Elimination of Positive Pattern Production in Geometrically Complex UHPC Forms

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Abstract

The boundary conditions of Architectural design in UHPC are shaped by three parameters; the design software, the mold, and the characteristics of the material itself. Both the software and UHPC have kept up with the need for ever expanding design in Architecture but the mold work used to create these pieces is still built in the same way as it was decades ago. Newer mold systems do exist but at a great cost to the budget of the project. This paper will explore the parameters of the mold and how new technologies can be utilized to create more complex precast shapes, however in a more simplistic and cost effective manner. The methodologies explored will be the development of double curvature geometries through a two way structural grid system, reconfigurable molds using servo pin orientation, and 3D printer technologies for mold production. Each of these strategies renders the creation of a positive prototype no longer necessary, and streamlines the process for creating complex precast pieces. By standardizing the complexity of mold creation, a new range of custom compound designs can be realized and the technological constraints that have defined the design rules thus far will shift.

Key Words

Ultra High Performance Concrete, UHPC, Ductal, Mold, Architecture, Complexity Reduction, Double Curvature, Reconfigurable Pattern.

Introduction

Since Ultra High Performance Concrete's introduction into the design world its performance characteristics has lead designers to dream of increasingly complex shapes and forms, allowing for an expanded design pallet. The collaborative effort between architects and precasters has grown.

A complex design shape can only be realized if a mold capable of casting the shape can be made. Traditionally a positive mold of the needed shape is made using digital technologies and in alternate materials. Afterward a negative mold is created around the positive form. Having to make the positive portion leads to material and time costs that drive the price of these complex shapes. In order to push more complex design into the architectural mainstream technology is trying to now eliminate the positive mold all together.

Background

Studies working towards developing technologies that will allow the elimination of the prototype mold are being conducted at Georgia Institute of Technology. Professor Tristan Al-Haddad has been leading a course in reconfigurable molding studies while also completing a fully realized complex sculptural piece called Stealth (Formations Studio, Sculpture completed 2015) without the utilization of a positive prototype form to negative form mold execution. (Brown) (Kelkar) These are two distinct, emerging technologies that are allowing for complex mold creation for UHPC casting.

Methods & Results

Stealth

Stealth is a contemporary urban sculpture designed by Tristan Al-Haddad and his team at Formations Studio in collaboration with Jim Case of Uzun + Case Structural. (Al-Haddad, Stealth) While this sculpture is a cast in place example, the formwork design can be studied for any precast element as well (Figure 1).

Figure 1: Stealth Sculpture in Reinforced Concrete

An excerpt from the ACI concrete award submission for "Special Category" discusses how the mold was created. "The formwork was designed as a two way structural rib system in ¾" plywood which was then skinned using three layers of ¼" marine grade plywood in order to create the synclastic and anticlastic double curvatures of the sculpture. The formwork was also carefully designed and digitally modeled to enable precise self indexing of each adjoining section to ensure tolerance controls and onsite form positioning. After the entire formwork system was designed and modeled each component was tagged in the database and nested into cut files. Each structural member was cut using a 3-axis CNC router and then fit up and checked for tolerance compliance in the shop. After each frame assembly was checked and verified it was skinned, finished, and prepped for casting in the field (Al-Haddad, Stealth) (O'Neill)(Figure 2).

