CASTING NON-REPETITIVE GEOMETRIES WITH DIGITALLY RECONFIGURABLE SURFACES

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Figure 1: Reconfigurable 3D printed surface detail.

Key Terms: Reconfigurable Molds, Panelized Surfaces, Precast Concrete, Digital fabrication and construction, 3D printing, Arduinos, Material Logics and Tectonics.

Abstract

While significant advancement has taken place within the precast and composite industry related to the production of molds for non Euclidean panel geometry, much of that process still relies on practices of milling one-off formwork that is neither sustainable nor at times practical for jobs require a large number of heterogeneous parts. This research examines the viability of a *digitally reconfigurable surface(s)* allowing for a range of geometric outcomes from a single formwork. Both applied and empirical research methodology are utilized to create digital and physical testing scenarios. Initial tests produce a range of physical samples combining traditional urethane mold making techniques with an adjustable stepper motor framework to provide a spectrum of panel geometries. Subsequent testing combines 3D printed surfaces that embed intelligent material and spatial responsiveness casting surface. (Figure 1) The current state of this ongoing research is a full-scale digitally reconfigurable formwork controlled by a computer model capable of producing a wide range of geometric outcomes and a full-scale panel prototype. The potential benefit to the precast or composite industry would be to reduce cost and production time while providing geometric flexibility not currently present in the traditional casting process. Digitally reconfigurable surfaces would effectively place the precast and composite panel production industry in a position to cost effectively implement mass customization into emerging design standards.

1 Introduction

The origins of this research started with an awareness that the industrialization to digitization transition is well underway. The construction and fabrication of building components has gained new levels of traction based on lean manufacturing, systems integration and a heightened sensibility towards sustainability (Timberlake, 2010). As a result, the need to expand design performance capacity as well as formal and aesthetic outcomes must be challenged by similar forces and examined through a similar lens. To that end, this research sets up prototyping scenarios for façade applications where heterogeneous panelization is required. (Figure 2) A growing number of panelized facades introduce the design challenge of leveraging an industrial sector where repetition and homogeneity are desirable for quality assurance and cost control however for design purposes architects seek non-standard panelized outcomes.

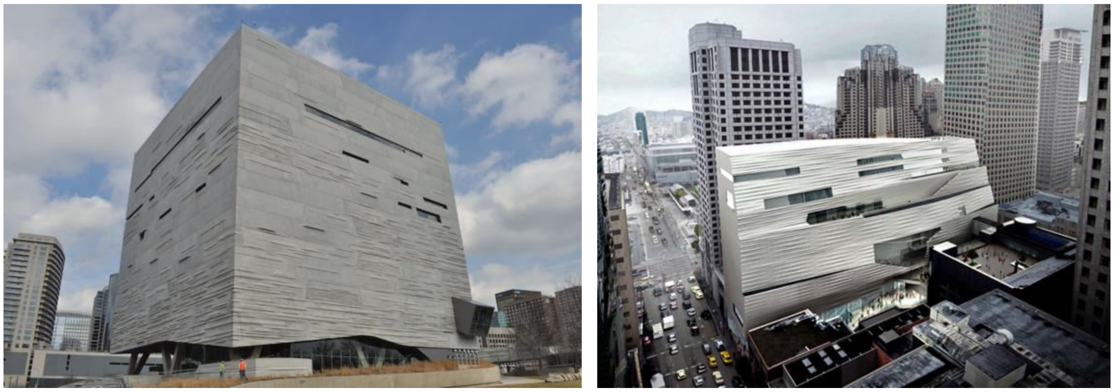

Figure 2: (a) Perot Museum of Nature and Science, Dallas TX designed by Morphosis. Façade manufacturing by Gate Precast. (b) SF MOMA designed by Snøhetta, San Francisco, CA. Façade manufacturing by Kreysler and Associates.

In manufacturing applications, whether it is concrete or composite, the manufacturing environments where production takes place tend to be self-reinforcing practices as opposed to speculative innovation since technology is in fact biased towards its existing hegemony (Feenberg 1991). The implication of this outcome is that manufacturing changes are less seismic and more incremental. However, the potential of this more digitized manufacturing process is the space between design and production can be compressed. The larger implication is this compression provides a new critical moment of authorship within the pre-rationalization and post-rationalization design dichotomy (Ceccato 2012) for casting in that the material behavior is now coupled with dynamic formwork capabilities to derive surface geometry.

