FORM COMPLEXITY–REWIND
“GOD’S EYE” SUKKAHVILLE 2013

ABSTRACT
The paper aims at re-approaching the design process of complex forms through the utilization of feedback systems integrating material properties, fabrication constraints, and construction logistics. As such, a series of input parameters based on industry standards, opposing costly inflated ad-hoc solutions, 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. It is further argued that the methodology presented allows for a complex yet efficient and affordable end result. Within the above framework and as part of a broader research conducted at [ARC], this paper presents the case study of “God’s Eye,” winning entry of Sukkahville 2013 International Design Competition.
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. The emergence of elaborate design standards posing new analytical difficulties, the demanding architectural briefs and the professional segregation in architecture and engineering, 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 (Fleischmann 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 2010).

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 reformulating 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 reexamines 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 favor towards form.

PROTOTYPE

The Prototype Structure, “God’s Eye” (Figure 1), was the winning entry of the Sukkahville 2013 International Design Competition. The competition called for design proposals on a temporary pavilion pertaining to affordable housing. “God’s Eye” was among the six shortlisted entries invited to be constructed in Toronto, Canada, in September 2013. 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 total footprint of the pavilion was in the range of 17.5 m² and it weighted less than 100 kg.

Key constraints that drove many design decisions during the project’s development phase were cost-effectiveness, construction efficiency and transportability, given that the project was aimed to be realized 9,000 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 PVC electrical conduit pipes, bent in place and secured using custom-made metal and acrylic digitally fabricated joints. The form was achieved by instrumentalising the bending forces induced on the pipes as defined by a computational model.

2. Structure-Membrane interdependent System
The membrane, serving structural and sheltering purposes, was realized by interweaving recycled single-sided corrugated cardboard strips on the secondary structural system. The total cost of materials was approximately 3,500 €. The complete structure was hand-carried from Cyprus to Canada in three sports equipment bags weighing less than 25 kg each. Construction time was less than sixteen hours over two days by a team of two students and three faculty members.

PHYSICAL TO VIRTUAL TO PHYSICAL—DEVELOPMENT PROCESS

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 (Fleischmann and Menges 2011).

Such an informational model was produced using a core parametric definition in Grasshopper 3D (Grasshopper 3D, Algorithmic Modelling for Rhino n.d.), a parametric extension plugin of Rhinoceros 3D. 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, transportability and constructability of the complex geometry framed the design problem while posing great challenges to the research team. Addressing logistics management extensively and the ability to adapt and design based on industry standards (sizes and profiles), without compromising the initial design intentions, were critical in meeting the budget and achieving a lightweight, easily transportable structure. Materials (PVC pipes and corrugated cardboard) were consequently selected based on a number of
properties including their pliability (effective capacity to describe a doubly curved shape), weight and cost. As a result, research on materials was conducted early on and a selection of locally available resources along with the above properties and performance was documented. The behavior of these materials was embedded in the computational model, while a series of simple physical tests verified their ability to be manually shaped as digitally predicted and respond to form complexity and structural efficiency.

Once material behavior was parametrically described, a computational form-finding process was empowered. Even though the number of possible design solutions was substantially tightened by a series of performance criteria (functioning of space/plan and optimum shape of bent pipes in terms of structural efficiency) and competition requirements (constraints on footprint and volume of enclosed space), there was still a significant amount of design solutions, to be evaluated in terms of cost, weight and form/weaving visual appearance. The main design objectives were therefore defined by the same nature of the initial 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 criteria 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 (Figure 3) and further explained in the following pages.

At first, since the buckling behavior of the PVC tubes was crucial to the definition of the geometry, a number of physical tests was undertaken in order to simulate the “bending-active” (Lienhard, Schleicher and Knippers 2011) features of the structure. During the physical tests (Figure 4), tubes of various lengths were manually deformed in several chord-length increments. At each increment, the length of the chord and the height corresponding to the deformed arch were measured. The lifting load at each increment was also recorded. An analytical equation associating the change-in-height to the length-of-chord of the main structure was generated (Figure 6). The graph could approximately relate the vertical deformation of the tube according to its initial length and the horizontal displacement. This analytical expression was initially integrated with the parametric model, instantiating a digital form-finding process, embedding within material properties and approximate performance characteristics (Figure 5).

The tubes’ curvature relationship to the destabilizing load, or the “lift force,” was also determined from the physical tests. This relationship enabled us to formulate the actual material stiffness to be used in a more advanced numerical analysis. In order to understand the stress distribution of the structure, a structural analysis was performed, in which the initial force required to deflect the tube was used as input parameter (Happold and Liddle 1975). The method was based on inducing a prestress force relative to the destabilizing load and performing a third-order analysis in a FEA software. The results of the method were integrated in and compared against the parametric model informing and improving its behavior.

As the shape of the pavilion evolved through digital prototyping and physical testing, its structural capacity was verified at all steps. In order to achieve interoperability between the parametric model and the FEA, an API plugin (“Application Programming Interface” 2014; Georgiou, Richens and Shepherd 2011) was developed.
Shapes generated using the parametric model incorporating material properties

Bending Analytical Equation
Given the tight timeframe, precise analytical expressions of the connectivity between the main structural members wouldn’t 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, rotational freedom was accounted for in the analytical models. Such assumption would also require its physical counterpart, a joint enabling rotation on 2-axis. This was resolved by combining pairs of plumbing pipe clamps, found in local hardware stores to form a two way 360° joint.

A similar notion was 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 PVC Tee joints and digitally fabricated acrylic parts was designed and evolved to both meet the single and double axis rotation requirements (Figure 7).

The interwoven membrane of the pavilion was also part of the parametric definition. This allowed the exploration of a large number of different weaving patterns aiming to achieve an aesthetic outcome consistent to the theme and spiraling configuration of the pavilion. The twill dutch weave pattern was chosen, revealing a series of ascending spiraling lines on the surface of the pavilion. The lines highlighted the twisting formation of the structure while deliberately directing the visitors’ sight towards the sky opening (Figure 9).

The membrane’s adaptation to the doubly curved shape was controlled using custom-written scripts that enabled the generation of variable-width cardboard strips responding to the changes of the structures’ curvature. Throughout its development, it was ensured that the membrane could be formed out of zero Gaussian curvature strips, which could be unrolled to flat, straight pieces. To facilitate construction, the strips were grouped in five sets of different widths, greatly simplifying fabrication logistics without compromising the overall appearance of the Pavilion (Figure 8).

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 PVC 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).
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 and adaptation to industry standards enables a major cost reduction as opposed to custom, post-engineered solutions. In line with the overall behavior of the structure, a flexible and adaptable jointing system minimizes analytical time, fabrication and construction logistics while accelerating the structural assembly process. Finally, the desired aesthetic complexity is achieved by allowing exploration of a considerable number of design solutions paired with the examination of a variety of weaving patterns effectively applied on the doubly curved form of the structure.
REFERENCES


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IMAGE CREDITS

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