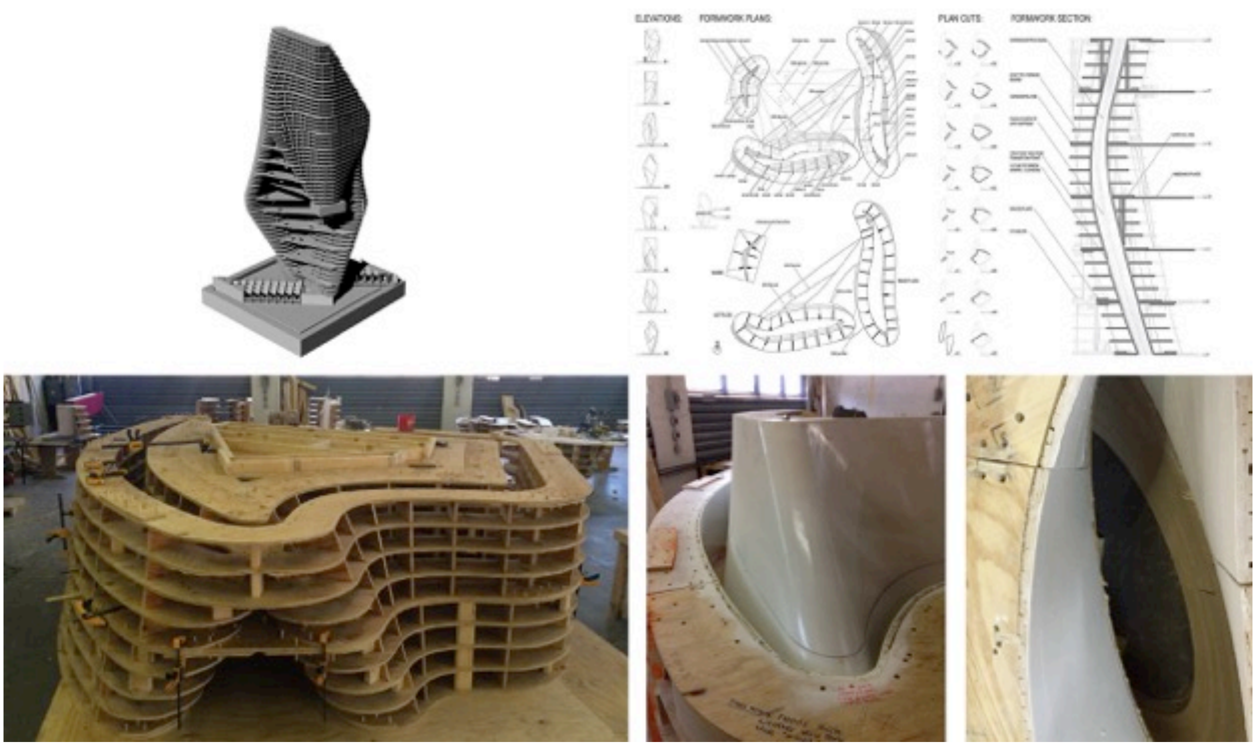

Figure 2: Top Left: 3D model of formwork; Top Right: Formwork Drawings; Bottom Left: Two way CNC cut frame; Bottom Right: Double curvature form being fit together for tolerance check

Reconfigurable Mold Geometry

Research led by Professor Tristan Al-Haddad in The Digital Fabrication Lab at Georgia Tech has been ongoing since 2006 to develop reusable-reconfigurable molding technologies for complex precast components. The first iteration of this research was exhibited at the International Contemporary Furniture Fair in 2007 as a highly variable interior concrete furnishing system (Figure 3) (Al-Haddad, Parametric Modulations in Masonry). This portion of the research was constrained to variable curvature in one dimension and then extruded to create varying one-degree curvature forms (i.e., conic and cylindrical sections). B-Spline geometries in the digital model were mapped to the behavior of polymeric sheet material so that a one-to-one mapping of model to mold existed. For every permutation of the model the design and fabrication team knew that a mold could be rapidly configured to the same geometry by controlling the inter-component connections and the ‘control points’ of the mold. In many ways this is analogous to curved edge forming in flatwork, but with much higher degrees of complexity, greatly improved finish quality, and higher cycle times for casting.