2 Precedents

At a general level there is significant research being conducted around the methodology for incorporating innovations into the production of complex panel geometries. TailorCrete, led by the Danish Technology Institute and funded by a four-year EU grant, has definitively established a public/private/academic research framework for examining these issues.[1] Even within the more specific area of reconfigurable casting surfaces molds aligned with this research there are several examples of industry working towards novel solutions. The work of Roel Schipper at Delft University of Technology on Flexible Molds has set a benchmark for reconfigurable surface cast panel research. Schipper's research clearly articulates the advantages and challenges of working towards a position of industry integration and large-scale production (Schipper, et al. 2014). As well, the Adapa Company, located in Denmark, has developed a single sided mold that can create double curvature in panel geometry. Using actuators and series of distributed motors the monolithic surface can be calibrated based on the digital model. The cast material is thick and can be rolled out like dough. The Adapa panels are typically 4-5mm thick and the final edge geometry being cut to size by laser to ensure the correct panel-to-panel alignment.[2] This manufacturing approach established an important benchmark for framing the research outlined in this paper.

As a preliminary and analogue precursor to the digitization of how the casting surface could be positioned, the first testing took place using urethane surface and a matrix of eyelets and strings. This beta test was established to demonstrate the capacity of the urethane surface to be articulated with customizable geometry, which is not the case in the Adapa approach. (Figure 3) The analogue mold had embedded eyelets in the urethane surface that made pulling it down more controlled. The mold also accommodated a variety of material outcomes. Both concrete and fiberglass were tested as panel geometries. Findings from this initial test established two important criteria for the digitized prototyping in the next steps of the research. First, the urethane, while providing the customizable surface option, has to be calibrated according to the durometer of the urethane to establish parameters of range of z-axis movement. This calibration becomes even more important if there is non-uniformity in the surface thickness. The second criteria is the importance of controlling the perimeter geometry of the panel if the cast unit is to serve as a module for a larger panelized surface. Perimeter control in relationship to rest of the surface establishes issues of continuity across the larger surface of combined panels but also has implications to the continuity of how normalized the geometry becomes as it resolves from the perimeter to the interior of the surface for each panel. As a result, these two issues serve as important points of continued resolution in the subsequent stages of the research.

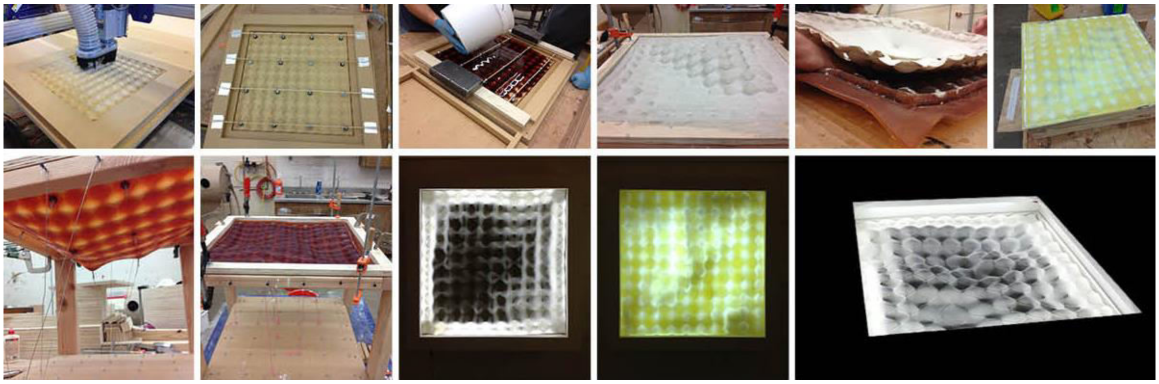

Figure 3: Milling and casting sequence for concrete and fiberglass surfaces. 24"x24".

3 Test One: Double-sided Urethane Surface Mold

A standard *Total Envelope Mold* for precast concrete allows panel geometry to be articulated on a single side of the mold face while the opposite side remains flat. By contrast a *Modified-Envelope Mold* can take on double-sided geometries to provide panels where both sides are parallel or responsive to independent conditions (Freedman, 2007). The first step in developing a double-sided urethane surface mold is to precisely calibrate material behavior. Material testing for urethane is done through twelve different durometer measurements readings (softer to harder) using the ASTM D2240 type A and type D scales.[3] Testing the durometer of the urethane provides a precise understanding of the balance between flexibility, rigidity, and thickness. The balance between these parameters allows accurate calibration of the physical casting geometry in reference to the digitally generated surface geometry from the software. The casting surface allows for adjustment in positioning through an embedded node that is cast into the surface. The node connection then threads onto a rod and is moved up or down for precise positioning.

