Affordable Complexity

'God's Eye' - Sukkahville 2013

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The paper presents a novel approach on the design of complex forms by re-formulating the relationships between form, structure, material, fabrication and construction. It is proposed that current design models are supplemented by feedback-enabled frameworks, integrating material properties, fabrication constraints and construction logistics. As such, a series of input parameters based on industry standards, filtered through physical testing and digital simulations, feed a central computational model. The outcome is weighed against a set of objectives towards an optimum design solution which embodies construction logic while ultimately opposing costly inflated ad-hoc solutions. Within the above framework and as part of a broader research conducted at [ARC], this paper illustrates a design methodology implemented at the case study of 'God's Eye', winning entry of Sukkahville 2013 International Design Competition. It is further supported that a high tech, interdisciplinary design process based on efficient material assemblies allows for a complex, yet efficient end result, through low tech affordable construction.

Keywords: *material-based design, design process, construction logistics, interdisciplinary design, computational design*

INTRODUCTION

Form has evolved from the continuum to the discreet; from a unified system, incorporating material logic into form, to the department of form from structure and their study as separate systems.

Elaborated code standards posing new analytical difficulties, demanding architectural briefs and the architect-engineer segregation shaped the years that followed. The end of the millennium was marked by the vision of mass customization through the use of computer-aided design and manufacturing, in place of machinery for repetitive production and assembly. In such context, the sacrifice of humanizing variety and form complexity in the interests of efficiency was no longer required (Mitchell 2004).

Eventually, a bottom up approach, founded on material logic and integrated professional knowledge was predominantly succeeded by ways of materialization, production and construction which were strategized only after the form was been elaborated, leading to top-down engineered, material solutions that often juxtapose unfitting logics (Fleishmann and Menges 2011). Even though such examples have demonstrated the desired degree of complexity, they turned out to be highly inefficient and expensive once they had been sold to a sufficiently funded client and entered the building phase; dissimilar Façade Panels needed to be curved in two dimensions or undergo exhaustive optimisation to approximate planarity, while large numbers of slightly differentiated joints dramatically increased fabrication and construction logistics (Scheurer 2009).

Recently, a number of researchers have supported that architecture is currently in a historic process of returning to its structural and material sources through material-based design and fabrication. Such a return calls for re-formulating the relationships between form, structure, material, fabrication and construction and re-considering our models of design (Oxman 2012).

Within the above framework, this paper aims to present a case study that re-examines the design process and realization of complex forms. Feedback mechanisms allowing decision making are driven by physical testing, computational simulations and industry constraints. This bottom up approach integrates material properties, jointing technology, fabrication constraints and construction logistics, while the outcome is constantly evaluated against a series of design criteria. The result is an interdisciplinary, high tech design process assisted by advanced computational tools, allowing for low tech affordable construction while fundamentally opposing the critique of digital architecture's favour towards form.

PROTOTYPE

The Prototype Structure, 'God's Eye' (Figure 1), was the winning entry of Sukkahville 2013 International Design Competition. The competition called for design proposals on a temporary pavilion pertaining affordable housing. 'God's Eye' was among the six shortlisted entries invited to be constructed in Toronto, Canada on September 2013.

Figure 1
'God's Eye' Toronto Canada

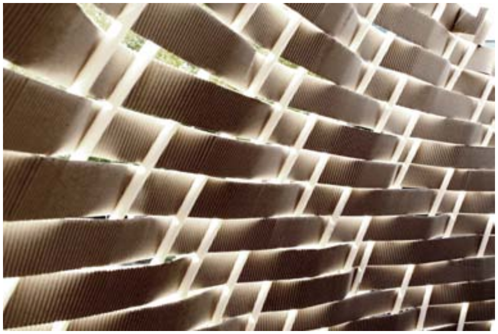
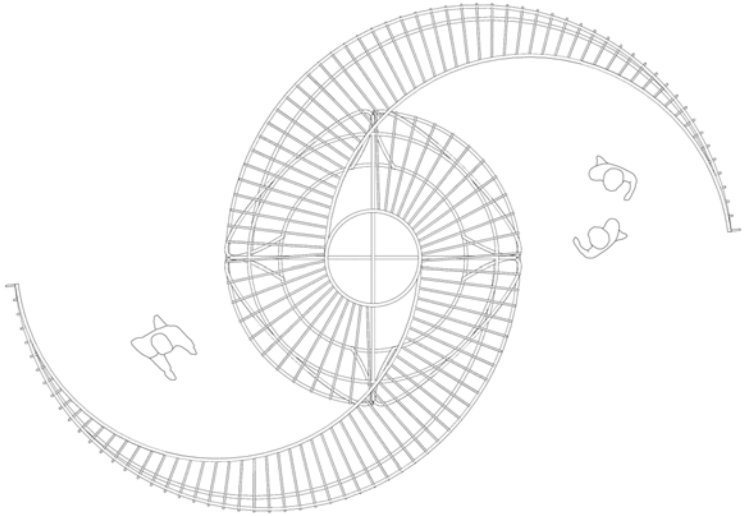


