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Egholm Pedersen, Ole; Larsen, Niels Martin; Pigram, Dave; Maxwell, Iain

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# A contemporary reinterpretation of Jorn Utzon's material and technological innovations

Ole Egholm Pedersen, Aarhus School of Architecture, Aarhus, Denmark, oleegholm.pedersen@aarch.dk

Niels Martin Larsen, Aarhus School of Architecture, Aarhus, Denmark, niels.martin.larsen@aarch.dk

Iain Maxwell, University of Technology, Sydney and supermanoeuvre, maxi@supermanoeuvre.com

Dave Pigram, University of Technology, Sydney and supermanoeuvre, dave@supermanoeuvre.com

## Abstract

*Standardisation and the use of repetitive production processes was a key determinant of achievable forms in the industrial paradigm, impressively displayed in the Sydney Opera House. Today, complex non-repetitive, yet readily achievable, forms can be designed using computational design techniques that explicitly embed structural, and fabrication logic from the beginning and which later enable the direct generation of instruction code for their accurate and efficient production via Computer Numerically Controlled (CNC) machines. This paper builds on the thesis that Utzon's approach - the consideration of technology as an integral part of the design process - can give rise to novel structures which take advantage of the new technological situation. Furthering earlier research by the authors[1] [2] [3], a method for constructing a hybrid grid shell structure combining timber and pre-cast concrete elements is proposed. The method is tested through the realisation of a pavilion in relation to the Utzon Symposium in Sydney in March 2014. The previous research shows how a grid shell structure of discrete concrete components can be produced with lasercut amorphous polyethylene terephthalate (PET) templates. The casting method minimises the material use for templates in relation to customisation. This paper concerns realisation of a hybrid construction through integration of customised plywood components. Furthermore, the concrete construction is improved. Precision is improved through stabilisation of the template and modification of the geometry. Stability of the construction is achieved through new joint solutions. Reinforcement and joints are treated as a single element, thereby simplifying both production and assembly. In previous case studies scaffolding was a major task, and this aspect is minimised with the method described here.*

## A contemporary reinterpretation of Jorn Utzon's technological innovations

Utzon/40 is a project that celebrates the combination of design, engineering and construction innovation embodied within the Sydney Opera House 40 years after its completion. The project recalls Utzon's original material palette of concrete, glass, ceramics (enamel) and structural plywood and attempts to channel Utzon's original design thinking and technological ambitions (Figure 1). The project team echoes the original mix with Australian architects supermanoeuvre working in collaboration with Danish architectural researchers from the Aarhus School of Architecture and the original engineers ARUP. A company who have risen to international fame based on the pioneering work of their founder Ove Arup on the Sydney Opera House [SOH].

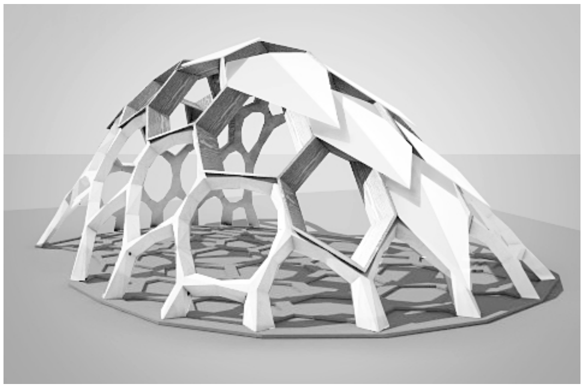

Figure 1: Rendering of the Utzon/40 research pavilion

*The Industry of Standardisation*

Standardisation and the adoption of repetitive production processes is too frequently a key determinant of achievable forms in architecture. At an industry level it is ensconced by the production of massive quantums of generic, dimensionally stable, flat and square products: from the ubiquitous 2440*1220mm sheet (plywood, plasterboard, etc) to the truckable precast panel. The monopolisation of material processes by generic industries leads to a constriction of material - and therefore design - possibility in two ways. First, process evolution is slowed because it can only happen infrequently, as industry is disincentivized by the costs of retooling and the increased risk entailed in making stronger commitments to larger-scale shifts. Second, as material differences are invisible to the machines of industry, they must be kept within strict limits in order to preserve the viability of all artefacts and production processes. This demand has exerted a strong filter on the kinds of materials that are industrially deployed and on their style of deployment, away from the volatile and toward the inert or homogenous. The inherent sensory capacity, adaptability, and resilience of CNC fabrication technologies can counteract both of these tendencies, which are essentially conservative and anti-speculative. The commodification of material is deeply embedded in the story of Utzon and the Opera House.

