanding and engagement with the complexities of context, form, behaviour and volume that heretofore have been crudely approximated, or poorly grasped. As the designer's array of digital tools to propose and make their ideas has become significantly enriched in recent decades, the component of armoury that has remained out of step with potential has been the means to navigate, embed and verify design outcomes as they emerge in context. LIDAR technology has begun to transform this problem.

Without such tools, the exploitation of greater levels of precision, complexity, and dynamic composition in design representation, is curtailed by unmatched resources in execution and delivery. Today, through affordable 3D LIDAR technology and it facilitation of high accuracy data capture[x], this gap is narrowing. Complex design propositions in a number of file formats may be tested and developed within three dimensional point cloud files that are accurately referenced into real environments. Likewise, built work may be scanned and cross referenced to the design information from which it was produced, thus offering a clear mapping of the real upon the ideal. Yet to date, the subject of high accuracy, zero tolerance design production has been exclusively published through didactic, scientific and mechanical themes. How does the technology work? How is it used, etc? This publication will explore such themes on a level of creative and speculative critique, that range from its stretch capability to how it challenges the role of the designer.

Residing within the context of adjacent themes on high definition, examples of work to be argued in this context include the self-assembly works of Skylar Tibbets at MIT, information production, flow and procurement at Gehry Technologies, and the boundaries of surveillance technology explored by Andy Hudson-Smith at the Centre for Advanced Spatial Analysis, UCL, and others who will be referred to later in this paper. Running as a critical subtext is a discussion on the role and value of zero tolerance as a design and fabrication standard. Negotiating zero tolerance asks us to define an appropriate proximity to high definition technology within an industry still very far removed from the laboratory facilities of its automotive or aeronautic cousins.

Fig 5.3.5 Incisions in the Haze from the Prosthetic Mythologies project by Kate Davies and Emmanuel Vercruysse of LiquidFactory (2012). The alchemy of the sand casting is magical. The foam form is buried in sand, packed down and engulfed in its cocoon, molten metal is poured into it, dissolving and replacing the foam - transfiguring it - when the form boxes are opened a fiery hot object shrouded in smoking burnt black sand emerges. Materials: Sand, Aluminium, Gas.

"There is a great deal of mythology associated with craft – and with professional practice generally".

Peter Dormer – The Art of the Maker (1994)[xi]

Not To, but Through

Over the past three decades computation in architecture has developed an array of powerful tools for the development and evolution of geometric complexity. It has also provided the design and construction industry with additional tools and processes that modify the protocols and connectedness of visualisation, production and procurement[xii]. Yet crossing the material threshold raises significant questions regarding; the objective of digital information as an instruction to make, the subsequent status of the built work being generated, and the difference between simulation and fabrication. Prior to the adoption of computer-aided design (CAD), architectural drawings were made using cumbersome tools that had not changed in any radical sense for more than 2,000 years. Other than the evolution of more precise instruments and more stable materials on which to draw, the standard toolset of the architectural designer remained remarkably consistent until the late twentieth century. For the architect who has wished to break from tradition, one of the greatest challenges has been to transcend the limited possibilities of these tools and understand the difference between design propositions that are possible to make but difficult to draw, or possible to draw and difficult to make[xiii]. Lurking within this equation was intent, a design intent that existed between the drawing and the artefact, and one that relied upon conversation with other disciplines, trades and experts to be fulfilled as a physical entity[xiv]. Implicit information on the specific production tools that might be used to make the design, or how such tools should be used, maintained, deployed or controlled, was limited.

Fig 5.3.6 Terra Therma by Peter Webb (Bartlett School of Architecture MArch Unit 23, 2008-10). Ideas and materials are metaphorically and literally extrapolated from a site in North London and developed as prototypical building components for a space of variable temperature and humidity. The elements are extruded through a digitally controlled variable jig. Materials: London Clay.

Only in instances such as the illustrated profile of soft joints, or the geometry and materiality of a specific mould and surface for casting, might visual information alone and the technique of how the desired result be made become synthesised. If not conveyed in this way, or augmented in specification clauses, decisions on production tooling were placed in the domain of the fabricator who took responsibility for the selection of appropriate tooling, standards, craft, durability, use, appropriateness of specific material samples, finish, delivery, and so on. In this context, it was understood that the architectural drawing as an instruction to make was highly constrained and limited, and that its primary focus was to define and secure the required outcome while allowing essential room for negotiation on how this was achieved. For the architectural design to be made, other drawings, such as shop drawings, were required as a rehearsal to making.

The nature of this exchange has been significantly altered by CAD/CAM, the fusion of drawing and manufacturing technologies that plug design information with the production equipment that makes what is described. Despite the many advanced levels of capability, this technology provides, its potential to release design constraint, open new frontiers, and extrapolate results not previously achievable has the potential to bypass many of the essential transactions between design and making that are incorporated in the exchange between either field of expertise. Thus not only has the architectural drawing altered its role as a carrier of design information, so too has the architectural model, the prototype and the speculative construct. The neat divisions that once commissioned, sequenced and qualified these key productions are converging, and the degree of cross-fertilisation between each mode of representation provided by digital tooling has generated a turbulent network of information flux.

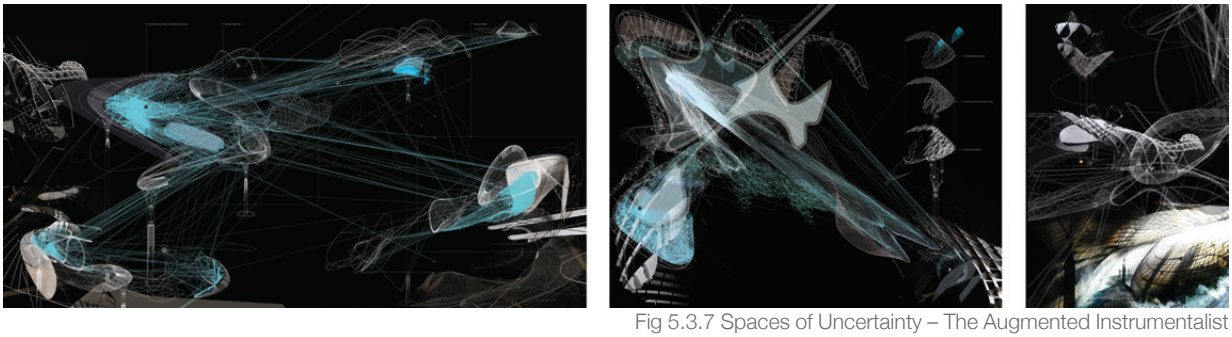

Fig 5.3.7 Spaces of Uncertainty – The Augmented Instrumentalist by Emma Kate Matthews (Bartlett School of Architecture MArch Unit 23, 2010-11). Composite model, acoustic simulation, and sound perspective of a small listening chamber for a proposed performance space on the Venice Moses Barrier. Design as a hybrid of digital representation, physical representation, manufacturing data, sound clips and environmental simulation. Materials: Steel, concrete, air.

The transposition of the performance of physical materials into a computational realm that subsequently decants what is explored back into a physical realm is a sequence of challenging translations. In the first instance it seeks to identify a direct relationship between the performance of digital and physical matter, and secondly it seeks to interpret highly complex, dynamic and living systems as a template for form generation. Quite apart from the inevitable selectivity involved, such an approach has the potential to reduce architectural production to a systematic selection exercise devoid of the immeasurable and immaterial qualities that make it more than the sum of its parts[xv]. It is the manner in which design information allows for indeterminacy and anticipates the possibility of how it can be made that make it work in the form of a built artefact. The skill in describing architecture before it is built is to make design information that anticipates, rather than dictates, how it is translated through time, site, materials, fabrication processes, assembly and use, and to understand the difference between the first prototype and the last.

One of the potential problems facing the age of digital fabrication is its heightened reliance upon data made by experts with a lot of experience in representation, geometry, form, and the illustration of materials, but less with experience in how things are made or perform. Unless the designer is located in the place of production and is at least a witness to on site decisions on issues such as tool paths, machine rates, material orientation, and makeability, the integrity of their information is a risk. And without such critical links, the built artefact is at risk of becoming no more than a physical render of a projected image where the exploration of its performance as a construct ceased at the point of simulation. With the exception of highly simplistic or linear tasks such as mono material 2D cutting or 3D printing, the jaded phrase ‘file to factory’ is a overly simplified term. A more accurate and helpful term to describe the communication of data between designer and manufacturer might be ‘file through factory’. The key change conveys more clearly how the journey is not entirely one way, nor does it cease to evolve at the moment it is transferred from the former to the latter[xvi]. This argument has been further developed as an idea of persistent modelling by Phil Ayres at CITA[xvii].

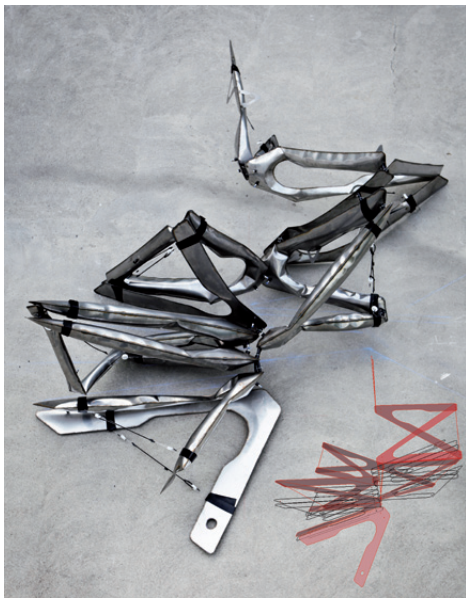

Fig 5.3.8 Digital Material from the Persistent Model Project by Phil Ayres (2010).

The Birth of the Protoarchitect

Constraints of any kind have long provoked designers both positively and negatively, but as the means to describe design escalates and expands, and the imagination of form, language and complexity is stretched, the question of what conceptual strategies inform the making of a design has become increasingly ambiguous. Key to ensuring that design concepts acknowledge manufacturing constraints is the need to remain critically aware of the difference as well as the similarity between drawn and made things, and how both are produced. Digital manufacturing processes have nevertheless injected a lot more freedom in the domain of the designer, and ideas that might have remained as an experimental esquisse in a previous age are being manifested in physical form to levels of fabrication completeness previously in reserved for the finished article[xviii]. Such early resolution presents the work in a category beyond conventional notions of the prototype, but outside conventional notions of building. They are, I would argue, protoarchitectures of a particular kind; constructs that seek to test, validate, or exhibit speculative design propositions that have emerged through digital investigation of the visual and theoretical; as well as the technical (for example structural performance) or practical (for example workmanship). Such protoarchitectures provide a form of translated architectural evidence between the digital to the material, and as a consequence, exist as a form of proof of concept for research and design questions that lie beyond the artefact on view.

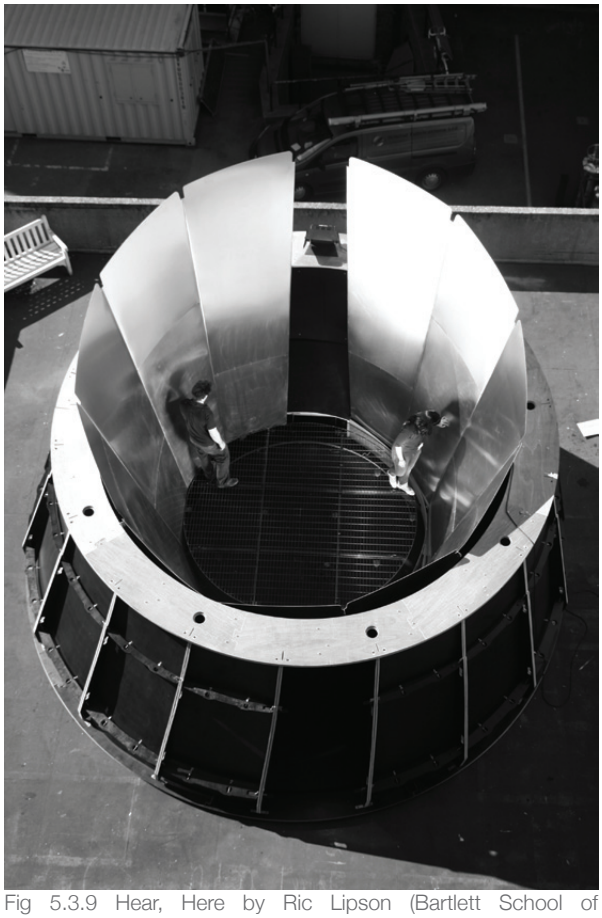

Fig 5.3.9 Hear, Here by Ric Lipson (Bartlett School of Architecture MArch Unit 23, 2007-09). A digitally prefabricated protoarchitecture that tests acoustic properties of a large-scale listening ear. Materials: Plywood, glue, paint.

These steps are further enriched by the resurgence of 1:1 built artefacts being produced at an increasing number of leading architectural research centres and schools of architecture around the world. The past decade has witnessed an incremental surge of investment in digital fabrication equipment by these organisations; including in some cases the commission of new prototyping laboratories or new forms of shared and expanded facilities with other parallel disciplines, such as civil engineering or computer science. Some have been additionally facilitated by establishing new facilities upon existing traditional workshops, where the experience and inventories of analogue conventions are informing hybrid disciplines, cultures and practices. In parallel to the development and analysis of design information in simulated environments, such fabrication environments are refuelling the visual and visionary exploration of experimental architecture through the essential gains of self production. Central to the significance of this resurgence are two ingredients, firstly co-production (that is the making of protoarchitecture by either by designers in collaboration with technical colleagues, or multi-disciplinary staff who operate in both realms), and secondly the location of design practice within the place of production[xix]. With both components in place such actions and facilities have the capacity to respond to clear requirement for new hybrid disciplines within the construction industry across design, fabrication, computation, and project management. Such new roles will also lead to strengthening the new relationships that are emerging between academia, practice and industry, triggered by the same shifts in technology.

Fig 5.3.10 Manufacturing Protoarchitecture 2: The fully assembled '55/02' shelter at the factory of Stahlbogen GmbH in Blankenburg, prior to dismantling, finishing and delivery to site. Material: Steel.

For the Protoarchitect set within this context, the as-built speculation provides critical feedback and essential verification unattainable in representation alone. Evidence obtained on how the work operates as a feasible and conceptual construct is derived by cross-referencing physical and digital tectonics, and by measuring how closely the built work resembles both the intent and embedded information of its digital master. Difference between both realms is a measure of its transformation through production, where the cause may not always be clear. This is of particular significance when specific claims are made for the status of the built work in relation to methodology of representation, technique, or associated generative rules that are transferred by its digital master. In this context, if an evident difference between the digital and the physical is not recognised, the resulting construct can only be regarded as a reality of a very exclusive kind; a beta-reality that is stage managed to demonstrate theoretical challenges in design, but not in manufacture, use, occupation or context. Where it is implied in particular that materials are synthesised as physical and digital matter[xx], one could assume that the palette of architectural materials selected for the physical construct should be capable of matching the behaviour of its avatar and visa versa. With the many challenges such an approach presents, this paper will now looks at a number of recent projects that cross the digital and analogue threshold where the difference between drawing and making is a defining principle of the work explored.

De-Fabricating 55/02

Adopting a built work as a test bed for these ideas, the 55/02 shelter in Kielder by sixteen*(makers) and Stahlbogen GmbH, was captured in 3D LIDAR one year post completion. As previous texts record[xxi], the shelter was designed as an oscillation of design decisions made in drawn and fabricated format at Stahlbogen's factory in Blankenburg. Although substantially digitally fabricated, the as built shelter carried many decisions that were made on the shop floor without being recorded on the digital design file. Some of these decisions involved component removal, others component augmentation or adjustment, where judgement varied between the practical and the visual, and also the work's identity. Key to understanding why such changes relate to the points above, is that all were made by the co-authors of the digital design file, who were also co-makers of the work, and they were decisions solely informed by the built work as it evolved, not decisions dictated by the drawing that preceded it.

As previous texts also record[xxii], this practice was adopted from the very beginning of the shelter's fabrication, notably on decisions surrounding the number, proximity and geometry of folds in the shelter's sheet steel skin. Had the facility of scanning been available at these stages, rather than post completion, many further decisions might have been effected. In the first instance, availability of 3D scan data for the chosen site rather than the GIS mapping (which was supplied) would most certainly have influenced primary design decisions such as site configuration, proximity to existing trees, footings layout, and more specific referencing to immediate context. Yet the availability of the technology soon after completion still offered scope to extract lost, hidden or new information, and to gain a deeper understanding on the utilisation of scanning technology as a design tool. For detailed description of LIDAR technology, how it functions, and is controlled, see Vosselman, et al (2009), or Bryan, et al (2009).[xxiii] For additional insight into the role of representation in developing 55/02 see Sheil 2012.[xxiv]

The scans that were subsequently captured and processed by ScanLAB Projects[xxv] were developed through the following illustrated steps. Through each step, this paper will conclude by examining the most significant consequences for design and fabrication strategies provided by the information acquired, and speculate on implications or revisions that might be adopted in future design or fabrication strategies now that technology is readily available. In the first instance, developments on how the data has been analyzed and visualized stem from a single visit to site in 2010. Similar to the manner in which LIDAR technology is deployed in forensic work,[xxvi] capturing was fully executed without clear expectations on what the data would be used for, or indeed what it would reveal. In this regard, capturing is a pure exercise in the comprehensive recording of high definition geomatic data that is tied into accurate positional coordinates, the greater the saturation of information the greater the scope for later analysis. To following steps illustrate the exercise, which was carried out by ScanLAB Projects, who also advised on the key insights described.

Fig 5.3.11 Data Acquisition

001 Data Acquisition [Fig. 11]

The image shows the placement of reference geometry and markers within the scene. Markers were placed to be visible from as many scan locations as possible, and 6-7 markers were visible from any singular capture point to provide redundancy and cross checking within the reference network. In future, such markers could be embedded within the built fabric as discrete permanent tags, and thus behave as design life registers as the work is made, transported, assembled, installed and used. Positioning of such built-in tags

may be reverse calculated to optimize later capture, thereby potentially easing the task of attaching applied reference marks on site.

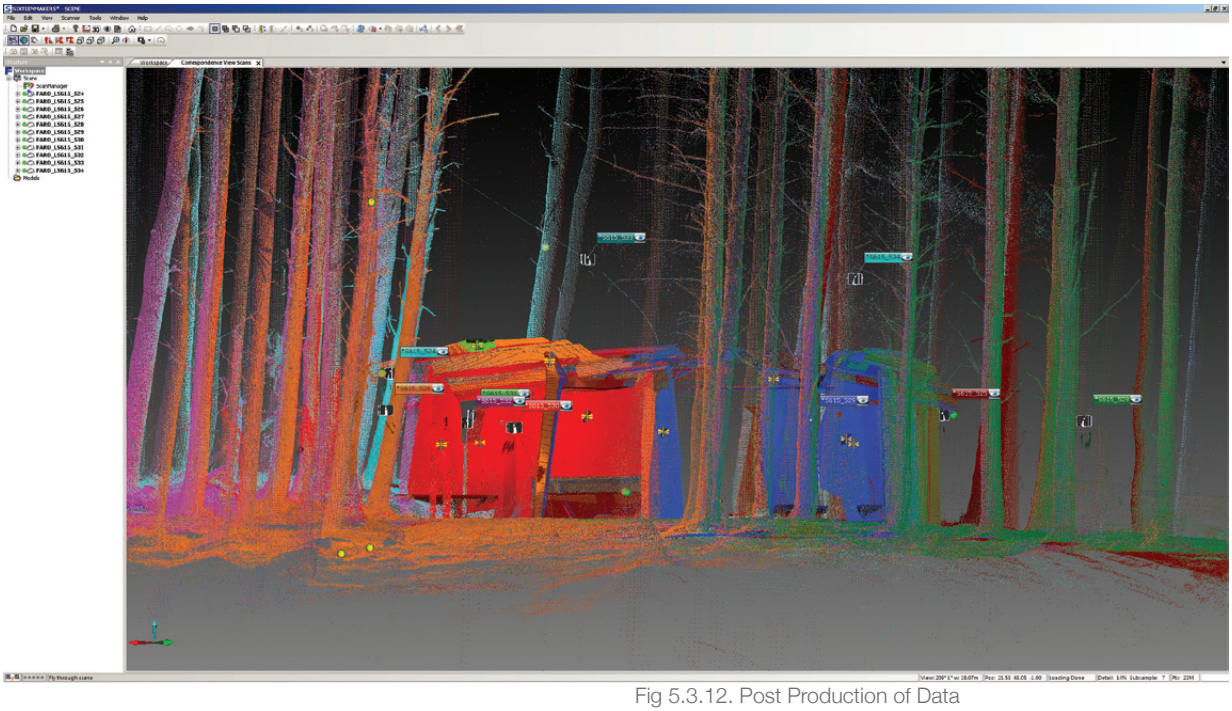

Fig 5.3.12. Post Production of Data

002 Post Production of Data [Fig. 12]

Scan data, including imported RGB values for every point in the cloud, is then passed through conversion software to produce a series of discrete point cloud models that are subsequently stitched together to produce a single cluster by snapping reference geometries. External geo-localisation of the data then places the cluster within a global context and a digital clone of the built work is generated. At this point the model has exportable value as a surveyed, visualization and interrogative tool in both 3D & 2D as animated or still imagery, or vectorised data. The Digital clone has clear value as an accurate record of the built work, but also as the data is rich in definition, it introduces value to the clone as a visually explorable and spatial record of the construct. In this regard, such data and its various visualization exports have currency as a rich 3D archive and verification tool, allowing later changes or removals to be compared against the ‘original’ built work. Examples of such applications are present in the museums and collections industry where the stable conservation of objects as well as spatial organization has particular relevance.

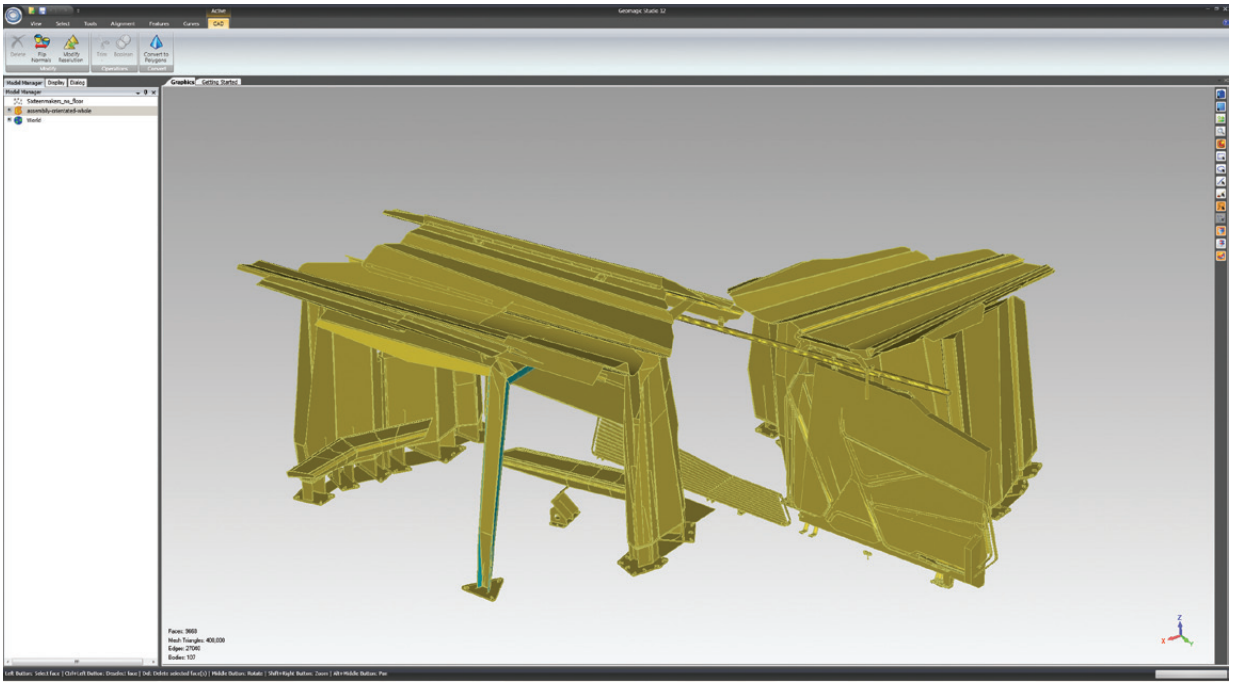

Fig 5.313 Import Digital Fabrication Model

003 Import Digital Fabrication Model [Fig. 13]

Although designed and made for amongst other purposes as a critique of design and manufacturing integration, the making of 55/02 reflects many of the challenging issues facing the construction industry on information flow and verification, albeit on a small scale. Whereas for 55/02 such bureaucratic hurdles were turned into a creative advantage for its hybrid and resident designer/makers, the industry at large faces a continuous challenge in grasping the multitude of unrecorded changes or amendments that are common to complex projects. Underpinning this cycle of continual verification of the 'as-built' back to the 'as-designed' is the stringent requirement to build the design that was agreed with planning and building control authorities prior to construction. Cross referral of as-built data as captured through 3D scanning to BIM data clearly offers an option on whether to concede or adjust these constraints. The next step in this sequence therefore is to import the final CAD model and 3D point cloud model into an environment where both may be superimposed.