Figure 2
Structure-membrane interdependent system

The design consists of a pair of interweaved doubly curved surfaces, forming a central vaulted enclosure (focal point) which corresponds to a small roof opening. The spiraling configuration of the project results in two entrances/exits enabling the visitor to progressively experience a protected space (Figure 3). Despite its scale, the structure manages to combine the elements of surprise and interaction thus further enhancing the overall experience of the user. The choice for a woven cladding highlights the idea of shelter, family and bonding whereas the proposed materials (recycled corrugated cardboard and recyclable UPVC pipes) underline the ideas of affordability, ephemerality and fragility, fundamental requirements of the competition brief. Key constraints that drove many design decisions during the project's development phase were cost-effectiveness, construc-

Figure 3
'God's Eye'
Structure Plan



tion efficiency, and transportability, given that the project was aimed be realized 9000 km away from the base of its designers. Material assemblies encountered in textile and weaving have been adopted early-on and have been in the core of the project's development process. As such the characteristics of lightness, elasticity and suppleness have been determinant factors in selecting materials and defining their organizational logic.

The pavilion was accordingly developed as a structure-membrane interdependent system (Figure 2). The structure (Primary and Secondary) was made out of recyclable locally produced (Cyprus) UPVC (EN 61386-21:2004) electrical conduit pipes, bent in place and secured using custom-made metal and acrylic digitally fabricated joints. 32mm width pipes were used for the primary structure and 16mm width pipes were used for the secondary structure. The form was achieved by instrumentalising the bending forces induced on the pipes as defined by a computational model.

The membrane, serving structural (diaphragm) and sheltering purposes, was realized by interweaving recycled single-sided corrugated cardboard strips of variable widths on the secondary structural system.

Finally, a set of jointing techniques and custom-made joints were developed and constructed during the design process to respond to different needs and performing criteria.

The realized pavilion weighted less than 100kg with a total footprint ranging at 17.5 m^2. The total cost of materials was approximately 350€. The complete structure was hand-carried from Cyprus to Canada in three sports equipment bags weighting less than 25kg each. Construction time was less than 16 hours over two days by a team of two students and three faculty members.

INFORMATION WORKFLOW

A great challenge for designers today is to integrate the physical behavior of materials and their structural and geometrical characteristics in computational models that enable full control over their solutions (Fleishmann and Menges 2011).

Such an informational model was produced us-

Figure 4
Computational
Model

ing a core parametric definition in Grasshopper 3D [1], a parametric extension plugin of Rhinoceros 3d (Figure 4). The model was used throughout the design and construction process, continuously fueled with information originating from testing parallel simplified physical and digital models from and to which there was a direct transition. Affordability, Constructability and Transportability posed great challenges for the research team that addressed logistics management extensively to respond to the above areas. The ability to adapt and design based on industry standards (sizes and profiles), without compromising form complexity was critical in meeting the budget and achieving a lightweight, easily transportable, structure. As a result, research on materials was conducted early-on and a selection of locally available resources along with their properties was documented. The pallet of materials became part of the input parameters feeding the computational model. The main design objectives were therefore defined by the same nature of the design problem. As such, cost, weight and aesthetics, became the evaluation criteria for the outcome of the process. Filtering each design solution against the above standards enabled constant revisiting of the input parameters which resulted in further testing and development of the solution. Once a sufficiently fit outcome was achieved, the computational model facilitated the production of construction information and documentation.

The above information workflow is illustrated in the diagram below and further explained in the following pages (Figure 5).