**Utzon: The Paradigm of Repetition**

Critical to the realisation of the SOH was the coupling of a controlling geometric system - the sphere - to a repetitive system of construction elements - segmented ribs and surface patches - in order to permit a suitably economic and viable structural geometry. The power of this approach is that any line (arc) or surface (patch) extracted from a sphere demonstrates an equivalent curvature. Thus any operation of subdivision - be it of an arc into segments or a surface into tiles - yields repeatable elements. For Utzon, the establishment of a repetitive geometric system produced both an economy-of-scale and higher-orders of production control via modes of prefabrication. Critical attributes he would employ in the construction of the post-tensioned concrete ribs and ceramic-faced surfaces that composed the roof shells.

*What would Utzon do now?*

Utzon's fascination, understanding and ultimate deployment of emerging material systems and construction technologies - embedded within the very logics of design - underpinned the realisation of arguably the most demanding, innovative and beautiful structures of the twentieth-century. A project surely amongst the most significant achievements in architecture and engineering to-date.

In recasting the innovative spirit of Utzon, one must consider the technologies poised to transforms today's prevailing modes of practice. The arrival and spectacular evolution of computing constitutes a significant technological paradigm shift since the 1950s. Today's 3D modelling and analytical softwares (structural, acoustical, environmental) - supported and extended by increasing computational literacy in the form of algorithmic design - are massively transforming contemporary design practice. Not only do such technologies allow for an accelerated drawing of complex geometries, they also permit the establishment of novel information pipelines between: the design process and the resulting artefact (formation embedded design); the architect and engineer (cross-disciplinary design); the architect and advanced Computer-Numerically-Controlled (CNC) machinery capable of producing non-repetitive building elements (file-to-factory) [6]. Critically, when computational processes of form generation are coupled to CNC processes of fabrication via custom design-to-production workflows, the constraints of material and making become embedded within the design method, allowing their influence to be understood, tuned and ultimately co-evolved towards a truly integrated and richer design solution.

*Utzon/40: Case Study*

The Utzon/40 pavilion demonstrates the potential of a performative algorithmic design framework coupled to advanced modes of digital fabrication to achieve a symbiosis of design, structural and construction logics in line with the aspirations of Utzon's scheme. The point of difference however, is that the methods employed here permit a challenging of the economies of repetition so famously necessary 40 years ago. The project therefore, is both deeply inspired-by and a projective embodiment-of Utzon's unique contribution to architecture.

Much research to-date in the fields of computational (algorithmic) design and digital fabrication privileges a single material logic. Architecture's recent fascination with 3D printing technologies serves as a prime example. Like the SOH, Utzon/40 recognises that architecture operates at the complex intersection of multiple materials, scales and trades. To that end, the project synthesises two material research trajectories: pre-cast concrete and structural timber. Further, rather than establishing a typical material hierarchy, that is, structure in one material and cladding or secondary structure in another, the pavilion offers a hybrid structural approach. The concrete elements are primarily positioned lower in the structure or to form edges and openings while the lightweight timber frame spans between. The timber frame also holds unique heat-formed acrylic cladding panels; a technique used by Utzon in his own house in Hellebæk, Denmark. The concrete visually 'grounds' the pavilion while the twisting-nature of the timber frame affords a striking play of light and shadow.

## Developing an expanded form-finding method

### *The Traditions of Form-Finding in Architecture*

The traditions of form-finding within architecture trace our efforts to embed material as an active agent within the design process via the abstract modelling of material organisations as they negotiate internal and external influences. This trajectory includes the invention of abstract descriptive devices such as the catenary curve - hanging chain - in order to direct the design of compression-only masonry arch and vaulted structures. Exemplars of form-finding include: Antonio Gaudi's nested hanging-chain models - or analogue computational machines - to resolve highly complex load paths; and Frei Otto's study of minimal surfaces - soap-film bubbles - to realise highly novel membrane structures. Curiously, the research of Otto has proven to be equally informative to the design of complex concrete shells despite the seemingly enormous material differences. Resulting is a wealth of heuristic principles and modelling practices that redirects architectural production away from the shaping of static objects towards a deeper understanding of the formational processes of material behaviour that underlie form generation. Furthermore, such processes no longer deal with singular objects, but are instead capable of producing multiple formal outcomes all implicitly aligned to structural stability and material logics. Form-finding therefore affords architecture new levels of material, space and form-making prowess.