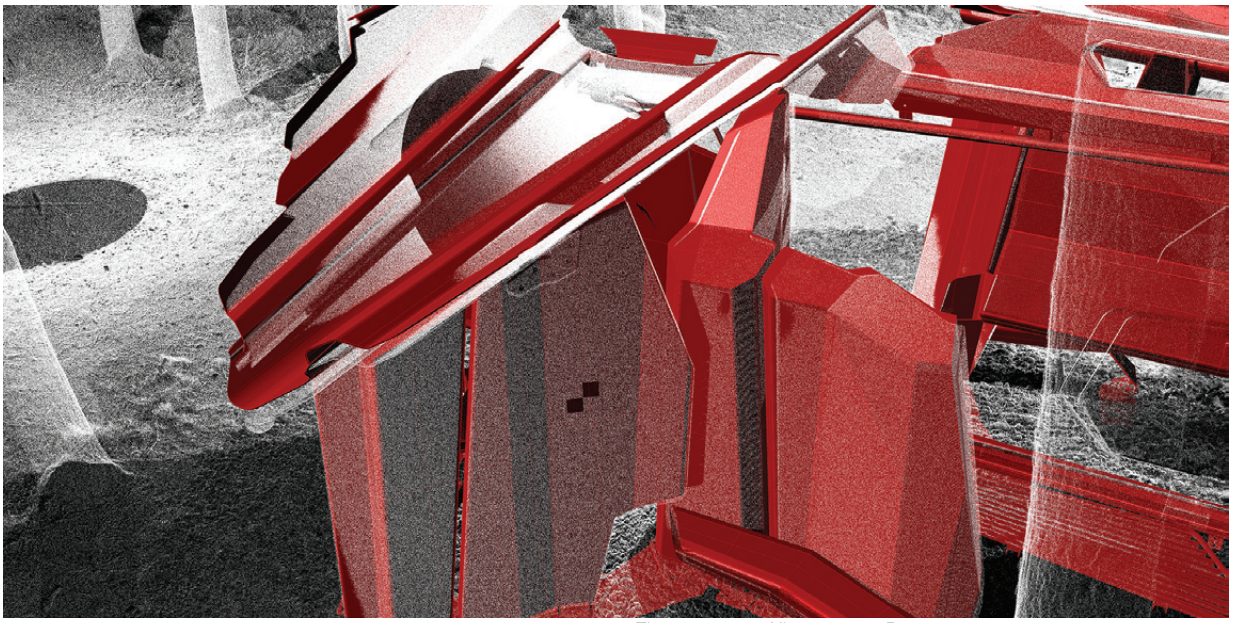

Fig 5.3.14-15 Alignment of Data

004 -005 Alignment of Data [Fig. 14 – 15]

This set of images show CAD data and Scan data aligned to each other where best fit algorithms refine the position of the whole assembly based on sub-sampling the data sets. Where 55/02's vermilion colour shows at full strength, the surfaces of both models are aligned. Ghosted areas highlight noncritical misalignment in some of the tank areas and roof elements, either component by component, or chunk by chunk. As a purely speculative exercise, none of these 'faults' have any significance in the performance, functionality or quality of the shelter, and an exact fit was never set as a requirement in the first place, however the data clearly has value in establishing the presence of difference between the digital model and the final assembly. Clearly additional observations could have been recorded had the shelter been scanned and verified against the digital model as it was first fully assembled in the factory. In this case, it would therefore have been possible to attribute where differences originated in journeys between design data, prototyping,

fabrication, factory assembly, transport and site assembly. In the construction industry, we are not fully accustomed to the protocols of precision manufacturing, where it is common practice to tag components with a host of information, including the identity of the fitter (e.g. Rolls Royce engine assemblies). However, mapping of 3D scan data upon BIM modelling is beginning to roll out in the construction industry,[xxvii] and will soon be a regular exercise in updating design files against verified 'as built' data. There are of course at least two ways this asset may be utilised. One, it may focus entirely on the notion that difference = fault, and fault = claim. Alternatively, it may offer a complex and cumbersome industry with the tools to accommodate design decisions through the production of the work. This route would of course reach all the way back to concept design and subsequent immediate stages where a speculative proposition is locked into an expected final delivery. To date parametric design models have offered considerable flexibility in allowing for mass customisation or precision manufacturing prior to the point of production, and to some extent during production. However, progressive feedback from LIDAR data upon design and production modelling now offers greater capability to absorb difference as a regular rather than irregular occurrence.

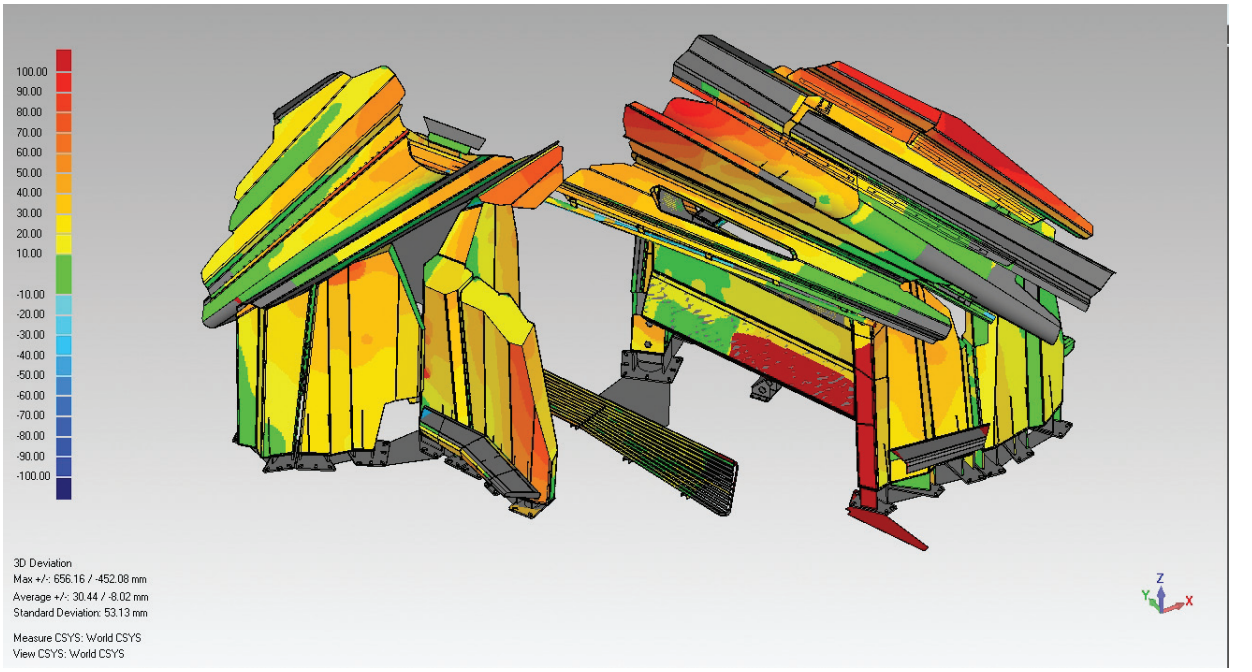

Fig 5.3.16. Deviation of Assembly

006 Deviation of Assembly [Fig. 16]

This slide illustrates a transposition of deviation calculations shown upon the CAD model alone. It more clearly highlights any areas of conflict or disparity. In this instance the spectrum spans from red to grey, signifying elements of 'perfect match' to those of 'total absence'. In the case of the latter, components shown in grey were either taken out or substantially reconfigured between the saving of the final CAD model and the assembly of the final construct. Referring to earlier comments above on the embedding of registration marks as a 'built in' array, equally such marks may be deployed to facilitate calibration and alignment of construct assembly, and furthermore, may be associated with new technologies in material marking.[xxviii]

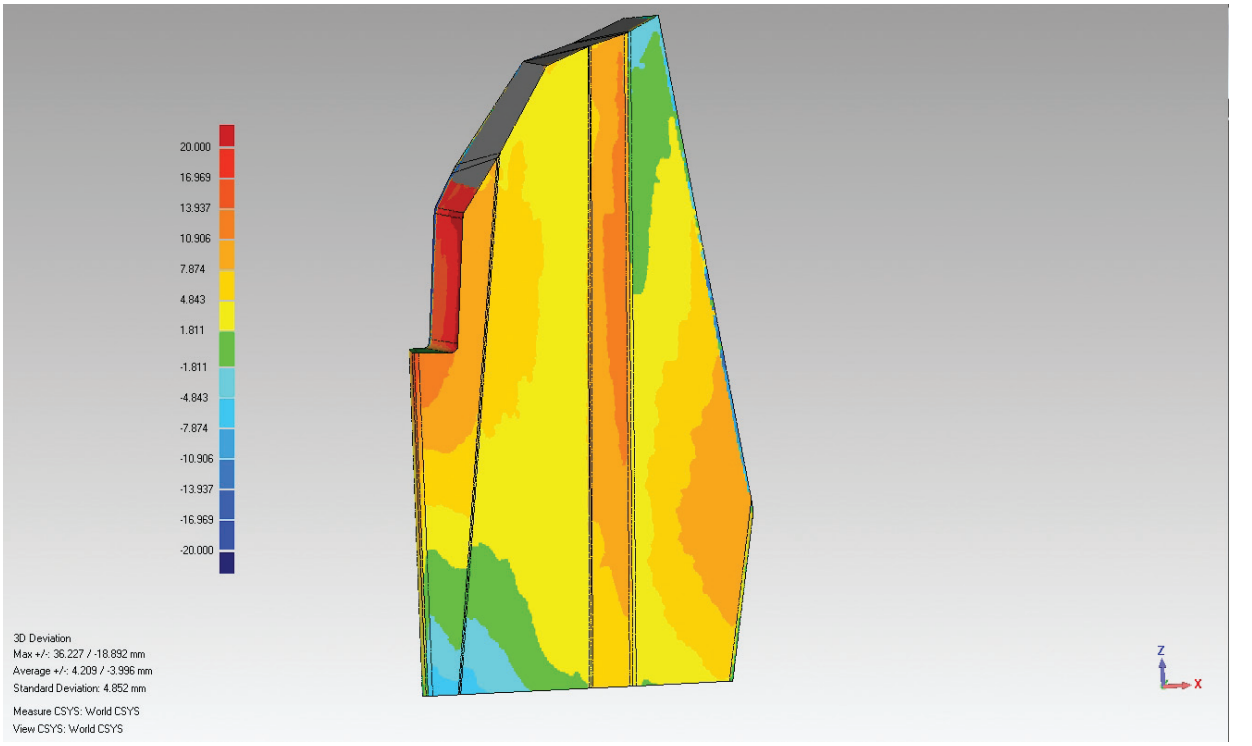

Fig 5.3.17 Deviation of Component

007 Deviation of Component [Fig. 17]

The final step in this sequence illustrates alignment analysis for individual components. Again, in this instance 'errors' are non-critical, but the information offers feedback to the manufacturer and designer in much the same way that a prototype should. It provides heretofore-unavailable data that refines knowledge on the scope of tolerances in the production process.

Fig 5.3.18 Manufacturing Protoarchitecture 3: Setting out jigs lie on site prior to commencement of final assembly of the 55/02 shelter. Such physical tools are entirely derived from the digital file that generates the architectural assembly, and thus act as 'difference' verifiers.[xxix]

Conclusion

Zero tolerance in digital manufacture is both theoretically and practically achievable, however the construction industry must negotiate its expectations on how valuable such accuracy is. Rather than seek finite calibration between the drawn and the made, such tooling as described above aught to be used for continuous renegotiation on their differences. If for no other reason, acknowledging the gap between both disciplines respects the immeasurable and vital contribution of the craftsman. This paper therefore concludes that the status of the dynamic and adaptable digital design model in relation to the physical results that are built from it, is one of adaptability and facilitation, and conditions that must remain open to the design opportunities that reside in manufacture and production. It concludes that the status of the resulting physical assembly is an architectural prototype, perhaps better identified as protoarchitecture, and the difference between the drawn and the made is a rich territory for collaborative and creative engagement.

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ix Emitting upwards of 100,000 pulses per second LIDAR technology involves a scanning and ranging laser system that produces pinpoint accurate, high-resolution, topographic maps. The original technology has been in existence for 20-30 years, but the commercial applications for LiDAR generated topographic maps have only developed within the last decade. Today the entire process of airborne laser mapping is highly automated from flight planning, to data acquisition, to the generation of digital terrain models. The basic components of a LiDAR system are a laser scanner and cooling system, a Global Positioning System (GPS), and an Inertial Navigation System (INS). Information obtained from Airborne 1 (http://airborne1.com/). See also USGS Center for LIDAR Information Coordination and Knowledge.

x In 2009 3D LIDAR scanners cost in the region of £100k, today compact units are available for £20k

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xxv ScanLAB Projects is run by Matthew Shaw and William Trossell, both of whom have backgrounds in architecture and fabrication, http://www.scanLABprojects.co.uk/

xxvi http://www.faroasia.com/products/laser-scanner/sea/forensics-and-accident-scenes.html

xxvii Thomas Graabæk (of BIM Equity) lecture at Confluence Symposium at CITA, Royal Academy of Fine Art Copenhagen. https://vimeo.com/55766548

xxviii See Signature Materials Project at the Institute of Materials, Minerals and Mining.

xxix Images credits: Fig. 1-2 © sixteen*(makers), Fig. 3 © John Wiley & Sons, Fig. 4 © Matt Shaw, Fig. 5 © Liquidfactory, Fig. 6 © Peter Webb, Fig. 7 © Emma Kate Matthews, Fig. 8 © Anders Ingvartsen, Fig. 9 © Ric Lipson , Fig. 10 © Bob Sheil, Fig. 11-7

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5.3
HubPod: A Prototypical Design System for Acoustically Diffused Enclosures

Nicholas Williams, John Cherrey, Brady Peters and Dr Jane Burry [i]

FabPod is a prototype meeting enclosure located in an open knowledge space. It was developed to address acoustic performance criteria within a broader architectural brief; bringing together existing knowledge of acoustic diffusion[ii], computer numeric controlled (CNC) prototyping and digital workflows[iii] and craft traditions of making. In addition to acoustic research agendas, two primary lines of research were established: Firstly the integration of performance feedback within the design process, with the potential to rapidly cover a series of design iterations and directly use this knowledge in design. Secondly the enabling of a high degree of geometric and material customisation up to a late stage in the production process, in order to provide significant design flexibility. This challenged designers to work with design methods more common to other design disciplines, utilising design tools and collaborative practices translated from aerospace design and exploring material properties and processes more common to product and furniture design than architecture. The full-scale FabPod was designed and prototyped over the period of four months.

FabPod seeks to be both a prototype leading to future development and a semi-permanent piece of architecture. As such the project seeks to be both highly exploratory in its design and research as well as fundamentally 'real', working within a series of constraints around material, process, time and money. It seeks to span a divide between academic research and architectural practice. The research involves the conception and development of a generic 'design system'. This was trialled as part of its development before application to the full-scale fabrication process. It is underpinned by a holistic workflow, from early schematic stages through to the complete fabrication of the prototype. A series of digital tools are central to the workflow and it has been well documented that digital workflows have significant impact on both the richness of design potential and quality of the built outcome[iv]. As well, manual assembly processes were utilised as required to assure a high quality of result. The resulting full-scale prototype is for day-to-day use as a meeting enclosure within a larger office space. It was fabricated and constructed within a University course of 16 students, testing and evolving the design system and tools over a four month period to realise the prototype.

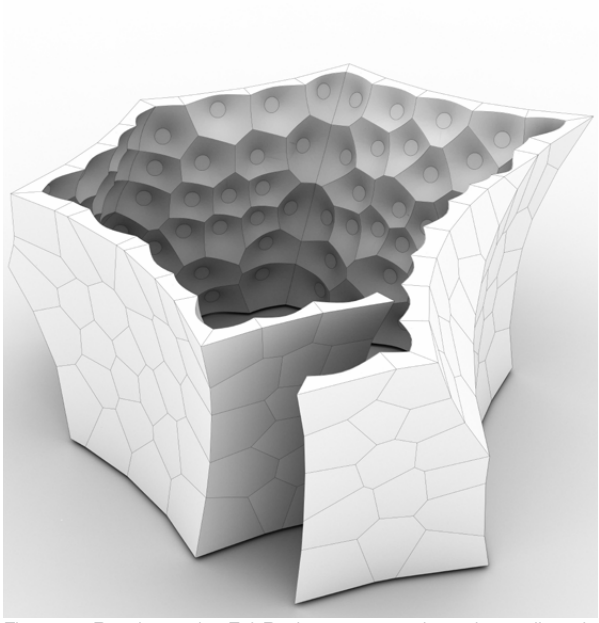

Fig 5.3.1 Render of the FabPod geometry selected for full-scale prototyping

Background: Previous Research and Development of the Brief

Anecdotal evidence suggests that the interior of the *Sagrada Família*, completed and opened in 2010, is acoustically a highly diffuse space. This challenged expectations, as well as some acoustic simulations, that the almost exclusively stone and concrete surfaces might cause reverberation problems. It has been already well acknowledged that the doubly-curved hyperboloid geometries of this interior surface were excellent for diffusing light. The hypothesis was formed that they might be equally good at diffusing sound.

FabPod follows a lineage of research in response to this, first addressed in the Responsive Acoustic Surfaces workshop at the *SmartGeometry* conference in Copenhagen, 2011[v]. Through this four-day workshop a series of scaled models were produced as 3D rapid-prototyped prints. These were used in a series of laboratory tests to measure acoustic diffusion. They were produced with the explicit understanding that they were at a scale of 1:10 and results could be directly scaled to provide data for full-scale acoustic behaviour. Also produced in the workshop was a curved wall at full scale, used to demonstrate and qualitatively identify acoustic effect.

In contrast to this exercise of testing and demonstration, the brief for the FabPod was nuanced in its ambition to serve day-to-day requirements. It called for an enclosure for meetings of a maximum of 8 people to sit within a larger open knowledge environment, part of a new facility at RMIT University. This enclosure was to provide an internal acoustic suitable for such small meetings and externally to improve the overall acoustic in its larger space. A more specific interpretation of this acoustic requirement was made by researchers in the choice to focus on the potential for an acoustically diffuse space.

Beyond these acoustic measures, the Pod was conceived to function around the existing electrical and mechanical systems within the building and provide lighting for the internal space. The space was already fitted with a standard array of furniture and so existing sizes were used as a guide for the Pod's furnishings, while existing audio-visual facilities were also to be incorporated. Importantly, the project came with the understanding that the enclosure would be a prototype for further development, with results to be evaluated and research extended to further iterations. While future briefs would be for similar situations, it was clear that a design system was required that was sufficiently flexible and open to be applied to range of other scenarios, producing a series of unique but related structures. The research team considered this an ideal context for the application of parametric modelling tools and flexible digital workflows.

The Role of the Prototype

The project further aspires to engage much contemporary architectural research focussed on the realisation of speculative, full-scale prototypes. Such prototypes act, firstly, as a proof of concept, demonstrating the strengths and weaknesses of a series of design ideas and processes. They provide unique understandings of specific architectural effects including the aesthetic and spatial relationship to an occupant, uninfluenced by media used for representations[vi]. The permanent nature of the Pod brief requires that while the prototype is sufficiently novel, the finish quality is high and the architectural detail sufficiently resolved for day-to-day use. This situates the prototype in an identifiably problematic position, between the "proto-architectural" research typical of academia and the outcome driven needs of practice [vii]. Further, the FabPod prototype will be used for acoustic testing. This will help to develop not only tools but also strategies for their application in design. Such full-scale and in situ testing is highly valuable to the acoustic research.

Parallel Research Strands

A great deal of knowledge used in the FabPod is not in itself new. Antoni Gaudí's utilisation of second order ruled surfaces (including hyperboloids) in the Temple Sagrada Família serves as a precedent. The geometrical framework known and utilised for many years has been refocused through the application of contemporary digital tools and techniques, making such geometry readily accessible to designers. This offers immense design potential but holds risks that many details of what is being designed are poorly understood. In a similar vein, knowledge of physical production processes and the creation of complex form is deeply embedded in day-to-day objects that comprise our physical world and economies that we inhabit[viii]. Some of the significant knowledge once held in craft traditions has, to varying degrees, been developed and integrated in contemporary manufacturing while other aspects remain with manual production processes. Here again, digital tools, rather than offering entirely new processes, largely make tools and techniques more accessible and processes more rapidly executed by those previously unskilled. For architects to engage these meaningfully, it is important that fundamental constraints and opportunities of processes are appreciated by the designer.

While there is scope for demonstrating and exploring applications of emerging digital fabrication technologies through novel formal outcomes, this research aspires to engage a broader context than simply demonstrating such novelty. Having identified that much knowledge made accessible by digital tools is not in itself new, there were still significant

implications of the speed and accuracy in applying conceptual knowledge. This led to the identification of two research foci. Firstly, the integration of simulation feedback in the design process, that of acoustic simulation within the design process required the testing and development of specific design strategies. Secondly, the potential for utilising computer numeric controlled (CNC) manufacturing tools to facilitate geometric and material customisation to a late stage in the production process, required the development of clear but flexible information management.

Learning from other design disciplines

There have been many calls for architects engaging digital design and manufacturing tools to variously take on aspects of automotive design, ship-building and aerospace design. These have carried varying motivations. While the production of form for the FabPod is not closely linked to these disciplines, strategies and software tools for both interdisciplinary collaboration in design as well as strong information management and communication were [ix]. The utilisation of parametric models formalised key relationships but allowed the refinement of these relationships. As a software package, the use of CATIA for a detailed FabPod fabrication model has a direct lineage to the aerospace industry[x].

The fabrication and assembly processes can be more clearly identified as relating to product design as well as furniture making. Discussed later in more detail, this requires the realisation of a series of related but unique parts, requiring a manufacturing strategy with potential for mass-customisation, a requirement of many industrial products. The scale and materials used were at times directly those of furniture and the required sub-millimetre tolerances led to the adoption and modification of a number of machines used in these disciplines as well as craft-based industries. Further, the accessibility of CNC fabrication tools to designers and their use in producing non-standard forms has demanded that holistic design, fabrication and assembly processes be addressed in parallel [xi]. These machines produce highly accurate results, to sub-millimeter tolerances quite uncommon to architecture. There is little room for error as such problems make final assembly physically impossible, pieces refusing to join as intended. As such clear interfaces, checks and strategies for managing tolerances are required.

The FabPod Design System

The FabPod research team conceived and developed a ‘design system’ spanning the complete process, a series of tools for and strategies for the design, detailed development and fabrication and subsequent testing of the prototype. This was conceived as a modular workflow comprising a series of clearly discrete parts and spanning between digital and material media. Contrary to using a single model or information repository, such modular approaches have been shown as highly significant in allowing for flexibility, good management as well as meaningful interaction with the tools by designers [xii] (Davis, 2011). It was particularly vital here as strategies for design and fabrication were developed in parallel and required to inform each other. As such, the aim of the design system was to provide for the consistent production of processes and parts, while maintaining a design space open enough to be architecturally rich.

Design Tools

The design of the enclosure was mediated through the use of three parametric digital models to describe consecutively the overall form, material distribution on enclosing surfaces and detailed surface patterning of these. These three steps were identified as being useful aspects of the design, which might be independently studied and refined - for example strategies for identifying density and distribution of the cells articulating the surface could develop without a broader set out geometry being finalised. These steps relate to the required inputs to acoustic simulation software and the tests for which they are designed. Commercial simulation software packages used in this project such as Odeon are designed for day-to-day application on flat or geometrically simple surfaces. As such, the doubly-curved geometry of the hyperboloids required relatively radical simplification in order to be simulated.

Further details of this design process are not the focus of this paper. It is simply worth noting that a series of feedback loops for designers to negotiate, further refined by responding to parallel laboratory testing of full-scale prototype parts. Through a weeklong intensive program, a significant body of design iterations were proposed and tested against acoustic performance in response to form, surface patterning and material distribution as well as broader architectural criteria. This interaction allowed for a strong understanding of the specific scenario to grow and provided for the designers to develop strategies and heuristics of how the tools might be applied to the design process.

