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A Method for the Realisation of Complex Concrete Gridshell Structures in Pre-cast Concrete

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Abstract

This paper describes a method for the design and fabrication of complex funicular structures from discrete precast concrete elements. The research proposes that through the integration of digital form finding techniques, computational file-to-fabrication workflows and innovative sustainable concrete casting techniques, complex funicular structures can be constructed using prefabricated elements in a practical, affordable and materially efficient manner.

A recent case study is examined, in which the methodology has been used to construct a pavilion. Custom written dynamic relaxation software was used to define the overall form and successive algorithms then defined each component's unique geometry, unrolled into flat shapes, and nested all parts into cut-files. PETG Plastic sheets were 2-Dimensionally laser cut and folded to produce the unique casting molds. The case study was carried out in collaboration between the Aarhus School of Architecture and the University of Technology, Sydney (UTS). Basic research in casting techniques defined the framework for the design process, and a custom written dynamic relaxation software application became the primary form-generating tool in the design process of a constructed pavilion. Fabrication and construction constraints were embedded within the design of both the overall structure and its components. Finite Element Analysis [FEA] was completed in order to verify the form-finding results, to ensure structural stability, and to direct adjustments of the structure during the design process.

The constructed pavilion case study, constructed in a very short time, for low cost and with relatively unskilled labor demonstrates that the integration of algorithmic form-finding techniques, CNC fabrication workflows and the use of innovative PETG folded mold techniques enables the practical realisation of freeform funicular structures in pre-cast concrete.

Keywords. Gridshells; pre-cast concrete; folded molds; dynamic relaxation; file-to-factory; form-finding; computational design; zero-waste production.

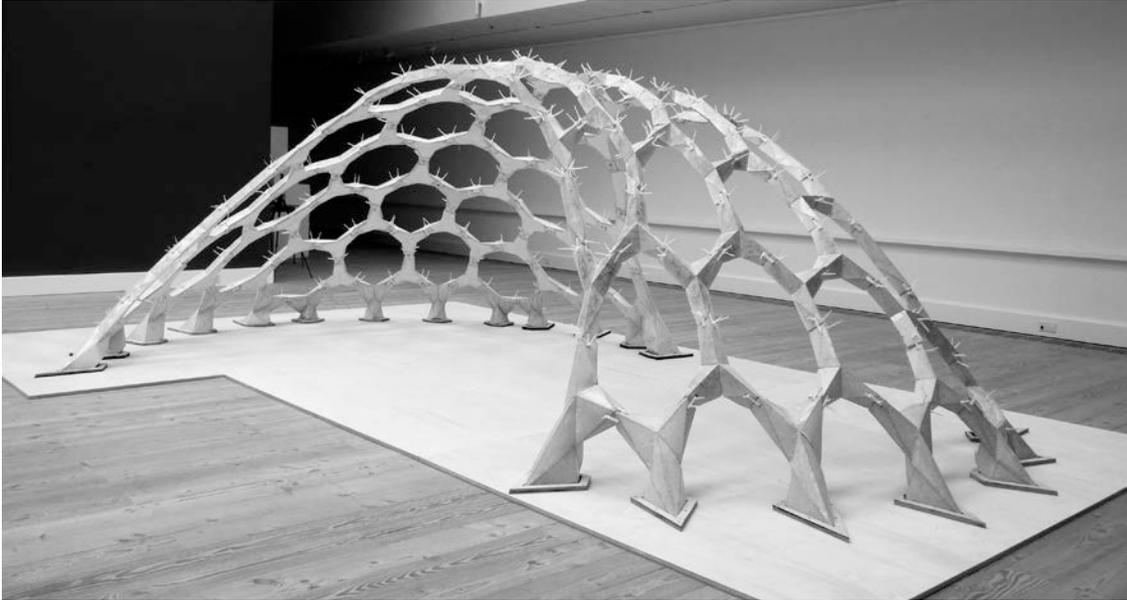


Figure 1: Concrete gridshell pavilion, first installation, Aarhus School of Architecture, October 2011.

1 Introduction

Concrete's potential for taking on complex shapes has been impressively exploited by Pier Luigi Nervi and Felix Candela, who built numerous form-found compressive vaults throughout their careers. These projects were all cast in-situ, and required large amounts of timber formwork to be constructed. Although relatively complex, the designs all contained degrees of regularity and repetition in order to simplify formwork production. Such casting principles are increasingly rare today because in-situ casting is costly, and it is easier to achieve high precision and high quality concrete when casting elements in a controlled environment. Also, despite their inherent complexity and fluidity, the need for a repetitive geometry limits the ability to adapt such construction principles to different situations.

