JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES

FORMERLY BULLETIN OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES

Prof. D. h-C Eng .E. TORROJA, founder

Vol. 55 (2014) No. 4

December n. 182

ISSN: 1028-365X

Journal

VOL. 55 (2014) No. 4
n. 182 December

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COVER: *Figure from paper by B. Descamps and R.F. Coelho*

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SODEGRAF ISSN: 1028-365X Depósito legal: M. 1444-1960

JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES: **J. IASS**

ROBOTIC FABRICATION OF COMPONENTS FOR CERAMIC SHELL STRUCTURES

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Editor's Note: The first author of this paper is one of the four winners of the 2014 Hangai Prize, awarded for outstanding papers that are submitted for presentation and publication at the annual IASS Symposium by younger members of the Association (under 30 years old). It is re-published here with permission of the editors of the proceedings of the IASS-SLTE 2014 Symposium: "Shells, Membranes and Spatial Structures: Footprints" held in September 2014 in Brasilia, Brazil.

ABSTRACT

This research investigates the assembly of funicular shell structures using a single layer of flat ceramic tiles. The objective is to synthesize recent advances in structural prediction software with existing means and methods of on-site assembly. The primary area of investigation is at the scale of the tectonic unit - most specifically how introduction of geometric intelligence at the scale of the unit can simplify the assembly of forms that are difficult to realize in the context of modern construction. The project simulates an industrial production scenario in which components for a given shell structure can be fabricated using a wire cutter-equipped 6-axis robotic arm. It aims to increase the adaptability and applicability of ceramic shell structures.

Keywords: *Robotics, Fabrication, Ceramics, Construction Systems*

1. INTRODUCTION

Recent advances in structural prediction software have facilitated the design of increasingly free-form funicular structures. While it is possible to realize these complex forms using standardized modules and traditional construction techniques, the process is not without its drawbacks. Variation within masonry vaulting systems usually requires variation in assembly tolerances between standardized modules, or the on-site modification of modules. The need for a skilled labor force, multiple overlapping layers of masonry units, and the implementation of expensive temporary formwork also contributes to making the realization of these forms technically difficult and cost-prohibitive in the context of the modern construction industry. Reducing these complexities could increase the popularity and applicability of this building system.

Simultaneously, the development of robotic fabrication systems for ceramic materials has permitted mass-customization at the scale of the ceramic module. An opportunity exists to shift the moment at which shell structures are resolved into individual components away from the building site to a controlled industrial production environment.

2. RESEARCH CONTEXT

The construction technique developed by Rafael Guastavino eliminated much of the formwork historically required by masonry vaulting systems. The material innovations of Eladio Dieste "transformed our perception of brick as a traditional material associated with heavy, vertical construction elements into one that allows for extreme thinness and long spans" (Bechthold [4]). The hanging-cloth models and full-scale constructions of Heniz Isler hinted at an infinite number of formal possibilities for compression-only shell structures (Chilton [8]). It is now possible to fully describe, model and understand the geometry of free-form funicular structures. While advances in software have facilitated the design of increasingly complex, irregular forms, the techniques used in their fabrication and assembly have not made equal gains. It remains difficult to resolve complex curvature into construction elements.

The following research is situated within a context of several other projects that explore the relationship between free-form compression only structures and construction technique. Catalan vaulting – also known as Timbrel or Guastavino vaulting – is the technique that many of these projects seek to improve. While this technique is formally flexible and possesses a high strength to weight ratio, it also requires multiple layers of tiles adhered by a bonding agent, elaborate formwork/guidework and skilled labor. Our research found that recent projects that have explored this area of study have resolved the challenges of constructing non-developable surfaces with two distinct approaches.

2.1. Novel Processes

One approach has been to design novel assembly processes using existing building materials and methods. In these projects, surface curvature is resolved by varying the assembly tolerances between modules. Shear resistance is accommodated for using the traditional Catalan method: adhering two or more layers of tiles laid at differing orientations with a bonding agent. Standardized modules are cut on site to accommodate for edge conditions. In the Free-form Catalan Thin-Tile Vaults project (Beorkem [5]), the BLOCK Research Group makes use of a novel scaffolding system and form-finding process for compression only shells. Architects Marta Domènech and David López López recently made use of this construction system in the Bricktopia project (Map13 [1]). In these projects, the construction innovation is more explicitly related to the design of a system of scaffolding and guidework that adapts a traditional construction technique to complex form. While the overall form of the shell, the formwork used in construction, and even the aggregation patterns of the tiles make use of digital modeling and fabrication techniques, irregular surface geometry is still accommodated for via on-site manual modification of standardized modules.