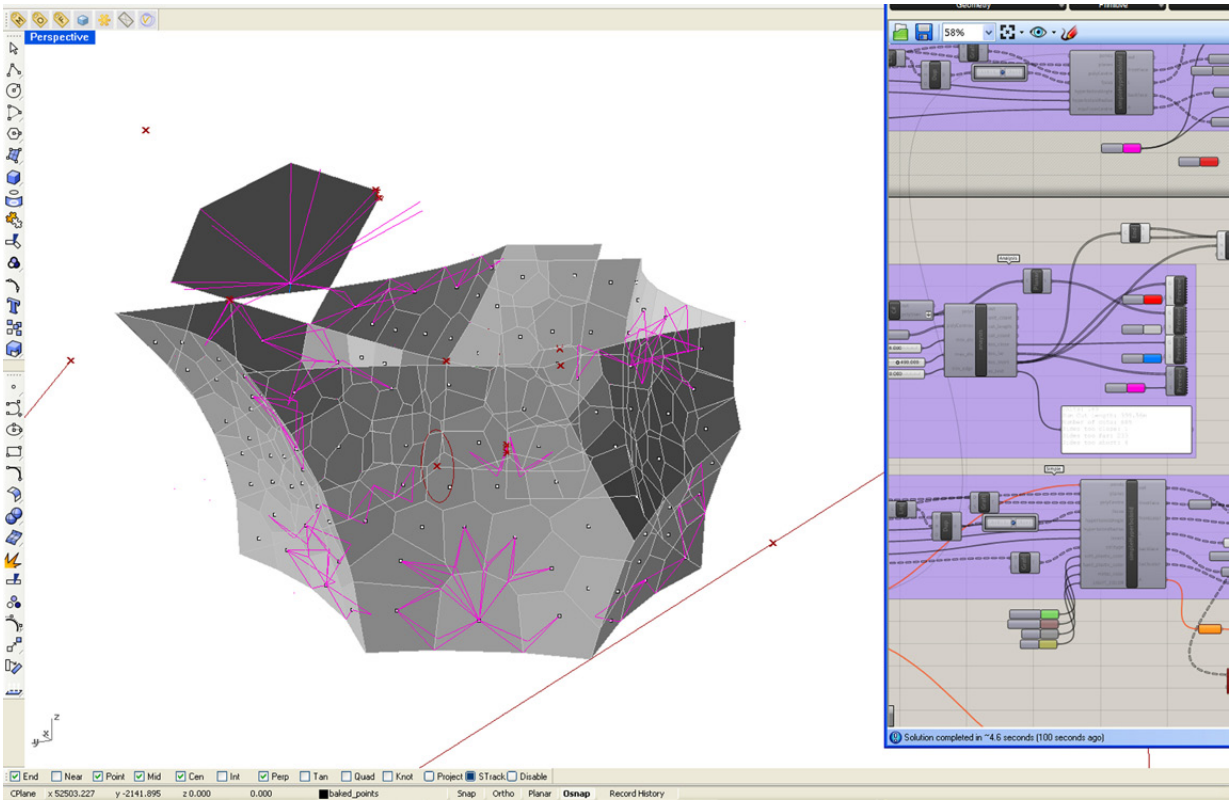

Fig 5.3.2 Screenshot of a parametric design model in use, showing workflow

The Fabrication Concept

One of the first project aspects conceived was the fabrication system based on the assembly of a series of 'cells'. This was a direct extension from the demonstration piece built in an earlier workshop, themselves derived from techniques used in the Sagrada Familia Basilica in Barcelona. These cells were appealing for a number of pragmatic reasons: they might be moved and assembled by one person; they might easily fit through doors and in conventional elevators; they might be easily fabricated from a series of pieces cut on the machines available and; finally, they might be rapidly assembled on site, minimising the time in which interruptions might be made to the working space in which they were to be assembled.

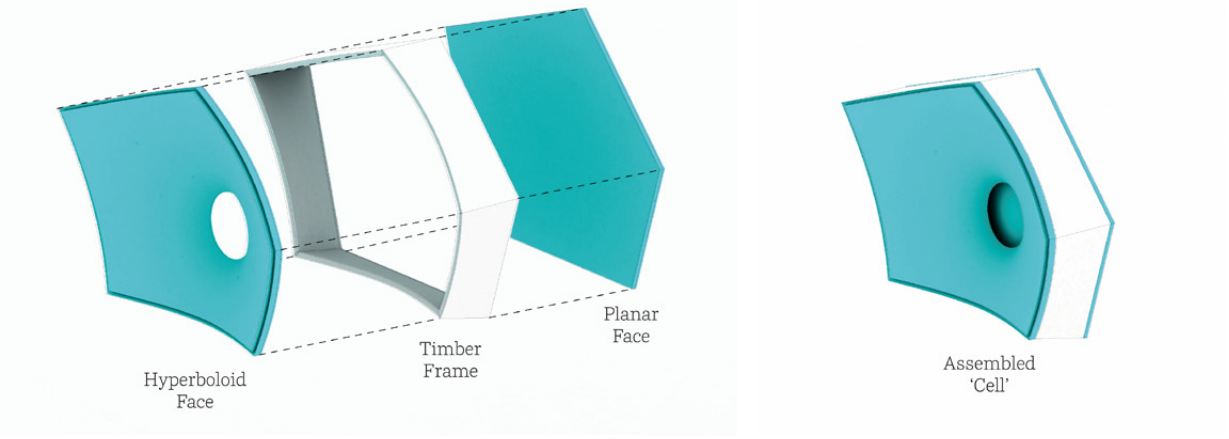

Fig 5.3.3 Render showing the consistent set of elements making up each cell

The FabPod cells were conceived as being comprised of a hyperboloid face and opposite a planar face, which would combine to form the interior and exterior surfaces of the Pod enclosure. The material of these primary faces could be varied independent of each other and in relation to the larger assembly. These were to be connected to a frame, providing for structure and defining shape as well as acting as to achieve acoustic separation. This last aspect was tested in the laboratory in order to verify that sufficient transmission loss would be achieved - undue noise coming from the outside would negate any designed acoustic effect. Finally, the centre of each cell was identified for providing lighting and a series of windows for some basic connection from inside to out.

Prefabricated into a standalone unit, each cell could therefore be considered a hybrid component. They were comprised of a consistent set of elements but which could each be highly customised in material finish to achieve desired design objectives and performance criteria. Each could further be a unique geometric piece, its boundaries and form dictated by its relationship to the overall assembly in which it was designed.

This fabrication concept shaped not only a set of possible permutations but also provided constraints fed into the design tools. In order to achieve a high quality of finish, it was identified that the frames would be made from sheet material and that the boundaries of cells should be planar. This informed a broad geometric system of spherical set out geometries for the enclosure surfaces. Further, as fabrication details developed, constraints of minimum and maximum sizes and angles could be added as checks within the design tools.

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Implementation - Fabrication

Whilst various materials clearly existed that could be utilised for the frame, the use of 12mm E0 medium density fibreboard (MDF) was ideal in providing a material of uniform density and thickness, a smooth and fine finish, and excellent machining qualities. Wood based materials are generally easy to use and modify and are well suited to a university environment.

Fig 5.3.4 Biesse Rover CNC 5-axis router cutting unique frame components

Each of the frames edges and an associated internal stiffening panel was machined using a Biesse Rover C 5-axis CNC flatbed router. This produced very finely toleranced components, making later assembly sufficiently accurate. Tool position data and subsequent machine-ready files were directly generated through a digital workflow from a detailed fabrication model, one generated with parametric software but independent of the design model. Components for two cells were fitted onto each 2.4 x 1.2 metre sheet and machining time was approximately twenty minutes per sheet. In designing the frames, provision was made for later assembly with scallops along each edge of the internal bracing plates and aligned holes for bolts, electrical wiring and levelling feet.

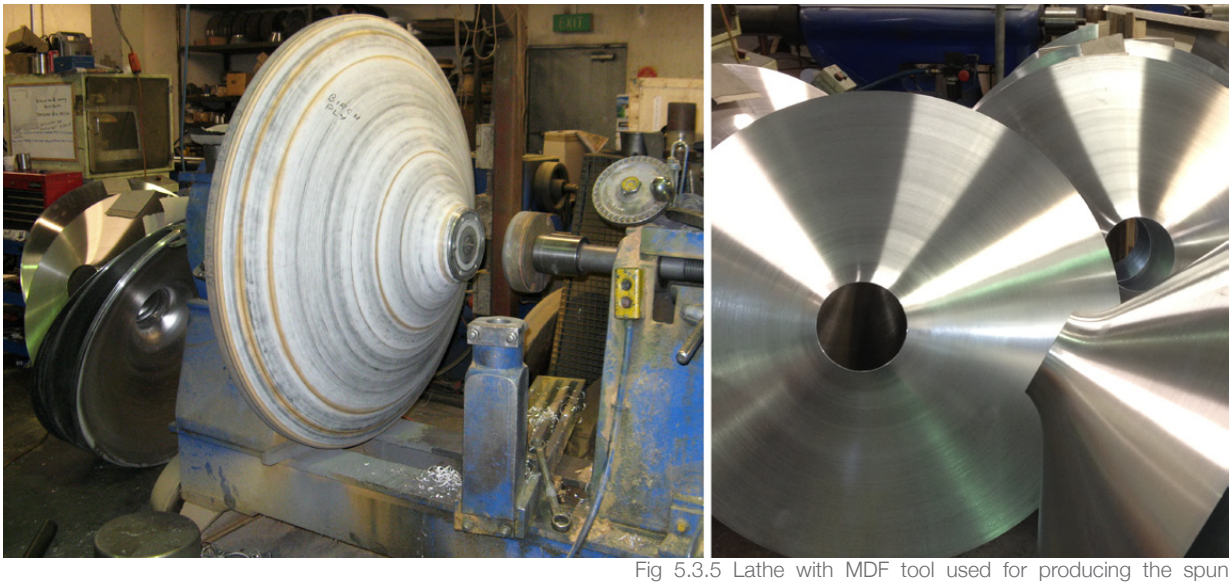

Fig 5.3.5 Lathe with MDF tool used for producing the spun aluminium hyperboloid panels

As discussed earlier, acoustic design proposals required the use of both reflective and absorbent material for the geometrically hyperboloid face. The choice of material was limited to that which could be readily formed into the required shape and ideally one where the forming process was direct and rapid. Equally it was important that the material mix produce a visually coherent whole. After some consideration and exploration of options, spun and anodised aluminium was chosen as a reflective material. Spinning met the criteria of being both direct and rapid in production and allowing the creation of large forms. Importantly, it is also a technique for which in this context of producing only limited units, the cost of making the tooling was relatively low. In this case the tool over which the metal is spun (stretched) was quickly turned from a stacked block of 35mm thick MDF sheets and the required form checked against a laser cut one to one sectional pattern. The 1.5mm thick blanks were all spun to a single 1035mm diameter, which removed the need for multiple jigs to be made and used in the anodising plant.

Frosted acrylic was the second “reflective” material used in the project, in this case an inexpensive white translucent acrylic commonly used in skylights with a matt finish to one side only. Vacuum forming is a process well understood and commonly used in the forming of a range of thermoplastics. For the FabPod, the acrylic hyperboloids were formed using plug assisted vacuum forming where the material being drawn into a female mould under vacuum pressure is assisted with a ram which in turn pushes down through the centre axis of the mould to ensure accurate and complete moulding at the base and narrowest part of the form. The mould was made using stacked cross laminated birch ply and machine to shape using a three axis router to create the final female mould. In the design of the mould careful allowance had to be made for shrinkage of the moulded acrylic to ensure an accurate to the MDF supporting frames. Following machining, the mould was filled and finely sanded and sealed to minimise surface marking on the acrylic during the forming process.

Fig 5.3.6 Four cells with demonstrating the geometric flexible achieved through the design system

The soft and sound absorptive material used both on the hyperboloids to the interior of the pod and for the bulk of the exterior surface, was a product a PET based product of felt like appearance and quality. Being PET, this material like the acrylic was formed using a modified vacuum forming technique. During the design phase, it was envisaged that anodised aluminium, the acrylic and the felt PET hyperboloids would be cut to size over the male form tool (similar to that used for the metal spinning) with the pieces held in place over the tool with vacuum clamping. The cutting was to have been achieved using a waterjet cutter fixed to a robot arm. Unfortunately budget limitations dictated the hand cutting and finishing rather than the more efficient and elegant digital/CAM solution. The crafted solution required the aluminium and acrylic to be roughly cut to size on a bandsaw and finally sized, once fixed to the frames, over a woodworking surface planer. The felt PET hyperboloids were simply trimmed to size manually a using sharp knife and following the angles determined by the frames.

The flat exterior panels presented only minimal issues in being accurately fabricated. Acrylic was cut using a 3-axis CNC router taking the profiles directly from the Rhino model, nesting and applying tool radius compensation. The felt PET however, whilst sized on the 3 axis CNC router required additional processing. The PET cut well with a knife and water jet but using rotary cutting the edge quality is low. Final sizing of this material was achieved in the manner similar to that already outlined for the felt PET hyperboloids although cutting was undertaken using an oscillating saw.

Lighting the interior space of the pod was a problem considered from the outset of the design. Oculi at the base each hyperboloid provided an obvious “window”. Openings are weighted toward the one side of the design making use of natural light entering the larger space in which the pod is located. The design includes 25 clear windows and a further 25 translucent panels, which are intriguingly also used as a source of artificial illumination. What appears during daylight hours as a clear opening, transforms into a milky white disk of light when lighting is powered. The fabrication of these lamp elements makes use of a new to market acrylic product, which contains colourless diffuser particles providing bright and uniform illumination when edge lit. Acrylic disks were laser cut to provide window elements with an accompanying ring 6mm larger in diameter onto which lengths of LED strip was adhered. Each ring carries 85 LEDs providing an output 420 lumens.

The capacity to handle problems of tolerance is critical in the making and assembly of the smallest to the largest objects. The solution for this project was the use of 3mm thick laser cut spacers set between each adjoining cell face. Should the need have arisen, these spacers could have been thinned or packed to provide assembly adjustment. During production each of these was cut with holes to correspond with those on the cells and each was etched with an identifying number. The spacers also functioned during the assembly phase as frames that located the exterior panels. It should further be noted that in developing this project a good deal of thought had to be given into simplifying the fabrication given that the assembly work was to be done by students with very little making experience and no craft skills.

Assembly

The assembly phase should be understood in two phases, first that of cell component assembly and second assembly of the completed cells into the final pod. Component assembly started with removal of the CNC machined frame material from the sheets. Tabs were removed before each cell was assembled. Assembly was a straightforward task of fixing together cut pieces but required care to maintain the close tolerances. Each of the mitre joints, at the end of the frames sides, was glued with PVA adhesive and the joint held in place with a combination of masking tape and vinyl tape. Next the stiffening plate was glued around its edge, placed on spacer blocks and the frame placed over the top. A brad gun was used to fix the plate and frame together. Spacer blocks of different heights were used to locate the stiffening plate at the correct height relative to the frame size and thickness of material of the exterior cladding material. Once dry, cells with PET felt backs had additional blocks glued to the stiffening plate to carry adhesive Velcro tabs. The stiffening plates of cells with grey translucent backs were fitted with removable 3mm MDF perimeter each plates and the surface painted matt black.

The hyperboloid faces having been roughly sized were fixed using three different ways depending on the face material; the acrylic was fixed to the frames with white pressure sensitive mirror tape, the anodised aluminium using black glazing tape and polyurethane sealant adhesive and the PET felt glued using construction adhesive in a two surface contact application. Acrylic window panels were clear silicone fixed and those with LED lighting rings were fixed with a small 25mm annulus that located both window and ring. This LED ring, window combination was then further sealed with black sealant to prevent light bleeding into the cavity space of the MDF frames.

Fig 5.3.7 Rows of assembled MDF frames awaiting facing panels and final finishing

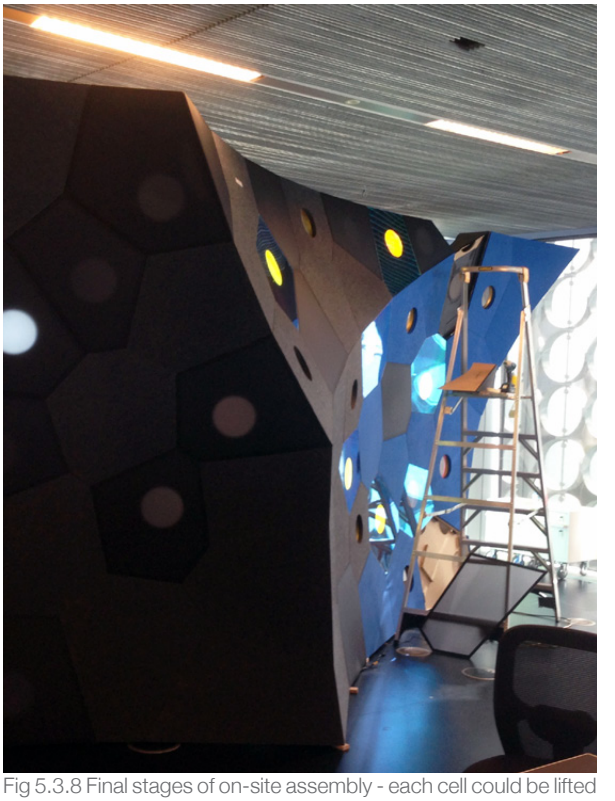

Fig 5.3.8 Final stages of on-site assembly - each cell could be lifted into place by one person and fixed with simple bolt connections

Once completed, the one hundred and eighty unique cells were transported to the site for installation. Assembly commenced laying the bottom row of cells in place, bolting these together and levelling the whole using the built in adjustable screw feet. Assembly then proceeded rapidly with the entire work assembled in just two and half days. Assembly required nothing more than placement of cell and spacers plates and connection and fixing with one M6 bolt per edge into an adjoining tee nut. Wiring connection of the LEDs followed and lastly PET felt and acrylic backs were pressed into place and held firmly by preinstalled Velcro tabs. Cleaning of the windows completed the job.

Initial Successes and Failures

The full-scale FabPod has proved broadly successful in its aspiration to both explore novel applications of fabrication strategies as well as be sufficiently resolved to serve as a semi-permanent architectural piece. The fabricated prototype is installed and in use, following initial documentation. A broad palette of materials was utilised, a total of 14 permutations of material and finish quality were achieved, and a high quality finish was achieved. While detailed acoustic testing is yet to be undertaken, initial impressions are excellent. Internally, speech is clear and requires little exertion while sound transmission in and out of the space are minimal.

Several aspects of the physical prototyping are worth noting for their success. First and foremost, production tolerances in the overall cells were sufficiently controlled and elements sufficiently robust in order for the 180 cells, to be transported to site and assembled without major reworking. A key strategy for this was the inclusion of 3mm tolerancing strips, expressed architecturally as shadow-lines. These allowed for the manipulation of pieces during installation in order for a snug fit to be achieved. In several worst case scenarios the designed 3mm shadows are 3.5mm, however, generally these are in the range of 0.1 - 0.2mm . This difference is not perceived by occupants.

On several occasions in-house testing enabled the research team to push the capacities of external industry partners beyond their previous experience. The use of the 5-axis router to produce some 1200 unique timber components, each cut made with unique angles and at times doubly-curved ruled surfaces proved relatively straightforward. This was, however, significantly different from the application of the machine and the perceptions of its operator. The forming of the acoustically absorptive PET panel also extended the application of the material. While forming was known to be possible, a ready method to achieve was not at hand and had to be developed over several trials. Perhaps the most obvious, recurring challenge was the identification of sufficiently robust fixing methods. Where adhesives were used, these required significant testing on each of the palette of materials. On several occasions items had to be re-fixed and tapes replaced with epoxy-based glues. The simple bolting together of cells proved to provide a generally stiff connection, however in extreme conditions such as corners of the overall enclosure, these were augmented with a further two bolts to provide greater stiffness to the overall structure.

Fig 5.3.9 Interior of the FabPod

Fig 5.3.10 A further view of the interior of the FabPod

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Future Development

This successful realisation of this prototype indicates an underlying robustness of the design system. Having said this, there remains significant future testing in order to test its boundaries. It is intended that this will include iterations testing scale, overall topology as well as a significantly broader range of materials. There is room for significant further automation to be utilised. It has already been noted that the materials formed into hyperboloid shapes were intended to be trimmed using a water-jet cutter mounted on a robotic arm. Such trimming would add significant production efficiency. Similar processes could be applied enhanced in achieving the required accuracy of flat panels. The assembly of frame components might also be made significantly faster, and perhaps accurate, through the development of geometrically flexible jigs.

Conclusion

This FabPod research covers prototyping of not only a physical enclosure but also a broader design system. The results are a full scale prototype for testing and evaluation as well as a robust system of interrelated tools, materials and processes and the key constraints and opportunities that exist around these. The research sits between the speculative realm of the University research and research engaging a broader discourse in architectural practice and in the construction industry. It engages a broad and grounded knowledge base through engaging with industry partners, while speculating on possibilities for future applications for currently available technology.

Acknowledgements

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The Laminex Group
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References

i The authors' affiliations are: Nicholas Williams, The Spatial Information Architecture Laboratory (SIAL), RMIT University, Melbourne, John Cherrey, The School of Architecture and Design, RMIT University, Melbourne, Brady Peters, The Centre for Information Technology and Architecture (CITA), The Royal Danish Academy of Fine Arts, Copenhagen and Dr Jane Burry, The Spatial Information Architecture Laboratory (SIAL), RMIT University, Melbourne.

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5.4
Soundforms

The design, development and fabrication of a 1:1 scale mobile acoustic performance shell prototype

Paul Bavister [i]

Soundforms is an acoustic shell developed for natural acoustic reinforcement for external ensemble performance. Discussions on the project started in 2007 in conjunction with conductor Mark Stephenson, and a team was established with Jason Flanagan, Paul Bavister of BFLS and Ian Knowles of Arup Acoustics, who collaboratively developed the brief into a full patent for a mobile acoustic performance shell. It was decided that a prototype should be developed prior to commencing commercial production. This was to be sure that the costs of production were feasible, the engineering brief was realistic, the notion of mobility and portability was practical, and of course, that the core acoustic idea could be verified through acoustic tests in performance. A fully working prototype would also enable potential clients to test the concept, and 'kick the tyres'. The ultimate goal of the project was to take music outside of the concert hall with a higher quality of acoustics than was previously available.

Fig 5.4.1 Soundforms: Mobile Acoustic Performance shell

Portability & Democracy

The history of externalised performance goes back to ancient times, spontaneous performances taking place before any assembly of people large enough to form a willing, or unwilling audience. In some cases this was in front of fixed site, such as a well, and many established theatres have taken their name from the original well that marked the site of the original performances, such as Sadlers Wells. Whilst impromptu performances that took place in front of fixed locations have lead to permanent theatres, economic conditions often prohibited the establishing of a purpose built housing for performance, and have led to travelling performances that would establish themselves temporarily at fairs and other public locations before moving on to new locations. A typical example of this is the Commedia dell'Arte, where players performed on temporary open-air stages, using props instead of scenery. If successful, they were funded primarily by the towns and cities where they played. Extra funds were generated by the passing of a hat amongst the audience, this ensured that the performances were not exclusive, and everyone was able to view free of charge.

Fig 5.4.2 Verona Arena, Boeve, Ervina, 1772

In conjunction with a desire to take performance outside of the theatre is the development of architectural technology that utilizes industrial techniques of construction that allows for rapid deployment and transportation. Developed in the early twentieth century to improve the quality and speed of construction, such buildings by Buckminster Fuller, and Charles and Ray Eames buildings had a new level of flexibility that freed the building from the more traditional constraints of site and permanence.

Existing acoustic conditions

Prior to the development of Soundforms, all exterior acoustic performances took place in fabric tents that protected performers from the weather yet offered no acoustic

reinforcement on the stage. Musicians use this acoustic reinforcement, or room feedback, to modulate and improve their own performances and take timing cues from other players in the ensemble. Without this, such as a typical tent, the performance suffers, and with it, the experience of the audience. Performance shells exist for internal spaces to make up for architectural inconsistencies in spaces not intended for music performance. These can be flown from fly towers, and use a host building's structure for support. They are not designed for external use. Fixed and permanent external structures do exist for performance, the Hollywood bowl is a classic example, but due to the weight of the components to distribute the sound to an audience, these structures have remained solidly fixed to the ground.

Procurement

Where Soundforms differs from typical architectural projects, is that at the outset there was no client, or direct revenue source for the project in this instance. The design team self-funded the early design- concept phases of the project, enabling further funding to be in place for the development of a 1:1 scale prototype. The early phases of design were intrinsically linked to the development of a working acoustic brief that could be digitally proved to be fulfilled as a proof of concept. The Soundforms team analysed 3 differing typologies of acoustic performance, and developed the product to acoustically optimise each of the conditions. These were a string quartet, a small chamber ensemble, and a full symphony orchestra, each acoustic condition having differing requirements that required their own spatialised solution. Each of these conditions could be defined by a set of acoustic ratios, being the defined distances between reflective surfaces inside the shell. These ratios were then distilled into UK patent application no. 2472238. Once a patent was in place, funding could begin with the aim of developing the finished product for industry testing, and ultimately commercial production.

Brief

The origins of the brief lie in Mark Stephenson's work with Arup Acoustics work in trying to develop a shell for touring use in larger indoor spaces in the UK, that were not originally designed for use by a small touring orchestra. These spaces were usually corporate atria, and exhibition spaces such as galleries. In an effort to control the acoustic, a small portable shell idea was conceived. Whilst the resulting shell was fabricated, and tested with mixed results, and went into a slow period of development, leading to larger scale deployments in sketch form. The shell remained in this state until 2007 when Mark Stephenson discussed the project with BFLS who took on the challenge of developing the basic principles into a reality. Arup Acoustics were again appointed to optimize the shape and the materials for a fully outdoor portable orchestra shell that will be used for the performance of outdoor classic music.

The core brief items were:

- That the orchestra shell would be optimized to help the projection of sound towards the audience and to provide good performance conditions for the musicians on stage in the context of an outdoor venue;

- The overall dimensions of the orchestra shell would have to be directly proportional to the size of the orchestra;

- The size of the orchestra would be related to event location and repertoire and because of this three standard orchestra sizes would be considered to cover the most likely platform sizes to accommodate the following types of performance / repertoires;

- Romantic era orchestra, based on up to 100 musicians;

- Chamber music orchestra, based on a small group of up to 50 musicians;

- Small ensemble, such as a quartet or quintet.

Development

The early forms of the shell were exercises in practicality, and were developed to test the principles of the brief. The acoustic principles were a core driver, as was the existing stage engineering technology that would have to be applied to the shell. These practicalities were then synthesised into a holistic design. The core idea for the form came from the notion of a seashell that mythically is able to project the sound of the sea to a listener. The form is one of the most beautiful in nature, and perfect match for the acoustic principles of the design, that of a throat, that projects sound. The form was developed as part of a torus, as the repetition of its geometry is cost effective and simple to fabricate. A portion of torus then formed the outer enclosure, with the hard surfaced interior fitting neatly within it. The extended portion of the torus shell formed a peak that was later to form a key acoustic driver of the project. As with all free standing / stand alone projects, the difficulty of the design is how the over all form hits the ground in an elegant and considered manner. This was resolved in the case of Soundforms by creating an inward undercut to the torus, much like a pebble on a flat surface. The designed form was developed via 3d printing technology and prototyped with each iteration. The resultant model could be viewed in 360 degrees, and viewed in the round, allowing a greater understanding of its possible deployment. Interestingly enough, as the models produced were a clearly independent form with a beauty of their own they were also used for marketing, and many were retained by interested parties due to their desirability as objects in their own right.