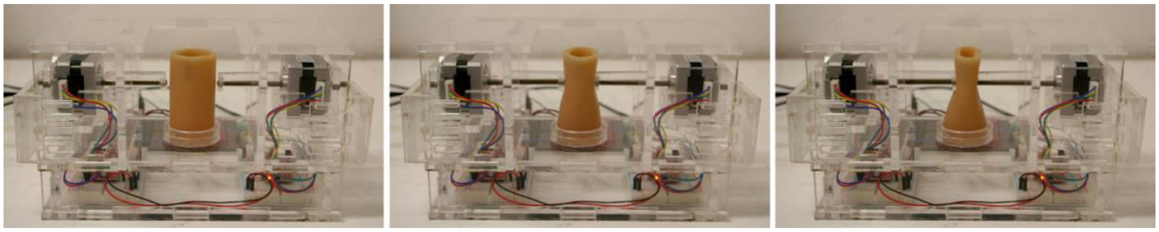

Figure 4: Arduino and stepper motor controlled compression of urethane cylinder.

The digital interface between software and hardware provides a preliminary a proof of concept test where by the urethane surface is manipulated by digitally controlled interface. By initially setting up an Arduino microcontroller to manipulate a urethane cylinder via two stepper motors it is clear that deformation is possible on the magnitude of what is needed for the larger casting surfaces. (Figure 4) On a parallel track to the material performance testing it is necessary to establish the digital geometry control parameters. By establishing a series of façade criteria a surface geometry can be developed. The software is capable of subdividing and indexing a larger surface, or for the purpose of illustration the entire façade, and producing a set of coordinate points for each panel. (Figure 5 & 6) The corner points establish the bounding geometry in relationship to the casting mold. Additional aspects that are accounted for are the mounting bracket geometry since the perpendicular relationship to primary structural geometry will always be changing. The software is able to precisely communicate the corner position of each panel, relative to the other points on the panel as well as the other panels adjacent to it, and then establish the number of rotations on the connection rod and stepper motor needed to move the corner into position for the correct geometry. In so doing, each panel is an iteration of a larger system of components.

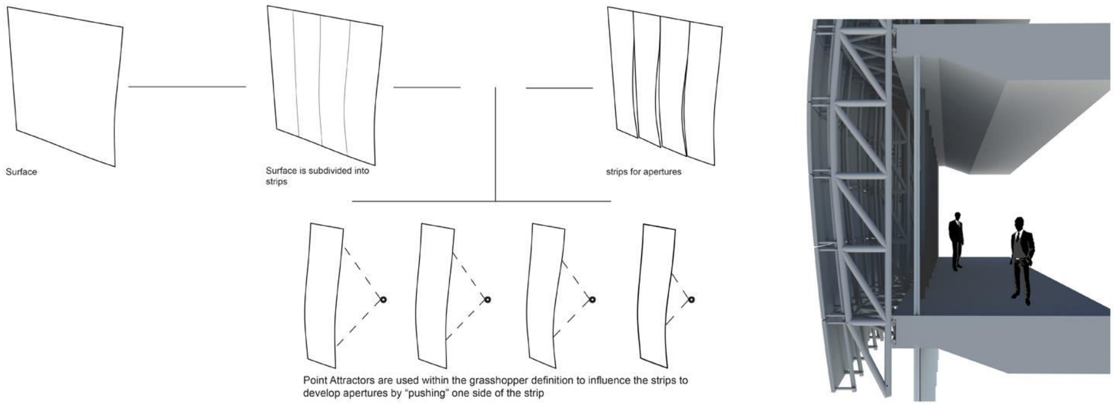

Figure 5: Façade panel to structure interface.