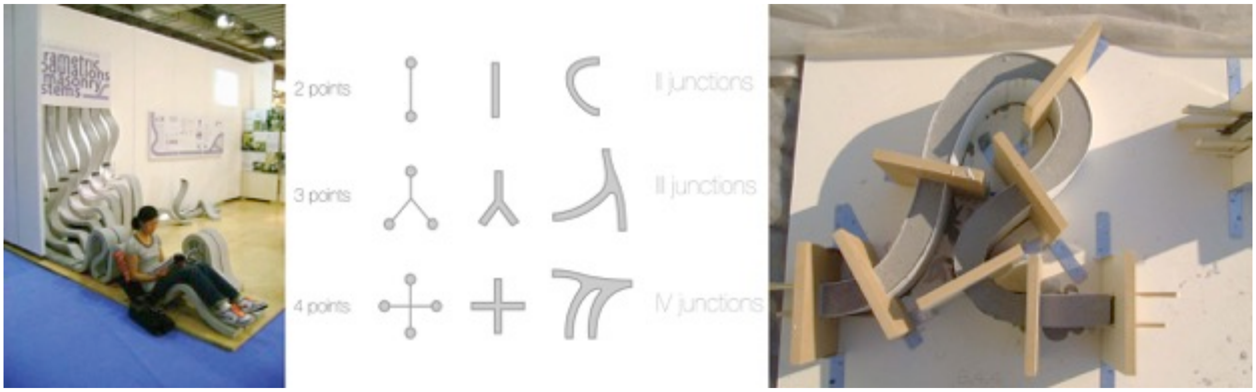

Figure 3: Left: Variable concrete components cast from a single reconfigurable mold; Middle: Mold topology diagram; Right: Component curing in mold.

In 2009 Lafarge used a more simplified system to the Discrete Die machine, and it can be seen as the first iteration of the emergence of this type of casting technology. By vacuum forming flat, thin molds with UHPC already cast within and then draping them over a curved barrel form, a quick evolution of the repeatable complex mold began. Next came the need to industrially produce thousands of panels with distinctly different curvatures as was designed in the Foundation Louis Vuitton building. CNC technology was used to create the positive curved shape in a less expensive foam material that was then used as the positive barrel to shape the curved vacuum formed mold. (Simon Aubry)(Figure 4)

Figure 4: MSV molding Process

The research at Georgia Tech then took a dynamic step further by looking into the technologies being used to form sheet metal in the aerospace industry and addressing the challenges of appropriating this technique to the precast industry. In 2011 The Georgia Tech team pushed the research from one-degree of reconfigurable curvature into two-degrees of non-uniform curvature starting from a well-known approach of Discrete Die (DD) forming which originated in the aerospace industry to produce cost conscience wing mockups for aerodynamic testing (Walczyk DF). The new project entitled *CNC controlled reconfigurable and reusable molding mechanism for thin shell Ultra-High Performance Concrete Cladding systems* set a goal of creating a system that allows for the production of continuous geometric variations in thin shell cast UHPC from a single reconfigurable mold, thus reducing the amount of time, material, and energy consumption required to produce unique components. The research here proposed an approach to non-standard construction through the development of a continuously variable cast concrete system working with topologically defined reconfigurable forms that can be mapped to and driven by flexible parametric models, thus making a significant leap forward in bridging the gap from the digital representation to the material artifact, also known as *File to Factory* (Figure 5).

