BLOOM: Materialising Computational Workflows

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Abstract

The paper presents ongoing research, aiming towards affordability of complex forms in architecture. The research supports that the above objective can be approached by re-examining and integrating materiality and form-finding techniques in computational feedback models. Within the above framework, a computationally enhanced design process is proposed and presented through a realised case study.

Keywords: form finding, computational design, materiality, gridshell

1. Introduction

The paper presents current developments and outcomes of ongoing research, aiming towards affordability of complex forms in architecture. The research supports that the above objective can be approached by re-examining and integrating materiality and form-finding techniques in computational feedback models. As such, an enhanced design process is proposed and presented, incorporating a series of digital simulations verified by parallel physical testing aiming at feeding a core computational model.

Materiality and computational form finding techniques are presented as design tools enabling major cost reductions as opposed to custom, post-designed solutions. Notions such as “active bending” are integrated through finite element analysis in an attempt to fully assess and exploit the behaviour and nature of the materials used. Such behaviour is computationally simulated and physically verified while it is further enhanced by additional linear elements instrumentalized to optimize structural performance.

This paper expands upon the findings of a case study, the latest (fifth) of a number of prototypes that have been constructed within the framework of the research to investigate affordability of complex forms in architecture. As such it presents a number of developments and shortcomings as follows.

The current prototype, called Bloom, departs from its predecessors (Georgiou et al. 2015) as it belongs to the category of gridshells. As such it is the first prototype that embodies the potential of a non-temporary structure which hasn’t been adopted in previous examples. The structure was made out of recyclable UPVC electrical conduit pipes, secured using custom-made rubber and UPVC joints. The gridshell was assembled flat on the ground and was bend in place by a team of eight volunteers without using mechanical means. The form was achieved by instrumentalising the bending forces induced on the pipes using a digitally fabricated formwork as defined by a computational model. The gridshell structure was finally braced using steel wires secured on the gridshell joints.

The design process of Bloom has involved Bending-Active and digital Form-Finding Simulations implemented using Kangaroo for Grasshoper. In parallel the result of the simulations were verified using full 1:10 and partial 1:1 physical models. Finite Elements Analysis using dummy cables was employed to simulate and verify the bending active performance and also to optimise bracing layouts. These simulations have also been verified using a 1:10 and 1:1 scale models. Furthermore, a digital Lift/Assembly simulation was carried out to define the construction workflow. Finally a digitally Fabricated Temporary Formwork has been employed during construction to reach the required shell geometry. On the other hand, construction logistics was the domain in which substantial shortcomings have been highlighted. The complex requirements of the jointing system, which had to perform on multiple levels, paired with the need for affordability have imposed a narrow field of design solutions. Even though the system functioned as planned, during lifting, assembly and throughout the life of the Pavilion, it has proven extremely labour intensive and time-consuming during construction and installation.

2. The Prototype

The Prototype Structure, named 'Bloom' (figure 1), was a winning entry of the International Open Call: Second Nature part of Pafos 2017 European Cultural Capital Events. The competition called for design proposals on affordable temporary structures to raise cultural awareness and to enrich neglected areas of the city of Pafos. 'Bloom' was among the seven shortlisted entries invited to be constructed at the Municipal Garden of Pafos, Cyprus.

The design consists of a single doubly curved surface, blooming out of central pillar to form a vaulted enclosure with four entrances/openings. The central pillar hosts a bougainvillea plant which is supported by the aforementioned structure. A cantilevering bench made out of twelve individual seating elements, frames the central pillar. The bench is made out of 2.5 mm mild steel sheets, using a waffle substructure and was digitally fabricated using an industrial laser-cutter.

Key constraints that drove the development of the project were cost-effectiveness and assembly efficiency. Additionally, the research team strived to achieve higher levels of structural capacity than previous prototypes without compromising the above strategic goals. Similar to preceding attempts, the characteristics of lightness, elasticity and suppleness have been determinant factors in selecting materials and defining their organizational logic.

As such the research team investigated the possibilities presented by gridshell structures while capitalising on materiality knowledge and construction experiences gained from already completed projects. Consequently the construction of Bloom involved the use of recyclable PVC electrical conduit pipes as a structural system, shaped and secured using custom-made PVC/rubber joints. The pavilion was assembled flat on the ground and was bend-in-place by a team of eight volunteers without using mechanical means. The form was achieved by instrumentalising the bending forces induced on the pipes using a digitally fabricated formwork as defined by a computational model. Finally the gridshell structure was braced using steel wires secured on the above-mentioned joints.