Recent work at the University of Manitoba by Mark West and others has seen experimentation into the use of precast concrete elements within load bearing shell and vault structures, using flexible formwork and allowing gravity and hydrostatic pressure to generate form. The method described in this paper differs from West et al.'s approach in that it uses more rigid, foldable molds to cast smaller planar elements where the overall curvature of the system is a consequence of angled joints.

Two trajectories of previous research have been combined to form the fabrication methodology that is the subject of this paper. The first is the architectural application of furnicular form-finding techniques based on dynamic relaxation previously developed by Dave Pigram and Iain Maxwell from the design firm Supermanoeuvre. The second is a production technique based on concrete casting in PETG foil developed by Ole Egholm Pedersen in the beginning of 2011 at the University of Technology, Sydney (UTS). The proposed method combines these techniques and has been tested via a case-study project, a pavilion, completed in September 2011 in Aarhus, Denmark (Figure 1). Together with

the researchers and consultants, a group consisting of students from both UTS and the Aarhus School of Architecture participated in the development and realization of the pavilion.

The project's goal was to investigate how computation, material innovation and digital production technology enable feedback loops in the design process, to establish stronger connections between design and production, and to elaborate new sustainable production methods.

2 Form Finding Through Dynamic Relaxation

The form finding method was based on the principles for generating optimized vault structures, as famously utilized in Antoni Gaudi's hanging chain models for the Sagrada Família cathedral in Barcelona. Through physical self-organisation, the chains take forms that contain only tensile forces: catenaries. When the hanging form is inverted, the forces are translated into pure compression, resulting in funicular forms optimized for construction in materials such as stone. The self-organising process can be described by using 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 formula is implemented in the computer application ReVault, previously developed by Iain Maxwell and Dave Pigram. The application is able to simulate the self-organisational behaviour, seen in the hanging chain models by Antoni Gaudi. By performing the simulation digitally the possibility of real-time adjustments of factors such as spring length is provided. In turn, this provides a massive increase in the number of possible solutions that can be explored within a limited time span, as compared to physical models. For the case-study pavilion, the time for establishing the geometry of the structural mesh represented a total of three working days for one person. In this time literally hundreds of simulations were completed, allowing the designer to develop a sophisticated intuition as to the behaviour of the digital system (Figure 2).

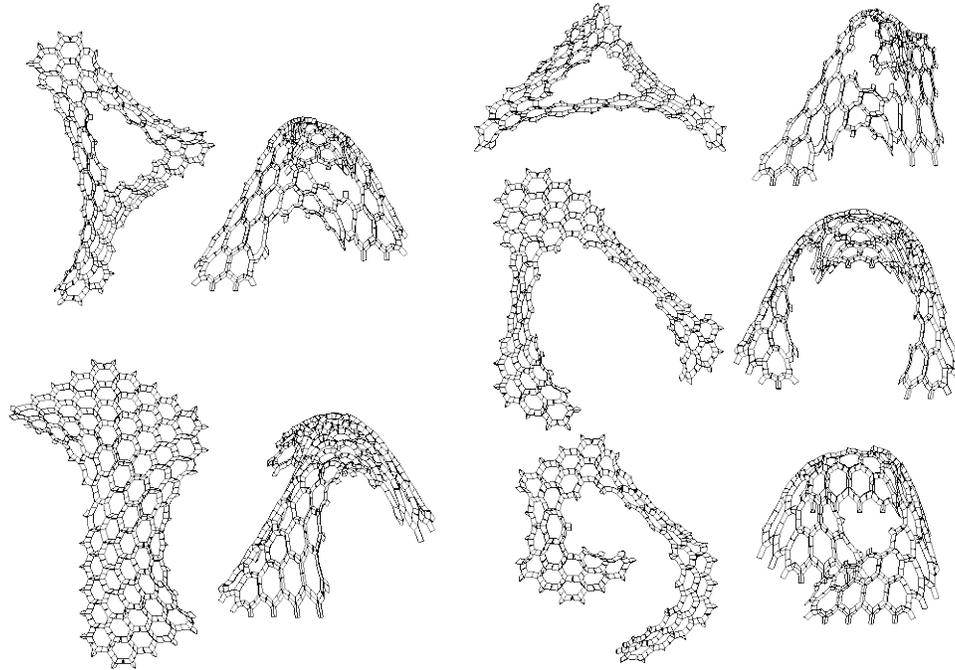


Figure 2: The generative tools allow a series of formations to be explored.