2.2. Novel Components

The second approach has been to design a module that accommodates for double-curvature in its overall form. In general terms, this technique has the advantage of being able to produce systems with precise assembly tolerances and intelligent part geometries that simplify assembly. A potential drawback emerges when these specialized components become non-developable themselves. The raw materials available for the manufacture of these custom modules are usually available as some form of cuboid. It follows that the dimensions of the raw material needed to manufacture a given component must be at least the size of the orthogonal extrema of that component. When the interior and exterior faces of these modules are non-planar they require a greater amount of machining. Barring a method of reusing the offcuts from these processes, manufacturing building components with complex curvature on all sides inherently generates more material waste than an orthogonal component of equal size. A module with surface curvature on all sides can also complicate shipping and material handling. BLOCK's Hyperbody (Feringa, et al. [9]) project introduces complexity at the scale of the tectonic unit, and introduces holes at unit intersections to reduce the number of complex joints and provide daylighting, however it is only realized in high-density foam. Andreani, et als. Flowing Matter project introduces the concept of the volumetric seam to traditional construction techniques (Andreani, et al. [3]). Re:VAULT by Supermanoeuvre (Kaczynski [10]) adapts joint complexity to a masonry unit but the proposed unit fabrication process generates a relatively large amount of waste relative to traditional techniques and necessitates machining surface curvature onto each tectonic unit.

2.3. Research Opportunities

In short, it is possible to construct complex, double-curvature surfaces in a number of ways. The research presented attempts to capitalize on the advantages of each method. Highly customized assembly modules that follow a given surface geometry with high fidelity are able to simplify the assembly process, increase assembly tolerances, and introduce other performative characteristics. Standardized, flat modules are well suited to the production capabilities of the building industry. The research team began this project with the following research questions in mind:

1. What performative gains can customization and complexity at the scale of the tectonic unit afford at the scale of the overall form?

2. How can customization and complexity at the scale of the tectonic unit simplify and expedite construction techniques?

3. What particular advantages can the use of ceramics have on the manufacturing process?

3. OBJECTIVES

This project seeks to synthesize select aspects of the projects described above to create a construction system that can reduce the need for skilled labor and complex formwork while adding a minimal amount of material waste and complexity to the manufacturing process. The variables manipulated by the research team include the following: the size and shape of the assembly modules, and the type of bonding agent used, the allowable assembly tolerance between modules.

3.1. Methodology

The research team proposes a new methodology for the fabrication and construction of unreinforced thin-shell structures using a single layer of flat ceramic tiles. The objective of the proposed production scenario is to reduce technical complexity during the assembly process by adding formal complexity to the tectonic unit. More specifically, the research team posits that the introduction of variable ruled surfaces at the contact faces of each unit can impact assembly at the scale of the construction system. The implementation of variable ruled surfaces at the seams between units provides increased shear resistance much in the same way that multiple layers of tiles with a bonding agent in between do in Catalan vaulting systems. By using triangular panels, the proposed construction system is able to approximate dual-curvature surfaces with planar components. The project uses prefabricated concrete tiles and a water jet equipped 6-axis robotic arm to approximate a low to medium-volume industrial production scenario in which extruded clay slabs can be wire cut to the specified geometries.

3.2. Proposed Production Scenario

As with most industrially produced masonry systems, the proposed system employs off site production of individual units. The production scenario approximated is one in which an industrial clay extruder is paired with a wire cutter equipped 6-axis robotic arm. Other tooling options that the research team considered were the use of a rotating drill on either leather-hard or fired clay. This option was abandoned due to the inherent messiness of using rotating tools for material removal and the prospect of tool wear in the case of using fired clay slabs. The research team also attempted a test to waterjet cut leather-hard clay slabs, but found that the unfired clay was affected by the water to a high degree and that the tiles were too brittle for handling in their unfired state.