Fig 5.4.3 Example of an early 3d model developed by BFLS

Acoustic elements

For large orchestras playing in internal venues, the ability of the musicians to hear each other, in particular for the sections far apart on the platform, relies on the relationships of the enclosing walls and ceiling. Part of the sound reflection between platform walls and ceiling help the communication (ensemble) between the musicians and part of this sound is reflected to the audience. For a smaller orchestra the proximity of the musicians helps the ensemble and the shape and angle of the walls and ceiling will have been considered to project more sound towards the audience. Comparing an orchestra shell used for internal spaces, as in theatres or churches, and an orchestra shell that is used outdoors, the main difference is that the orchestra shell used indoor can rely on the sound reflection caused by the internal surfaces of the building in which it is placed. This assists the sound level on the audience plane. In the outdoor case there is generally a lack of reflection from the environment. To increase the sound level to the audience a 'Peak' was developed to project beyond the conductor to reflect as much sound as possible down to the audience. The peak then performs in a similar manner to the ceiling of a concert hall or a flown array in larger halls. As mentioned earlier, this key inventive step came from the development of the geometry of the torus, and the over hanging peak that was developed at the cut line.

The images below show the sound reflections (in red) from two sound sources on the platform with and without the orchestra shell Peak. The "Peak effect", shows the additional benefit of sound reflections that the Peak is able to provide towards the audience.

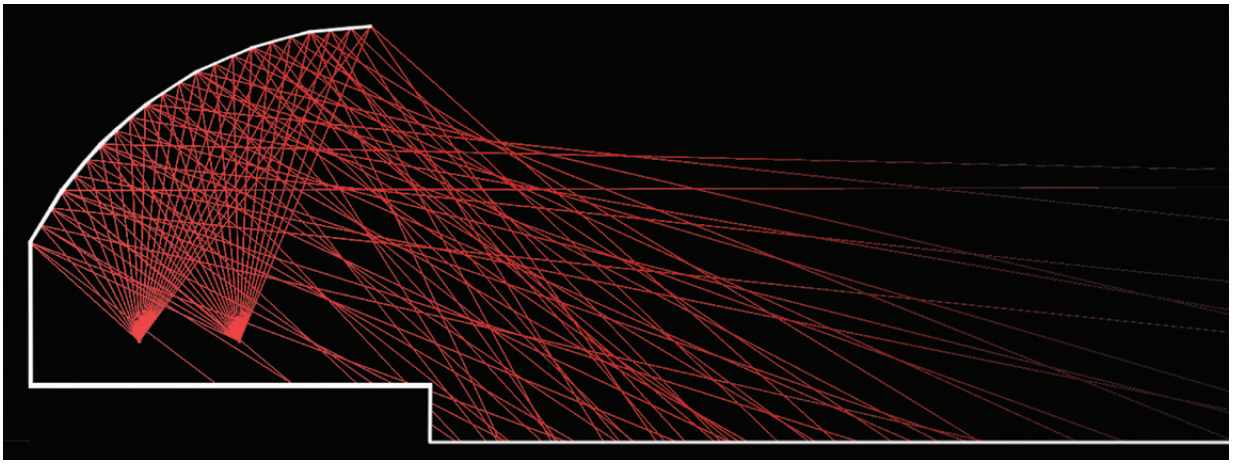

Fig 5.4.4 Acoustic modeling of the shell without peak

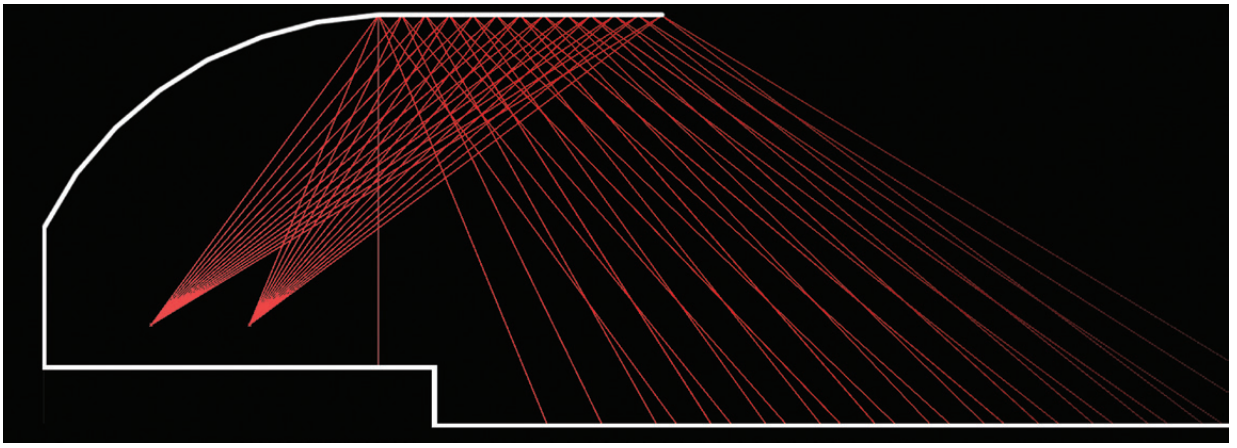

Fig 5.4.5 Acoustic modeling of the shell with peak

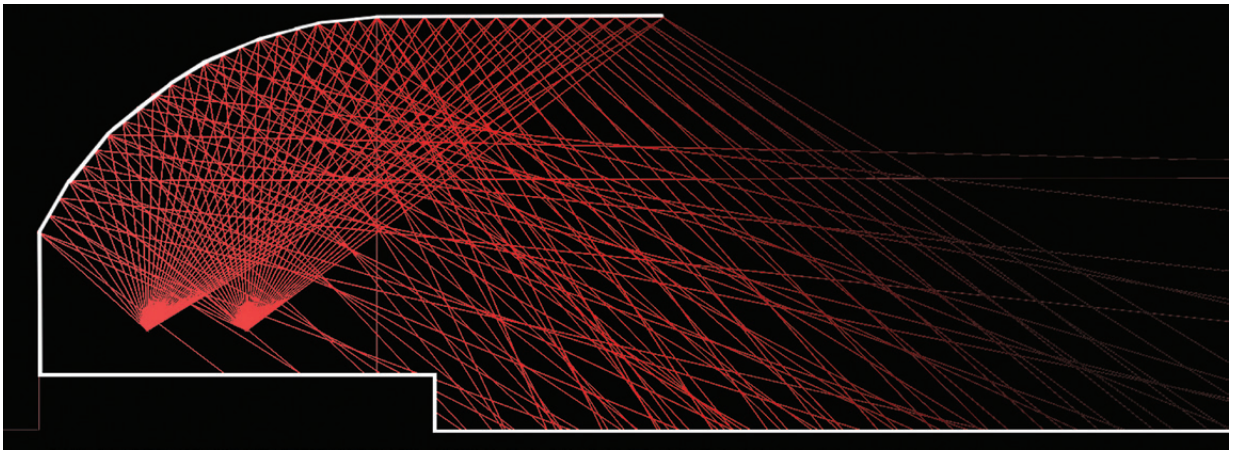

Fig 5.4.6 Acoustic modeling of the shell and peak, showing a greater distribution of sound toward to the audience

As shown in the images below the use of the orchestra shell improves the acoustic condition for the audience increasing the level of sound naturally transmitted. However, despite this increase, the use of a sound amplification system might be still required depending on the location, existing background noise and audience size.

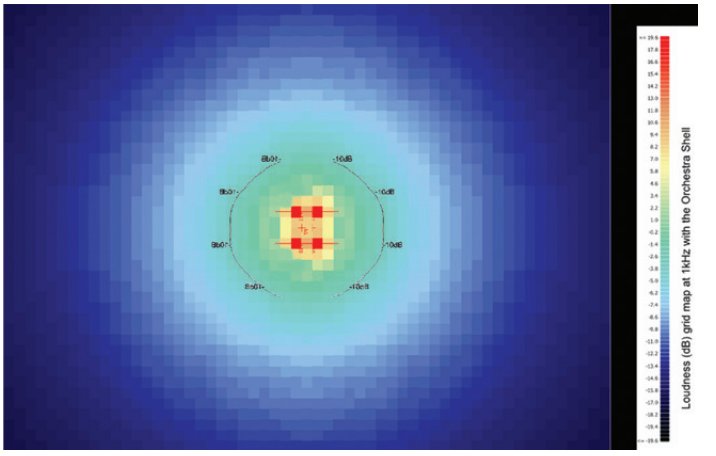

Fig 5.4.7 Sound propagation on the platform: with traditional fabric enclosures sound is free to spread evenly with no control.

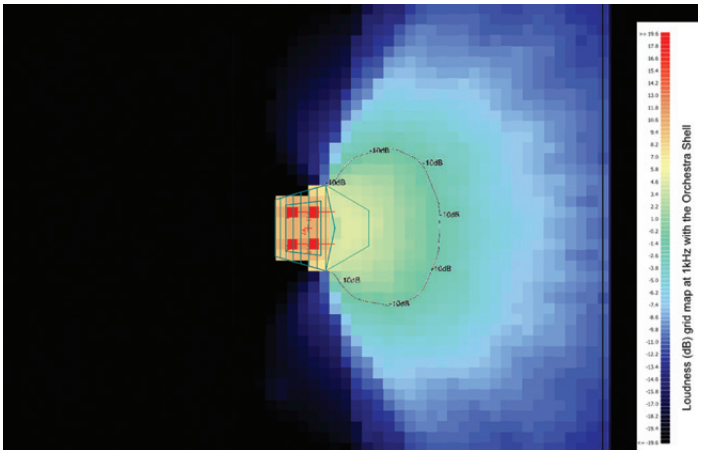

Fig 5.4.8 Sound propagation on the platform: with a shell in place, the sound is controlled and directed toward the audience.

The listening conditions will be affected negatively by a high background noise resulting in a reduction of the signal to noise ratio particular affecting the audience far from the stage. This situation may require a sound system to guarantee acceptable acoustic condition to everybody in the audience. The existence of a built environment around the orchestra shell will affect the sound propagation and could cause negative sound effects such as an echo, so the shell location and orientation on a given site needs to be chosen carefully, of course, orchestral music is usually listened to in a space with reverberation. This provides added warmth and musicality to the performance. In an outdoor event, there is no reverberance for the audience, and so a PA system is likely to be needed for some events where an electronically enhanced sound could provide this effect if the performance requires it.

Structure

The development of the structure had to address the need to support the outer skin, hold up the acoustic panels, address the concerns of the required form, be easy to assemble, and be easy to demount. The individual elements had to be large enough to work efficiently, yet be small enough to fit onto a typical shipping container. This size constraint was a fairy powerful driver in the development of the structural brief developed by the engineer.

In order to protect against uplift, the structure is mounted on a steel base, holding 40 tonnes of ballast. This ballast can be concrete or tanks containing water or sand, or any material that is easy to transport to and from the proposed site of erection. The shell is supported by an aluminium-trussed structure. For the size of the shell, it was decided that steel would have been prohibitively expensive for the majority of the structural elements. The structure is formed of a series of arches made of interconnected 3 chord truss elements. These were developed digitally with the fabricator; so all elements of the structure could be modelled and coordinated with other elements of the build. The arches were then stiffened by a series of lateral ladder trusses that ran at right angles to the primary arches, holding them in place.

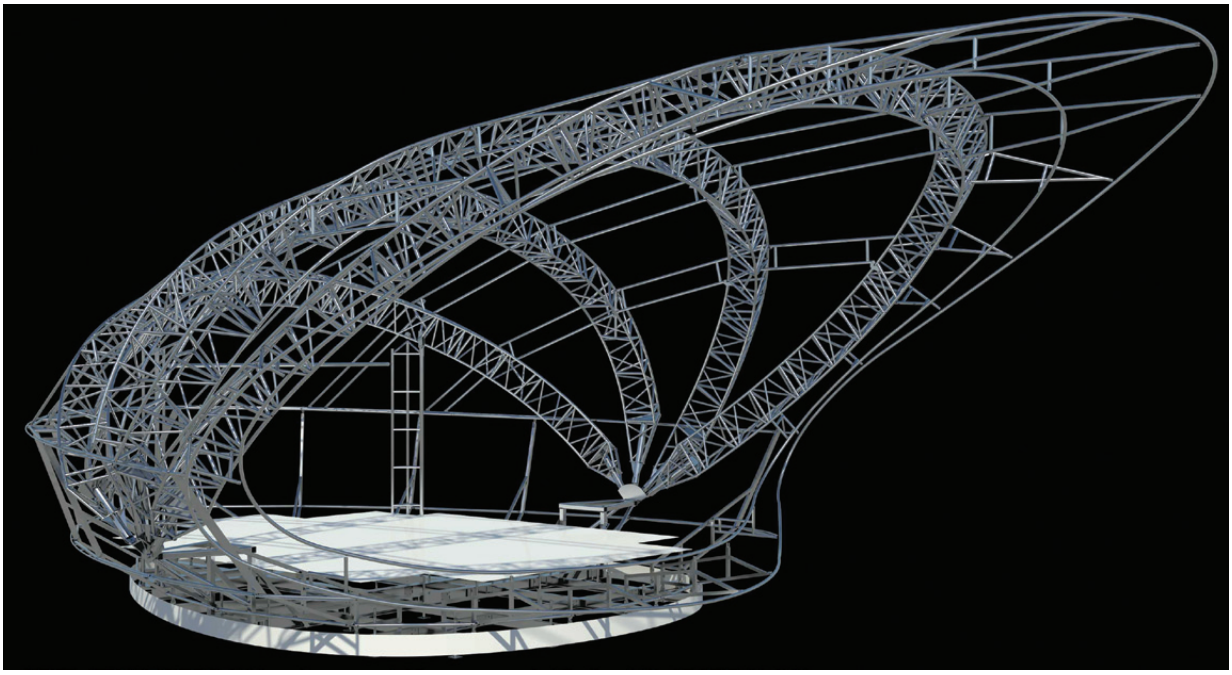

Fig 5.4.9 Working digitally and in three dimensions the team was able to coordinate efficiently, and quickly.

The assembly methodology is based on a pram lid type design, with all of the primary arches being fixed to one rotating pivot point, allowing simple erection by a small team of operators. The first element erected being a simple goal post truss, allowing all subsequent trusses to be braced off this established element. This can be done with a simple forklift truck, or small site oriented vehicle. Cranes are not necessarily required.

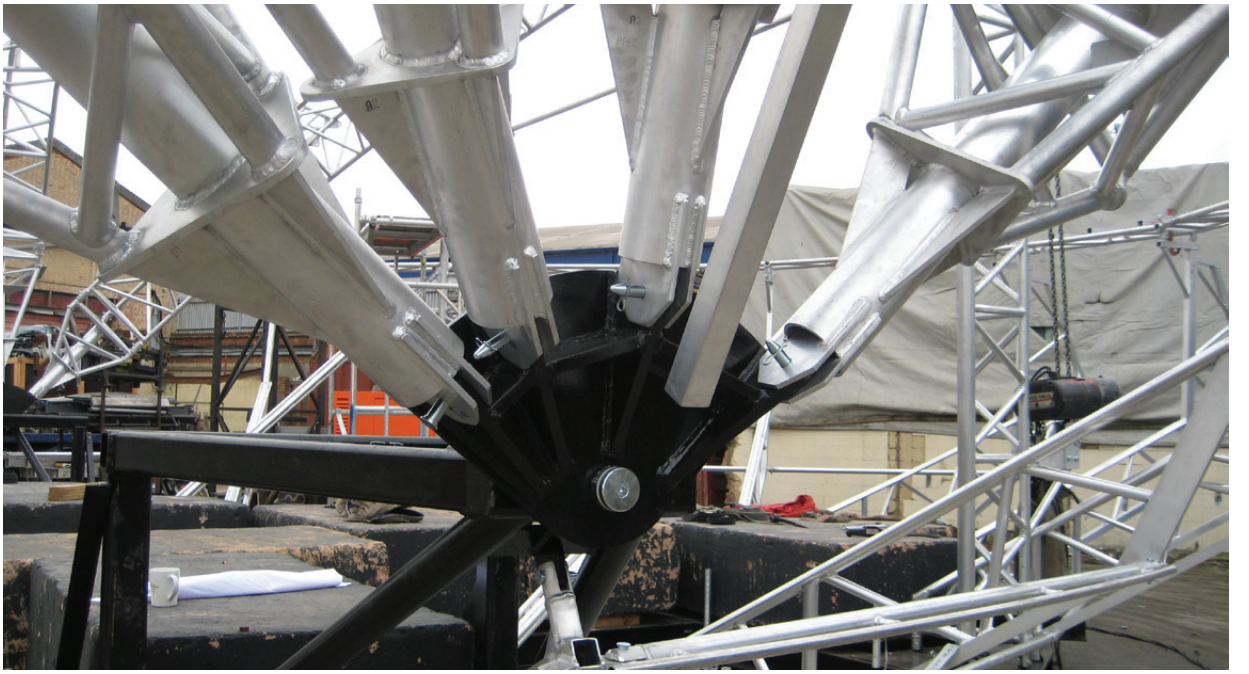

Fig 5.4.10 Photograph of the pram lid joint during the test assembly.

The outer front lip of the shell was of special concern, as it was a defining feature of the form, yet was double curved, and because of cost limitations had to be formed from single curved 40mm CHS. The double curvature was modelled in Rhino, and then optimised into single curved elements; this formed a template for the cutting of the CHS into a single complex curve. The pressures that acted on the curve had to be carefully considered, as the point where the fabric touched the steel varied, and was not ever in the same place twice along the line of the steel.

Fixed acoustic elements

In order to meet the acoustic brief established by the acousticians, a rigid inner skin had to be designed. The skin had to be robust enough to meet the densities required to bounce the sound back to the musicians, and meet the rigors of a touring demountable structure that would take a lot of knocks on the road. The elements that made up the also had to be light enough to be lifted and mounted easily by the shells operators. These conflicting requirements were resolved by way of a series of demountable panels that could be hooked on to a flying truss above the stage. They were easily lifted by a single operator, and were able to be stacked neatly in a manageable collective for easy of transportation. Ultimately the orchestra shell's acoustic skin had to comprise of a series of profiled reflectors constructed from a rigid material with a minimum surface weight of 10kg/m2. This was achieved by fabricating the panels out of 18mm ply, and suspended from the underside of the primary structure by way of simple clips for ease of application / removal. The profile of the reflectors was performance determined, and had to be coordinated within the overall aesthetic of the shell. Concave reflectors were not considered due to the focusing that would occur on the stage, and would confuse the musicians, rather than support them. Flat panels were also not considered due to specular reflections that can lead to a harsh sounding acoustic, a bit like a tiled bathroom. A convex profile was chosen, as this had the effect of distributing the sound around in an even and balanced manner. Their deployment was defined by the acoustic performance within the shell. They had to balance amplitude

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and proximity, if they were too close, there would be too much acoustic feed back to the musician, and deemed too loud, if the panels were too far away, they would be ineffective.

The final layout of the panels was optimized for a small chamber orchestra in the case of the Soundforms that was actually developed to completion. The panels as designed, have a convex plane with, in some cases a plane flat surface running along the rear. This rear surface gives the panels a saw tooth profile along the longitudinal line of the shell. The aim of this profile is to balance the amount of sound that was aimed at the orchestra, and the sound that was directed towards the audience. The size and number of these planes in relation to the convex surfaces had to be sensitively balanced and considered in terms of both acoustic performance and aesthetics. The optimization process was digitally undertaken in Rhino and the genetic algorithm plug in Galapagos. The output of this process was then tested in Odeon acoustic simulation software. When a shell layout was accomplished, it was sent to the architects digitally for integration into the main model. It was then adapted to fit. Obviously this compromised the acoustic in some way, and the model then had to be returned to the acousticians for further modelling. This iterative process continued until there were no longer any compromises, and the aesthetic of the inner shell could be considered as being a visual model of the working acoustics.

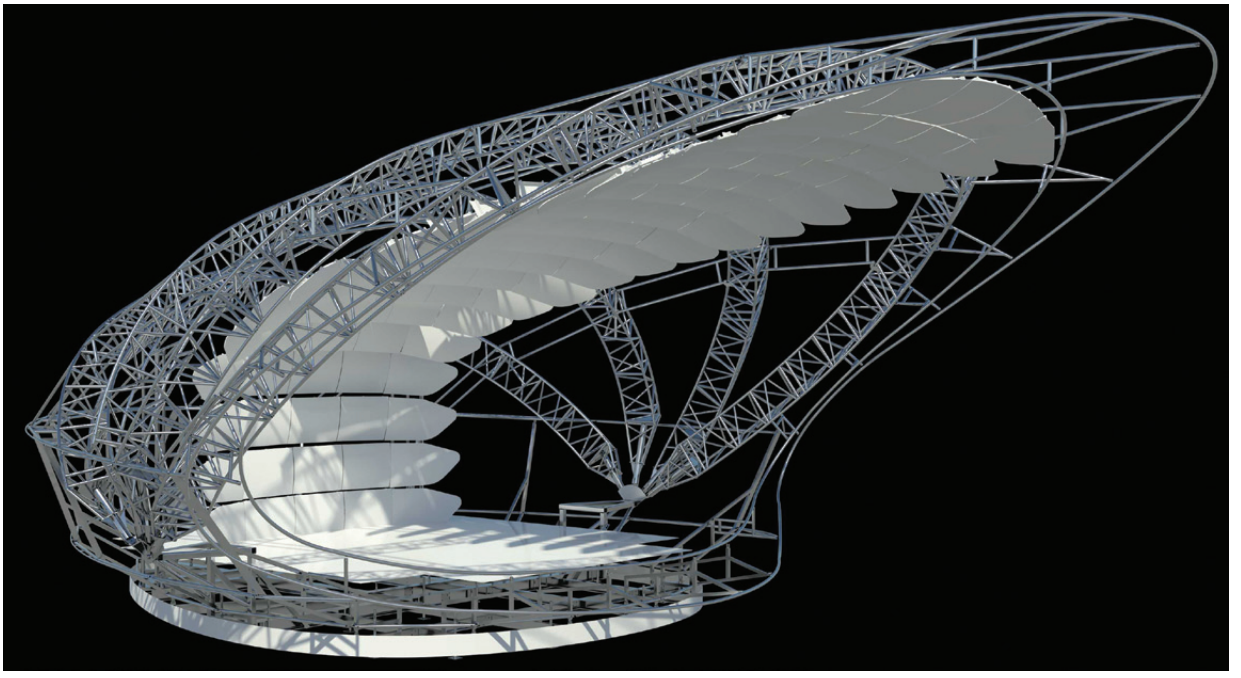

Fig 5.4.11 Computer model showing the acoustic panels in place with the structure

The digital models of the approved panels were then sent to the fabricators, Fineline of Bristol, to be CNC out of large sheets of ply. Originally the diffuse surface required by the acousticians was to be fabricated out of timber battens on a flat surface. This was not in tune with the organic nature of the form, and a curved surface was developed. The curved surface was formed by a series of small channels routed into the rear of the panel, allowing the material to curve, this was held by a simple ply former that was cut to the appropriate radius as defined by the acoustic testing, and then fixed in place. This had to be mocked up as a series of prototypes, and approved prior to fabrication.

A few differing methodologies were considered, not to create a series of different shapes, but to develop a fabrication technique that would speed up the manufacturing process and use less material. The side cheeks of a typical chamber hall perform in a similar way to the other surfaces and are critical in the acoustic performance of the shell. As the shell that was to be constructed was to suit a small chamber orchestra, these would have to be fairly close to the musicians to be effective. This was in conflict with access issues to the stage, it was decided that the acoustic side walls of the shell could be mounted directly to the inner structure of the shell, with the side cheeks of the stage being created out of a fabric material that would allow the transfer of sound without absorption or colouring it in any way that was detrimental to the core acoustic required. This enabled the core acoustics to work as intended, with the visual aspect of the shell being maintained by a fabric liner. This inner lining is made from Joel elastic, an acoustically transparent material, and totally flexible, performing a little like Lycra.

Fig 5.4.12 Photograph showing the interior during a performance at the Olympic Park, London

The development of the acoustic panels on the interior of the shell utilised no two dimensional drawings in any way, and was developed exclusively through the exchange of computer models and three-dimensional files. Another innovation used was the use of an architecturally trained acoustician from Arup Acoustics based in BFLS office, dealing with acoustically aware architects. The roles of the team were not constrained by traditional office based constraints, and an atmosphere of true collaboration pervaded.

Fig 5.4.13 The acoustic panels being lifted into place during the test in London's docklands.

Skin

As with any mobile structure, the main defence against the weather is key to the success of the structure. This must be light, and easily deployable. Whilst a fabric in some form was a natural starting point for the scheme, there were a few design iterations to be explored prior to deciding on the final version. Tensile fabrics were considered, as were fully inflatable versions, with no reliance on an internal structure. These were looked at, and discarded when issues arose that didn't fully conform to the working design brief. As the process developed, hybrid solutions were considered and modelled. The innovations learned from discussions with fabricators were fed back into the design process, leading to a surface that was seemingly independent of the structure, and was able to curve to the now developing design principles. Ultimately, the design brief was resolved by inflating the outer skin of fabric, rather than a typical tensioned solution.