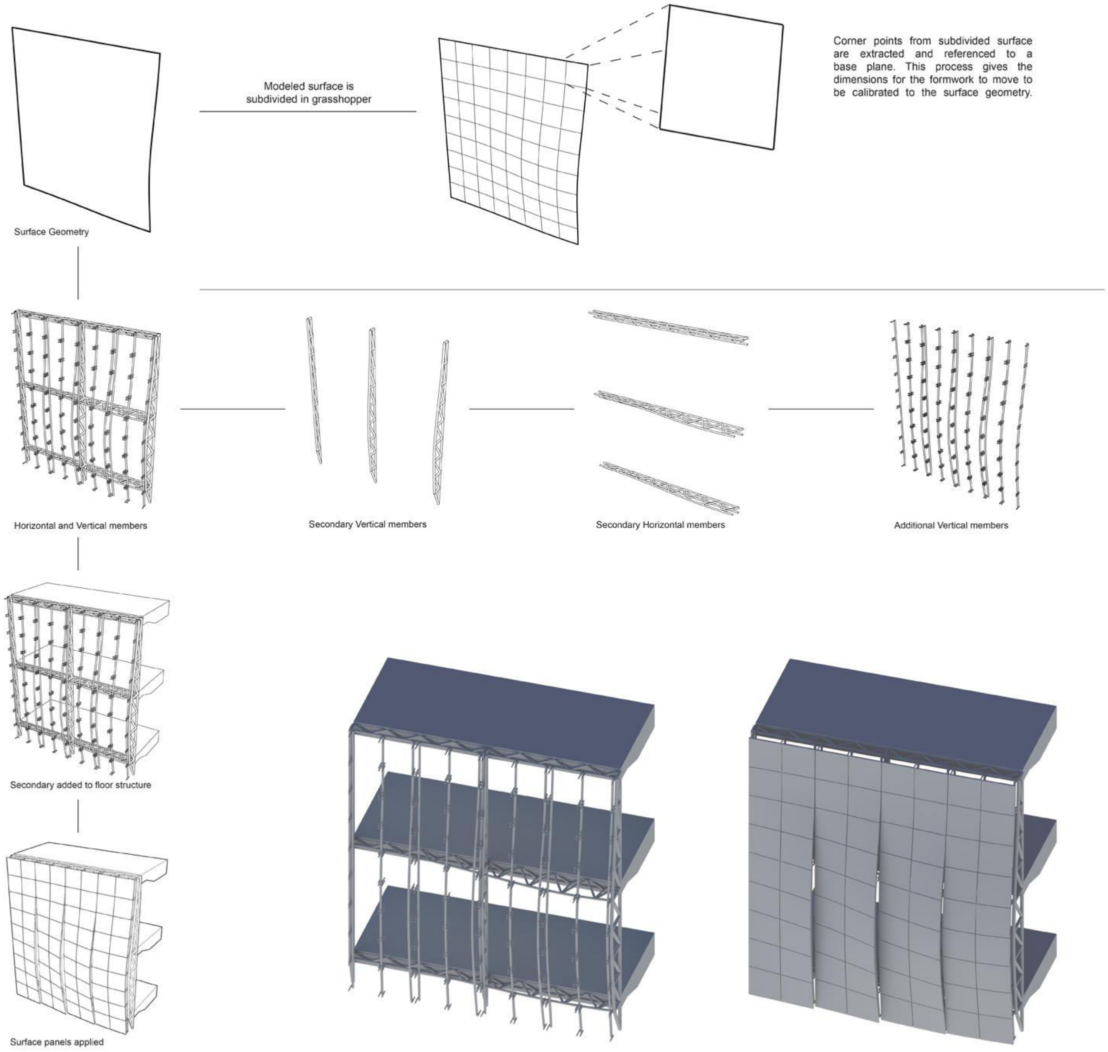

Figure 6: Penalization of surface and connection to façade structure.

4 Test One: Prototype Fabrication

The prototype is a primary conduit for innovation in the post-digital design development process (Stacey 2013). Within this context the transition from representation to performative evaluation provides quantitative data points as part of an information feedback loop. The double-sided urethane surface mold establishes an overall surface of 48” x 32” comprised of 16”x16” panels. The casting surface is articulated by a relief of three interlocking ellipsis. The backside of the casting surface provides for a mounting bracket to be inserted and adjust to a perpendicular position relative to primary structure. Along the edge a seal is developed by a concave edge that flattens out when forced into compression by the casting box. The panels are moved into position by the stepper motors and then locked into place by a frame that encloses three of the four open sides. The last remaining open side is the opening where the concrete or cast material can be cast. Once all panels are cast the attachment to the primary structural system follows a standard bolting connection from the flange that is cast into the panel. The one key consideration is that the connection is cast so it can pivot to adjust to the curvature of the primary structure in relationship to the panel. (Figure 7,8 & 9)

