FLEXIBLE FORMWORK: A METHODOLOGY FOR CASTING FUNICULAR STRUCTURES

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Abstract. This paper describes a method for design and fabrication of funicular structures from discrete precast concrete components. It has a critical look over traditional casting techniques and proposes a new methodology to fabricate a flexible formwork. The design process is engaged with a thorough series of analytical models and employs digital computation techniques to test their structural efficiency. Scripting, modeling and prototyping have been integrated to investigate several case studies through which a set of criteria was developed. Digital modeling tries to keep a limited number of varied components that have certain conditions at joints and flexible in other parts. This variation helps to meet the structural criterion and the flexibility of formwork results the efficiency of fabrication.

1. Introduction

This paper will expand upon previous research done into the design, simulation, analysis and fabrication of funicular systems. Through this research, parametric structural members are defined by linkage to their loading and moment diagrams. Various loading creates changes in these diagrams, defining changes in the cross-section of each relative component design. (Beorkrem, 2012) This component design has been developed through a thorough series of digital and analogue tests, performed at full-scaled models.

2. Previous Research

Funicular structure has been introduced by Antonio Gaudi for the first time in the structural design of the crypt of the church of Colonia Guell near Barcelona (1898-1914). However, the application of this principle to thin membranes in three dimensions was successfully developed by Swiss engineer Heinz Isler in the 1950s. In the middle of the 20th century, recognized masters of reinforced concrete Eduardo Torroja, Felix Candela and Pier Luigi Nervi constructed shells more slender. (Chilton, 2010)

Gaudi's hanging chain models illustrates a clear image of structural behavior of Catenary systems. When suspended between two supports under its own weight and action of gravity, a flexible chain, cable or rope is subject only to tensile forces and forms a curve known as a catenary. Under the same load, this catenary, when inverted, is subject only to compression forces [Figure 1]. The use of the inverted catenary to form an efficient arch was known as early as the late 17th and early 18th centuries. (Chilton, 2010)

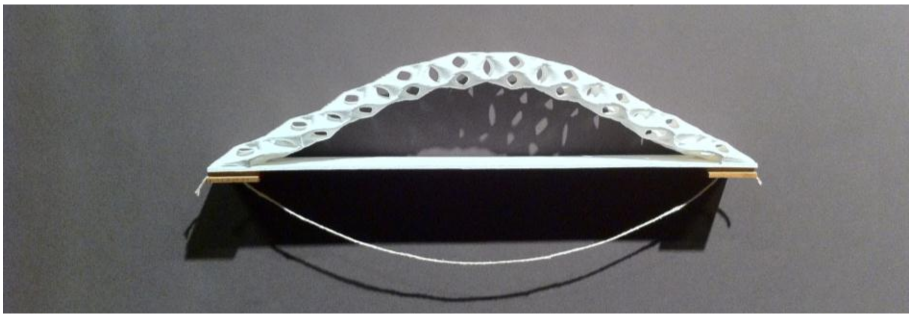

Figure 1. Inverted Catenary rope shows the compression-only Arch

While the earlier examples of compression-only systems were based on simple mathematical formulas like spherical dome segments or hyperbolic paraboloids, the most recent ones are heavily based on digital computational techniques and analytical simulations mainly done by parametric plug-ins like grasshopper, rhino vault and finite element analysis. By the same token, the recent projects tend to use modular units like brick or stone blocks to make such forms. The reasons of this decision are based on the lower cost, higher speed and convenience of such system with bringing assembly logic to design and fabrication process.

3. Form Finding

3.1 ANALYSIS OF FORCES

The form-finding method was based on the principles for generating optimized vault structures, employing Rhino's plug-in "rhino vault" to design a funicular structure. Rhino vault is based on the Thrust Network Analysis (Rippmann et al, 2012) and analyzes the equilibrium of the structure in two steps, first, solving horizontal equilibrium and second, solving vertical equilibrium. The software takes a two dimensional plan of the structure with a certain curvilinear form (concave for open edges and convex for supporting ones) as an input and generates reciprocal diagrams (form and force) [Figure 2, 3]. These diagrams visually express the force dependencies between different parts of the structure. By modifying each of these diagrams, the other one updates in real-time and this modification enables the designer to explore novel and expressive vaulted geometries that are very close to freeform surface structures. Forms generated through the dynamic 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 Robot Structural Analysis.