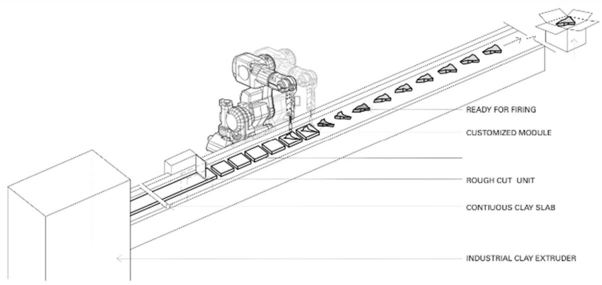

Figure 1: *Proposed industrial production sequence*

The research team speculates that it is feasible to create a low to medium-volume production scenario in which an extruded clay body is cut during the plastic or leather-hard phase. A major advantage of this process is that the portions of the original extrusion that are not used in the shape of each unit module can be recycled and used to create the next round of clay tiles. These tiles would be able to lay flat during cutting, firing and transportation. Additionally, if variables such as the moisture content of the clay, drying time and firing schedules were systematized and controlled, the shrinkage of each module could be predicted and accommodated for in the generation of the initial tool paths.

4. PROTOTYPES

The research team developed two prototypes to test different aspects of the proposed construction system. A full-scale prototype shell was developed to test the potential of the assembly system. For the construction of the prototype, the research team chose to simulate the proposed ceramic production process using industrially produced concrete pavers and a water jet-equipped robotic arm. The use of concrete pavers allowed the research team to avoid many of the challenges encountered in earlier clay tile studies – including irregularities in the slab production and firing process and the differential shrinkage of tiles. The waterjet was chosen to approximate an industrial wire cutter because of their similar geometric capabilities – most notably the ability to produce variable ruled surfaces through the entire depth of a given material.

4.1. Prototype Shell

Figure 2: *Photograph of completed shell prototype*

The initial surface geometry for the prototype shell was generated using Rhinoceros 5 and the Thrust Network Analysis tools available in the RhinoVAULT plugin (Block et al. [7]). From the initial funicular geometry, the research team generated a triangular grid with a spacing dictated by the size of the stock concrete tiles used in the shell construction. Once the surface was divided into individual triangles based on this pattern, and extruded to the thickness of our raw material, the team mapped a specific oscillating curve to each vertex. This curve was scaled based on the specific edge lengths of each surface. The specific oscillations of each curve were confined to the maximum achievable by the waterjet cutter – roughly 45 degrees from vertical. Each module was then oriented on a model of the concrete tile stock. Wireframe geometry that described the edges of each module was used to define toolpaths for the robot. Cutting paths were generated in Mastercam X7, then verified and checked for collisions in Robotmaster. The research team produced several studies to determine the optimal cutting speed for the waterjet on the given material.

The size of the prototype was determined by requirements for transportation to and from the available fabrication and assembly spaces. While the inherent geometric logic of the modules helps to specify the intended assembly sequence, the 24 modules used in the construction of the prototype used a hand-applied numeric coding system to help expedite the assembly process. In more elaborate installations, this logic could be combined with an assembly drawing and automatically applied numbering system to facilitate onsite assembly. To ensure stability during transportation to and from the assembly site, a small amount of polyurethane adhesive was used to secure the tiles to one another. Further research is required to determine how much – if any – adhesive would be required to assemble the shell structure in a more permanent location. Four custom-designed springers contained the thrust of the shell. Each springer supported one of the shells “feet” at a direction normal to the thrust at the ground condition. In an effort to elevate the shell for display purposes and provide ample space for formwork, the springers supported the shell at a height of 12” above the ground plane.

Figure 3: *Photograph of wire cut tectonic units after firing*

The prototype required the design of a proprietary formwork system for use during assembly. The geometry of the formwork components was generated from the original Rhinoceros model of the prototype and designed in such a way that each tile could be at least partially supported during assembly. A temporary 1-ton capacity jack was used as a central support for the shell. This allowed the research team to accommodate for any unforeseen discrepancies in assembly tolerance by raising and lowering the formwork as needed. This method also permitted the team to de-center the shell gradually, and to easily re-install the formwork during transit.