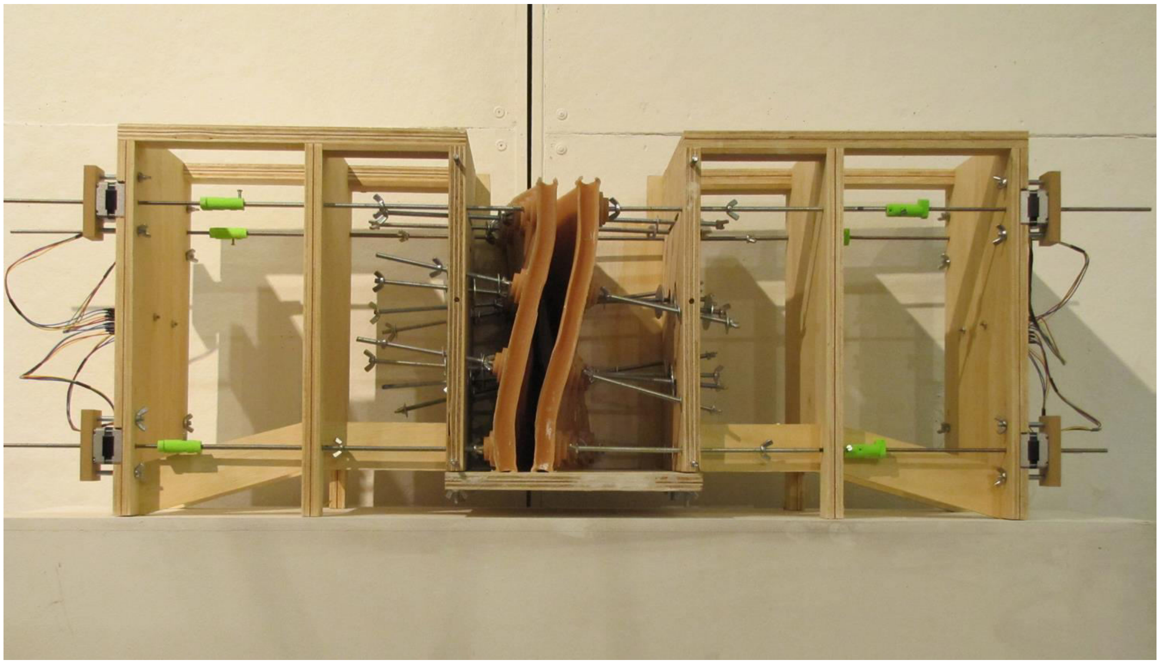

Figure 7: Double-sided urethane surface mold.