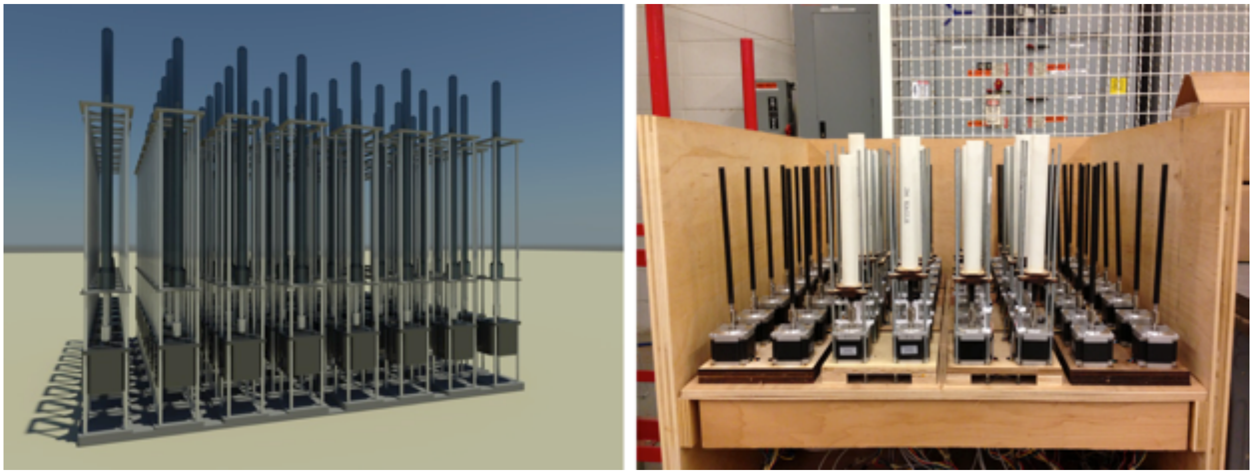

Figure 5: Georgia Tech Reconfigurable Mold

The DD method is well described in many publications (Kelkar), but Al-Haddad’s team understood the challenges of taking a technology that was developed for sheet metal forming and appropriating that technology for wet casting of a viscous material, i.e. UHPC. Discrete pins are just that, discrete. Casting requires a continuous surface to act as a containment vessel. The common solution to this problem of discrete versus continuous is to use a flexible member at the end of the pins to create a continuous surface. The problem with this method is that flexible membranes do not create a sufficiently accurate representation of free form surfaces because they have no ‘smoothing’ functionality to create well interpolated geometry. The characteristic of flexibility while being useful when the mold is changing shapes also generates a problem when a load is applied to it during casting of forms, it deflects. Additionally, the edge conditions are typically not considered.

Al-Haddad's team proposed three novel approaches to overcoming these problems.

1. Variable stiffness through sectional depth. By varying the sectional depth of the rubber membrane the natural stiffness of the rubber creates a 'smoothing' function and helps interpolate the surface transition between pins. This gives a much more accurate representation of the design geometry in the physical mold (Figure 6).

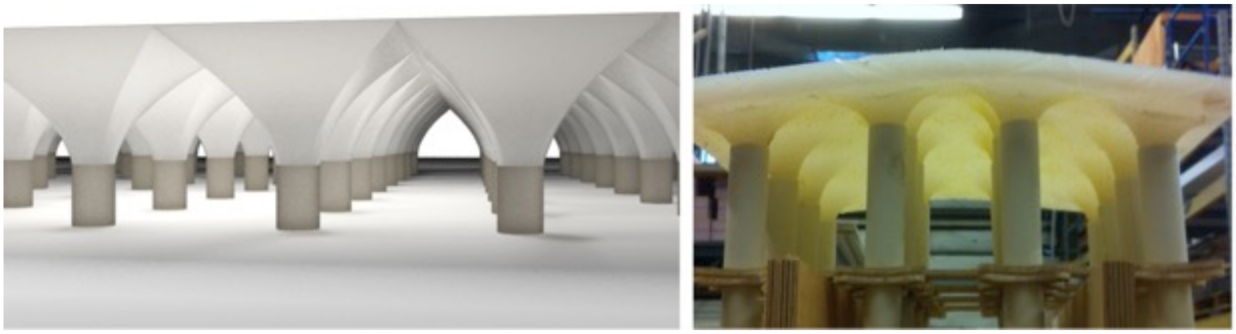

Figure 6: Variable stiffness of membrane created by sectional depth

2. Jamming Phase Transition. Work at Cornell University in the robotics department informed an approach to solving the stiff versus flexible problem of the membrane (Brown). The Cornell team used the phenomena of *Granular Jamming* to allow for a dynamic end effector on a robotic arm that can shift from flexible to rigid by applying a vacuum force to granular materials. This approach was appropriated to allow the membrane to be flexible while the mold was reconfiguring and then stiff during casting or forming (Figure 7). The membrane has an integrated bladder packed with granular materials to which a vacuum force can be applied, thus making the surface very rigid when the vacuum is constant. For example, a vacuum sealed package of coffee is as rigid as a brick with under vacuum and becomes completely 'loose' when the vacuum is broken.