The weather protection material is a low-pressure inflatable surface that supported the external surface of the shell forming the iconic shape. This was developed by Bath based Tensys, engineering consultants providing specialist services for the design and construction of lightweight stressed membrane structures. The skin had to be analysed in terms of efficient form finding, load analysis and patterning. The original form of the shell was developed by BFLS, and sent to Tensys as a surface model. The core drivers that defined the development of the skin were the performance of the material used to fabricate the skin and the patterning required to form the shape required with an even air pressure applied. The patterning was crucial in the operation of the shell, and the aesthetics, as every panel of the shell was clearly readable on the surface via connecting seams. BFLS worked closely with Architen Landrell the fabricators, and Tensys to establish the rules that governed the application of seams, and their visual impact on the final product.

Tensys used their own software called ‘inTENS’ to develop the shell. The output of the computer modelling was sent to BFLS digitally for evaluation. Following a series of iterative transfers, a final approved shell was developed. This met the requirements in terms of effective patterning that held the shape, matched the logistical demands of the manufacturing process being cut within the size of the source material and had seams that were complimentary to the shape, and not detrimental. Key to the success of the patterning is the depth of the membrane that varies to equalize the air pressure, and keep the external element smooth. The skin was developed as a series of 8 removable waterproof PVC coated polyester cushions. A single skin being too unwieldy to install in one attempt as would be required, the panels were fixed to the structure via industry standard ratchet straps. This is a common fixing methodology in the rigging industry, and would be easily understood by operatives unfamiliar with the shell. The outer skin was fixed via a series of coordinated airtight zips. These were developed by NASA in space suit design, and now commonly used in dry suit manufacture for the diving industry. The inflatable panels were put in place as the structure was assembled, so both elements could be fitted simultaneously, allowing a shorter rigging time. The skin was inflated via a small pump located in the back of the shell. It is housed in an acoustically attenuated box, so as not to disturb the performance. It is a speed controlled centrifugal blower operating at 0-10 volts. The internal pressure of the skin is constantly monitored by sensors that modulate the airflow from the pump, keeping the form in place. The skin is inflated to 50psi, which was found to be sufficient to provide a stable form even in high winds.

Fabrication & Assembly

Architen Landrell based in Chepstow made the skin, the Total Solutions group in Birmingham made the structure, and the acoustic panels were made by Fineline fabrications in Bristol. The structure was assembled in by ES Group in the Docklands. March 2012. The test build took a week to complete, and did not represent the speed of a proper deployment of the shell if commercially deployed, which currently takes three days to erect, and takes two days to demount.

Testing

In March 2012, the prototype was tested in London's Docklands with players from the London Philharmonic, Nicola Benedetti, and Charlie Siem. The weather was bitter, and the space used to assemble the shell was directly under the flight path of City airport, creating challenging conditions for the performers. Whilst a PA system was present at the test, the shell was tested without amplification, to establish that it worked. The team was looking for two main outcomes in the testing, that the musicians felt the reinforcement that the shell was intended to provide, and that the audience could appreciate a clearer acoustic than previously experienced at external concerts.

Fig 5.4.15 Testing the shell in London's Docklands

The varied nature of the potential sites for the product made acoustic testing fraught with inconsistency. It is impossible to determine where the form will ultimately be deployed, so any test results gleaned from the test site would be meaningless in the context of future deployment. It was simply decided that a series of test performances would be conducted within the shell that represented typical intended uses of the product. These were performances for a solo piano, a solo saxophone, and string ensembles of varying sizes. Each of the performers and selected audience members were interviewed afterwards for comments on the performance of the shell.

The performers commented extremely favourably on the shell, and all felt that the experience was beneficial to their playing. They felt that despite there being no full enclosure, there was enough feedback from the acoustic panels to support their performance. The main points made by the musicians were focused on the 'clarity' of sound in tandem with warmth to the reverberation in the shell.

Charlie Siem, International solo violinist observed: 'I think there is no standard for performing outside, it (has been) just a tent. The difference with Soundforms is enormous.

There is a real sense of the sounds being lifted; its like a concert hall stage, you can hear everyone very clearly, but it feel a lot more intimate. Usually you can't hear anything when playing out doors; this allows for real music making.'

The London Philharmonic noted: 'Very enthusiastic about the whole thing … really enjoyed the experience of playing in it … the sound was great and it is a very exciting idea. It looks fantastic. Everything inside the structure was good, lighting, space to move, acoustics etc.'
Iain Bellamy, Saxophonist ECM Label concerned: 'The Soundforms acoustic performance shell took me quite by surprise! From an audience perspective I beheld a futuristic and magically illuminated stage … that projected the music with perfect clarity. From a players perspective I enjoyed its acoustically comfortable performing environment and clear sonic focus from which I could sense the quality of sound emanating from the stage as I played. I expect to see the shell become a regular sound and sight at music events in the near future.'

The audience comments were equally favourable, with many members who were asked commenting that they had tested the scope of the shell by walking in, and out of the zone of support given by the shell. By way of analogue testing in this manner, it was confirmed that the shell did indeed project acoustically towards the audience, improving the natural acoustic for the audience members.

Lessons learned

Whilst the acoustic of Soundforms was an unqualified success, the team learned a great deal from the prototyping experience, and have agreed a few design changes that have come about from the experience. The aluminium structure will now be constructed of steel, to last longer, and be more robust. The three-cord truss system was deemed to take up too much space, and has now been developed into a series of ladder trusses that are flatter, and can be easily stored. Finally, the ratchet system that holds the skin in place on the structure, was developed as it allowed an operative to individually tailor the tensioning of the outer skin on the structure proved too flexible, and created irregularities along the key system lines of the fabric. It has now been decided to use a less variable shotgun profiled extrusion to key in the raised rubber edge sewn into the edge of a fabric panel, the cada, this keeps the skin in constant tension, and smooths out the final form.

Deployment

The testing process was successful enough that it was then selected by LOGOG for deployment in the Olympic Park for the 2012 London Olympic Games, where it hosted almost continuous performances for the duration of both Olympic and Para-Olympic games. Despite being used by mostly amplified ensembles, the feedback from the performers was wholly positive.

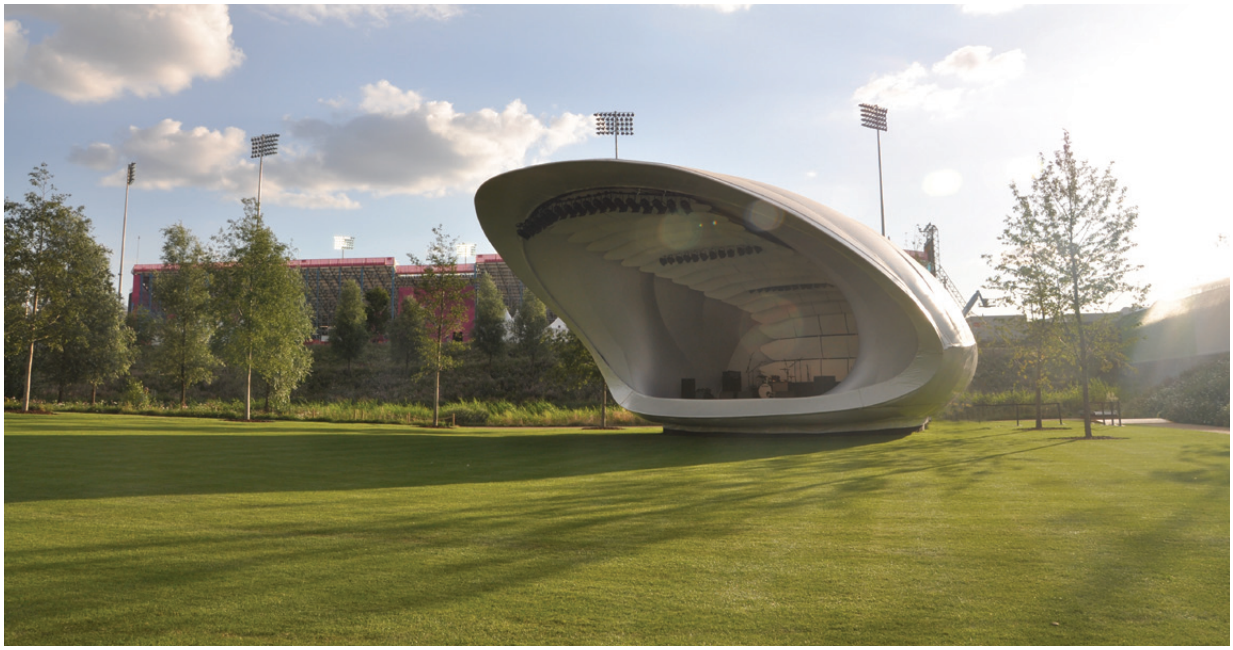

Fig 5.4.16 The shell in the Olympic park.

Fig 5.4.17 The shell in use in the Olympic park.[ii]

Credits

Design Team:
Mark Stephenson, Conductor
Jason Flanagan, BFLS
Paul Bavister, BFLS
Ian Knowles, Arup Acoustics
Olly Watts, ESG
Engineering:
Malcolm Richards:
Andy Prescott
Skin development:
Tensys
Fabrication:
Total Solutions Group
Fineline
Architen Landrell
Acoustic Modelling:
Luca Delatore
3d Modelling:
Armando Elias
Matthew Donkersley
Andrea Vannini

References

i Paul Bavister graduated from the Bartlett School of Architecture in 1999, and is an Associate Director at BFLS, and a Director of Soundforms.

ii Image Credits: Fig.1,11-12, 15 and 17 © N Guttridge, Fig. 2 © Hekman Digital Archive, Fig. 3, 9-11,14 and 16 © BFLS. Fig. 4-8 © Arup Acoustics.

5.5
Soft Kinetic Prototypes for Adaptive Architecture

Glynn Ruairi, Zoi Karagkiozi and Theodoros Themistocleous [i]

Recent developments in soft & compliant robotics as an innovative generator of kinetic systems with no rigid links or rotation joints seeking to break new ground for applications in responsive architectural design. Applications of robotic systems within architectural design and research have shown growing interest in material assemblies that compose dynamic forms able to be transformed through time. In this context, this paper examines the important role of the prototype in the development of soft architectural components actuated by embedded pneumatic networks through two research projects. Each having been developed separately but within the same research programme using a reflexive digital and physical prototyping based methodology.

The first project explores the development of an SLS 3D printed monolithic auxetic structures actuated to a predefined form by an embedded pneumatic network. Taking the theoretical background from compliant mechanisms auxetic structures, stiffness optimization and pneumatics, have been developed initially in physical prototypes, which in turn informed the rest of the procedure, through an iterative process of feedback between digital simulation and physical testing. The understanding of compliant behaviour, which is not based in mechanical movements, but in the form of the matter, has been done through a process of implemented experiments, observations and redefinitions. By making explicit the laws governed its behaviour through this process, it was possible then to decode its “genetic” instructions and to predict the morphing phases of the artefact in relation to the composition of the matter. This analysis process eventually has been transformed to a synthetic algorithmic procedure of a material system, which produces prototypes with designed materiality and prescribed compliant behaviour able to self actuate.

The general framework of this study explores the deformation of different aggregates based on their inflatable silicone cellular structures. The research is focused on both the physical prototypes and computational design of those material assemblies while the aim is to create an algorithmic simulation that probes the relationship between the virtual model and its physical artefact. The proposed method involves a generative algorithm that establishes relational material topographies based on a research of the elastic deformation of silicone cellular structures under air pressure. The fitness of the method is determined first on a single cellular structure and then its efficiency is tested on larger assemblies when aggregating components. The result is the transformation of an initially entirely planar surface to a double curved membrane whose curvature is generated by attaching

hexagonal cells with different elastic attributes. Finally, the study has successfully achieved the challenge to explore and generate computationally the performance capacity of this intricate structure and moreover to scale up the physical model producing larger inflatable silicone aggregates with less structural damage.

In the above projects, the prototype is both the output and the input of information for the development of two kinetic adaptive systems. Two case studies were undertaken both with compliant behaviour but with totally different characteristics in their materiality and function. The first is formed from rigid plastic with limitations in its scale, needed higher pressures for its actuation but having stable structure, and the second made from elastic material able to scaled up and actuated from lower pressures but having unstable structure. Therefore a research space is still open for the exploration of a combination of those systems.

Introduction

Kinetic architecture today is understood as a response to technological, economical and social change (Kronenburg 2007) and its role is extended to the creation of an environment able to understand the needs of the user and to change accordingly. In this manner Sterk (2006) also argues for a recent shift in kinetic architecture due to environmental concerns and to the demand of a more sustainable built environment. Although the theoretical approach to kinetic architecture promotes the benefits of dynamic environments, its physical application is still less developed (Hoberman 2011) due to the limited options for kinetic systems able to transform or be transformed. For the purpose of this research is suggested the categorization of the structures in relation to their technological and behavioural characteristics in two groups: sustained (hard) and disruptive (soft) structures (Appendix 1). The first group includes the hard structures of which the function and design relies on rotational nodes and rigid links (trusses, pin joined, tensegrity) and they are made of many components. These structures have many disadvantages like heavy weight, large number of components; many assemblies, rigidity, high-energy consumption and they need very complex computation to control their movements (Pfeifer et al. 2012). On the other hand the less developed disruptive kinetic structures with soft behaviour are very promising as they use smartness in their composition to simplify movements and eliminate computation process during control. Furthermore soft kinetic systems due to their intrinsic compliance can safely interact with humans as it is stated for “Festo Bionic Handling Assistant”, and with the digital-driven fabrication and design technologies could be optimised, simulated and manufactured to adapt to specific conditions.

Material computation has been researched the last years as a method for form finding in architecture and for creating passive responsive systems borrowing computational methods from engineering (Oxman 2010, Menges 2012). Its main purpose lies to the optimization of the materiality of the architectural artefact in relation to external conditions. However, that research is focused mostly to the passive behaviour of material systems leaving almost unexplored the area of material computation in relation to active systems. In this manner this paper is examining the potential to find methods and create methodologies in a post mechanistic era to create soft kinetic systems with embedded actuation in architecture, by exploiting the advances of digital-driven design and fabrication.

From an iterative process of fabrication, observation and reformulation between physical and digital models both projects have been achieved using different materials and different algorithmic procedures to develop functional artefacts virtually and physically. From the results it is concluded that new design methodologies and new tools could be suggested in order to enable architects to direct and manufacture architectural choreographies based on the optimization of material's properties. This approach is aimed to bridge the gap, between kinetic systems, mechanical design and adaptive architecture, which exists in the sustained technologies and hard mechanics. Thus, it is argued that could create a new perspective in the conception and creation of soft dynamic environments in architecture.

Fabricated Pneumatically Actuated Auxetic STRUCTURES

Introduction

This project is following an iterative process and an informative dialogue between digital and physical prototypes to develop a novel 3D printed (SLS) pneumatically actuated auxetic morphing system, with the view to research potential applications in dynamic architecture. Auxetic behaviour is characterised structures with negative Poisson ratio able to form synclastic surfaces (Fig.1) while morphing denotes according to McGowan et al., (2002) mechanically simpler, lighter weight, and/or more energy efficient than conventional systems. Drawing on knowledge from material computation and compliant mechanisms has been composed both digital and physical prototypes with soft behaviour (Hanna and Haroun Madhavi 2004). Beginning with tests of 3D printed (SLS) bellows, which are known examples of compliant mechanisms actuated from internal pneumatic forces, has been tested to what extent those structures could be formed and function. Having achieved satisfactory results during the tests, the next step was to develop the simulation environment using finite element method, informed from observations gained after the juxtaposition of the 3D scanned (Kinect Camera) physical prototype to the digital one. Studying the relation of the scanned prototype's behaviour to the performance of the simulated model has been composed, an algorithm based on the emergence of final structure from the convergence of the behaviour of sub – structures. Therefore following a methodology based on the analysis and synthesis of the simplest sub-system has been achieved the development of an auxetic pneumatically actuated morphing system.

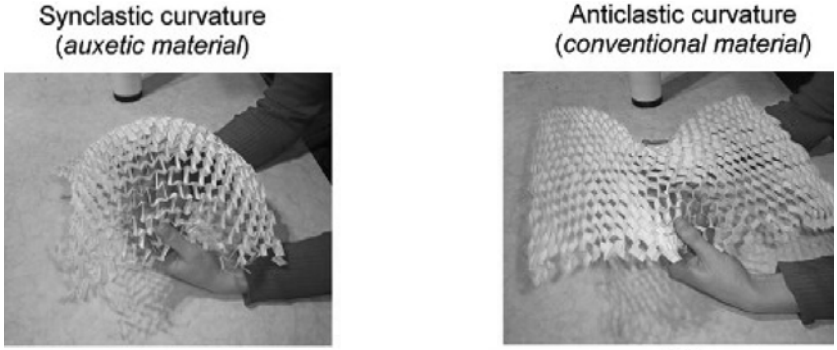

Fig. 5.5.1 Pure bending of (a) auxetic material (synclastic curvature) and (b) conventional material (anticlastic curvature), (Image: Alderson 2011)

First set of iterations, Soft deformations in one axis

The development of a pneumatically actuated compliant morphing system started from the study of a cell and its potential to deform under pressure. The cell studied in this project is re-entrant hexagon based on, the work of Evans (Fig.2) related to the development of auxetic structures and to the hypothesis that it could change shape from the deployment of forces at its internal walls. The first conceptual designs of the artefact lead to the conclusion that from its composition on one axis it is a common bellows. Therefore the first test and further knowledge of the understanding of the laws behind its movement informed by 3D printed bellows and literature review in this subject.

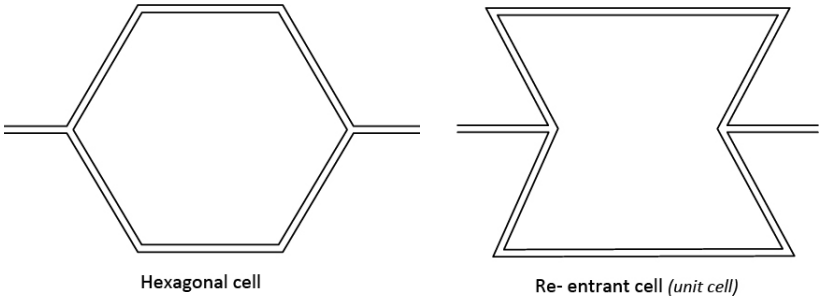

Fig. 5.5.2 Re - entrant cell proposed by Masters and Evans,
(Image: Masters and Evans 1996)

The first tests were exploratory and aimed to understand the relation of the material, geometry and shape to the behaviour of the artefact. The same cell has been developed in many shapes following several techniques (revolving, extrusion, lofting) and in several dimensions to evaluate the best relation of performance to shape. After many tests with physical prototypes has been evaluated that the selected unit cell could form 3D printed structures with compliant behaviour when pneumatically actuated. However the size of the unit cell and therefore the size of the structure was specified from the limitations of the printing area and consequently the thickness of its walls was set accordingly after several experiments. Having tested the hypothesis of a 3D printed one axis soft morphing structure the next step was to simulate its behaviour. For the simulation of its behaviour has been used the Direct Stiffness Method (Felippa 2004), a version of finite element method which analyses and solves a mathematical model made of pin-joined trusses. The performance of the simulated model based on the abstraction of the physical prototype to a mathematical model made of triangles and to the translation of pressure to forces acted on nodes. The evaluation of the success of this translation based on the correlation of the behaviour of the physical prototype to the mathematical model, a Kinect camera has been used to capture the movements of the physical prototype and have been juxtaposed to the deformation of the mathematical model. To test the adequacy of the simulation environment it was proposed that a digital model with anisotropic bending be fabricated and tested. The results showed a high correlation of the behaviours (physical and digital prototypes) and therefore the simulation environment is conceived successfully.

The relation to the overall behaviour of the structure to the shape of the unit cell

To optimise the behaviour of the structure has been suggested to change the length of the incident edges of the two vertices point 'inward' - towards the interior of the polygon of the unit cell, as it is described in Fig. 3. By adjusting the length of the edges it will differentiate the compliance behaviour of the upper and lower sides of the unit cell, compelling in this way the prototype to bend by preventing its uniform linear elongation.

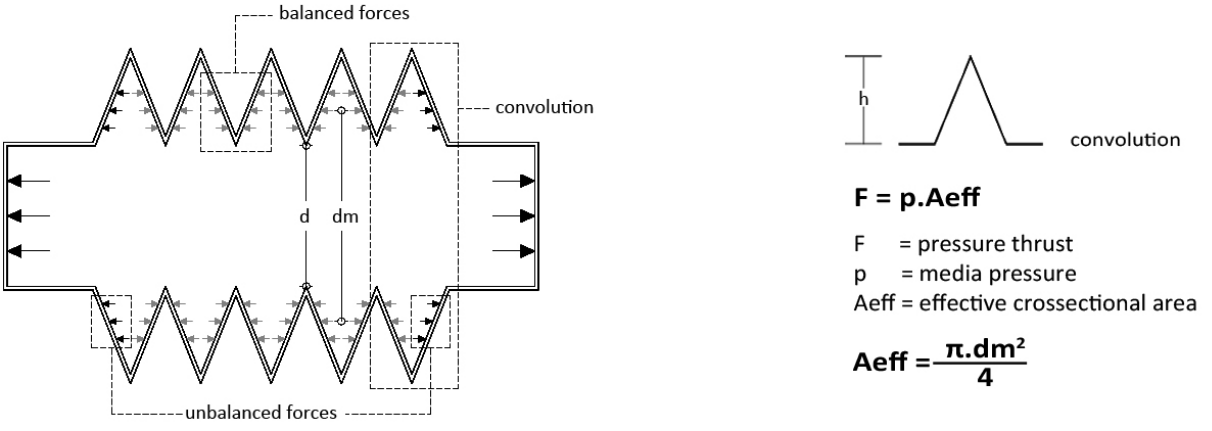

Fig. 5.5.3 Diagram of the engineering physics of bellow, (Image: Theodoros Themistocleous).

Second set of iterations, Soft deformations in two axis [Auxetic]

In the second set of iterations an auxetic morphing structure has been developed firstly digitally and then physically. The observations during the development of digital prototype informed the reformulation of the bellow-structure algorithm to an auxetic-structure algorithm and through this process has also been emerged the form of the physical auxetic model. The auxetic structure has been formed from the shape of the initial unit cell (re-entrant hexagon) which has been arrayed in a grid with an offset distance equals to the width of the cell. This grid then has been copied and rotated ninety degrees and placed between the cells of the first grid in a way that all the cells were connected at the same edges. The result was a two-axis array of cells able to bend in two directions and hypothetically to form an auxetic structure (Fig. 4). In the first attempt to test the auxetic mathematical model of the above geometry, it has been observed that the algorithm which has been derived from the first experiments (algorithm based on a continuous mathematical model) failed to simulate the behaviour of the artefact due to the huge number of elements that caused a huge amount of calculations.

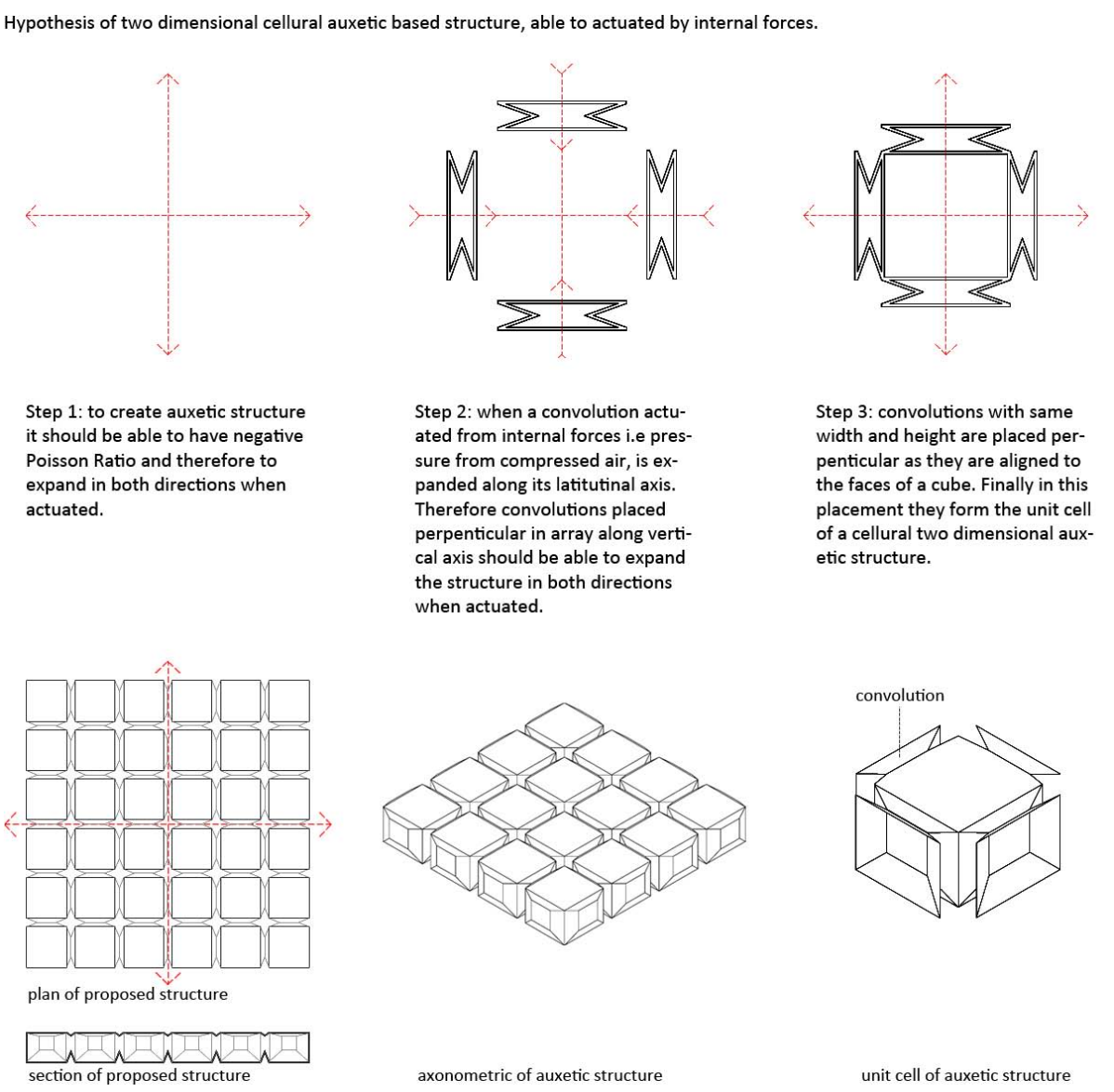

Fig. 5.5.4 Hypothesis of geometry of cellular auxetic structure, able to actuated by internal forces, (Image: Theodoros Themistocleous)

Reformulation of the algorithm and introduction of sub - systems analysis and synthesis

The solution to the problem came through the discretization of the model in sub – elements. It was suggested that the behaviour of each sub-system could be solved separately and following a hierarchical procedure of analysis and synthesis to emerge the behaviour of the whole. During the first iteration has been simulated a single sub-element on which would connect all the elements of the second iteration. The second iteration has been solved using the deformed displacements of the connection nodes of the first iteration as boundary conditions. During the third iteration have been solved all the elements connected to the elements of the second iteration using again the displacements of the deformed elements of second iteration as boundary conditions to solve the elements of the third iteration. This procedure would be followed until it solves the whole structure and therefore the algorithm would be able to simulate the compliant behaviour of all the elements. Finally using a transformation matrix have been combined all the solved elements together resulting to the prediction of the behaviour of the whole system.