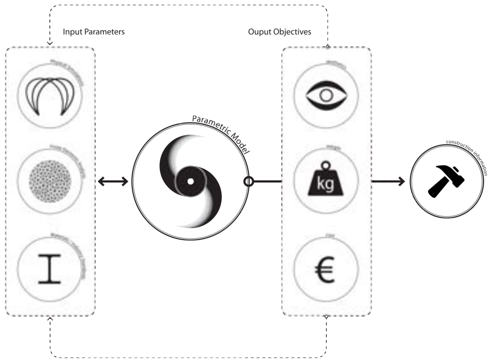


Figure 5
Information
Workflow Diagram

MATERIALITY AND PERFORMANCE SIMULATION

Through early physical prototyping, it became evident that the bending performance of the structural elements was a major factor in the geometric form-finding process. Due to the slenderness of the PVC tubes, relatively low forces induced large deformations and a significant increase in stiffness. This "bending active" (Lienhard et al. 2011) behavior is based on the elastic deformation of initially straight elements and their ability to store bending induced stresses, or bending pre-stress. Such a design method even if rarely used nowadays, was utilized as a governing principle in the design of timber gridshells, a great example being Frei Otto's Manheim Multihalle (Happold and Liddel 1975). Experimenting with locally produced, non-structural UPVC material however became a new challenge for the design team as such use was not previously documented. To record the UPVC tubes performance, an approach of integrating physical tests and computational design (both numerical and linear approximation methods) was followed.

At first, a number of physical tests were undertaken as a measure to determine the materials' physical properties. During these tests, the relation of the tubes' curvature to the destabilizing load, or the "lift force" was determined. These tests recorded the tube's modulus of elasticity and yielded the material's bending capacity. Furthermore, the data extracted from the experiments fed an analytical expression (Figure 6) associating change-in-height to length-of-chord of the main structure. This expression would be used as a geometric relation informing our parametric model, instantiating a digital form-finding process (Figure 7).

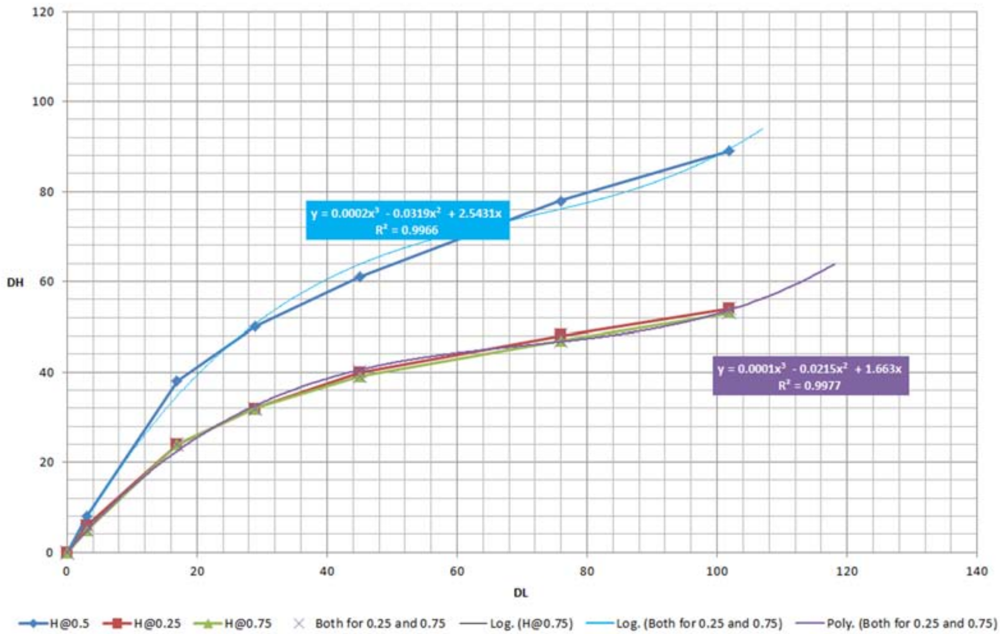


Figure 6
Bending deformation - Analytical Equation

Figure 7
Analytical Form-finding

In order to understand the stress distribution of the structural elements and in conjunction with the approximation model, a simplified analysis was performed, in which the initial force required to deflect the tube was used as input parameter (Happold and Liddel 1975). The method was based on inducing a support displacement on beam-element models and performing a third-order analysis in FEA software (Figure 8). However, as the geometric model evolved into a more complex geometry, this method proved to be inadequate and lost convergence. In an improved approach, a set of pre-stressed elastic cables were used to apply the desired de-stabilizing forces on the two ends of each tube.

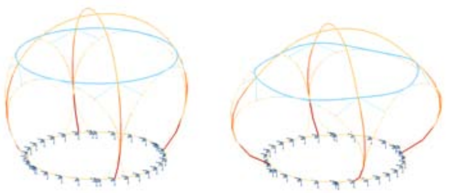


Figure 8
FEA Verification - Un-deformed shape (left) & Deformed shape (right)

As the shape of the pavilion evolved through digital prototyping and physical testing, its structural capacity and lateral stability needed to be verified at all steps. To overcome an arduous modelling process, usually featured in analyzing complex geometric problems, structural modelling capabilities were incorporated in the core parametric model. In order to achieve interoperability between the parametric model and the FEA, a developed API plugin [3], (Georgiou et al. 2011) was exploited.