Bloom has a footprint of 39.6 m², a surface area of 74.9 m² and an estimated weight of 200kg. It is the largest pavilion in terms of covered area attempted by the research team at double the size of the largest of its preceding projects. Its structural member's total length stands at 702.4 m and has total cable-wire bracing length of 870m (in double lines). It should be noted that Bloom's structural members, have the smallest diameter, 25mm of all previously erected research pavilions that utilised UPVC pipes as a structural system. On the contrary, it employs the largest amount of structural joints, 1368, as employed by its gridshell logic. The material cost for the pavilion (based on retail material/fixings prices in Cyprus for 2017/2018) presents a noteworthy figure of 50.5 €/m². The pavilion remained standing for a period of 12 months after which it was disassembled according to the contractual obligations. Over this period, it exhibited no signs of fatigue and end-of-life measurements indicated deformations from initial shape of +/- 25mm.

Figure 01: BLOOM Prototype, Pafos Municipal Garden, Cyprus.

3. Form Finding Techniques

The shape of the pavilion, defined by the site boundaries and constraints was developed using a computational form-finding process. Kangaroo for Grasshopper3d was utilised in order to simulate an inverted funicular structure, withstanding the external loading conditions while adapting to the proposed architectural layout. A parametric model controlling the translation of the supports and boundary conditions was initialised and was linked to the physics simulation modelling, optimising the shape respecting both the usable space dimensions and circulation while maintaining its structural integrity. Forcing the simulated elastic shape to adapt to a hypar-like shell structure meant that Bloom's design was differentiating from previously designed pavilions and their bending-active free-form shapes. The proposed gridshell would therefore utilise both the materiality and the form-found shape in order to achieve a lightweight structural result. In addition to the computational form-finding technics, the design team opted for developing precise and accurate physical mockups aiming at simulating a real-world response of the structure (figure 2). A careful selection of the materials and their structural behaviour was carried out in order to enable simulations of the structural performance using a 1:10 scaled mockup (Addis 2013). The elastic and snapping behaviour of the mockup materials was tested and compared against the proposed UPVC tubes. The scaled model revealed the actual deformation demands of the structure and the required rotational capacity and limits of the gridshell structural members and joints. The above mokups have also presented an initial proof of concept for the proposed on-site assembly strategy of bending the pavilion in shape starting from a flat surface.

Figure 02: Case study, 1:10 Physical Model.

4. Simulating Materiality

A great challenge for the project was to integrate the physical behaviour of the materials used and their structural and geometrical characteristics in computational models that enable control over design (Fleischmann and Menges 2011). As such the geometry was guided by such computational models, produced using a core parametric definition in Grasshopper 3D. The models were used throughout the design and construction process, continuously fuelled with information originating from testing parallel physical and digital models from and to which there was a direct transition and flow of information.

Research on materials was conducted early-on and a selection of locally available resources along with the above properties and performance was documented. The behaviour of these materials was embedded in the computational model, while a series of physical tests verified their ability to be manually shaped as digitally predicted and respond to form geometry and structural efficiency. Physical tests were conducted with the different sizes of UPVC tubes in order to identify the elastic behaviour of the material used (Lienhard, Schleicher and Knippers 2011) (figure 3). Simplified analytical expressions (Georgiou et al. 2014) were used to approximate the curved geometry of each member. These equations were initially integrated in the parametric models, enhancing the precision of the aforementioned digital form-finding process, embedding within, material properties and approximate performance characteristics (figure 4).

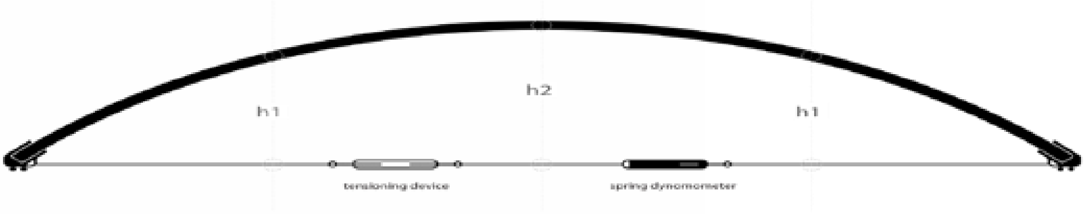

Figure 03: Bending physical test set-up.