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Auxetic structure - Final digital model and algorithm

In order to use the algorithmic process based on sub-elements analysis and synthesis to simulate the auxetic structure, the authors had first to specify the sub-element and then the hierarchy of connections and simulations. Therefore has been suggested a geometry which has been derived from the diagonal separation of four cells (Fig. 5) and the proposed algorithm (Fig. 6) based on three types of components in relation to the hierarchy of their connections to their neighbours. The first component C1 had eight rectangular Connection-Faces (CF) with their lower nodes fixed. The second component C2 had four fixed nodes at upper and lower corners of its rectangular CF and the third component C3 had two rectangular CF with eight fixed nodes at upper and lower corners of each face. The first component C1 was positioned in the centre, and was constructed only one time at the beginning. After its structural analysis the displacements of the edges of its CF have been applied as prescribed displacements to the fixed nodes of the CF of the components C2 that had been connected to the four CF of the component C1. During the third iteration a component C3 had been positioned between two components C2 after the displacements of the two CF of neighbouring C2 applied to the edges of CF of C3. The last two steps had been repeated proportionally to the size of auxetic structure.

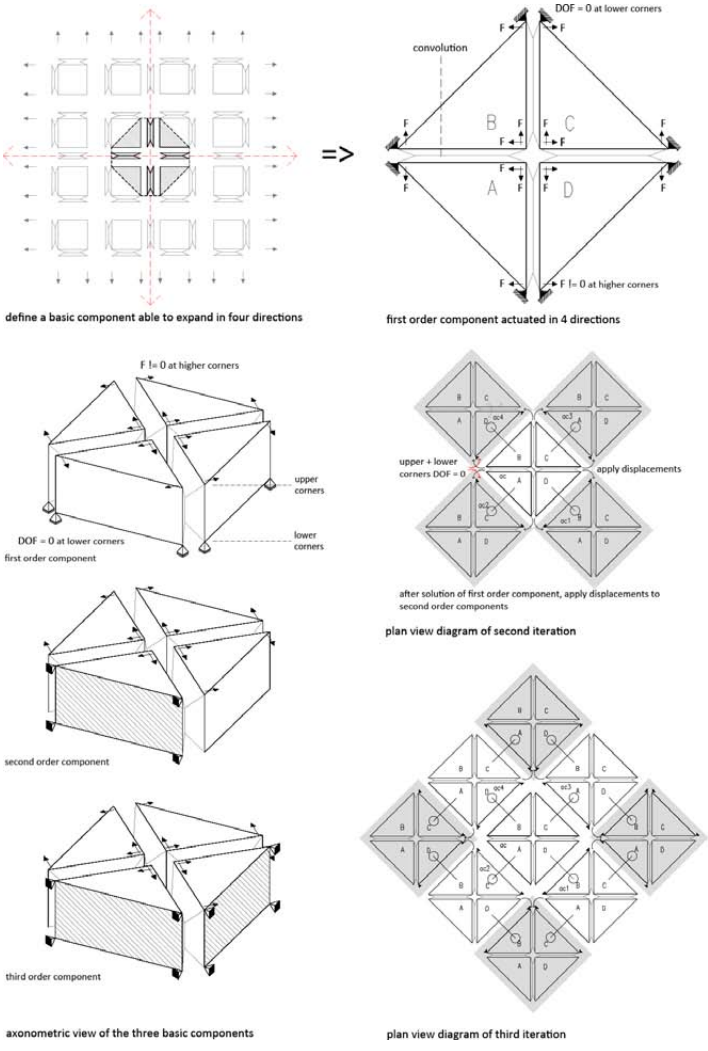


Fig. 5.5.5 Diagram of the mathematical model and basic steps of final algorithmic process, (Image: Theodoros Themistocleous)

$$\sum_{j=1}^{n} j = \{S(C1)\} + \sum_{i=1}^{2^{2\cdot n}} \{S(C2_i + |u1|).TR_i((\vec{w}1)\} + \sum_{i=1}^{4} \left\{ S(C3_i + |u2_{i-1}| + |u2_{i+1}|).TR_i(\frac{\overrightarrow{w2_{i-1} + w2_{i+1}}}{2}) \right\}$$

S = *Structural analysis,* Ck = *Component k ,* uk = *prescribed displacements derived from component k,*

$TR\ (\vec{w})$ = *(Transformation) + (Rotation matrix) of unit vector w*

Fig. 5.5.6 Final algorithm for the simulation of an auxetic structure, (Image: Theodoros Themistocleous)

According to the measurements, the simulation algorithm, proved able to predict the transformation of the structure and the mathematical model able to form synclastic surfaces, when the ratio of the heights of convolutions was not equal to one (Fig. 7). Therefore the curvature of the structure could be optimised according to the angles of the vertices point inwards the re-entrant unit cell and an auxetic 3D printed geometry actuated pneumatically could be derived from this mathematical model.

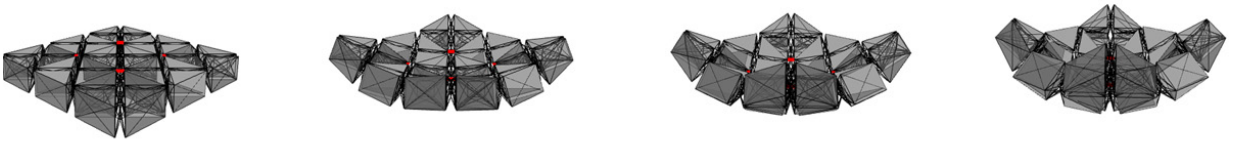
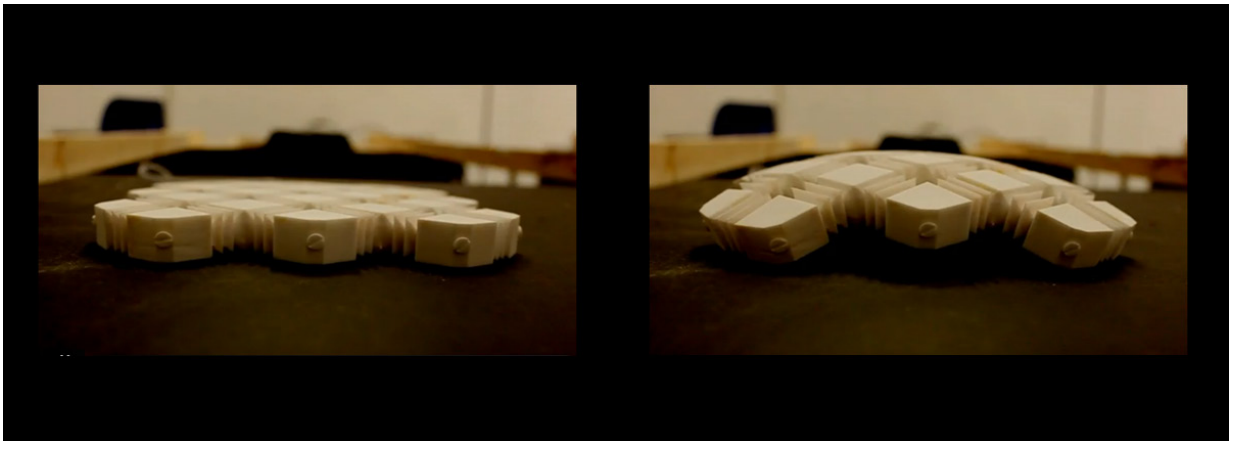


Fig. 5.5.7 Simulation of auxetic based structure in PROCESSING, (Image: Theodoros Themistocleous)

Final test - Fabrication (SLS 3D Printing) and actuation of auxetic structure

The final test of the algorithm and of the hypothesis implemented the fabrication of the suggested geometry and its pneumatic actuation. During those tests has been observed and recorded with a Kinect camera the behaviour of the physical prototype which then has been compared to the behaviour of the mathematical model. From the recorded behaviours have been created diagrams of curvature along the two axis of bending and through their comparison have been generated conclusions for the adequacy of the method. During those tests have been observed that the physical model performed as it was suggested, exhibiting an auxetic behaviour and forming synclastic geometries. The forces acted internally from the pneumatic actuation had produced the expansion of the structure in two perpendicular axes and therefore have created the auxetic behaviour (Fig. 8).



≤≤ Fig. 5.5.8 Caption of fabricated auxetic structure with three convolutions per unit cell during tests B, (Image: Theodoros Themistocleous)

From the above diagrams can be observed the auxetic - synclastic behaviour of both the mathematical and physical model. The fabricated auxetic structure has a similar behaviour along its axis (Fig. 9) with fabricated bellow structures.

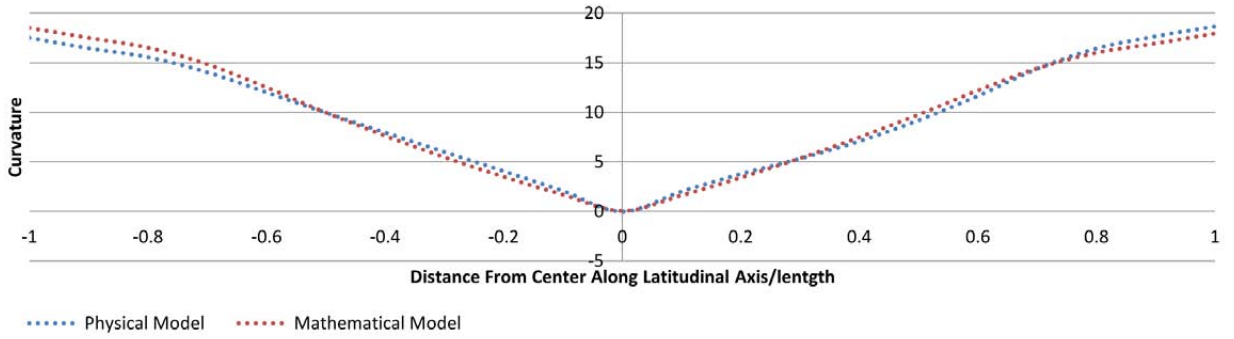


Fig. 5.5.9 Comparison of curvatures of mathematical and fabricated models with ratio 0.29 along their latitudinal axis, (Image: Theodoros Themistocleous)

Conclusion

The approach of research by design, making and testing, in combination with theoretical background constitute a successful method to conceptualise, design, fabricate and simulate a kinetic system. The combination of physical and digital models and the iterative experimenting process proved adequate in the creation of the hypothetical system and to the acquisition of its properties in a digital environment. This informative dialogue between physical and digital and vice versa was the basis on which structured the argument. Additionally the approach of sub - system analysis and synthesis had a fundamental role in the development of methodology. First it helped to create the geometry by starting of the basic component (unit cell), understanding its properties in relation to the tested material and finally combined it to a more complicate system until it created the suggested structure. This approach it didn't only work for the design of the geometry but also to the development of an adequate algorithm that simulates its behaviour.

Inflatable Silicone Cells

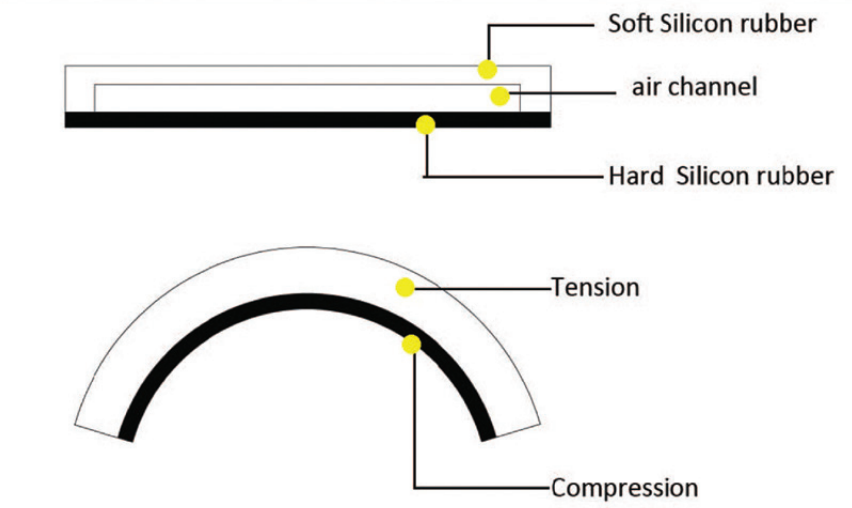
Introduction

In respect of the recent emergence of Soft Robotics as an innovative generation of robotics crafts, soft kinetic systems with no rigid links or rotation joints challenge new potential applications on responsive design. This study attempts to address the challenge to fully predict and control the deformation of inflatable silicone cells within a complex aggregate pattern. The general framework of this study refers to a design strategy that allows innate characteristics and behaviours of the material system to be engaged into the computational design that is constantly updated through feedback from the fabrication process of the physical model. The computational design tool is a generative algorithm that involves a process of negotiation between form and integrated constraints based on a particle spring system. An initial experiment is carried out to determine its fitness to the design problem of a single unit and then further tests are conducted to test and report its efficiency in more complex systems when aggregating multiple components. The methodology of the proposed design strategy is divided firstly into the fabrication process which covers the observation, selection of the structure geometry and experimentation of physical artefact and secondly the computational design which investigates an algorithmic process which goes deeper into exploratory properties to unfold the material assembly gestalt.

Fabrication

Observation of material system

Pneumatic networks based on silicone rubber components show an interesting deformation under air pressure. They perform a wrapping motion whereby one end would wrap completely into itself. Such curved formation of pneumatic structures is established due to the coupling of two different silicone rubbers, one hard and the other soft. The soft rubber part is basically the thicker layer, which contains the inner capillary channel. The strong part is the thinner layer that displays lower rate of elasticity in comparison to the soft rubber. The bend formation is operating towards the hard layer as its expansion rate is lower (Fig. 10).



<< Fig. 5.5.10 Bend formation towards the strong silicone layer, (Image: Zoi Karagkiozi)

This study is taking advantage of such combinational rubber layers to deploy both negative and positive curvature by changing the location of these layers. Attached hexagonal cells, as individual components with reversed layout of strong and soft layer, are forming a honeycomb aggregate pattern that allows various configurations by allocating such individual components differently. Although, silicone rubber is currently a homogeneous mixture, when it is used for building pneumatic networks, the material system is segmented into voids, which are the air channels. In that sense, silicone assembly evolves to a differentiated cellular structure. Its anisotropic attributes are due to the non-uniform distribution of air pressure inside the mould. Various configurations in patterns of input channel employ different inflated areas, thus different deformation and overall shape while air pressure increases.

Experimentation–Physical Testing

The first prototypes of silicone components get their shapes from two acrylic moulds with different internal channels. The shape of both two moulds is a regular hexagon. According to Fig. 11, the left mould presents a detailed layout of the capillary system. Unlike this, the right mould provides a less complex input channel which covers bigger area (Fig.11). Based on the physical testing of these prototypes, each of these two components deploys a rate of deformation, which is proportional to the amount of internal air pressure. The silicone hexagon cell based on the mould with the less complex channel, operated maximum inflation on upper layer with a slight and gentle curve on its overall range and presented maximum tensile strength compared to the other one. On the other hand, the detailed capillary channel performed higher overall bending, with minimum inflation on upper layer and minimum rate of tensile strength.

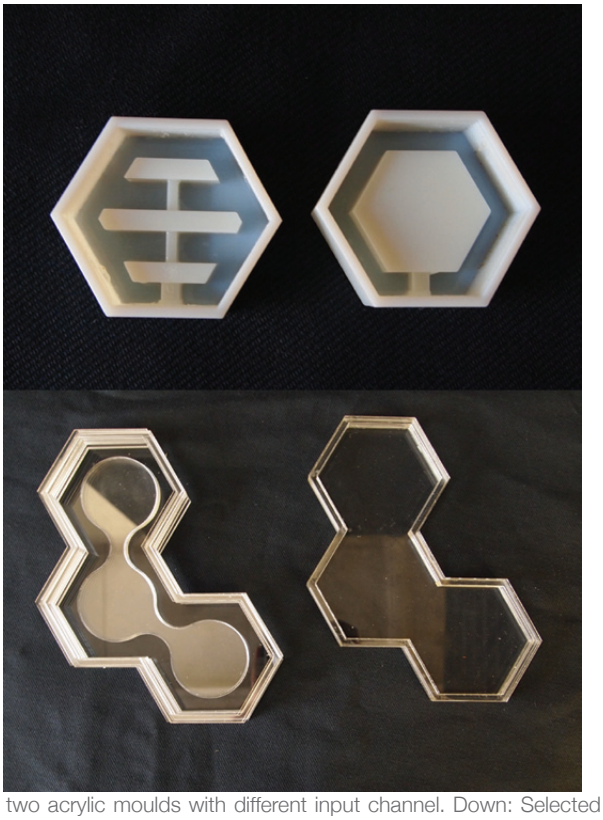


Fig. 5.5.11 Up: First prototypes of two acrylic moulds with different input channel. Down: Selected Acrylic mould with single big air channel for both silicone layers, (Image: Zoi Karagkiozi).

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Comparing the results of those two components, it can be seen that the shape of internal channel indicates the direction of air force towards areas with lower rate of stiffness. In the case of the simple big channel, the air force is towards the upper layer, which is thinner thus less rigid than the outer perimeter of hexagon. The result is that air pushes the upper layer to its elastic limit forming a big inflatable bubble and a slight and gentle curve on its overall range. Based on these observations and considering the fact that the single big channel deploys higher tensile strength during the experiments, the final shape of individual component is based on this channel type for optimum structural performance (Fig.11). According to this configuration, individual components are attached with each other to form aggregates that compose a double–curved membrane. This membrane is not solid and contains voids among its cells in order to allow greater rate of bend formation (Fig. 12). The components have been allocated with reversed distribution of their double silicon layer profile, thus some of them are performing positive and some other negative curvature (Fig.13). The experiments were carried out in four stages: the first test was the inflation of the single component, then the double component, following the 4-component aggregate pattern and last the 6-component structure (Fig.12). While aggregating components, each inflatable assembly is transformed from planar surface to an elastic double curved membrane, performing an upward or downward trend. Considering this bend formation, the first measurements were carried out to investigate the proportion of the horizontal projection (D) of the curve to its height (D1). Under different amount of air pressure, the horizontal projection of the curve is always inversely proportional to its height. In the case of the double component, two separately units (a, b) with the same allocation of the silicon layers, are attached together. In this case, under air pressure, the double cellular structure displays a well-shaped inflatable dome (Fig. 16 -17).

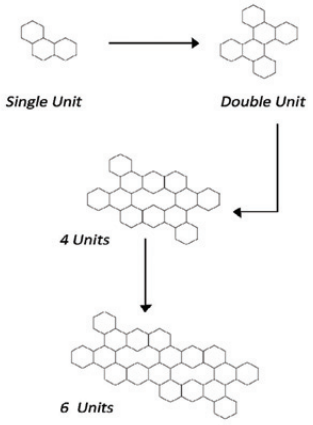


Fig. 5.5.12 Aggregate System: Four stages of the experiments, (Image: Zoi Karagkiozi)

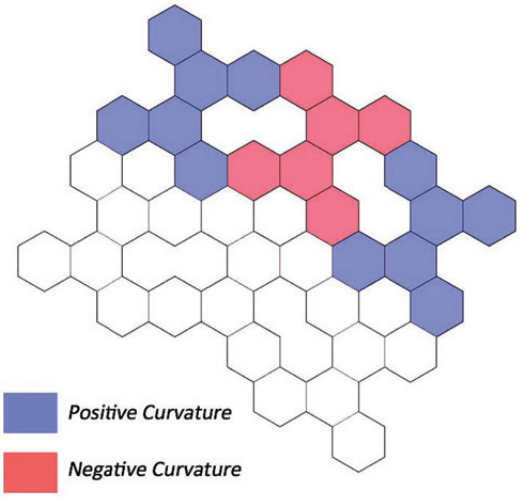


Fig. 5.5.13 Arrangement of different assemblies with reversed silicon profile structure, (Image: Zoi Karagkiozi)

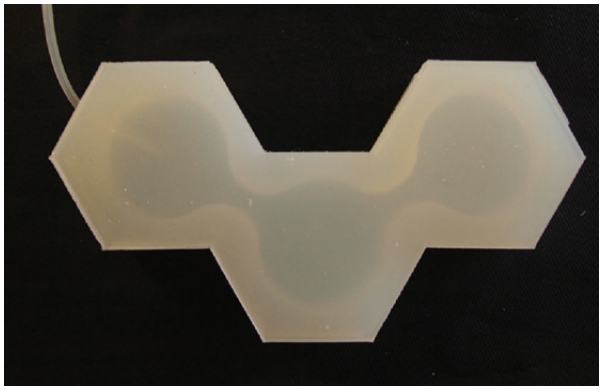


Fig. 5.5.14 Single component on equilibrium, (Image: Zoi Karagkiozi)

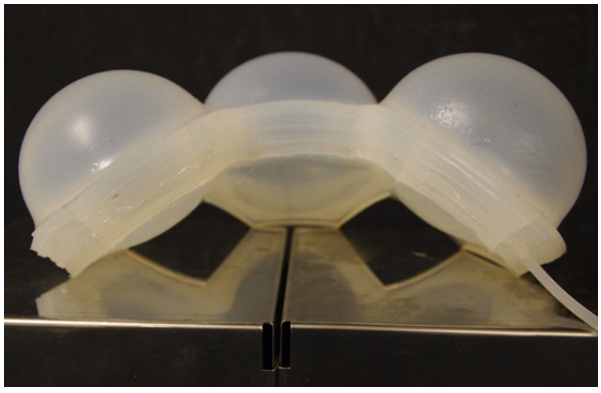
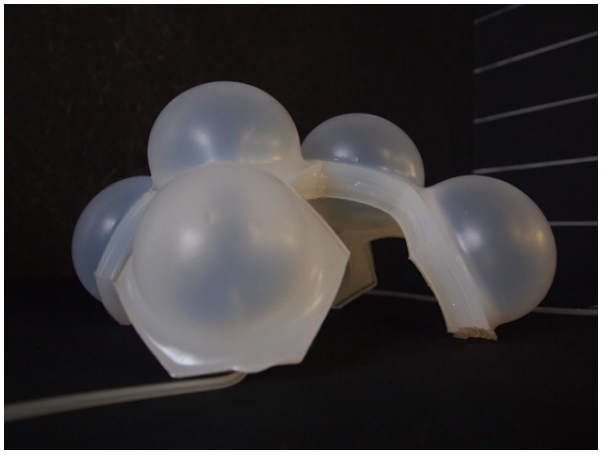


Fig. 5.5.15 Single component under inflation, (Image: Zoi Karagkiozi)



<< Fig. 5.5.16-17 Inflation of double component, (Image: Zoi Karagkiozi)

The following experiments were carried out for a four-component cellular structure with two positive units (a, b) being attached to other two (c, d) with negative curvature. In this case, the inflation is slightly influenced by the aggregation and unlike previously, there is a gentle decrease on curvature of each cell. The next and final task of physical testing was to attach six units together (a, b, c, d, e, f) with reversed distribution of silicone layers (Fig. 18-21). Unlike the predictable deformation of the single and double component, the behaviour of this inflated aggregate cellular structure was not easily predictable, particularly as the profile geometry becomes more complex. The experiments record a double-curved surface that is subjected to a uniform ripple formation. The local bend formation reflects the location of strong and soft layer, thus the overall bending behaviour depends on the distribution of each component within the honeycomb structure. In other words, an alternative combination of individual components would result to a different bend performance.