*Digital Chains: Formation Embedded Design*

The limits of analogue modes of computation, such as the examples offered above, is that they are intrinsically bound to physical laws (gravity) and the materials through which they operate. In order to develop an expanded form-finding model, one that not only negotiates material and structural efficiencies but one also capable of computing a greater number and quality of design influences, Utzon/40 draws upon a custom-written algorithmic context for the digital simulation of hanging chains. This tool - a suite of scripts - is written in the programing language of Python and implemented in Rhinoceros3D, an industry standard 3D modelling environment (Figure 2).

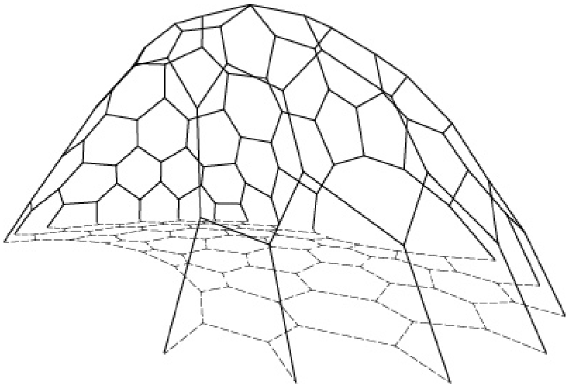

Figure 2: Form Finding: Hanging chains enacted digitally

While the digital implementation of 'hanging chains' itself is far from novel, what is unique to the design method presented here, is that it possesses a broad range of formal, material, structural and fabrication orientated response mechanisms simultaneously negotiated through a bespoke particle-spring solver. Essentially, the code is an implementation of dynamic-relaxation built upon Hooke's law, which states: that for elastic deformations of an object, the magnitude of its deformation (extension or compression) is directly proportional to the deforming force or load. Algebraically, Hooke's law states that the applied force F equals a constant k multiplied by the displacement (change in length) x, thus: F = kx.

The elegance of this approach is that shape design and control is now computed as simple vector-based operation applied to a given topological input represented as either a mesh or network of curves. Simply, each member (input curve or mesh edge) becomes a spring comprising modifiable attributes that can be coupled to higher-order goals: structural performance (global or local); part-specific fabrication constraints such as unit length (minimum and maximum), unit depth (minimum and maximum); CNC fabrication processes and sequences. In effect, all dimensional limits, rotations and the like can be fed directly to the constituent spring via its rest length, stiffness or damping rate. Thus the model is capable of not only negotiating gravity as per Gaudi or Otto, but a range of extended performance criteria such as fabrication and engineering constraints (min/max member length, member depth and member rotation) (Figure 3). Critically from a design perspective, each of these opportunities can be engaged through multiple channels of interaction: curated via an originating input geometry (mesh or curve network); manipulated through the use of multiple material gradings, strengths or resistances (read: multiple spring types and/or stiffnesses); varying material weights (use of mesh face areas or curve length multiplied by a scalar and then distributed through the mesh's nodes); finite element analysis supplied by an engineering consultant; or rather more explicit or intuitive curation by the designer (experimentation and play).

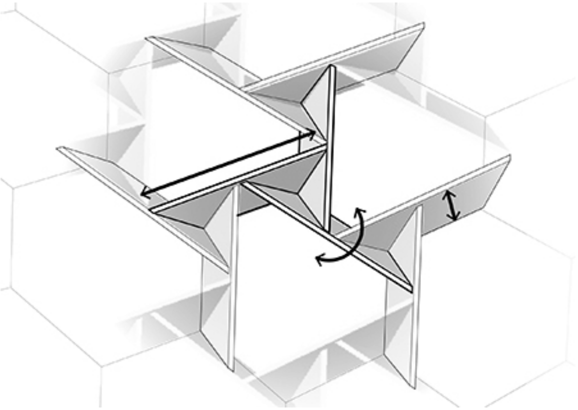

Figure 3: Performance criteria to be indexed to generative design method.