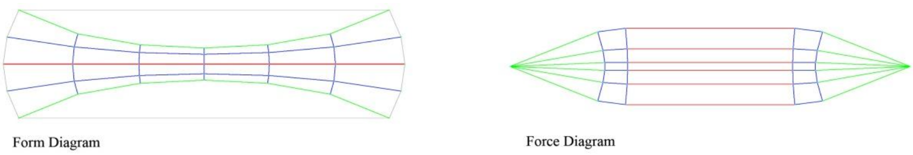

Figure 2. Reciprocal diagram of an Arch

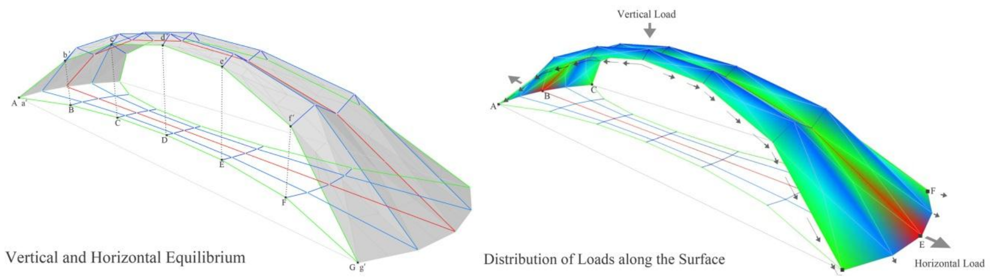

Figure 3. Vertical and horizontal equilibrium

4. Component Generation

4.1 PANELLIZATION

All of the precedent projects with complex shapes made of concrete were cast in situ and required large amount of timber formwork to be constructed. Although relatively complex,

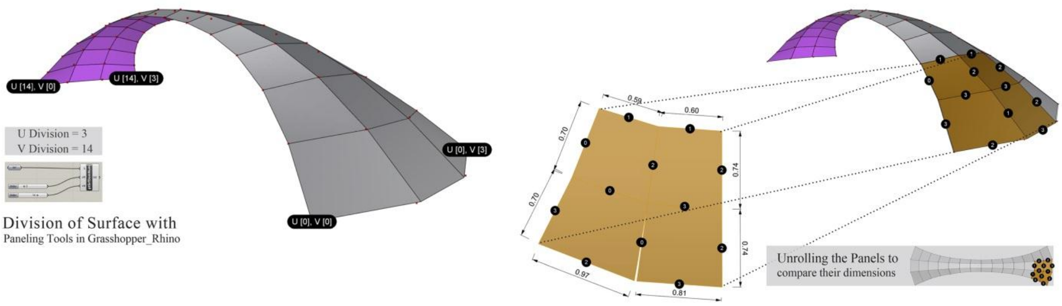

Figure 4. Panelized surface

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. (Larsen et al, 2012) Therefore, a grasshopper script was developed to panelize the surface of the shell structure which was earlier generated by rhino vault into a certain number of segments along U, V directions [Figure 4].

4.2 OPTIMIZATION

Since the shell structure should have a finite thickness, the panelized segments are getting extruded to form the vault. However, the normal vector of the extrusion angle of each face is different from its neighbors and it will make a gap between two adjacent segments. Thus, a third definition has been developed in grasshopper to find the normal vector of each face, comparing its angle to the neighboring faces and finding the bisector of four normal-vectors at each joint [Figure 5]. This methodology helps to find the new panelized offset surface from the original structurally-calculated vault form.