The ReVault application takes an initial mesh, or network of curves, with arbitrary topology as input (Figure 3 Left), and simulates a dynamic relaxation process, controlled by setting a list of essential variables, such as the relative rest-length of the members and the damping of the system. Through iteration the system arrives at an equilibrium state (Figure 3 Right), meaning that all the forces in the system have been balanced, and the velocity of the nodes is zero. In this state, the structure is in pure tension, or in pure compression, depending on the setting of the gravitational force. The generated three-dimensional grid is then exported to a 3D modelling program, as described in chapter 5.

Forms generated through the dynamic relaxation form-finding processes are optimized in terms of compression-only load distribution from the structure's own weight. In order to both verify the output of the form-finding software, and to calculate the structure's performance with various applied live loads, Finite Element Analysis is performed using Autodesk's Robot software.

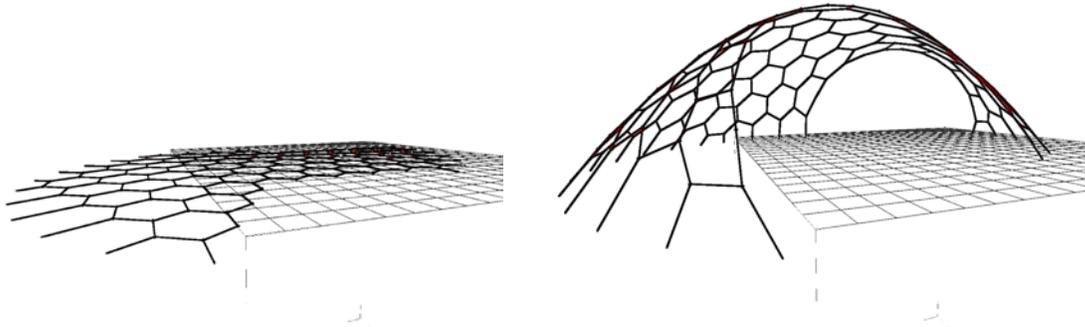


Figure 3 Dynamic Relaxation. Left: Input network. Right: Output Funicular Form.

3 Concrete Casting with PETG Plastic

The casting technique here described has been developed as part of a larger body of research into concrete casting techniques by architect and PhD candidate Ole Egholm Pedersen. By investigating material properties and fabrication technologies, this foundational research focuses on the development of new methods for producing mass-customized concrete elements. Computer Numerically Controlled [CNC] manufacturing and robotics are used to break away from the industrial paradigm of standardisation.

The mold fabrication technology here proposed is laser cutting which allows for the production of unique components, while maintaining high working speeds, as opposed to CNC surface-milling and 3D printing, also allowing individualisation. 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 and be effected by differentiations in the component design. In the case study pavilion, later described in detail, Y-shaped components (Figure 4) were practical, but the overall method in general and the casting method in particular can accommodate other component geometries and structural forms.

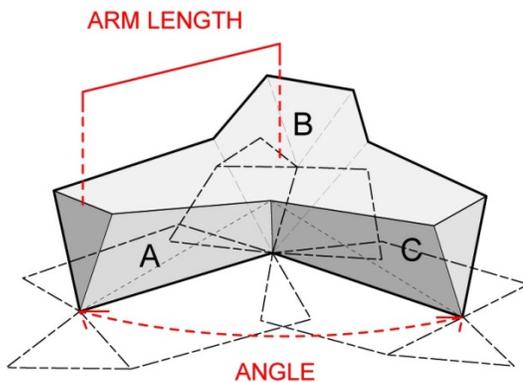


Figure 4: Parametrically variable Y-Shaped component mold formed by folding two-dimensional lasercut PETG.

The mold material utilized by this method is PETG plastic. PETG is a part of the PET plastic family, used for container like soda bottles. It is easily recycled, by melting, at 260 °C, evaporating only CO₂ and water. Importantly, it has a molecular structure that allows for infinite use and re-use without damage to the molecules. In terms of the cradle-to-cradle design-strategy, it is a technical nutrient and should remain in a closed recycling process with no degrading (McDonough and Baumgart 2002). Thus the casting principle used in this project provides the possibility of zero-waste production, since the plastic sheets used for molds can be melted and reused.

The plastic sheet is covered with a thin film, used to protect the material against scratches during transport. This film is left on during casting, and is then removed to leave a clean sheet ready for recycling. Since concrete adopts the surface properties of its mold, casting in plastic results in highly glossy concrete surface, resembling polished stone.