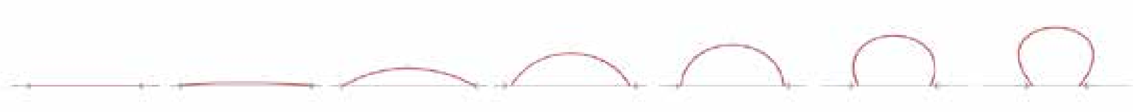

Figure 04: Shapes generated using the parametric model incorporating material properties.

Physical experiments defined the actual material stiffness in order for more advanced numerical analysis to be performed. The stress distribution of the structure was investigated by performing numerous analyses, during the numerical model was incrementally deformed (Happold and Liddel 1975). The results of the method were integrated in and compared against the parametric model informing and improving its behaviour. 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 numerical simulation software, a specialised plugin (Georgiou et al. 2011) was used (figure 5).

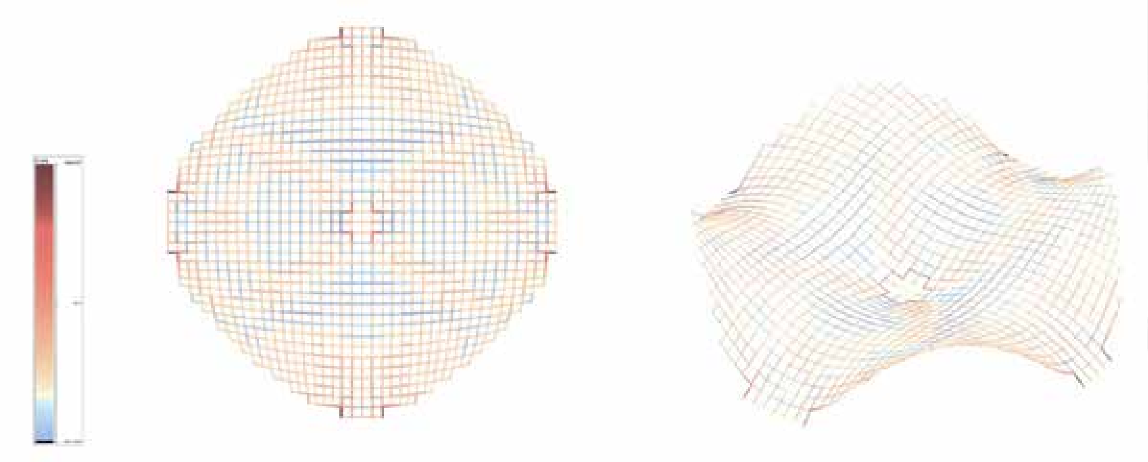

Figure 05: Structural Deformation Analysis.

5. Construction Assemby and Logistics

On-site assembly processes and construction logistics were determinant factors in achieving the desired degree of complexity while maintaining affordability and constructability.

On-site assembly has been an integral part of Bloom, and all previous prototypes, especially due to the limited construction time imposed by the competition rules. Moreover, assembly strategies proposed by the research team have been deliberately relying on unskilled personnel (students, volunteers and faculty members) promoting the concept of affordability from a workmanship perspective. Facilitating erection and complying with the above constraints was therefore taken on board since the early stages of design. Working with a gridshell structure logic enabled the proposition of a flat surface that could be bend-in shape without using mechanical means or skilled workforce (figure 6). The team reached proof of concept through a series of digital simulations using Kangaroo for Grasshopper 3D which were verified by physical models testing. The same scaled models that have been utilised to test deformation demands of the structure have been employed to test the proposed on-site assembly strategy and the requirements in personnel to achieve bending the pavilion in shape. The desired form was eventually reached by instrumentalising the bending forces induced on the structural members using a digitally fabricated formwork as defined by the computational model. The actual on-site assembly process involved additional temporary scaffolding elements, used to assist lifting the pavilion structure before bending it in place. The scaffolding has also been used to host the digitally fabricated formwork (figure 7). Once in shape, the gridshell structure was braced using steel wires secured on the gridshell joints.

Figure 06: Assembly process, conceptual diagram.

Figure 07: Assembly process, Scaffolding and digitally fabricated formwork.

Designing systems to streamline construction logistics was equally considered early on and different strategies were repeatedly revisited during the design and testing phases.

UPVC pipes were chosen to facilitate construction in terms of simplifying the connectivity of constituent parts. UPVC pipes presented an advantage as their in-build socket enabled the formation of long continuous members that would otherwise be very difficult to source.