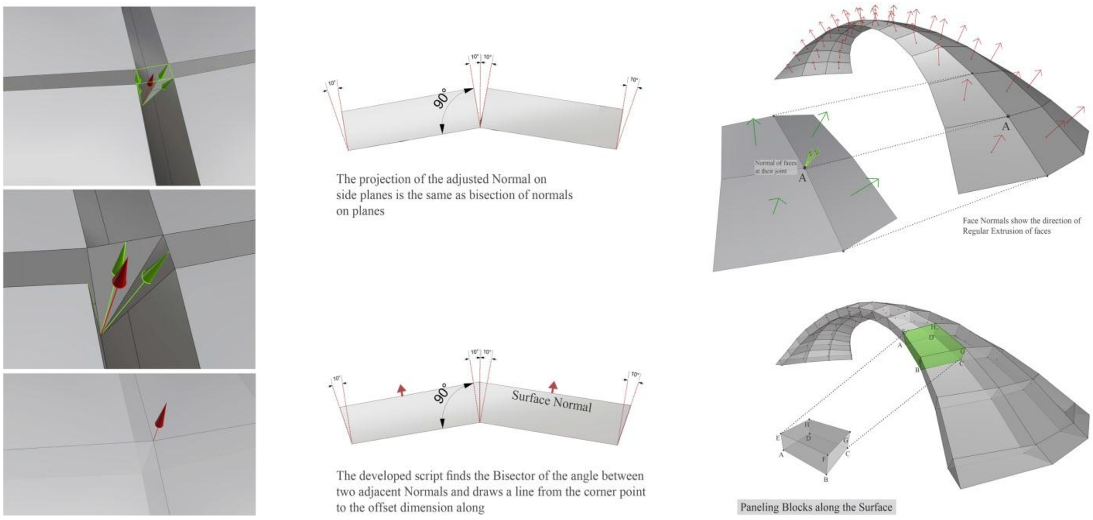

Figure 5. Optimization of face normal at joints

5. Fabrication

5.1 FLEXIBLE FORMWORK

In order to fabricate components using a casting technique, a flexible formwork has been devised which allows for fabrication of all pieces within a certain size variation from one mold. The flexible parts are based on the variables, angles and dimensions [Figure 6, 7].

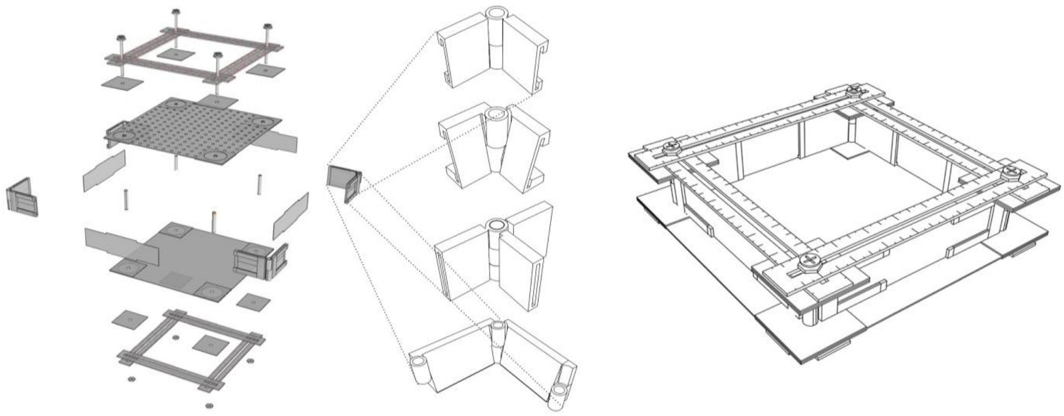

Figure 6. Exploded diagram of formwork

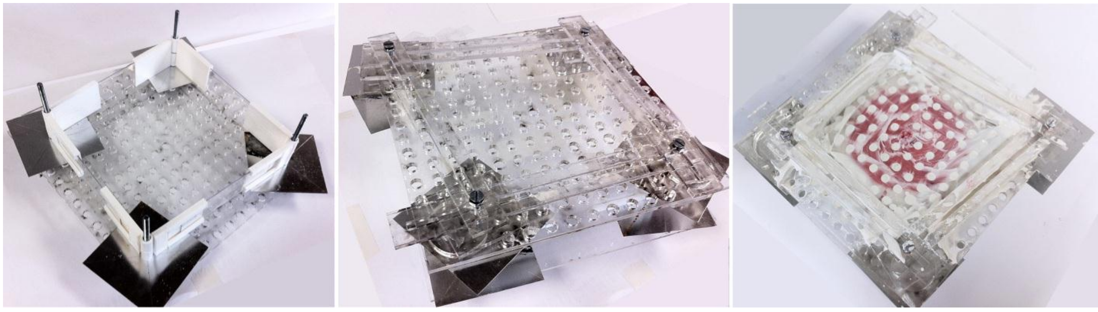

Figure 7. Custom-made flexible formwork

To achieve different angles with dimensions, a series of custom-designed hinges were fabricated with a “Makerbot” 3D printer, newest generation of 3D printers which are almost suitable for domestic uses. Besides, it uses polylactide (PLA) which is derived from renewable resources, such as corn starch or sugar cane. It is both commercially 100% compostable and 100% biodegradable which means it can be broken down into water, carbon dioxide and biomass (Online, access 18, 04, 2013). All the hinges have been 3D printed with this material and used over time to cast multiple pieces. In addition to the hinges there is a flexible framework for the mold which is made of laser-cut rulers from acrylic to check the dimension of each edge.