In order to achieve the crease angles necessary to produce components appropriate to this construction method, PETG sheet thicknesses of around 1mm are typical. When exposed to fluid concrete material, PETG foil has a high degree of deformation, which is solved by reinforcing edges with folds, triangulating large areas, and by limiting the area of planar surfaces. These measures contribute to the highly specific set of aesthetic characteristics that accompany this method (Figure 5).

Making the components essentially means setting up a production line with stations for folding the PETG, riveting parts together and adding features, such as reinforcement (Figure 6).

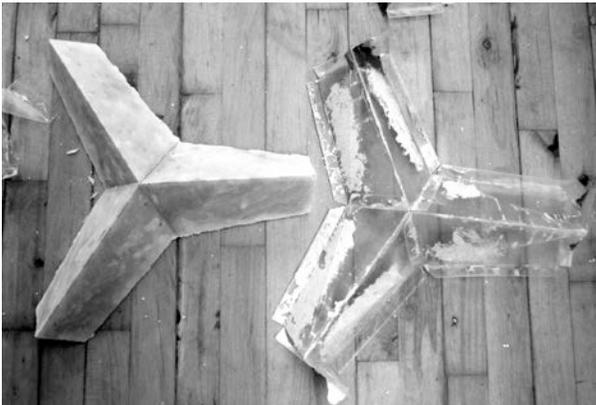


Figure 5: Prototype of Y-shaped concrete component and template of PETG plastic.



Figure 6: Production of concrete components. Left: Template assembled from PETG with rebar installed. Right: Template with concrete.

4 Ground Condition and Lateral Forces

Lateral forces that arrive at the springing point of a gridshell need to be resisted. This is most often achieved through in-ground footings but where such footings are impossible, establishing connections across the structure at the ground level can also resist lateral forces. In the case-study pavilion, for example, the forces were transferred through a plywood floor plate that engaged the bottom row of components.

5 Assembly of the Structure

Given the relative thinness of the elements used in this method it is extremely important that the constructed structure matches the computationally found form so that all load paths remain within the sectional profile. Additionally, as is typical in non-Catalan vaults, the structure is not stable in an incomplete form. As such it is necessary to use formwork to ensure the exact positioning of every component and to support them during assembly. Like the precast components, each scaffolding element is unique.

The scaffolding can be produced from cardboard, laser cut and assembled, first into triangular tubes, then into larger clusters forming hexagonal geometries, reflecting the plan of the concrete structure (Figure 7). The function of the scaffold is both to support the structure during construction, and to ensure the exact positioning of the components. The latter aspect being most important, since very small deviations from the spatial geometry made assembly impossible. The cardboard can be recycled after use.

Component placement on the scaffolding is directed by unique identifiers, referencing a component's arm to the corresponding arm on the neighbouring component.

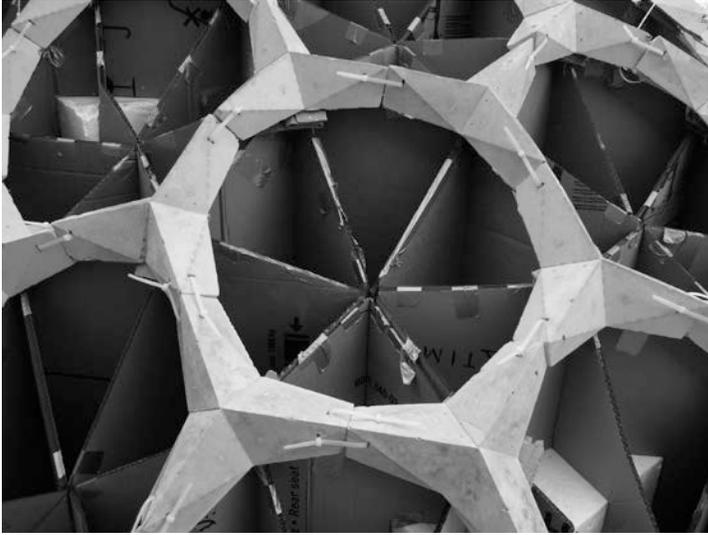


Figure 7: Scaffolding detail.

8 Case Studies

Two constructed case studies contributed to the development and testing of this method. The first case study was a deliberate test of a design that had known insufficiencies and thus represents something of a worst-case scenario. The second case study incorporated all of the lessons learned from the ‘worst-case’ prototype

8.1 ‘Worst-Case’ Prototype Test

Before the production of the final construction was initiated, it was decided to make a ‘worst-case’ test construction in order to practically discover many of the constraints that would guide the final method. The prototype was based on a triangular mesh, which was transformed with the dynamic relaxation procedure. The structure was completely symmetric unlike the final construction. Through generation of the geometry, the mesh was translated into the hexagonal pattern, shown in the final project.