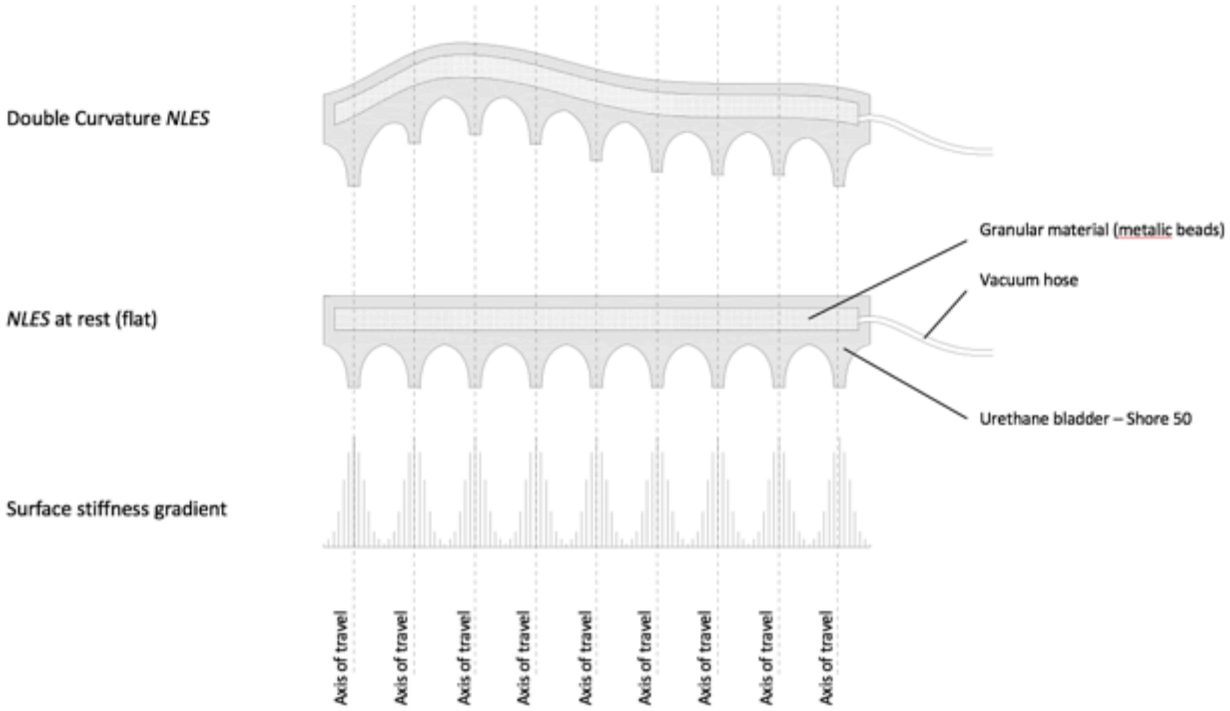

Figure 7: Jamming Phase Transition Bladder allows for the mold to go from flexible to rigid by applying a vacuum to the particle filled cavity.

3. Magnetic edge controls. Dealing with edge conditions on any component is one of the most challenging aspects of manufacturing. The typical flexible mold approach requires the component to have the same planimetric morphology as the mold itself. By mixing metallic particles into the granular particle bladder the form has the ability to be magnetically 'sticky'. Using flexible rubber strips with strong magnets cast inside the form can accommodate nearly any planimetric geometry. This is a similar approach to a flexible French curve or a Spline in ship building (Figure 8).

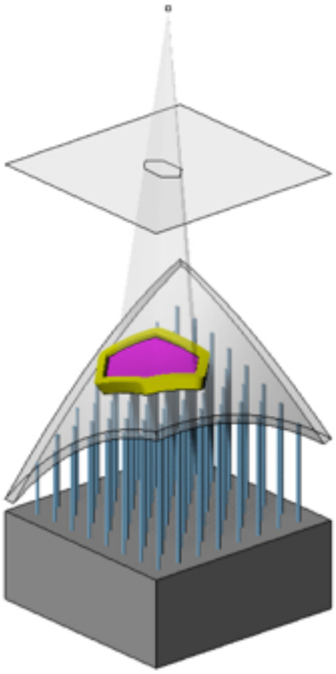

Figure 8: Magnetic edge controls of various planimetric shapes.

Conclusion

The work in both technologies, modular 3D shell design and reconfigurable molding, have definite applications in the development of complex casting molds for Ultra High Performance Concrete. The Stealth sculpture has already shown direct applicable use for the casting of large complex pieces that can be used as individual pieces or parts to a whole building cladding system for example. The reconfigurable molding can have a highly industrial use once the development of these types of machines becomes more main stream and affordable. Ultimately, for either of these technologies to develop into something that is commercially viable further collaboration between universities and industry is required.

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