*Real-Time Feedback*

As the case study shall demonstrate, computationally-literate designers are beginning to attain largely unprecedented access to structural heuristics, material behaviour and increasingly sophisticated fabrication processes through generative and open-ended algorithmic methodologies. Despite this, the secondary retrieval of structural analysis continues to deny the ability to validate solutions in real-time. This is currently more an issue of communication protocols than of computational power. As such, the development of a real-time pipeline between common engineering finite element analysis platforms (such as Arup's GSA and Strand7) and the generative design tools described above is an area of significant ongoing interest. This exercise is presently being undertaken in collaboration with Arup Engineers Research and Technology Group in Sydney. To date, the design team has automated the production of the necessary datasets and structures to supply ARUP's GSA software and before long we expect to setup a viable feedback framework similar to that outlined above for matters of fabrication.

## Concrete: Complex post-tensioned precast gridshell

*Utzon's use of Precast Concrete in the Sydney Opera House*

As observed, Utzon's proposal of a sphere-based control geometry was critical to the realisation of the SOH. This geometric system enabled a simple structural approach to the design of the roof shells: structural ribs comprising numerous smaller, more manageable, repetitively cast elements compressed through an elegant post-tensioning system. Indeed, the traces of the latter contributing significantly to the tectonic delight of the project. The extraordinarily high levels of finish was achieved through beautifully crafted, fully reusable, timber casting molds lined in fibreglass. The lining aided the release of the cured segments and also ensured the molds were impervious to water thereby guaranteeing their durability. The considerable investment of design and workmanship into these molds was of course only made possible by the fact that each mold could be used many, many times. Itself a reciprocal virtue of Utzon's system of repetition compensated equally by the project's generous budget. A virtue few architectural commissions benefit from!

*Contemporary Interpretation: Unique Elements*

The casting technique described forms part of a larger body of research into flexible casting techniques by the authors. By investigating material properties and fabrication technologies, this research focuses on the development of new methods for producing mass-customized concrete elements (where each part is unique). The combination of Computer Numerically Controlled [CNC] manufacturing and algorithmic design methodologies are used to break-away from the industrial paradigm of standardisation. [4]

The mold fabrication technology incorporates laser cutting which allows for the production of unique components, while maintaining high working speeds. The method was developed in preference to other CNC approaches such as surface-milling, which would also allow for customization, but at an increase of material wastage. Here, three-dimensional form is generated from flat sheets by means of folding, following scored lines. This means that pre-cast components can be designed with a number of parametric variables, which can cause or be affected by differentiations in the component design. In the case study pavilion, later described in detail, Y-shaped components were practical, but the overall method can accommodate other component geometries and structural forms.[5]

The material utilised is APET plastic. APET is a part of the PET plastic family, used for packaging and containers such as soda bottles. It is easily recycled evaporating only CO2 and water. Importantly, it has a molecular structure that allows for infinite use and reuse without damage to the molecules. In terms of the cradle-to-cradle design-strategy, it is a technical nutrient and could remain in a closed recycling process without degrading. [6] Thus the casting principle used in this project provides the possibility of zero-waste production, since the plastic sheets used for molds can be reused.

*Development of a Post-Tensioned Construction Method*

Given the relative thinness of the structure (effective structural depth), it is extremely important that the built structure matches the computationally found form so that all load paths remain within the sectional profile of the elements. Problematically, masonry structures (excluding Catalan vaulting techniques) are not stable in an incomplete form. Historically, it has been necessary to use considerable formwork to ensure the temporary support and exact positioning of each component during assembly. In a non-uniformly shaped vault such as the case study presented, like each of the precast elements, each scaffolding element would also be unique. Developing simple approaches to this challenge has defined much of the research undertaken by the authors to date [1][2].

A significant innovation of the Utzon/40 pavilion, is the introduction of a post-tensioning system that largely eliminates the need for excessive scaffolding during construction. Drawing inspiration from the approach of Utzon and Arup some 40 years ago, where each rib consisted of many concrete elements compressed by a series of cables running through conduits (duct) cast-into each element. Here however, precast elements are tied-together in pairs in a discontinuous post-tensioning approach, where again unlike the SOH, the tendon is a threaded rod spanning center to center of two adjacent elements secured by a nut assembly (Figure 4).