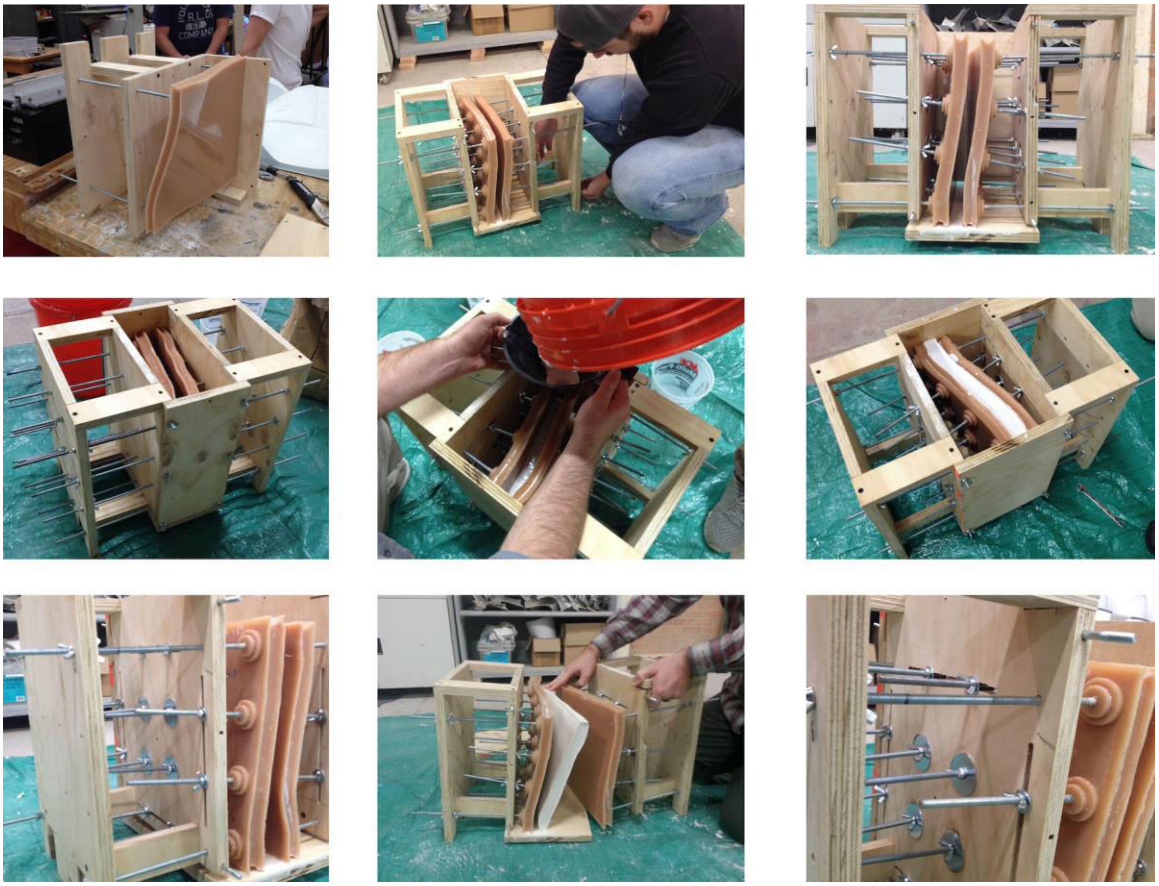

Figure 8: Test One casting sequence.

Post-production analysis reveals that the double-sided urethane surface mold provides the desired subtle surface deformation needed produce iterative differentiation across the surface. However, the edges lack uniformity in thickness or curvature and each panel produces too wide a range of variation in curvature. This results in a ‘lumpy’ effect in the overall surface and even with an imbedded surface articulation there is still an undesirable lack of general continuity in the macro surface. As well, a second series of issues are revealed during the actual fabrication process. The calibration of the stepper motors, the time taken to adjust each control rod, and the potential for the rods to fall out of alignment are all areas needing substantial improvement for next generation testing. So while the durometer is controlled based on preliminary testing, the double surface methodology and edge gasket does not render sufficiently precise edge geometry. This leads to reassess some very basic assumptions of the preliminary approaches for research approach and methodology.

Figure 9: Test One panels assembled front and onto substructure.

5 Test Two: Single-sided 3D Printed Surface Mold

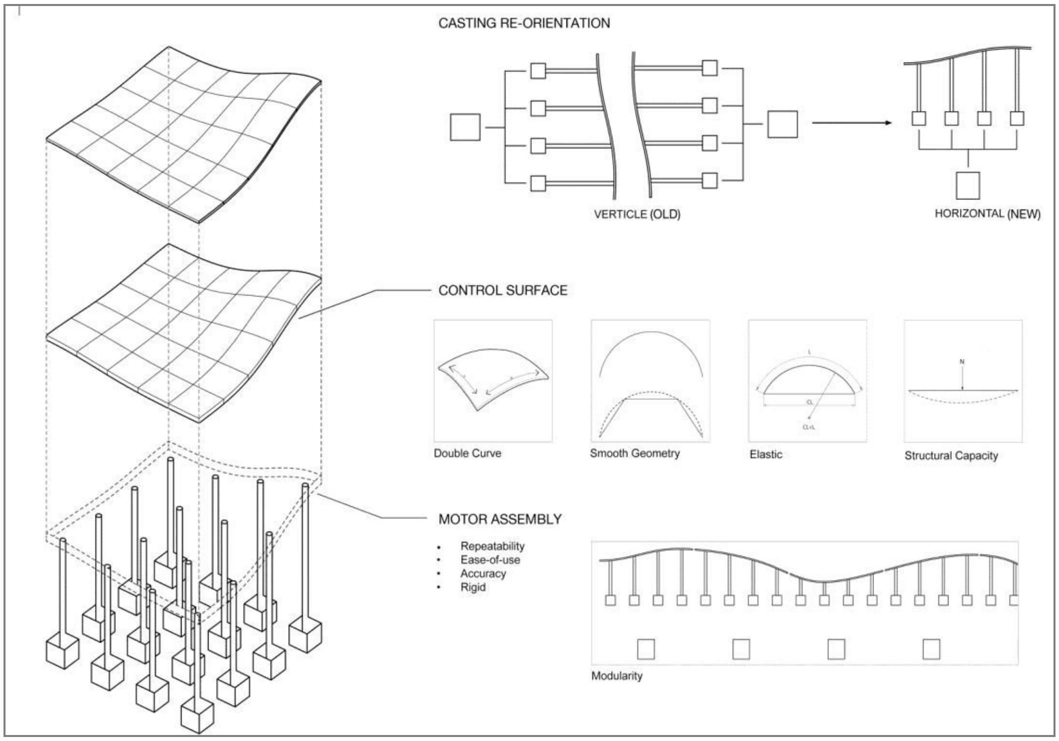

Figure 10: Test Two module and unit configuration diagram.