Finite Element Analysis showed key problems in the initial design, and provided essential information for realisation of the final structure. The first analysis showed that a method, where the hexagonal geometry was generated on basis of a triangular mesh, resulted in deviations from the optimized shape that were bigger than the component joints would be able to obtain. Therefore, the principle was changed so the base geometry was defined as hexagons, and represented the final geometry more directly (Figure 8).

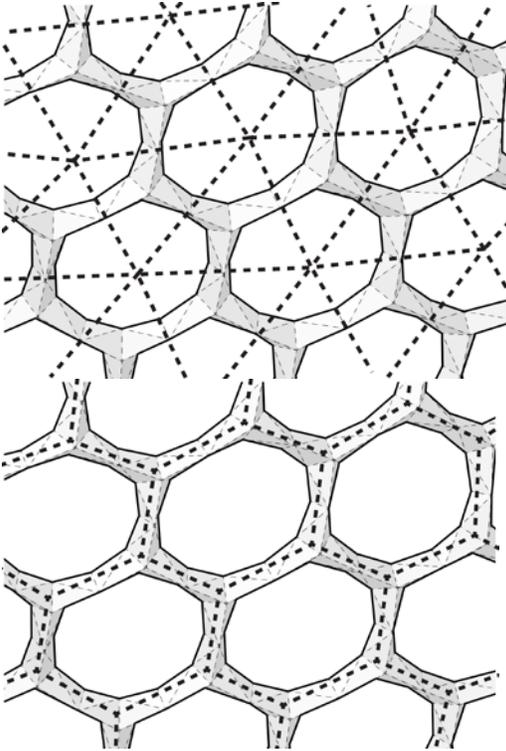


Figure 8: Left: Initially, a triangular mesh was translated into a hexagonal mesh. Right: Hexagonal mesh, corresponding directly with the final structure.

The prototype test illustrated the importance of connections. Correct positioning of each element is next to impossible without dealing with shear forces between the elements. This means that the assembled form will not match the computed load paths, the construction will not be compression-only (even only under self-weight), and will collapse due to the lack of tensile resistance at the joints (Figure 9).



Figure 9: The ‘worst-case’ prototype after structural failure.

This translation resulted in a noticeable deviation from the catenary gridshell. Coupled with the fact that the joints in the prototype could not absorb and kind of shear or tension forces, this meant that it was practically impossible to assemble the prototype. Another finding was the importance of correspondence between initial and final mesh geometry. The test also showed that the use of tension cables to counteract the horizontal forces proved difficult to control. In the final structure, the components were connected with structurally rated cable ties (Figure 10). Each cable tie can withstand approximately 0.9kN, providing a safeguard against unexpected forces, e.g. from human intervention.

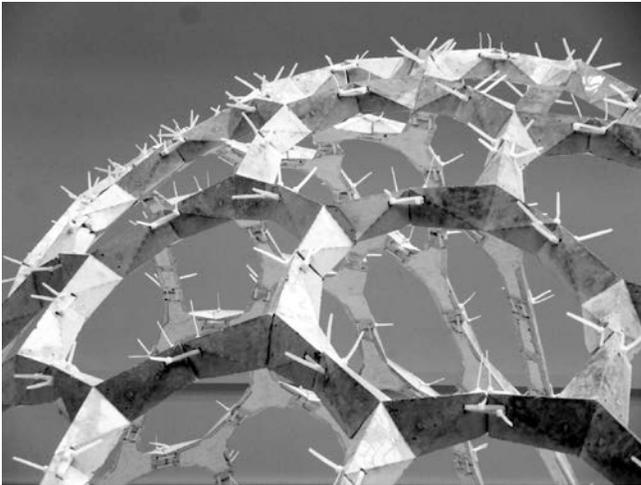


Figure 10: Structurally rated cable tie connections.

8.2 Case Study 02: Aarhus Festival Pavilion

The second case study was a pavilion used as part of ‘Kulturnat Aarhus’ - the 2011 Cultural Night Aarhus (Figure 15, right). Given the experimental nature of the construction, it was necessary to perform an initial test assembly to verify its structural integrity. Hence the structure was assembled and disassembled twice: once at Aarhus School of Architecture and once opposite Aros, the art museum in Aarhus (Figure 15, left). Anticipating this, the structure was designed with the capability of being disassembled. It was this requirement that made the use of many, smaller components the most suitable solution and which led to the use of mechanical (as opposed to cast) joints between them. It follows that the detailed design of a parametrically variable concrete component was a primary issue in the development of this method. The ultimate component design resulted from the negotiated input of a large number of constraints such as structural strength, reduction of weight, sufficient volume for reinforcement, fabrication tolerances and assembly time. Of similar significance and intimately related to the component design, was the challenge to find a suitable joint solution manageable in

terms of both production and economy. A production workflow, where the geometry was transformed between two and three dimensions according to the different parts of the process, was based on digital form generation and digital production logics. Algorithmic workflows allowed for the components to obtain their necessarily unique form and dimensions without major increase of the production time.