This novel post-tensioning approach allows assembly to occur row-by-row as the tensile member (threaded rod) permits each element to temporarily cantilever in space. As soon as the first row is complete, ring forces provide structural integrity for that row and the next one can be added. More akin to building an igloo as opposed to a traditional masonry construction which in relies upon the completion of stable arches. (Figure 4). Furthermore the threaded rods act as reinforcement once the structure is complete and counteract point loads. In earlier pavillons bending and fixing reinforcement proved labour intensive because of the complex geometry and small cross sections. Finally the discontinuous system of post-tensioning rods, in combination with the folded casting molds, affords increased orders of tolerance and part-alignment.

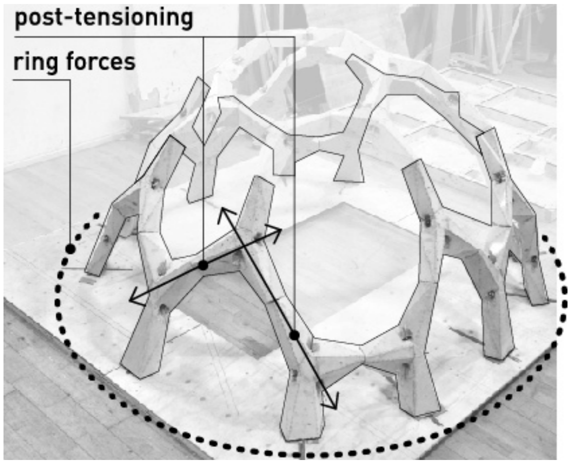

Figure 4: Diagram showing concrete element construction principle

*Alignment with plywood components*

In order to meet the plywood structure, the geometry of the concrete components adjusts. Given each plywood element bridges across two separate concrete elements, one face of each concrete element must be forced planar - and parallel to the timber - to ensure the two materials interface cleanly. The script responsible for generating the casting templates (unrolled concrete geometries) is also capable of detecting such situations and intelligently adjusting the geometry of the concrete arm accordingly. In certain circumstances, a concrete arm may even be omitted.

All concrete arms that interface with timber also include (cast-in) an additional two threaded U-bolts. To accommodate small deformations of the APET mold during casting, the concrete is 3 mm from the finished timber line. A critical development of the mold technology is the embedding of all part numbers, alignment holes and fixing locations for the post-tension rod conduits and U-bolts that interface with the timber. As such, all necessary fabrication instructions and design intelligence developed through the the digital and material prototyping becomes embedded within the APET molds themselves.

**Timber: Reticulated structural plywood gridshell**

*Relationship to Utzon/Sydney Opera House*

The use of structural plywood for the interior of Utzon's remains the most significant loss of Utzon's highly controversial resignation. Indeed, time has only calcified around the genius of Utzon, and his use of structural timber was poised to be of an equivalent marvel to that of the great ribbed shells. Utzon's interior proposal, a remarkable stepped ceiling system comprising radiating box beams and acoustic panels suspended from the concrete ribs was the result of a deep collaboration with Ralph Symonds Ltd. Again, Utzon harnessed prefabrication with all services and finishes being undertaken off-site before being bolted together in-situ. In a cruel irony, Utzon's intense engagement with a single - expert - contractor led to an environment of critique concerning non-competitive procurement.

*Development of the Reciprocal Joint*

Like the competition winning geometry of the SOH's shells, this material research focuses on the design and engineering of complex doubly-curved geometries that embed material (structural) behaviour and construction logics. The establishment of a generative algorithmic design framework, one that couples the formal generation of a design to file-to-factory protocols, the system challenges the reductive modernist constraint of repetition. The latter a consequence of economics and logistics than design intent.

The timber structure privileges a reciprocal frame tectonic. This strategy is valued for its ability to realise large spanning lightweight structures consisting of non-standardised short members cut from readily available flat sheet stock of 18mm Birch plywood. The use of large-format sheet stock and efficient computational strategies of part nesting significantly reduces material use. Reciprocal joints are an effective and pragmatic approach to a structure that must be assembled and disassembled many times using common bolt fixings. This joint strategy: increases the effective area of connection allowing for bolt placements to be made in a manner that does not remove significant material at a single location (i.e. the joint centroid); provides greater accessibility (tool clearance) to bolt locations on doubly-curving geometries; allows for increased orders of in-plane and radial stiffness through reducing the effective length of each structural member it receives (Figure 5).