6. Case Studies

The aim of studying different forms is to find a geometry of the interfaces that satisfies the needs of load transfer and mounting. Three case studies have contributed to the development and testing of this method and all these cases were panelized on the vault form, taken from “Rhino Vault”. The first case study was a deliberate test of a design and fabrication to clarify insufficiencies and thus represents something of a very simple scenario. While the first prototype is a hollow block, the second and third cases incorporated more complex geometries with openings on the edges to reduce the weight and bring architectural appearance to the structure.

6.1 CASE STUDY 1: PROTOTYPE TEST

Before further development of the flexible mold, it was decided to make a simple geometry in order to practically discover many of the constraints that would guide the final design of the formwork. The prototype was based on a box-shape block with a hollow sphere inside which was replicated on the panelized vault form, from rhino vault. The hollow space helps the structure to become lighter and decreased the dead load. To cast the hollow part based on the digitally computed form, an arduino was used to read the exact volume of the sphere from the grasshopper and inflate the balloon with an air pump accordingly [Figure 8]. The workflow is that the grasshopper reads the size of each sphere individually and sends data to arduino and it controls the air pump [Figure 9].

Figure 8. Balloon inflation with Arduino

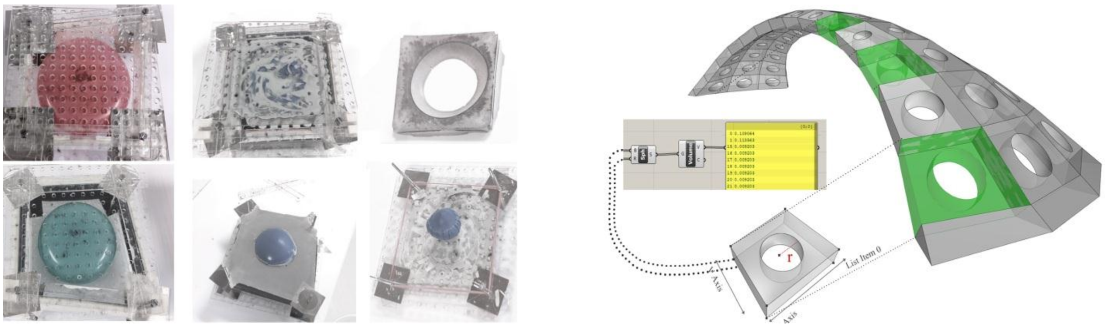

Figure 9. Digital computation to physical model work flow

The first prototype test illustrates the importance of the assembly logic of the modules which in details, it refers to connections and angled joints. Correct positioning of each element is only possible if shear forces between the elements have been dealt with. This means that tensile resistance at the joints should be seen before hand in the design of the formwork. Thus the design of the hinges changed and they were 3D printed angled on the sides and with extruded and excavated parts to bring the assembly logic to each component [Figure 10]. The result was to match the assembled form with the computed load paths and to make the structure a compression-only structure.

Figure 10. Joint condition of casted modules (left) 3D printed hinges (right)

6.2 CASE STUDY 2: DIAGRID PATTERN

In the second case study, the aim is to design a component which has the flexibility to change its form while keeping the topology of the geometry the same. The proposed scheme is one module of a diagrid pattern which becomes thicker as it gets closer to the supports. The components on top of the structure are the thinnest ones in order to reduce the weight of the structure. Here the mold is flexible in a sense that ten different modules could be casted in one mold [Figure 11, 12].