8.3 Generating the Geometry

The wireframe geometry, generated through the ReVault simulation, was imported into a 3D modelling program. In this case, Rhinoceros was used, together with the IronPython scripting module. The geometry was developed into 112 unique 3D components through the use of a number of scripted tools in order to generate the components as volumetric geometry (Figures 11 and 12). The script was able to distinguish between regular and base components, generating a flat base for the latter (Figure 13). In the same script, input for the manufacturing process was generated. This included scoring lines for folding, rivet holes, flaps for stability, holes for tube inserts to run the tension cables through, and the engraving of a unique number. The 3d component model was used for extracting the geometry of the scaffolding and for positioning of the individual components during the assembly.

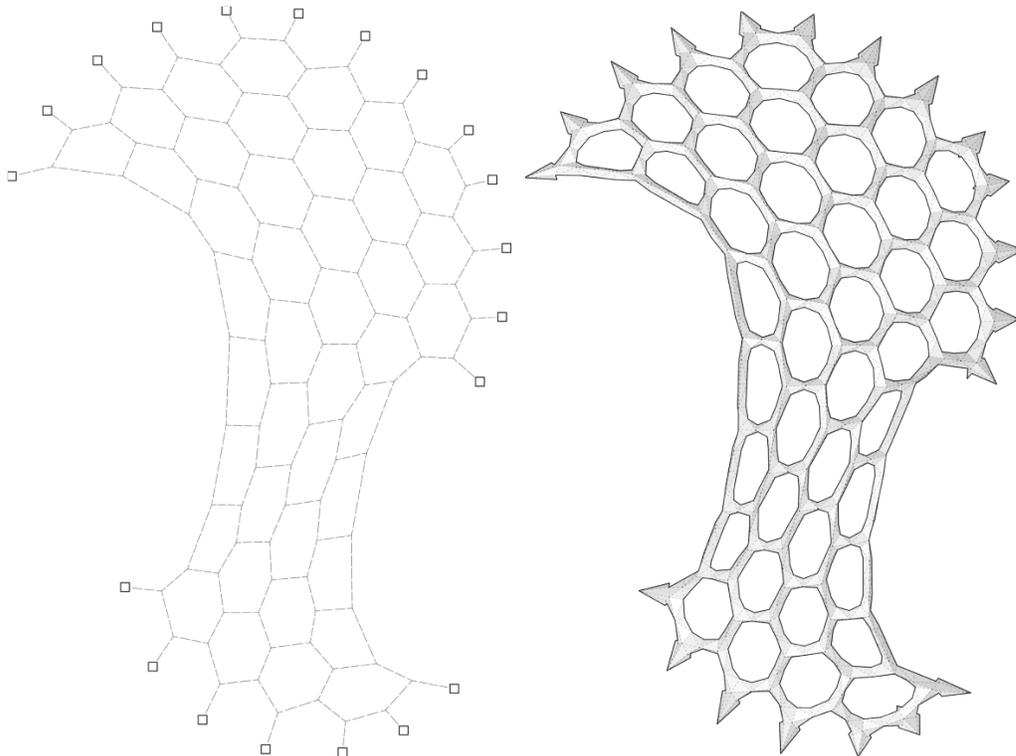


Figure 11: Plan drawings of the structure. Left: Wireframe mesh with anchor points. Right: The volumetric geometry.