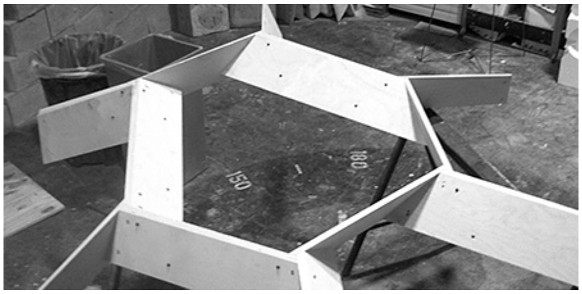

Figure 5: First prototype of timber 'hexagon' unit

*Difference and Repetition*

The tectonic design developed relies on higher-order principles to efficiently manage and fluently produce (file-to-factory) large populations of entirely unique parts. Despite all of the parts being geometrically unique, they are topologically consistent with each joint receiving 3 members at all times with exception of those joints occurring at the perimeter and which interface with the concrete elements. The benefit of this approach is that any part variations are differences of degree and not of type. Thus, all downstream fabrication processes such as the sequence of routing, sawing and drilling, attendant tool changes, or part attributes such as the number of sides, ordering of fixing holes and basic notation remains consistent.

*Fabrication sequence*

Each part stems from a blank, pre-cut from flat plywood stock. The blank is placed on a riser pod over a vacuum table and undergoes three operations via a 5-axis CNC workcell. Tool changes are performed automatically, and each part takes around 5 minutes to fabricate. The first tool operation mills two small slots to accept a concealed square threaded fastener. The second tool operation utilises a 300 mm saw blade fitted into a spindle. The saw was chosen due to the high feed (cut) rates achievable while equally exerting lower forces on the part as compared with a router. Low reaction forces are an important requirement, as the small surface area of parts makes vacuum-fixturing difficult. Thus the saw replaces all routing operations to create the complex edge bevels. Of note, counter to intuition it is also possible to perform variably swept edge cuts using the saw. The relevancy of this to the final pavilion is that entirely consistent members depth would result in stepping at each node as each the geometry and approach angles change. The final tool operation is to drill through the ends of each member to create the alignment holes for the mechanical fasteners (Figure 6). This fully-automated fabrication sequence was originally developed on a 6-axis industrial robotic arm, however, to increase part accuracies and to reduce construction tolerances, the production of the Utzon/40 timber elements was shifted to a 5-axis CNC gantry-style mill.

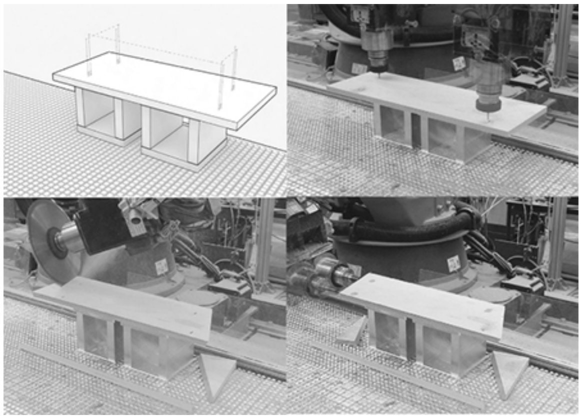

Figure 6: Fabrication sequence of timber frame element. (6-axis robotic arm fabrication method is shown)

## The evolutionary role of prototyping

Despite this paper's claim for the transformative capacities of algorithmic workflows and CNC fabrication methodologies, the success of the research to date stems equally from knowledge acquired during intensive periods of material testing and prototyping. This iterative approach to making has yielded many valuable insights into the detailing, logistical (packing, sorting, ordering, etc..) and technical (casting, assembly, sequence, etc..) challenges faced by high populations architectural assemblies of non-standard mass-customised parts. Each material experiment has led to a purposeful evolution of component design, either mold or joint development (Figure 7). Each learning outcome ultimately (re-) encoded within the generative design model. The importance of this process is that the tool does not define the outcome, nor does one outcome define the tool, rather they mutually develop and accrue intelligence and knowledge.