In response to the analysis of Test One and the challenges found in the results of the prototype, a different direction has been established for Test Two. For Test Two a single-sided surface mold is incorporated and the casting orientation rotates 90° to become a horizontal surface. (Figure 10) The logic for this change is so that greater edge control on the panel geometry can be produced thereby addressing one of the issues from Test one. There is also a realization that within the horizontal orientation that the surface must be more capable of controlled movement. It is this latter issue that has proven the most compelling for the next phase of the research agenda.

Figure 11: Origami studies.

Instead of using urethane surface a 3D printed surface is implemented because of the capacity to control the geometry and the more integrated connection to the threaded rods and other movable components. To develop a full range of motion for both convex and concave motion in a single surface, two surface behavior references are brought into the prototyping process. The first is the structural control and precision provided by origami. The tessellated patterning and the three-dimensional configuration of the surface provide a compelling methodological parallel for how to produce surface geometry that is malleable as a result of its 3D geometric configuration. More precisely, the star tuck and the careful calibration of incidental edges in relationship to the vertex (Tachi 2013) allows for a volumetric *uncoiling* of the surface to take place that facilitates the simultaneity of the concave and convex movement. (Figure 11) The second reference is chainmail for how it provides flexibility in movement but durability in material. The interlocking or connected components provide flexibility to be incrementally distributed across the surface. Richard Beckett's work on 'Sterrolithographic Fabrics' is of particular use as a reference for how it provides volumetric adaptation of various surface types and scales of material use[4]. The combination of the origami and chainmail strategies establishes the framework for how the 3D printer is brought into the research and the prototyping process. By using the *Objet500 Connex Multi-Material 3D Printer*[5] a heterogeneous surface can be printed that provides a synthesized combination of origami and chainmail like surface.

Several iterations have been evaluated for the appropriate surface performance. Because the printer can print with different material types, in this case hard and flexible rubber, it is possible to highly calibrate the *digital material.* For the surface prints a series of tests were conducted using Vera White Plus and Tango Black Plus – with the only variables being the quantity distribution of each type of material and slight geometric variations. Ultimately it is the combination of the materials that provides an appropriate blending to accomplish the level of movement in the substructure while providing the right level of rigidity in the top surface. (Figure 12)

Figure 12: Preliminary tests for 3D printed reconfigurable surfaces.

After the initial series of material and geometry tests establish an adequate range for performance criteria for the mold, a larger surface is produced that also takes into account the need for connection to the stepper motors, an adequate edge seal, and surface tension which is one of the important factors needing to be addressed from Test One (Figure 13) The Test Two prototype set-up runs off of nine stepper motors surface control and can produce panels of 12” x 12”. (Figure 14) The 3D printed reconfigurable surface is capable of working with GFRC or composite production and covered with a thin sheet of silicone to protect the reconfigurable surface as well as assist with creating an edge seal within the formwork. Preliminary testing shows a process using a composite fiberglass resin to create panels. (Figure 15) This initial test reveals a need to refine the silicone sheet in terms of thickness and capacity to create a seal within the formwork in positions where the surface deformation is in greatest extreme. There is also an opportunity to reintroduce patterning back into the silicone surface as was done in Test One to provide surface texture.