PATTERN EXPLORATION AND SHAPE ADAPTABILITY

The membrane was constructed using stripes of corrugated cardboard unrolled in the desired length, in order to fit the exact geometry, and interwoven in-between the secondary elements of the structure. Incorporating the parameters forming the outer surface in the global computational model was essential for controlling and optimizing the developed outcome. Therefore all the information relating to the design of the membrane was included in the core parametric model. This had also allowed the exploration of a large number of different weaving patterns aiming to achieve the desired aesthetic complexity (Figure 9). Due to the varying sectional curvature of the pavilion, the membrane's adaptation to shape needed to be controlled. This was enabled using custom written scripts that could produce variable-width cardboard strips responding to the changes of the structures' curvature. To facilitate construction, the strips were grouped in five sets of different widths, rationalizing without compromising the appearance of membrane. (Figure 10)

FABRICATION AND LOGISTICS

Jointing techniques and connection design were determinant factors in achieving the desired degree of complexity while maintaining affordability and constructability. Such jointing strategies were therefore considered early on and repeatedly revisited during the development and testing phases of the project. As such, material selection was partly based on facilitating construction in terms of simplifying the connectivity of constituent parts. In the light of the above, UPVC pipes presented an advantage, as their in-build socket enabled the formation of continuous members, as well as closed loops. Similarly the choice of corrugated cardboard was partly determined by its availability in rolls, enabling the production of continues cardboard strips. Finally weaving itself was based on frictional forces, eliminating the need of joints between the secondary structure and cardboard strips.

While the above strategies have effectively reduced the number of possible joints, the proposal required connectivity solutions between the structural members of the pavilion. Given the tight developing timeframe, precise analytical expressions of such connectivity would not have been possible. Additionally, fixed joints would have altered the pavilion's shape depending on their rigidity and would impose a far more rigorous design process. As a result, ro-

Figure 9
Weaving Patterns
Exploration

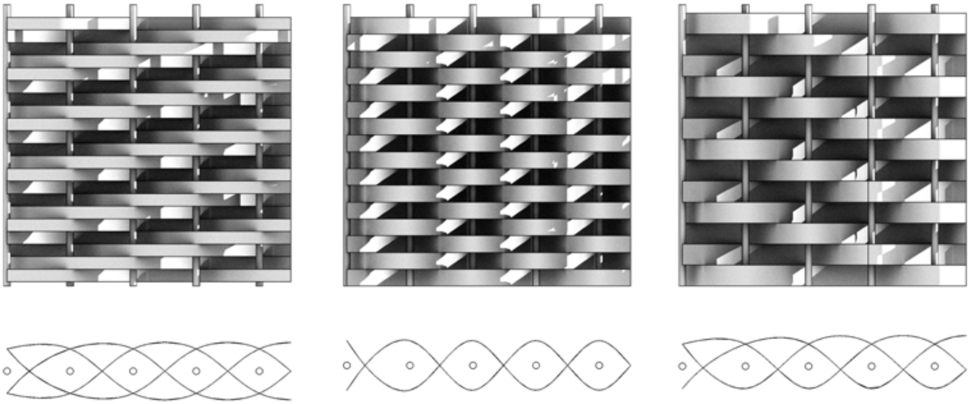
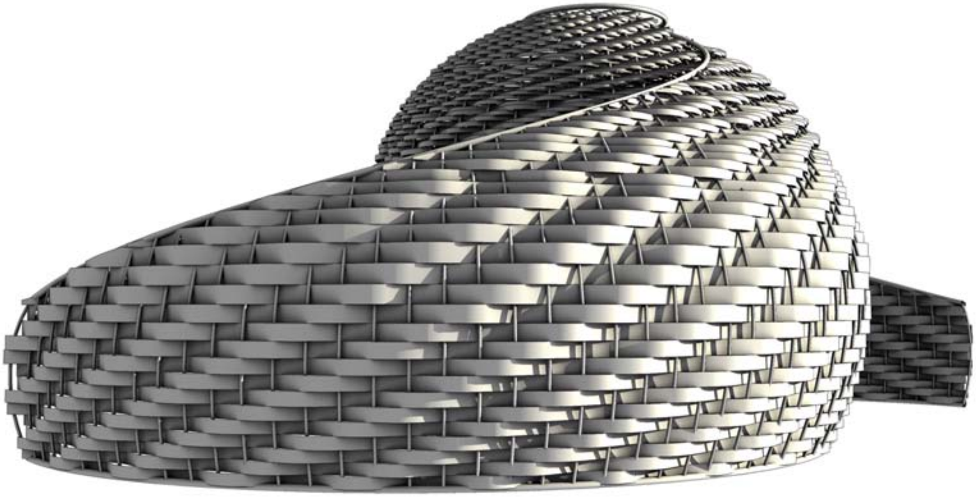