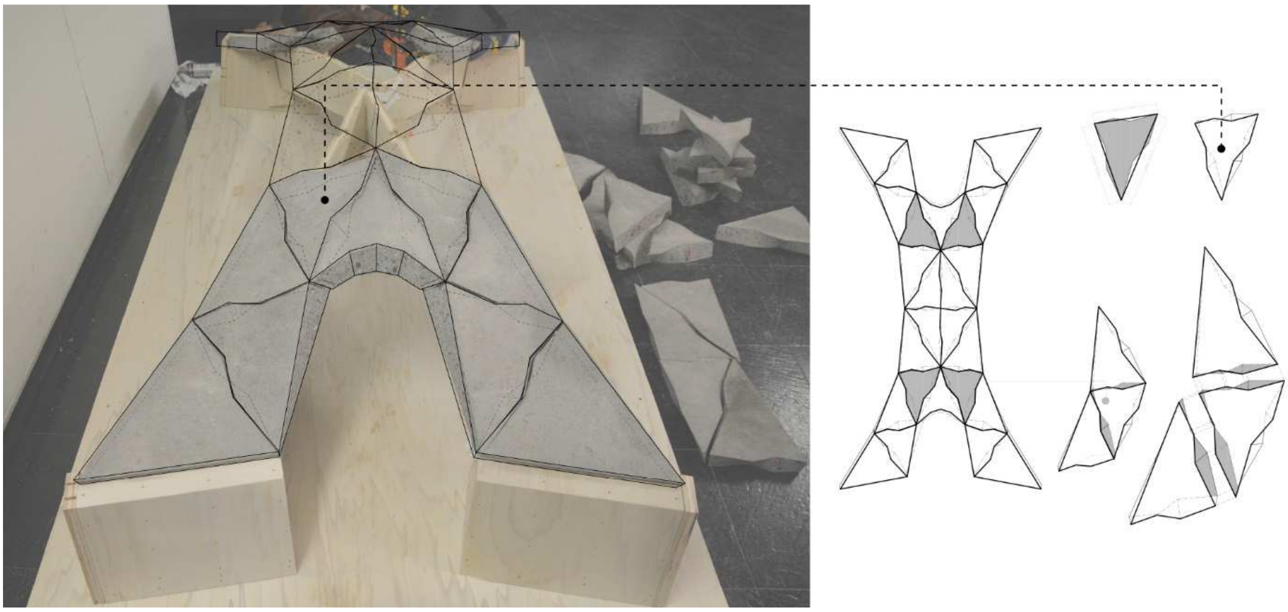

Figure 4: *Completed shell and diagram of assembly sequence*

The formwork system is tailored specifically to the particular shape of the prototype; more study is required to generate a more general set of characteristics and rules for future constructions. Larger constructions may benefit from a mix of standardized infill formwork and customized CNC-produced final formwork.

4.2. Prototype Tiles

In an effort to gain an understanding of the potential for clay tile shrinkage and deformation, the research team also developed a process for producing several prototype tiles out of earthenware clay. The research team produced a number of 1.5 inch thick clay slabs as an approximation of industrially extruded slabs. In order to accurately mimic the shape of the tiles used in the concrete shell prototype, the geometry of the top and bottom face of each module was laser cut from acrylic sheets. These pairs of laser cut sheets we used as guides to simulate a robotic wire cutting process. Registration holes in each acrylic plate were used to control the relative position of each pair of plates. Four adjacent tiles identical in shape and size to the concrete pavers were produced. While leather-hard, these tiles were able to fit together with a high degree of precision. Upon firing, the research team recorded shrinkage of 4-5% of the tiles total size. The tiles shrunk uniformly enough to still interlock with a reasonable degree of precision relative to their overall size.

5. FUTURE RESEARCH

The project proposes to strengthen the relationship between contemporary digital form-finding techniques and the process of assembly by infusing an existing method of production with computational design techniques and computer-aided manufacturing. The proposed tectonic system provides a simplified assembly method and increased structural performance through the design of the joints between modules. The implementation of variable ruled surfaces at the seams between units provides increased shear resistance much in the same way that multiple layers of tiles do in Catalan, etc. vaulting systems.

While the waterjet-cut concrete paver prototype exists as a proof-of-concept for the tectonic and formal goals of the project, combining the existing process of clay extrusion with robotic wire cutting could adapt this process to be a very low-waste method of producing double-curvature shells. The wire cutting system would allow for the low to medium-volume production of individually customized ceramic modules. Future work on this project can continue on a number of aspects, including; identifying the relationship between surface curvature and unit size, refining the swarf geometry generated at the contact faces, exploring the swarf geometry as it relates to the force diagram of a given shell structure and developing a more universal approach to a formwork system.

ACKNOWLEDGEMENT

This research was conducted under the guidance of instructors Nathan King and Rachel Vroman during the course: Material Systems: Digital Design, Fabrication, and Research Methods at the Harvard University Graduate School of Design; Cambridge MA; Fall 2013

Research supported by ASCER Tile of Spain; Harvard University Graduate School of Design, Design Robotics Group; the Office for the Arts at Harvard, Ceramics Program; and the Harvard Graduate School of Design, Fabrication Laboratory.

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