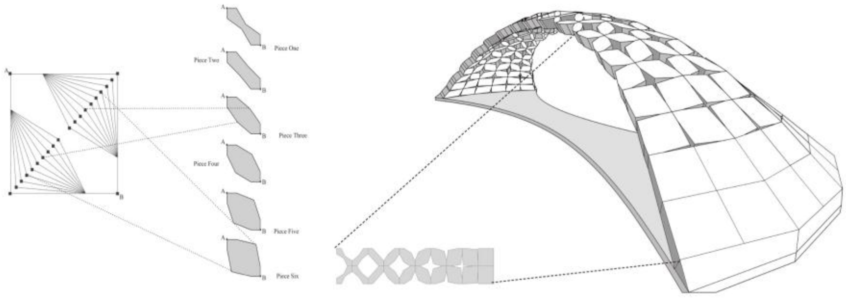

Figure 11. Mapping of overlayed components (left) Replication of components on the vault surface (right)

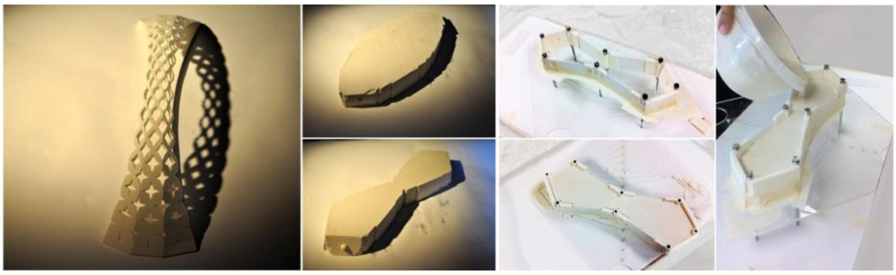

Figure 12. Casting process

6.3 CASE STUDY 3: TRIANGULAR PATTERN

The component design for the third case was resulted from the input of a larger 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 fabrication and production. Thus, a triangular pattern was developed in which each component has three interlocks with adjacent pieces, the result of which is fewer number of joints and reduction of assembly time [Figure 13].

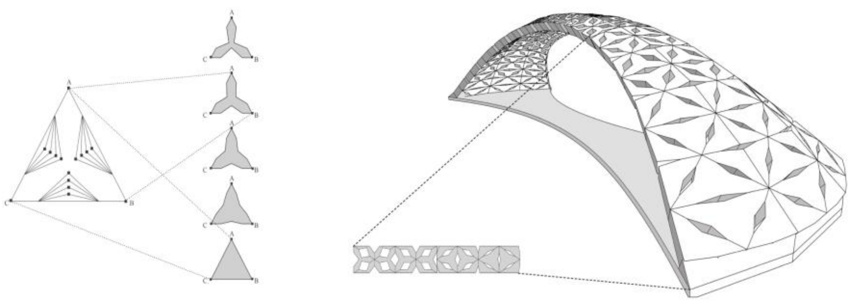

Figure 13. 2D mapping (left) digitally generated structure (right)

6.4 STRUCTURAL PERFORMANCE

It is clear that by designing a grid shell as opposed to a solid surface, overall weight is reduced considerably. If a 40 mm thick, solid surface shell has a total weight factor of one, the second and third case studies have a total weight factor of .68 and .76 respectively. Finally both second and third case studies where tested with a finite element analysis program called "Scan-and-Solve" in rhino [Figure 14]. The simulation demonstrates that the third alternative has a better flow of loads along the structure.

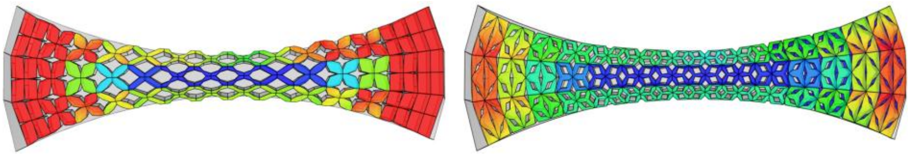

Figure 14. FEA analysis with Scan-and-Solve in Rhino

7. 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 loop between designing and making. The case studies demonstrate how computation can be applied effectively to define, control and realize variation across complex forms in architectural design and construction. Besides, it introduces a new methodology to fabricate precast funicular structures using a flexible mold. Unlike similar researches that usually the fabrication process is to make unique components, with unique molds, here the focus is to use a limited number of formworks to cast many pieces with variation in size. The method for generating form through analysis of structural strength and assembly logic was successful in terms of arriving at an optimized structural shape as demonstrated through FEA, final element analysis, testing.

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