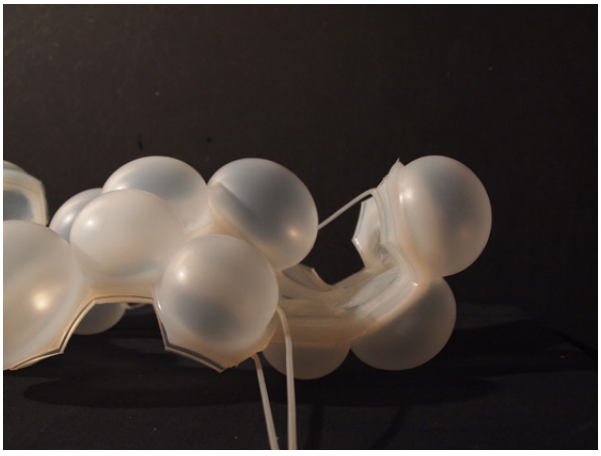


Fig. 5.5.18 (Image: Zoi Karagkiozi)

Fig. 5.5.19 (Image: Zoi Karagkiozi)

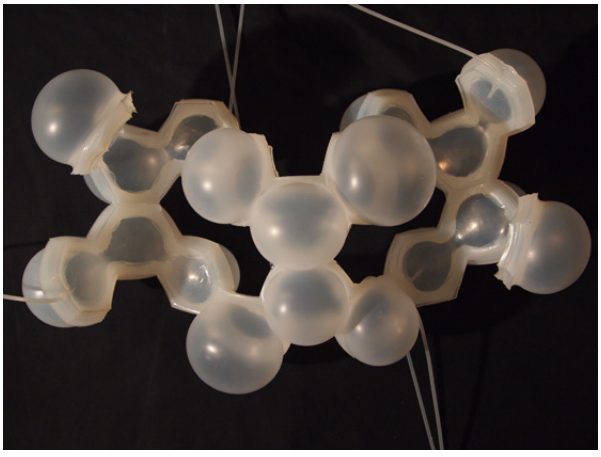


Fig. 5.5.20 (Image: Zoi Karagkiozi)

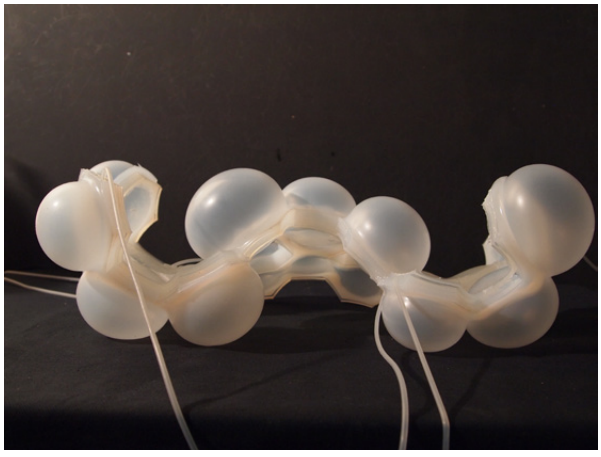


Fig. 5.5.21 (Image: Zoi Karagkiozi)

Computational Design

The fabrication aims to gather the material information needed to be embedded on the computational design. The algorithm proposed is an iterative process that simulates structural behaviour with the aid of springs that exert attractive and repulsive forces among mass nodes that are attached to (Gordon, 2003). Calibrating the material intent, the design environment is also updated by constraints that enable material systems to be self-organized and thus generate geometry and topology of the tessellated double curved membrane consisted of multiple hexagonal cells. The key role of the algorithm is the local distribution of spring connections in each cell with different expansion rates in order to control and define the bend formation with either positive or negative curvature.

The representation simulates the process of inflation of the physical model where the cellular structure from initially planar surface is subjected to a plastic deformation. Each digital cell bends according to the local distribution of differentiated spring expansion rates. The result is a double curved membrane that is subjected to uniform ripples, which represent the positive and negative local curvature (Fig. 22). By changing the expansion rates of each spring within a cell, the algorithm generates the form of the tessellated membrane with different degree of local curvature accordingly. The measurements that were taken on the individual component and each aggregate cellular pattern focus on the 3 main different aspects: 1) Deviation of nodes position in Z, 2) Horizontal projection of the curve, 3) Height of the curve. The rate of deviation in Z is proportional to the amount of air pressure that introduces to the internal channel. The graph on Fig. 23 represents the deviation of each node position in Z in accordance to the internal amount of air measured in cm3.

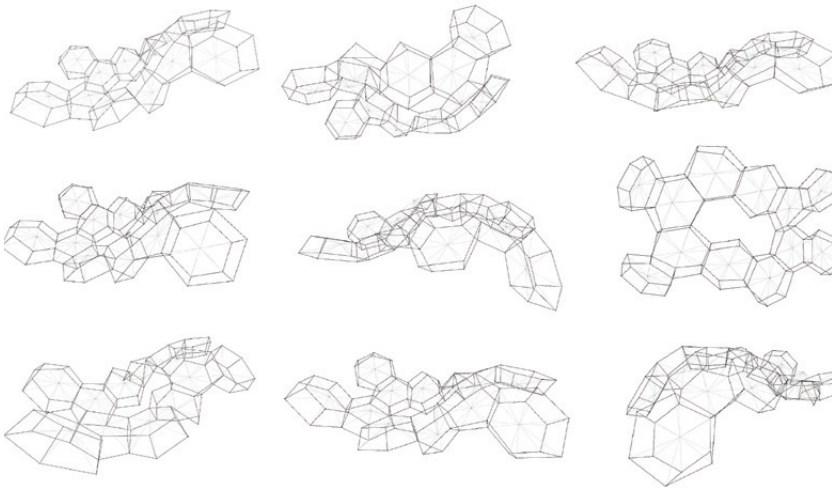


Fig. 5.5.22 Digital Representation of inflatable silicone assemblies, (Image: Zoi Karagkiozi).

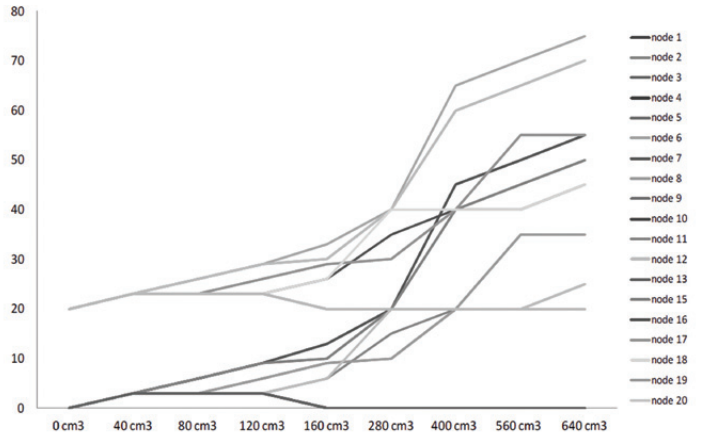


Fig. 5.5.23 Graph of deviation of node position in Z (mm) in accordance to different amount of air pressure(cm3), (Image: Zoi Karagkiozi),

Four observations were carried out that refer to different resulting ideal lengths for each spring type (Fig. 26). Each of these observations comes up with different results about the horizontal projection of the curve and its height for each unit. The purpose is to find the ideal combination of digital values of spring lengths to correlate with minimum deviation with the physical deformation. This method aims to find the minimum error occurred among these observations when considering aggregates. The graph in Fig. 24 shows the minimum deviation of node position between the physical and digital model for a specific observation. On the other hand Fig. 25 illustrates the maximum error occurring in the digital representation where the simulation deviates dramatically from the physical deformation.

The categorization of springs with different rest lengths and their local distribution within each hexagonal cell played the key role to control the bending behaviour of its cellular structure. The development of this elastic profile of each material system gives the designer opportunity to explore a range of different configurations within the design space. In that sense, by aggregating more components to form larger surfaces, the system can compute the same generative drivers in larger and more complex material assemblies. Thus, the scale of design is flexible according to the designer's intent. The tests on single unit showed that the algorithm is able to predict accurately with negligible average error the anticipated deformation of single cellular structure. Surprisingly, in the next stage when aggregating two components, the average error remained stable without any increase in its value. The algorithm is considered to provide valid results and predict with high accuracy the bend formation of the double cellular structure. Unlike the previous small aggregate system, when the number of elements is multiplied, the four components are subjected to higher deviation from the ideal ones, thus the result of simulation is less accurate. Clearly, this finding was anticipated, as the local transforms impact upon the whole. The global deformation ends up based on the interaction of spatial forces developed in each cell. Thus, the exact behaviour is less predictable as the system becomes more intricate. Based on the trend line of error occurred in each aggregate system, it can be estimated that as the profile geometry becomes more complex, the digital performance deviates gradually from the physical reaction of the artefact (Fig. 27). A high level of accuracy requires solving physical problems that can involve analysis of fluid mechanisms, thermodynamics and chemical kinetics. This entailed the advance of computational design by embedding material logics and calibrating these with finite element methods (FEMs) for simulation.

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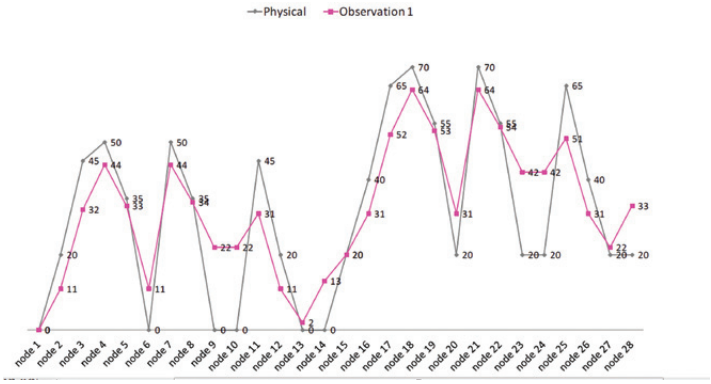


Fig. 5.5.24 Minimum deviation of node position in Z between physical and digital observation, (Image: Zoi Karagkiozi).

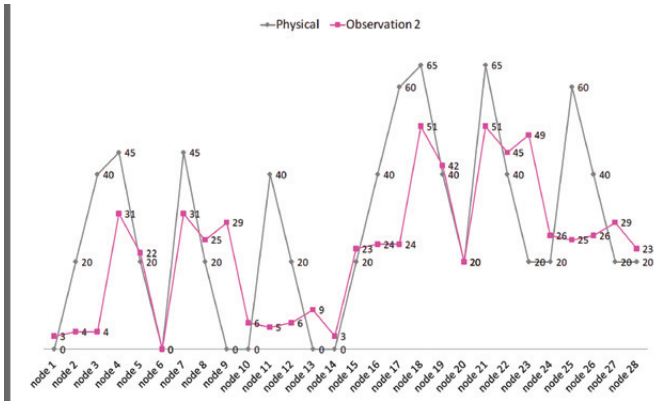
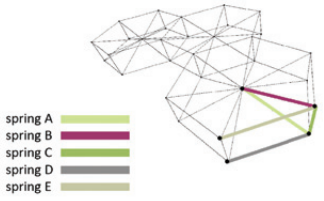
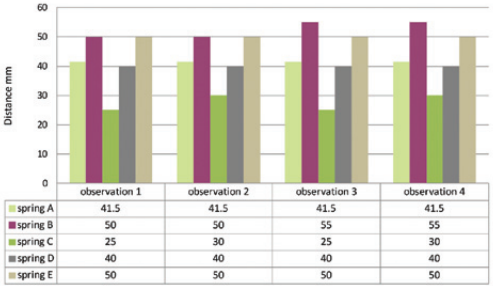


Fig. 5.5.25 Maximum deviation of node position in Z between physical and digital observation, (Image: Zoi Karagkiozi).





	observation 1	observation 2	observation 3	observation 4
spring A	41.5	41.5	41.5	41.5
spring B	50	50	55	55
spring C	25	30	25	30
spring D	40	40	40	40
spring E	50	50	50	50

Fig. 5.5.26 Up: View of five distributed spring connections within the hexagonal cell. Down: Column chart for the case of four observations that refers to each spring type A,B,C,D and D, (Image: Zoi Karagkiozi).

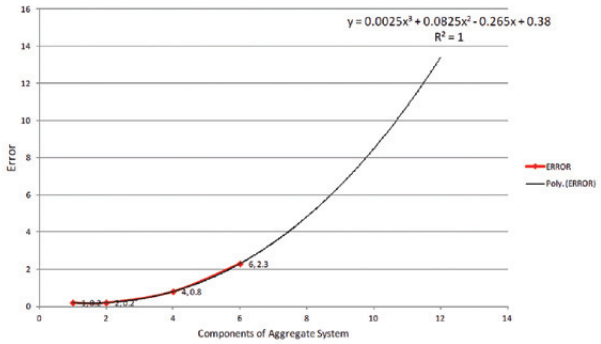


Fig. 5.5.27 Trendline for average error displayed by different aggregate patterns, (Image: Zoi Karagkiozi).

Conclusion

Despite the difficulties of working on silicone rubber anisotropic attributes, the physical model of aggregate pneumatic cellular structure was successfully implemented and displayed high rate of tensile strength during successive inflation. This accomplishment facilitates the experimentation and the overall process. In respect of the challenge to fully control the shape of deformation on soft robotics, it can be argued that by employing the proposed computational method to explore the performance capacity of the intricate structure and elastic behaviour of each cell, the study has met the challenge to control its deformation and moreover to scale up the physical model producing larger inflatable silicone aggregates.

Conclusions

The technological progress in digital fabrication has eliminated the boundaries between the prototype, in the means of the sample or test built structure and the artefact. Using digital fabrication as has been presented in the first project, architects would be able to design and print a functional prototype, which in this case is shifting its meaning from the sample-test model to the Greek definition of prototype **("*πρώτο + τύπος*")** that means the initial or original. This shift in prototypical architecture enables also the design of adaptive - unique soft kinetic systems able to be optimised using a simulation environment in order to perform prescribed behaviours. The design strategy of the second project allows innate characteristics and behaviours of the material system to be engaged into the computational design, which is constantly updated through feedback from the fabrication process of the physical model. The result that emerges from this interface is the development of a reliable digital design tool that simulates the material assembly behaviour under certain environmental influences. The study takes advantage of the feedback derived from physical testing and fabrication of the artefact and then engages changes and explorations within the digital design space accordingly. In that sense, innate characteristics, behaviour and capacities of the material assembly integrate computationally to the digital design.

Summarising, in the above projects the prototype has a fundamental role in the procedure of the computation of compliance behaviour. It is both the output and the input of information for the development of two kinetic adaptive systems. Two case studies were studied both with compliant behaviour but with totally different characteristics in their materiality and function. The first, formed from rigid plastic with limitations in its scale, needed higher pressures for its actuation but having stable structure and the second made from elastic material, able to scaled up and actuated with lower pressures but having unstable structure. Therefore a research space is still open for the exploration of a combination of those systems.

Appendix
Sustaining and Disruptive (Christensen 1997)
Sustaining innovation:

An innovation that does not affect existing markets, an innovation that improves a product in an existing market in ways that customers are expecting, for example fuel injection. An innovation that is unexpected, but nevertheless does not affect existing markets, for example the automobile.

Disruptive innovation:

An innovation that creates a new market by applying a different set of values, which ultimately (and unexpectedly) overtakes an existing market, for example the lower priced Ford Model T.

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Theodoros Themistocleous is an Architect-Engineer (NTUA Greece), Urban Designer (MArch UD, Bartlett, UCL) and Computational Designer (MSc AAC, Bartlett, UCL). He is researching the development and application of soft kinetic systems in architecture. Using algorithmic procedures he is developing fabricated (SLS 3D printed) material systems with inscribed behaviours able to pneumatically actuated to predefined forms. Zoi Karagkiozi is an Architect that holds a MSc in Adaptive Architecture and Computation. She has graduated from Aristotle University of Thessaloniki, school of Architecture in 2010 with her main research focus being the development of Technological University of Cyprus. In 2012, she graduated from MSc AAC course of the Bartlett School of Graduate studies where she specialized in Material-based Design Computation. Her main interest is concentrated to the development of soft actuated pneumatic networks and their application in Architecture. In her final Thesis, she explores the behaviour of different inflatable aggregate systems through the physical testing of their fabricated prototypes and their digital simulation. Currently she is working at Hodgkinson Design, located in West London providing architectural design services in residential and commercial projects. Co-author with Ruairi Glynn, all three authors are from the Bartlett Faculty of Built Environment, University College London.

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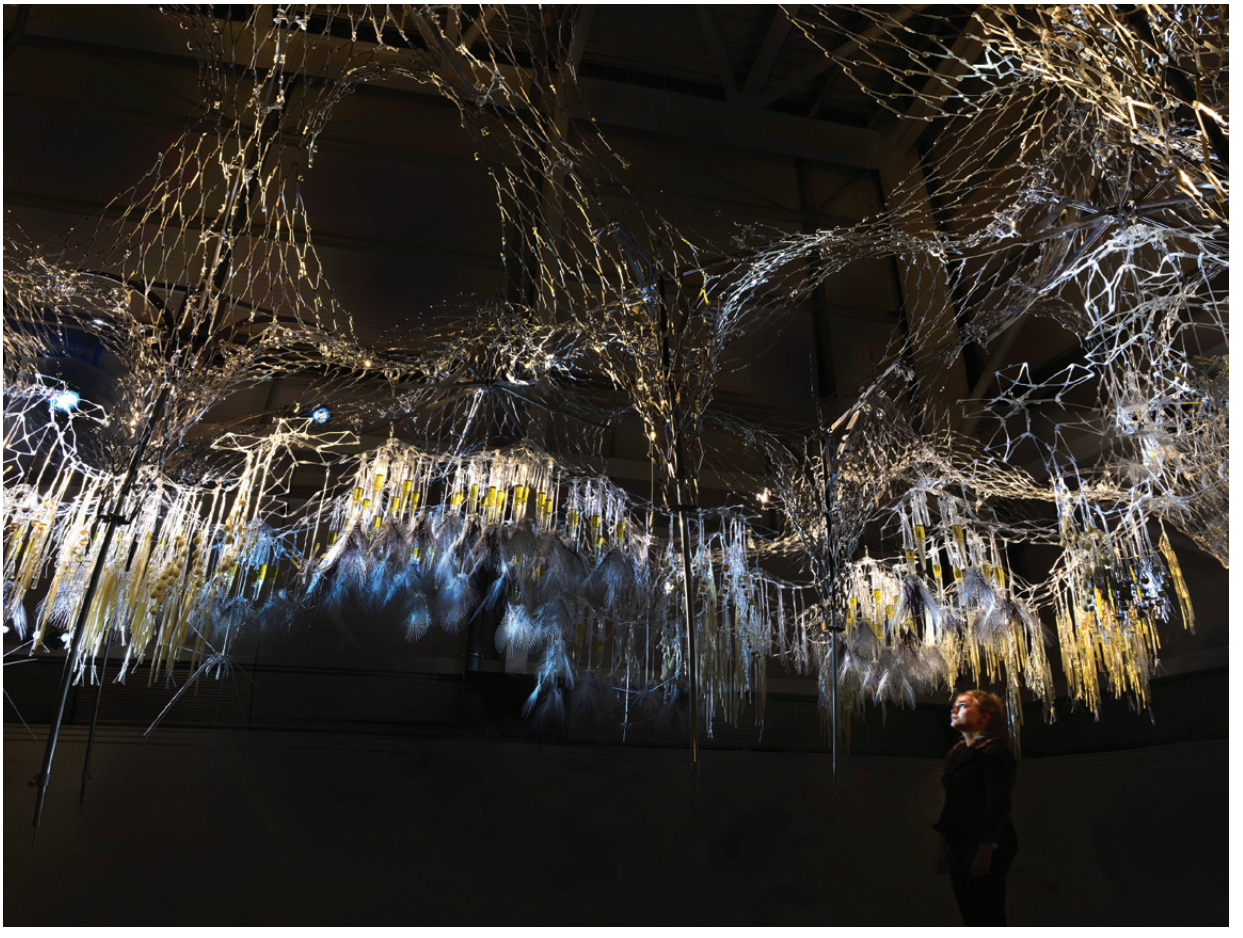
5.6
Keynote: Prototyping for Extimacy: Emerging Design Methods

Philip Beesley

Philip Beesley is a professor in the School of Architecture at the University of Waterloo. A practitioner of architecture and digital media art, he was educated in visual art at Queen's University, in technology at Humber College, and in architecture at the University of Toronto. At Waterloo, he serves as Director for the Integrated Group for Visualization, Design and Manufacturing, and as Director for Riverside Architectural Press. Beesley's Toronto-based practice, PBAI, is an interdisciplinary design firm that incorporates industrial design, digital prototyping, and mechatronics engineering. His work is widely cited in the rapidly expanding technology of responsive architecture.



INTERNATIONAL PEER REVIEW COMMITTEE

6
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James Timberlake, KieranTimberlake Associates and University of Pennsylvania;

Mark Goulthorpe, dECCOi and MIT;

Professor Ulrich Knaack, TU Delft;

Professor Bob Sheil, Bartlett School of Architecture, University College London;

Omar Kahn, University at Buffalo;

William McLean, University of Westminster;

Dr Chantelle Niblock, University of Nottingham;

and

Andrew Scoones, The Building Centre Trust.

CONTRIBUTORS

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CONTRIBUTORS

In the order of presentation:

Anne-Mette Manelius is an architect based in Copenhagen and a board member of the International Society of Fabric Forming (ISOFF). After finishing her Master at the Royal Danish Academy of Fine Arts, School of Architecture (RDAFA) in 2005 she joined the research staff at the school's Centre of Industrialised Architecture (CINARK). Her published state-of-the-art report of concrete technologies in architecture lead to a PhD project (2008-2012) about the architectural potentials of fabric formwork for concrete. The PhD project was sponsored by E. Pihl & Son and schmidt hammer lassen Architects as part of the Danish Industrial PhD Programme, and undertaken as research-through design. Anne-Mette blogs at www.concretely.blogspot.com

Samantha Oswald is a graduate student at the University of Waterloo in Ontario, Canada. Her fascination with the life cycle of materials has a profound influence on her research, design, and constructions. Clay brick, the current subject of her research, has led her to various locations around the world, including Rome, Italy, Warsaw, Poland, and Toronto, Canada. Her design practice, tAct, is based on action, tactility, and a profound sensitivity to site. These principles inform diverse processes of making and guide explorations in the power and potential of the material environment. www.tact-rdc.com

James O'Leary is an architect and installation artist. His work explores the inter-relationship between human beings and the spatial systems we inhabit. He is currently a Lecturer in Innovative Technology and Design Realisation at the Bartlett School of Architecture, University College London, where he leads the MArch Architecture Design Realisation Programme and is Unit Master in MArch Unit 14. http://www.unit-14.net/ He works collaboratively with poet Kristen Kreider to make performance, installation and time-based media work in relation to sites of architectural and cultural interest. Since 2003, Kreider + O'Leary have made work in prisons, churches, military sites, film locations, landscape gardens and desert environments, as well as in more traditional gallery venues across the UK, Europe, the US, Australia, and Japan. Their most recent work entitled Light Vessel Automatic was exhibited at Performing Architecture at Tate Britain in February 2013.

Yves Ebnöther is a Swiss industrial designer. Upon completion of his BA Hons., studies at Ravensbourne, London, he returned to Switzerland to work at numerous design agencies, including Hannes Wettstein's office. In 2003 he enrolled on Prof. Dr. Ludger Hovestadt's MAS CAAD programme at ETH Zurich, where he developed his series of experimental prototypical products. He subsequently founded and directed the Rapid Architectural Prototyping Laboratory RAPLAB at ETH's Faculty of Architecture. In 2011 he moved to Singapore to set up the Prototyping Facility at ETH's Future Cities Laboratory. Currently he lives in Zürich with his family, where he runs his own design practice, works as a lecturer and is a founding member of FABLAB Zürich.

Alan Dempsey RIBA: is the founding director of NEX, an award-winning studio working at the intersections of design, architecture, and infrastructure. Alan's design and research interests are focused on the integration of architecture, landscape, and infrastructure; and innovative approaches to project materialisation. He is the Director of the Independents' Group at the AA: a global network of academic and industry partners undertaking applied research into the use digital fabrication to develop innovative prototypes for the built environment. His professional work has received numerous awards and commendations from the D&AD, The Architects Journal, UK Technology Strategy Board, World Architecture Network, Building Design, and the Architecture Foundation. Completed projects have been published internationally, and he has been invited to present his work at institutions including the Central Academy of Fine Art in Beijing, the AA, ETH, the NAI, and MIT. He is the editor of the book Nine Problems in the Form of a Pavilion, published by the AA Press in 2010. In 2008, Alan was selected by the British Council as one of the six most significant Design Entrepreneurs in the UK, and in 2010 he was selected by the European Centre for Architecture and Chicago Athenaeum as one of the 40 most important emerging architects under 40 in the EU.

Stefan Rutzinger studied architecture at the University of Innsbruck and at the Bartlett, UCL, in London and graduated from the University of Applied Arts Vienna. He received several awards, including the Austrian Building Award 2006, the Recognition Award for Experimental Tendencies in Architecture 2008 and the MAK Schindler Scholarship 2008. He has taught at the University of Technology, Vienna and at the UCLA Future Lab, Munich. In 2012-13, Stefan is an interim professor for Spatial Design at the Academy for Fine Arts in Munich, Germany and a professorship at the Academy for Fine Arts Vienna. He is also teaching at the Bartlett, UCL London, MArch Unit 15 with Kristina Schinegger and Stefan Ritter.