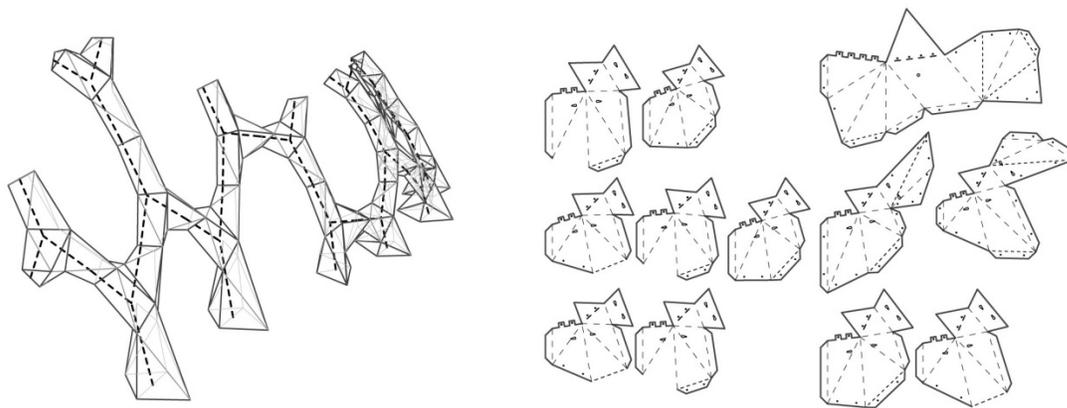


Figure 12: Left: 3d components derived from the wireframe geometry. Right: the components unrolled into two-dimensional cutting patterns.

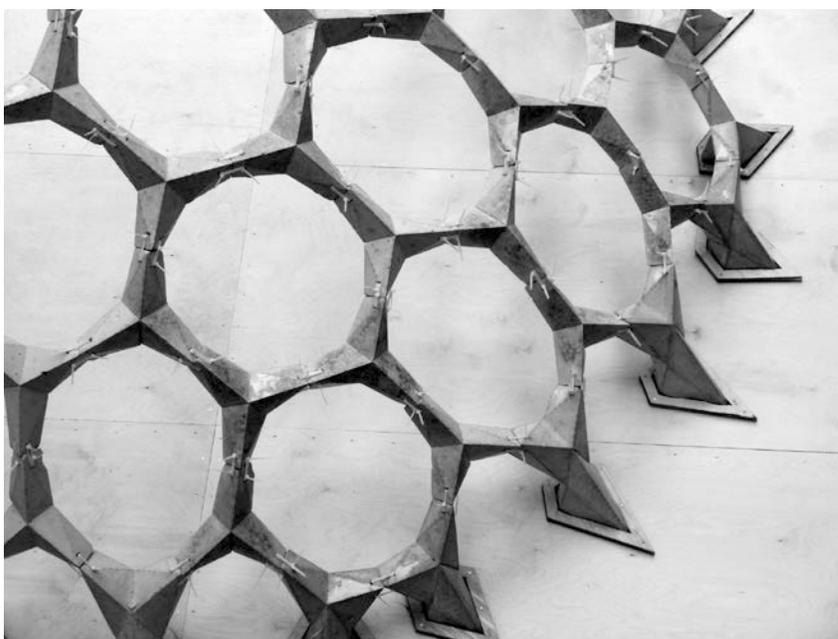


Figure 13: Base components.

In earlier testing of the Aarhus Pavilion's form Finite Element Analysis had revealed problems at the borders of the passage openings in the structure, which was expected (Figure 14, left). By defining the edges as approximately continuous members, it was possible to reduce the tension forces, which again was confirmed by use of the FE analysis (Figure 14, right). Furthermore, the analysis was used to calculate the shear forces in the joints, which again was used for making decisions regarding the joint design

and materials. Principally there would be no shear forces in the joints, the structure being in pure compression. In reality, shear forces did occur, due to the large passage openings in the mesh, and due to lack of precision, both in the production of the components, and in the process of assembling the structure.

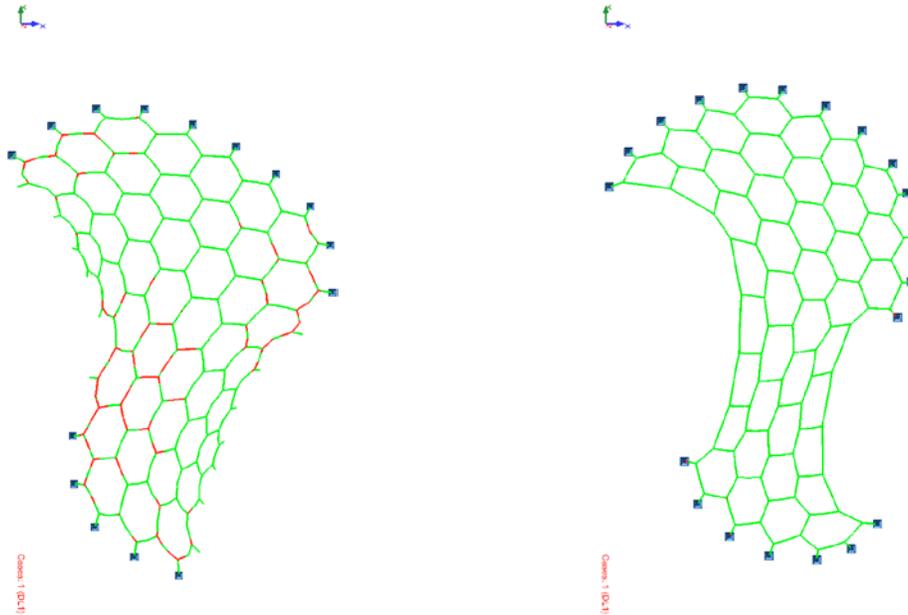


Figure 14: Plan diagram showing the bending forces in the structure. Left: Preliminary design. Right: Optimized final structure.