While the above strategy effectively reduced the number of possible joints, the gridshell nature of the proposal required a large number of other connectivity solutions between the structural members of the pavilion. As indicated in figure 8, the proposed solutions were reduced to three categories: 48 x Edge Condition Joints (Type A), 68 x Edge Condition Joints (Type B) and 1252 x Cross Joints (Type C). Due to the performance requirements and their increased number, an efficient resolution of Type C joints was essential in meeting the strategic goals of the project (figure 9). Type C joints had to allow sufficient rotation while erecting the pavilion while facilitating bracing connectivity. The team's initial approach was to form pin joints by pre-drilling the structural members. Physical testing proved the approach problematic as the rotational force exerted on the pin fixtures during erection was causing the structural members to fail. As a result, a non-destructive solution of controlling the rotational capacity by means of friction was proposed and adopted. The solution called for rubber sleeves to be installed at every type C and B joints coupled with an innovative tie wrap bond inspired by nautical knots. The tie wrap bond was intentionally left unfastened to allow sufficient rotation during the lifting of the pavilion and was tighten once the pavilion was in shape. While the above solution had successfully resolved type C joint connectivity the issue of attaching and securing the bracing was still unresolved. Finite Element Analysis and testing on the 1:10 physical model proved that reduced bracing could still perform adequately. As a result the design team proposed an optimised bracing layout, at every second type C joint, effectively reducing the amount workload and bracing components to half. Additional elements made out of UPVC were proposed to host the wires of the bracings. These UPVC clips were designed to saddle on the type C joints and secured using a set of tie wraps. The clips carried a machine screw on which the wire bracing was fastened using common electrical cable connectors. A custom washer was digitally fabricated to facilitate holding and tightening of the wire connector. A digitally fabricated acrylic washer, an abstract representation of the characteristic regional almond blossom, was added to cover and protect all underlying parts of the joint. The total of 636 such flowers provided a unique surprise for the visitor at the interior of the pavilion.

Even though the above described jointing system functioned as planned, during lifting, assembly and throughout the life of the Pavilion, it has proven labour intensive and time-consuming during construction and installation. The multi-component joint that had to be installed at various stages of the construction process, coupled with the large number of such joints significantly increased the design and assembly time of the project. Future work will focus on addressing type C joint disadvantages towards investigating improvements to the aforementioned system.

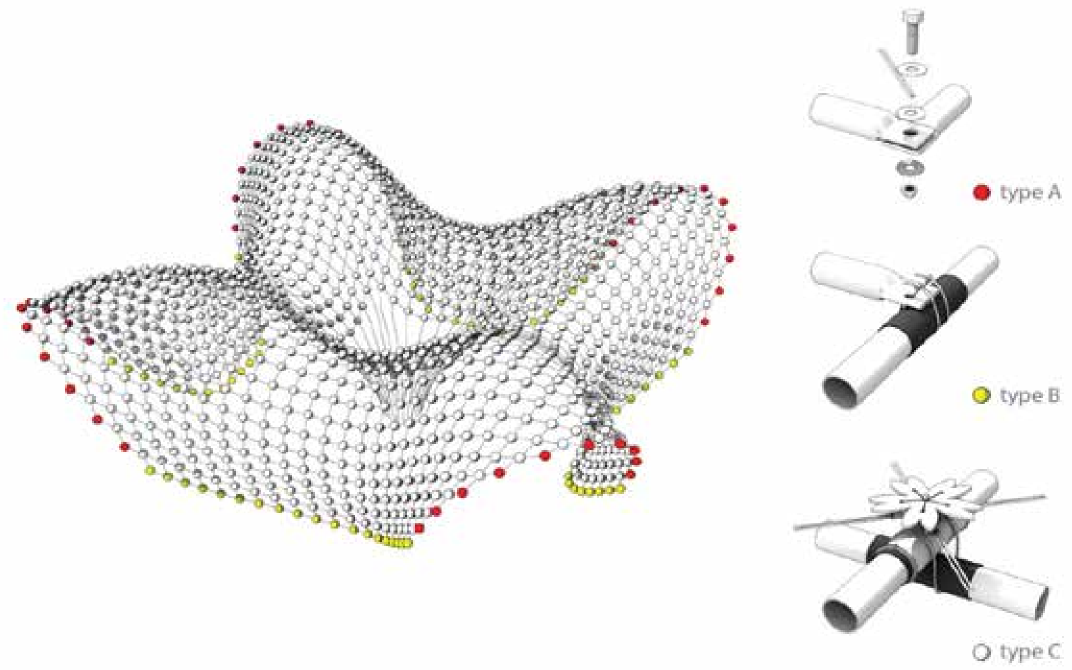

Figure 08: Type of Joints.