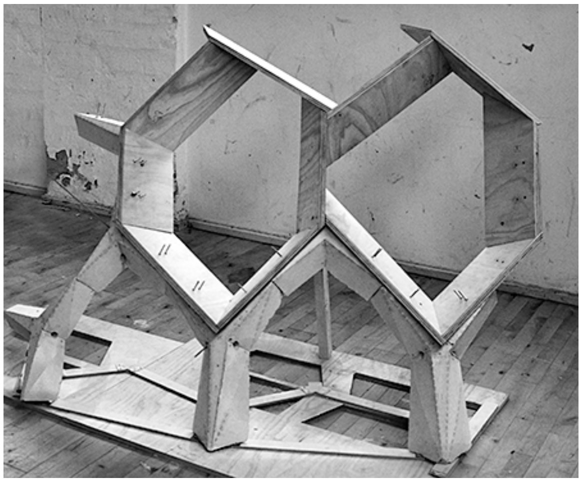

Fig. 7: Prototype of timber and concrete interface

## Future work

The Utzon/40 pavilion constitutes an important milestone of a longer research trajectory. It is a working prototype of a larger structure set for realisation in 2015 which will further investigate the architectural potentials of the building methods. In the short-term, future work centres on the development of a real-time pipeline to analytical engineering softwares as previously discussed. Further and more detailed development of an architectural cladding system also remains an area of activity. It is intended that the latter shall again draw knowledge and inspiration from Utzon's remarkable ceramic surfaces.

## Conclusion

As Jorn Utzon's Sydney Opera House epitomizes, the true potential of architecture lies at the threshold of design, material and technology. Computational techniques form the basis of a robust new design method capable of ensuring structural integrity and fabricational viability within highly complex, mass-customised structures. The pursuit of automated workflows is not without disciplinary consequence. The field of digital fabrication has been lauded by many (the authors included) as allowing the Architect to take back possession of the production of the architectural artifact, who prior, was divorced from the process of making. The significance of this reclamation is not only to return to architecture as a material praxis, but in doing so, to increase the number and quality of feedback loops between design, material systems and the means of architectural realisation. Streamlining the transition from design-to-production is therefore not meant to be reductive, but instead aid in the development of a reciprocity between designing and making. As the Utzon/40 pavilion demonstrates, the successful application of computational design methods demands a rigorous commitment to physical testing, mockups and prototypes - akin to the manner in which Jorn Utzon worked - to ensure critical experience and knowledge of material, tectonic and production processes are obtained, and ultimately embedded in the generating techniques of design. Thus the pursuit of computational design methodologies and automated technologies of production can be framed as the search for a new form of design intelligence, one where the decisions of design and maker intermingle within an extend context of the traditions of form-finding in architecture: formation-embedded design.

## Acknowledgements

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## Notes

[1] Larsen, N. M., Egholm Pedersen, O., & Pigram, D. (2012). *A method for the realization of complex concrete gridshell structures in pre-cast concrete*. I Cabrinha, M., Johnson, J. K., & Steinfeld, K. (red.), *Synthetic Digital Ecologies.* (s. 209-216). United States of America: The Printing House Inc, WI.

[2] Larsen, N. M., Egholm Pedersen, O., & Pigram, D. (2012). *Realisation of complex precast concrete structures through the integration of algorithmic design and novel fabrication techniques.* I Hesselgren, L., Sharma, S., Walner, J., Baldassini, N., Bompas, P., & Raynaud, J. (red.), *Advances in Architectural Geometry 2012.* (s. 161-174). Wien: Springer Publishing Company.

[3] McGee, Wes; David Pigram and Maciej P. Kaczynski (2012) *Robotic reticulations: A method for the integration of multi-axis fabrication processes with algorithmic form-finding techniques*, Proceedings of the 17th International Conference on Computer Aided Architectural Design Research in Asia / Chennai 25-28 April 2012, pp. 295–304

[4] Larsen, Niels Martin (2012), *Generative Algorithmic Techniques for Architectural Design*. Ph.D. thesis, 1 edn, Arkitektskolen Aarhus, Aarhus, Denmark, pp. 42-48.

[5] Pedersen, O. E. (2013). *The Tectonic Potentials of Concrete*. Ph.d.- dissertation, Aarhus: Aarhus School of Architecture. (pp.131-147)

[6] McDonough, W., & Braungart, M. (2009). *Cradle to cradle: Remaking the way we make things*. London: Vintage