Figure 15: Second assembly. Left: The 3D model was used for referencing. Right: Eventually the construction served as landmark for a cultural event.

9 Findings

9.1 Structural Performance

The case-study pavilion demonstrated that the forces simulated in the form-finding software, corresponded to the forces acting on the physical structure. It also demonstrated that the method of translating an abstract wireframe mesh into physical concrete components worked and yielded a precise enough outcome to make for a viable construction.

It is clear that by designing a shell as a grid as opposed to a solid surface, overall weight is reduced considerably. If a 30mm thick, solid surface shell has a total weight factor of one, the case-study Aarhus Pavilion shell, with its y-shaped components, had a total weight factor of 0.65. Additional advantages of the y-form resulted because, by gathering the concrete in compression rods, the thickness of concrete never reduced to a point where there would have been no room for reinforcement, a factor that limits the possible minimum surface thickness in solid surface shells.

Finally the case study pavilion proved that it is possible to achieve a large span using thin components. In the case study pavilion the span was 6.7 meters, using components with a side length of seven centimeters, a span-to-element-height ratio generally not associated with load-bearing concrete constructions.

9.2 Fabrication Tolerances

Calculations from the engineers showed that a very high level of precision is needed for such a thin structure to rest in a catenary gridshell. The direct translation of computer generated form into the laser cutter meant that this precision was maintained, and concrete elements could be cast with a tolerance less than a millimetre. In practice the tolerance was a little higher, because some molds skewed or twisted when the heavy concrete was poured. Further development would include upgrading the script to generate supports preventing such deformations.

9.3 Construction Considerations

Despite having the capability to induce tension to pull the joints together, using the zip-tie connecting elements, it was difficult to make the component end-points meet without small displacements. Further development of the component, especially at larger scales could include creating an interlocking end condition, dictating the exact meeting between two components. The amount of information that was added to the unroll script in this case study imply that it is possible to add such an update.

Due to the temporary nature of the case-study pavilion and the requirement to assemble it on two occasions, the zip-tie connection proved very suitable. For more permanent scenarios it is proposed that the employment of cast joints would be an appropriate variation to the described method.

Despite the success in terms of implementing the digital tools, it should be pointed out that human labour played a large role, mainly in the component production phase. Improvement of the described method could imply optimisation and automation of the

processes of production and assembly, particularly in case of implementation in a larger scale.

During the construction of the first 'worst-case' prototype it found that approximately 40% of the components were incorrectly produced due to erroneous assembly of the flat-cut mold parts. There were two sources of this error. One occurred when legs were attached out of sequence. The other occurred when legs were folded upside down such that valley folds became mountain folds and vice-versa. For the final case-study pavilion the unrolled mold design was modified such that: (1) the mold was only split into two pieces: one two-legged and one single legged; and (2) the hole pattern made it impossible to connect inside-out legs. These changes entirely eliminated production errors due to mistakes in mold assembly.

In the case study pavilion the components did not fit very well as they were laid out on the scaffold. Based on experience from the failed prototype, the misalignments were ignored, and they disappeared as all components were locked in place, and started to transfer loads.

10 Conclusion

This paper is part of the expanding field of algorithmic design and fabrication. The key characteristic of the field is a drive to increase the number and quality of feedback loops between designing and making. The case study project demonstrates how computation can be applied effectively to define, control and realize variation across complex forms in architectural construction. The method for generating form through self-organisation was successful in terms of arriving at an optimized structural shape as demonstrated through FEA testing and by the realisation of the case-study pavilion. Material characteristics and constraints were embedded in the form generating process, and algorithmic workflows allowed for the production of unique component molds incorporating a large number of parametric details responding to fabrication constraints and opportunities.

The constructed pavilion case study, constructed in a very short time, for low cost and with relatively unskilled labour demonstrates that the integration of algorithmic form-finding techniques, CNC fabrication workflows and the use of innovative PETG folded mold techniques enables the practical realisation of freeform funicular structures in pre-cast concrete.

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