Figure 10
Adaptation to
curvature



tational freedom was accounted for in the analytical models. Such an assumption would also require its physical counterpart; a joint enabling rotation on 2-axis. This was resolved by combining pairs of plumbing pipe clamps using set screws, found in local hardware stores to form a two way 360-degree joint. A similar detail was used to develop a 3-way structural joint to connect the bracing arches to the main structure of the pavilion. In this case three clamps were welded together to form a co-planar 3-way fixture, the only non-rotational type of joint featured in the prototype (Figure 11).

The notion of joint rotational freedom was also adopted for the secondary structure. As revealed by the computational model, the complex shape yielded a large number of different connection angles which would be impossible to design and fabricate within the available time and budget. A universal, innovative joint combining commercial UPVC Tee joints and digitally fabricated acrylic parts, was designed and evolved to both meet the single and double axis rotation requirements (Figure 12).

In terms of construction information, cutting patterns for the cardboard strips were managed by the computational model taking into account the exact weaved lengths. A similar process was applied for the UPVC pipes, where cutting and marking schedules were generated for all the primary and secondary structure parts. This enabled waste elimination and simplified the construction process. Finally, automated processes were used for packing the structure and meeting transportation requirements (size and weight).

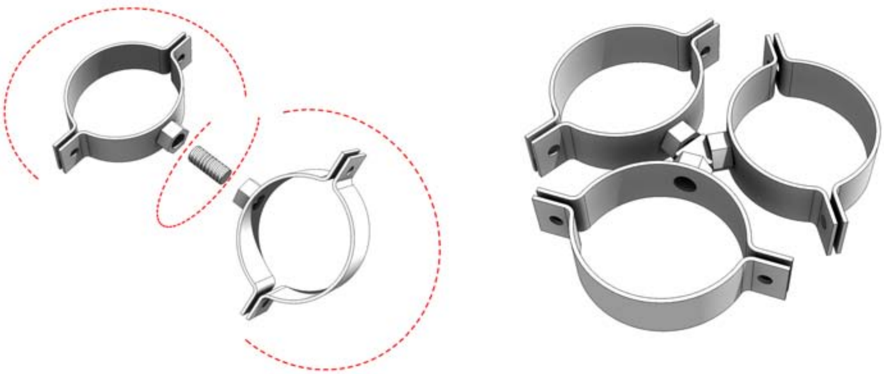


Figure 11
Two-way 360-degree joints (left) & Three-way fixed joints (right)

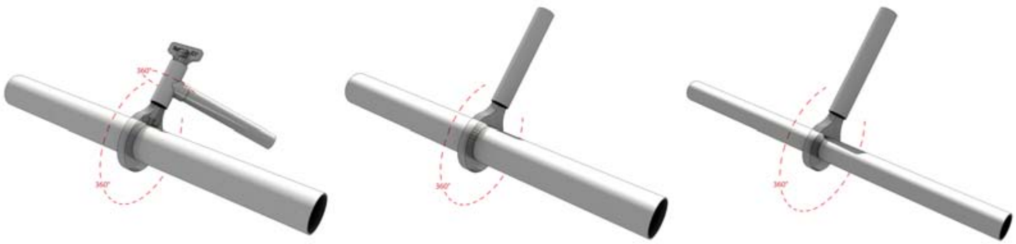


Figure 12
Universal UPVC + digitally fabricated acrylic joints

CONCLUSIONS

A fully informed computational model forms the core of the design process presented above; by implementing material properties and their organizational logic, the model allows minimization of analytical time and optimization of the end result through the exploration of multi-objective solutions. Embodied materiality, adaptation to industry standards and a series of waste management techniques enable major cost reductions as opposed to custom, post-engineered solutions. A jointing minimization approach paired with a flexible, adaptable jointing system that responds to the overall behavior of the structure, decreases analytical time, fabrication and construction logistics while accelerating the structural assembly process. Finally, aesthetic complexity is achieved by allowing exploration of a considerable variety of weaving patterns while effectively applying them on the doubly curved form of the structure.

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