Kristina Schinegger studied architecture at the University of Applied Arts Vienna and at the Bartlett School of Architecture, UCL, in London. She received several awards, including the Austrian Building Award 2005, the Recognition Award for Experimental Tendencies in Architecture 2006 and the MAK Schindler Scholarship 2008. Kristina is a contract assistant professor at the Institute of Architectural Sciences, Department of Architecture Theory at the Vienna University of Technology. Currently she is teaching at the Bartlett, UCL (MArch Unit 15)

Jan Knippers Prof. Dr. Ing. Studied Structural Engineering, Ph.D. at University Berlin. Following this he worked as a project engineer and project manager at the Germany firm Schlaich Bergermann and Partners in Stuttgart. Since 2000 he has been Vice Dean, Professor and Head of the Institute for Building Structures and Structural Design at the Faculty for Architecture and Urban Design at the University of Stuttgart. He is engaged with research and teaching, dealing with efficient wide span building structures and innovative building materials. In 2001 he co-founded Knipper Helbig Advanced Engineering based in Stuttgart, they specialize in façade and roof engineering with focus on the development of special solutions for complex parametrical generated geometries for steel and glass construction as well as innovative materials as fibre reinforced polymers. He is a member of various national and international engineering associations, of various national and European Codes Committees and of the Chamber of Engineers Germany.

Florian Scheible Dipl.-Ing. Architect, LEED Green Assoc. Trained as a draughtsman for steel construction in German before going to Krupp Stahlbau Berlin where he Studied Architecture, following this he gained his Diploma in Architecture at the University of Braunschweig from which he received a SDW Scholarship. He then went on to lecture at the Institute of Building Structures and Structural Design at the University of Stuttgart Germany. From 2003 he has worked as a project manager and architect at Knippers Helbig Advanced Engineering based in Stuttgart Germany and since 2010 held a position as one of the Director at the practice. He is a member of Chamber of Architects Baden-Württemberg Germany and the International Association of Shell and Spatial Structures.

Odysseas Kontovourkis, Ph.D., is currently Lecturer in the area of Architectural Communication Media in the Department of Architecture at the University of Cyprus. He received his Diploma in Architecture Engineering from the National Technical University of Athens, Greece. He conducted research studies in the Department of Architecture Engineering at the University of Osaka, Japan, and Ph.D. studies in the Department of Architecture and Civil Engineering at the University of Bath, United Kingdom. His research and teaching interests focus on the integration of computational design and fabrication strategies with architectural design process aiming at the optimization of architectural design and construction according to functional, structural, environmental, and morphological architectural design criteria. Currently his research covers the fields of digital architectural design based on generative and parametric processes, digital fabrication strategies and human movement behaviour simulation with emphasis on pedestrian modelling in the built environment.

Marios C. Phocas received his Diploma degree in Architecture including in depth studies in building technology and structural design from the University of Stuttgart in 1995. He completed his doctorate on earthquake resistant structural building design, at the Institute of Building Structures and Structural Design (ITKE) at the Faculty of Architecture and Urban Planning at the University of Stuttgart in 1999. Dr. Phocas is currently Associate Professor and Interim Head of the Department of Architecture at the University of Cyprus, since 2009 and 2006 respectively, as well as co-principal of the Archimedes Research Centre for Structural and Construction Technology, since 2005. From 2004 until 2009 he served as Assistant Professor at the Program of Architecture. Prior to his appointment at the University of Cyprus he was Main Research Associate, Academic Teaching Consultant,

and extraordinary Dozent at ITKE of the University of Stuttgart, from 1996 until 2004. He is the author and/or co-author of numerous publications in the areas of integrated architectural design, structural and construction design, kinetic structures and earthquake resistant structural building design. He has received several architectural awards for project designs in Germany and Cyprus.

George Tryfonos is currently conducting his Ph.D. research at the University of Cyprus on the integration of computational design and fabrication strategies with architectural design processes. He holds a B.Sc. in Architecture, 2011, and a Diploma of Architect – Engineer, 2012, both degrees from the University of Cyprus. His Diploma thesis on kinetic and interactive architecture was awarded the Acknowledgement for Excellence in Architectural Design 2012. His research interests are in kinetic and interactive architecture, automation systems, design methods and digital tools.

Panel Chair: **Will Mclean** is joint head of technical studies teaching in the faculty of architecture at the University of Westminster. He has co-authored three books with Pete Silver, Fabrication; The Designers Guide, Architectural Press, 2004, An Introduction to Architectural Technology, Laurence King, 2008 and Structural Engineering for Architects: A Handbook, Laurence King 2013. Between 2005 and 2010 McLean wrote a column for Architectural Design (AD) entitled 'McLean's Nuggets', which appeared in more than 30 issues of the magazine. In 2008 he established Bibliotheque McLean an independent publisher of architectural titles. Publications include Sabbioneta: Cryptic City by James Madge (2011), which was recently awarded a commendation in the RIBA presidents medals for research; Quik Build: Adam Kalkin's ABC of Container Architecture (2008), and a book on the work of Italian architect Dante Bini due for publication later this year. As a designer McLean has worked the last decade on a series of public projects with artist father Bruce McLean, most notably Dalry Primary School in North Ayrshire.

Keynote: **James Timberlake** FAIA is a partner at KieranTimberlake, a prominent architecture firm noted for its integration of research and practice guided by a deep environmental ethic. The firm is the recipient of the 2008 Architecture Firm Award and the 2010 Cooper-Hewitt National Design Award. In addition to his practice, Mr. Timberlake teaches at the University of Pennsylvania. He is the co-author of five books on architecture, including refabricating ARCHITECTURE, an examination of the manufacturing methodologies poised to transform building construction.

Nathalie Rozencwajg and **Michel da Costa Goncalves** of RARE architecture, an office for research, architecture and experimentation. Projects range from the scale of the object to the urban. Granted the RIBA and RICS Awards, RARE operates worldwide from offices in London and Paris. RARE exercises an ethos of mixing commissions with research to produce tailored work using new materials, innovative typologies and advanced modes of design and production to offer sustainable, efficient and distinctive projects. The practice is currently working on several high-end residential and commercial projects for public and private developments throughout Europe and Asia. In parallel, the office pursues the design and manufacturing of furniture and object collections.

Manuel Kretzer is a researcher and educator and Chair for Computer Aided Architectural Design (CAAD), ETH Zurich. He is responsible for coordinating and leading the postgraduate Master of Advanced Studies class's digital design and production modules. His doctoral research aims at the notion of a soft and dynamic architecture with a specific focus on new (smart) material performance. He is also partner at responsive design studio, based in Zurich and Cologne, a collective with special interest in vivid architectural geometries that interact with their user. Just recently he founded the materiability research network, an educational community platform that brings together various disciplines engaged in the use of smart materials in architecture and design.

Johannes Rauff Greisen M. Arch. Ph.D. scholar at CINARK, RASA, finalizing his work on architectonic potentials in utilizing robot fabricated formwork for concrete building. He is a university teacher and author of five articles on concrete and architecture. He also provides commercial consultancy on robot driven concrete solutions. Johannes is employed by the Danish Technological Institute and provided contributions to the Danish research project UnikaBeton. He is currently engaged in three EU-FP7 research projects: TailorCrete extending form potentials for concrete building, Light2Cat embedding solar driven catalytic systems into concrete surfaces, and DigiStone making digital signage applicable within concrete street furniture.

Guillermo Guzman Dumont is a Chilean Architect who studied architecture at UBB, Chile. Currently he is the BA Architectural Studies Course Director, Web Manager and the Alumni Network Coordinator for the Department of Architecture and Built Environment of The University of Nottingham. From 2007 to 2010 he was the editor of the Department's Yearbook. He is member of the Faculty's Architecture and Environmental Design Research Group. He is a researcher at the Creative Energy Homes Project and was the Communications Director at the Nottingham HOUSE project, which represented the UK at the Solar Decathlon Competition in Madrid, 2010.

Sanhita Chaturvedi prior to receiving her MArch in Architecture and Urbanism at the Design Research Lab from Architectural Association, was founding director of Hexagram Design in New Delhi. A graduate from the School of Planning and Architecture, New Delhi-India, she has worked as an architectural and landscape consultant to various firms in UK and India. Sanhita has been actively involved in landscape design research for conferences, books and films. She is currently working at Foster + Partners, London.

Esteban Colmenares is a Project Director with John McAslan+Partners in London. He graduated as an architect from Universidad Nacional de Colombia and holds a MArch from the DRL at the AA. Esteban explores in his projects the optimization of construction processes through digital techniques. Previously he has practiced in Los Angeles for 7-years, and he has been visiting Lecturer at Uclan and invited as critic to the AA, SciArc and Iaac.

Thiago Mundim holds a MArch from the DRL at the AA. After graduating as an Architect from the Federal University of Mato Grosso (2006), Thiago practiced as architect in Brasil and the UK. Thiago is the founder of XLAB (Experimental Laboratory for Architecture) which is a practice focused in exploring parametric and generative design, based on studies of self-organization, collective intelligence and complexity on social and biological systems.

Sean Ahlquist is an Assistant Professor of Architecture at the University of Michigan. He is a part of the Cluster in Computational Media and Interactive Systems, which connects Architecture with the fields of Material Science, Computer Science, Art & Design and Music. His research is centred on the topic of material computation, developing means by which complex material behaviours can be instrumentalised to formulate integrated and variable spatial capacities. He continues this research also as a current doctoral candidate at the University of Stuttgart in the Institute for Computational Design (ICD), with expected completion of the doctorate (Dr.Ing.) in 2013.

Martyn Dade-Robertson PhD., is Lecturer in Architecture in the School of Architecture Planning and Landscape at Newcastle University. Martyn originally undertook a degree in Architecture at Newcastle before embarking on an MPhil and PhD at Cambridge University (Darwin College) with a thesis entitled Information Architecture in Screen Based Semantic Spaces. This Ph.D. research lead to a number of successful cross disciplinary projects and collaborations and internship at Microsoft Research and the book The Architecture of Information published by Routledge in 2012. His most recent research has been into the role Synthetic Biology and Architectural design with an emphasis on material practices and prototypes.

Meng Zhang PhD., studied for her BSc in Biotechnology at Shan Dong Agriculture University, China. In the UK she was then rewarded Overseas Research Scholarship by UK Universities, and studied for a PhD in Proteomics research in Northumbria University. Meng is currently a research fellow at Northumbria University where she works on Proteomics and is also R&D manager for the university enterprise Nzomics Biocatalysis, which is a university enterprise in Northumbria. Meng has published widely on Proteomics and Molecular Biology and is currently investigating applications of Synthetic Biology.

Tobias Schwinn is a research associate and doctoral candidate at the Institute for Computational Design (ICD) at the University of Stuttgart, Germany. In his research he is focusing on the integration of robotic fabrication and computational design processes. Prior to joining the ICD in January 2011, he worked as a Senior Designer for Skidmore, Owings and Merrill in New York and London applying computational design techniques to parametric form-finding, rationalisation, complex geometry, automation and aspects of sustainability. Tobias studied architecture at the Bauhaus-University in Weimar, Germany and at the University of Pennsylvania in Philadelphia as part of the US-EU Joint Consortium for Higher Education. He received his diploma-engineering degree in 2005. He has been invited studio critic at Columbia GSAPP, Harvard GSD, Pratt Institute, AA in London, and the Staedelschule Frankfurt and has internationally taught various workshops on scripting and algorithmic design.

Emanuele Naboni was born in Italy and has a Master in Architecture and PhD in building Science from Politecnico di Milano. He is Associate Professor of Sustainable Architecture at the Royal Danish Academy of Architecture, Design and Conservation. He consulted foremost international architectural offices supporting the sustainable design of cities, buildings, components and technologies. He has been a researcher at Lawrence Berkeley National Laboratory, and has worked with the Performative Design Group at SOM in San Francisco. His areas of interest are the creative and qualitative aspects of sustainability and performance simulation.

Jesper Nielsen was born in Denmark and has a master degree in architecture from The Royal Academy of Fine Arts in Copenhagen. Jesper is partner and design director in "SoftCells", a commercial company developing building components and systems. He is also associate professor in design at The Royal Danish Academy Fine Arts, Schools of Architecture where he has been affiliated since 1992. Jesper basing his interest and work in component design for architecture on several years with Foster and Partners in London and later with Henning Larsens office in Denmark. He has designed several timber case study houses for private clients.

Alessandro Maccarini was born in Italy and has a Master's Degree in Aerospace Engineering. Following his passion for sustainability, he pursued a specialization in "Physics and energy efficiency in buildings" at University of Padua. He is an Assistant Researcher in building energy simulation tools at the Royal Danish Academy of Architecture, Design and Conservation. He worked as engineer in Italy and Switzerland on topics related to renewable energies and low-energy building services. His main area of research is the thermal and fluid dynamics analysis of buildings.

Panel Chair: **Alan Jones** RIBA FRSA is the Director of Architecture (Education) at Queen's University Belfast and President of the Royal Society of Ulster Architects 2012-14. Coming from the Northern Irish tradition of manufacturing and constructing, his built work embodies his interest in "a constructed reality" and the value added through design to relatively common low cost materials. The editor of the Architects' Journal described him as ".. a sincere critic and an architect who builds what he preaches...." and Aran Betsky wrote that his work "mines the meager surroundings for maximum effect". He is a member of the RIBA Research and Innovation Committee.

Chantelle Niblock, MArch, PhD, is Course Director of MArch Technology and Lecturer in Architecture at The University of Nottingham since 2010. She is co-convenor of a Diploma Studio [RIBA Part 2] in Digital Architecture and Fabrication, which focuses on developing design methodologies and innovative facade design. She is a member of the Architecture & Tectonics Research Group at The University of Nottingham. Her research and teaching interests include: architectural design thinking (pedagogy and practice), digital fabrication,

prototyping in architecture, and collaborative design across disciplines. Her current research includes the Living Architecture research programme with the University of Waterloo, School of Architecture and University Southern Denmark, Center for Fundamental Living Technology, this research is funded by Social Sciences and Humanities Research Council, Canada. Her PhD investigated the influence of free-form modelling on the process of designing, using a comparative protocol study between expert and novice architects. During her Masters of Architecture course she specialised in CAAD and explored a pre-digital design by Frederick Kiesler.

Stephen Melville BEng MSc DIC MIStructE FRSA, leads the Ramboll Computational Design Team which is dedicated to the research and application of digital tools for building and masterplan design. Stephen writes a weekly blog for Building Design and is a member of the Bristol Urban Design Forum and RIBA education panel. He is also a part time tutor at the Oxford Brookes School of Architecture and has also tutored or lectured at TU Delft, Texas, Copenhagen, Bristol and Cardiff Universities.

John Harding BSc BA MSc is a current doctoral candidate in computational design at The University of Bath. His research is in parametric modelling, multi-objective optimisation and the application of complex systems theory in the design process. Recent advances in computing modelling and analysis have involved rethinking the relationship between architect and engineer, particularly at the concept design stage. His practical application of computational design theory to real world projects has led John to collaborate with various architectural practices during his research.

Harri Lewis MEng MPhil, enjoys collaborating with architects and artists to help them develop innovative structures. He completed his MPhil degree at the University of Bath as part of their Digital Architectonics program where he developed a number of interactive software applications to help designers create elegant forms with embedded structural logic. Since returning to Ramboll he has combined this with his structural engineering background to help deliver a number of intricate projects.

Stephen Melville, John Harding and Harri Lewis helped set up Ramboll Computational Design in 2010 after a number of years researching and developing digital design tools for the built environment.

Mike Tonkin, of Tonkin Liu Architects, graduated in Architecture at the Royal Collage of Art, London, then qualified as an architect in 1989, after studying at Leeds Polytechnic School of Architecture and Bath Technical College. Mike has taught and lectured at numerous schools of architecture in England and the Far East, and he currently teaches at the University of Bath. He lectures on a number of subjects including world vernacular architecture, using the experience and photographs taken from his extensive travels.
www.tonkinliu.co.uk

Lorenz Von Seidlein was born in Germany and attended medical school in Dublin, Ireland. He completed a pediatric residency in Miami, an Infectious Disease Fellowship at UCLA and a PhD in epidemiology from the London School of Tropical Medicine and Hygiene. From 2000 through 2010 Lorenz worked with the International Vaccine Institute in Seoul, Korea where he managed several large vaccine projects including projects in Mozambique and Zanzibar. From 2006 Lorenz coordinated a large trial of a malaria vaccine candidate in Tanzania. From 2003 Lorenz worked with the Mahidol-Oxford Tropical Medicine Research Unit, Bangkok, Thailand on a large multicentre trial on severe malaria. He is currently coordinator at Menzies School of Health Research in Darwin, Australia.

Jakob Knudsen was born in Denmark and has a bachelor degree in medicine from University of Copenhagen plus a master degree in architecture from The Royal Danish Academy of Fine Arts, Schools of Architecture, Copenhagen. Jakob is currently practicing architecture as head of “Ingvartsen Architects“ in Copenhagen. He is also associate professor at The Royal Danish Academy Fine Arts, Schools of Architecture where he has been affiliated since 1994. Jakob lived with his family in the 1990s in Tanzania and has returned regularly. Jakob has designed several projects in Europe, Africa and Asia. Some of his works can be seen at www.ingvartsen.dk. A recurrent theme in his works is sustainability and climatic design.

Ron Fitch has worked in the modular metal cladding industry since the early 1980`s when high tech was the current trend. He worked on projects with many of the new generation architectural studios such as the Renault Centre [Foster & Partners] two Stirling Prize Winners [Hodder Associates & Wilkinson Eyre] and one Millennium Design Award Winner [Wilkinson Eyre]. In the mid 80s he set up a design consultancy to develop metal based modular construction systems for many leading manufacturers within the building industry. He has lectured at the many architectural schools and was guest master at the 2006 innovations in practice masterclass at the Berlage institute, Rotterdam. Ron also won an award for designing Best Technical Literature for Construction Products, demonstrating expertise in design and technical graphics and has written articles for the Architects Journal.

Tim Lucas is a structural engineer. He joined Price & Myers after graduating from Leeds University in 1996 and became a partner there in 2007. He founded Price & Myers’ Geometrics group in 2001. His work includes unique and iconic buildings, bridges and sculptures. He enjoys creating exciting structures that are simple to make and build. He and his team make use of advances in computer modelling and manufacturing technology to create buildable structures. This is underpinned with a sound knowledge of engineering theory, principles of geometry and the nature of materials.

Davide Costa is an architect and Associate at Rogers Stirk Harbour + Partners, projects include The Berkeley Hotel Canopy, Termal 5, Haethrow Airport and Monte Carlo Sporting D’Hivers.

Dirk Krolikowski RIBA Dipl.Ing. (Dist) is architect and Associate at Rogers Stirk Harbour + Partners, projects include The Berkeley Hotel Canopy,The Leadenhall Building and One Hyde Park. He is also a Lecturer in Innovative Technology and Design at The Bartlett University College London.

Keynote: **Mark White** is Chief Technical Specialist, Jaguar Land Rover [JLR], where he is responsible for all Body Engineering, System Strategy, and Research and Advanced Projects at JLR, with focus on design and development of new body structures, including new platform development and light weight vehicle (LWV) development. He has worked for JLR for over 25 years having graduated from The Coventry University with an Honours Degree in Automotive Design. The Range Rover 2013 is the third generation of lightweight body architecture Mark White has researched, designed and developed with his team at JLR and industrial collaborators, in particular the UK aluminium industry.

Keynote: **Frank Barkow** studied architecture at Montana State University and the Harvard GSD. He is Professor at the Royal College of Art in London and has recently taught at the EPFL in Lausanne, Harvard GSD, and University of Wisconsin in conjunction with his firm winning the Marcus Prize for Architecture. In 1993 Frank Barkow and Regine Leibinger founded their practice in Berlin. Their interdisciplinary, discursive attitude allows their work to expand and respond to advancing knowledge and technology. Recent projects include a gatehouse and factory-campus event space in Stuttgart Germany and the TRUTEC Office Building in Seoul. Current research projects have focused on digital laser cutting; infra light concrete, facade systems, space-frames, and ceramic elements. Current projects in Berlin include a high rise near the main train station for CA Immo Developments. Barkow Leibinger's research work was shown recently at the 4th Marrakech Biennale and was included in the 11th Architecture Biennale, Venice, Arsenale Show. It was shown at the Architectural Association in London and 032c Gallery in Berlin in conjunction with the publication of the catalogue An Atlas of Fabrication. Their work is in the permanent collections of MoMA, New York where it is currently on display, the Heinz Architecture Center, Pittsburgh, and the Deutsches Architektur Museum, Frankfurt.

Bob Sheil RIBA is Professor in Architecture and Design through Production, and Director of Technology and Computing at The Bartlett School of Architecture (BSA) UCL, where he also runs MArch Unit 23 with Emmanuel Vercruysse and Kate Davies of LiquidFactory. He is a founding partner of sixteen*(makers), whose work in collaboration with Stahlbogen GmbH '55/02' won a RIBA award for design in 2010. He has edited two seminal editions of Architectural Design (AD); 'Design through Making' (2005), and 'Protoarchitecture' (2008). He Co-Chaired the highly acclaimed international conference 'Fabricate' with Ruairi Glynn at UCL in 2011, for which he also co-edited a substantial parallel publication. In 2012 he published two books, the AD Reader 'Manufacturing the Bespoke' (Wiley) on prototyping and making architecture in the digital age, and '55/02: A sixteen*(makers) Monograph' (Riverside Architectural Press). He is presently working on a new build project, and a third AD due for publication in January 2014, under the title 'High Definition: Negotiating Zero Tolerance'. His work as an international educator, critic, researcher, practitioner, designer, maker, and writer is a transgression of making, craft, digital fabrication, design processes, and the impact of evolving design technologies on architecture.

Nicholas Williams is an architect and researcher at the Spatial Information Architecture Laboratory (SIAL) at RMIT University, Melbourne. He holds a Masters of Architecture from the Architectural Association, London and his design work has been regularly published and awarded for excellence. He has over five years experience in architectural practice and has extended this into direct engagement with digital fabrication technologies through his work at design-to-production, Zurich. His research focuses on applications of digital technologies, both in applications in architectural design and novel prototyping.

John Cherrey is a Senior Lecturer in the School of Architecture and Design at RMIT University. He is trained as an architect, photographer and furniture-maker among and has explored a range of crafts. His professional interest and passion lies in the process of making in a direct, hands-on capacity. Since the mid 1980's, when John first used laser cutting for a student model, he has been interested in the application of CNC / CADCAM & digital technologies in transforming the design and making process.

Paul Bavister graduated from the Bartlett School of Architecture in 1999, and is an Associate Director at BFLS, and a Director of Soundforms. Whilst at BFLS, Paul was project architect of the RIBA award winning Royal Welsh College of Music and Drama in Cardiff. Paul has had work published in the RIBA Journal, Building Design, AD: Hypersurface Architecture and the AD Tom Kovac monograph. Paul is an active member of sound art group Audialsense, and has given lectures on the relationships between sound art and architecture at universities across London. Paul co-runs Unit 14 at the Bartlett School of Architecture.

Theodoros Themistocleous is an Architect-Engineer (NTUA Greece), Urban Designer (MArch UD, Bartlett, UCL) and Computational Designer (MSc AAC, Bartlett, UCL). He is researching the development and application of soft kinetic systems in architecture. Using algorithmic procedures he is developing fabricated (SLS 3D printed) material systems with inscribed behaviours able to pneumatically actuated to predefined forms.

Zoi Karagkiozi is an Architect that holds a MSc in Adaptive Architecture and Computation. She has graduated from Aristotle University of Thessaloniki, school of Architecture in 2010 with her main research focus being the development of Technological University of Cyprus. In 2012, she graduated from MSc AAC course of the Bartlett School of Graduate studies where she specialized in Material-based Design Computation. Her main interest is concentrated to the development of soft actuated pneumatic networks and their application in Architecture. In her final Thesis, she explores the behaviour of different inflatable aggregate systems through the physical testing of their fabricated prototypes and their digital simulation. Currently she is working at Hodgkinson Design, located in West London providing architectural design services in residential and commercial projects.

Keynote: **Philip Beesley** is a professor in the School of Architecture at the University of Waterloo. A practitioner of architecture and digital media art, he was educated in visual art at Queen's University, in technology at Humber College, and in architecture at the University of Toronto. At Waterloo, he serves as Director for the Integrated Group for Visualization, Design and Manufacturing, and as Director for Riverside Architectural Press. Beesley's Toronto-based practice, PBAI, is an interdisciplinary design firm that incorporates industrial design, digital prototyping, and mechatronics engineering. His work is widely cited in the rapidly expanding technology of responsive architecture.

Panel Chair: **Michael Stacey** is Professor of Architecture and Director of the Architecture and Tectonics Research Group at the University of Nottingham, and Director of Michael Stacey Architects. His professional life combines practice, research, writing and teaching. His portfolio of projects and products demonstrates a commitment to design excellence, which has been recognised by national and international awards, including twice winning the Shapemakers Award for the innovative use of aluminium, a Bureau International du Beton Award and an Award form the Campaign for the Preservation of Rural England. Key projects include: East Corydon Station, Thames Water Tower, Enschede Integrated Transport Interchange, Art House in Chelsea, Expertex Textile Centrum and Ballingdon Bridge. He is the author of a wide range of publications and books including Component Design, 2001, Digital Fabrication, 2004 and Concrete: a studio design guide, 2011. For the International Aluminium Institute he authored the exemplar case study architecture of the Future Builds with Aluminium website, http://greenbuilding.world-aluminium.org/. Themes within his research include: architecture as a discipline, digital fabrication, form finding, offsite manufacture, façade systems, tectonics, durability, emergent materials, zero carbon architecture and human ecology.

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