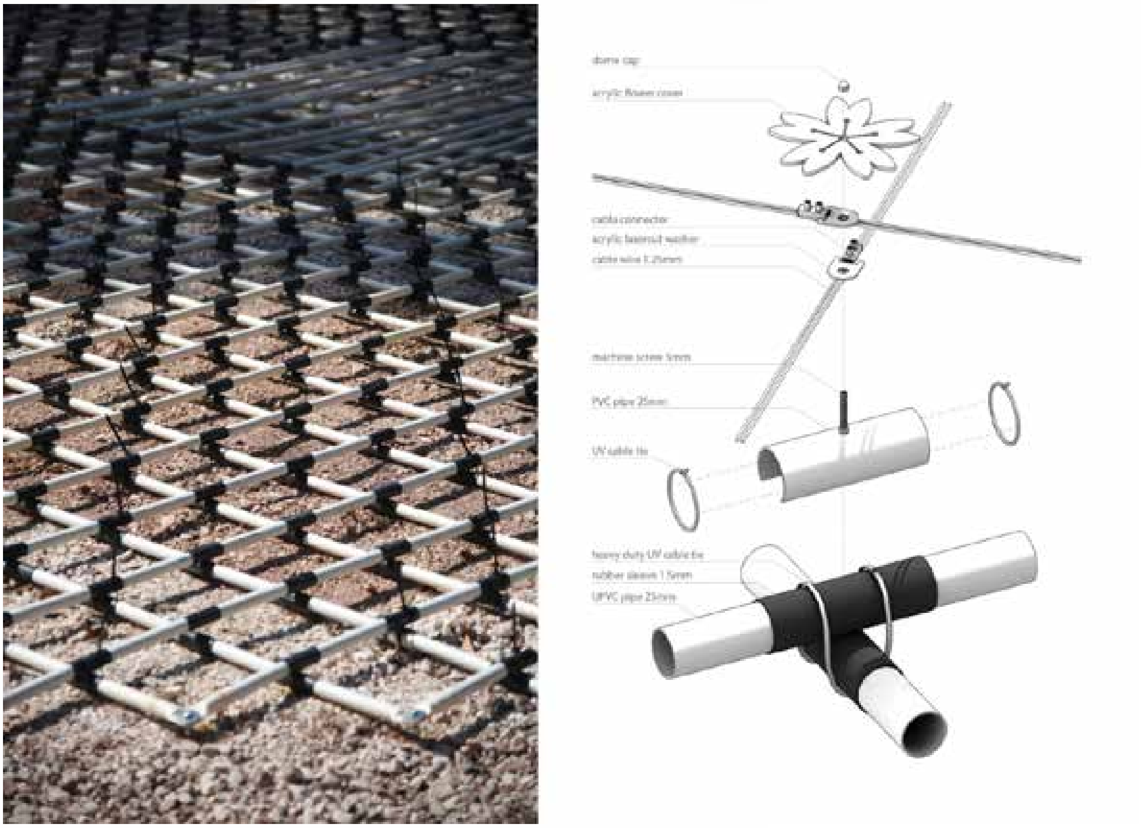

Figure 09: Type C Joints.

6. Conclusions

The research presented in this paper sets new grounds for affordable complex structures. Bloom was designed and realised under tight constrains and limited resources which provided fertile ground for testing another affordable paradigm.

Within the above framework, it was illustrated that integration of materiality, form-finding techniques in computational feedback models with parallel rationalization and adaptation of construction logistics enables significant savings throughout the design and construction phases of the project in terms of materials, human resources and time.

The design was supported by a central computational model able to form-find and simulate the physical behaviour of the structure. Increased levels of understanding and control over the physical response of the structural members were achieved during the development of Bloom, which maintained adequate structural performance for a period of 12 months, before it was disassembled.

Facilitating on-site assembly was achieved through laying the pavilion flat and shaping it in-situ returning significant reductions in workload and personnel. Simultaneously, streamlining construction logistics at various stages of the design and construction process was attained and illustrated. Adaptation of the joints to respond to assembly and bracing requirements allowed for minimized analytical time and additional efficiency in construction. On the other hand the same flexible and adaptable jointing system imposed increased construction logistics, delaying considerably the assembly process. Future work aims at addressing the above issue.

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