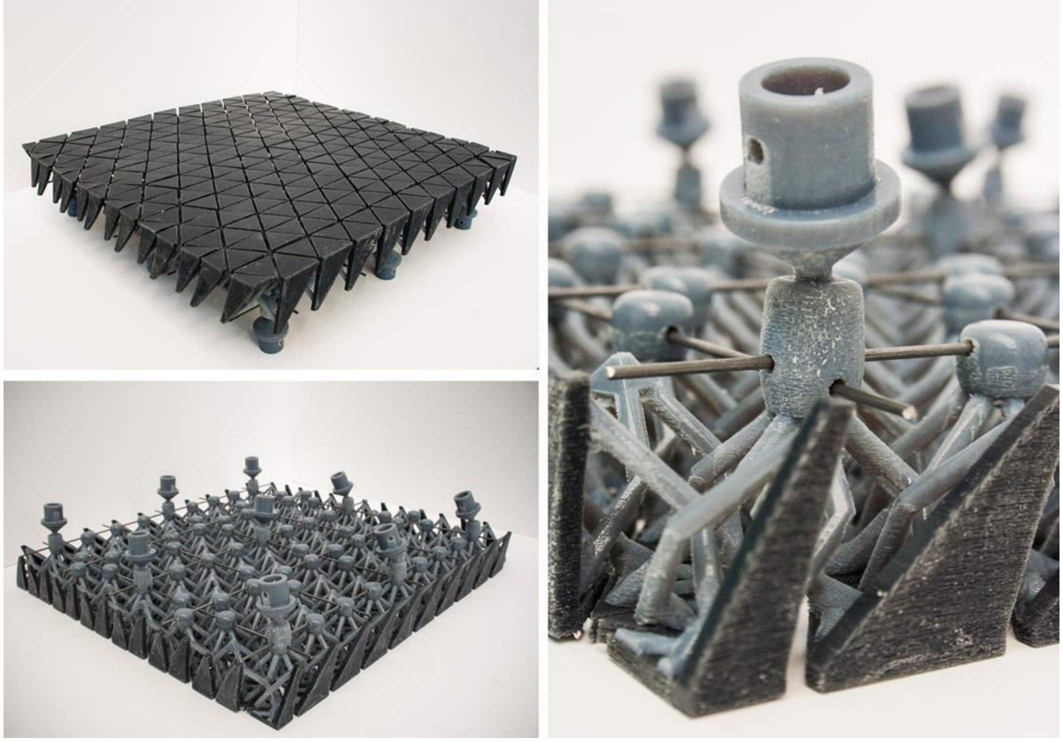

Figure 13: 3D printed reconfigurable surface showing top and underside with detail of connection node where stepper motor threaded rod attaches to surface.

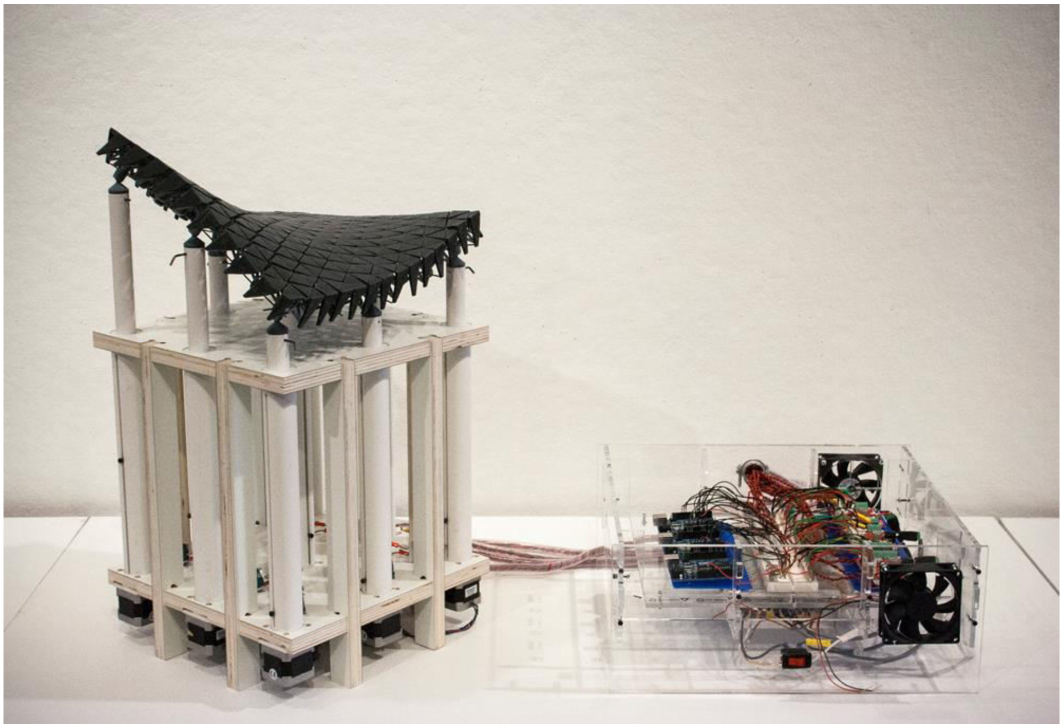

Figure 14: Test Two set up showing reconfigurable surface with nine stepper motors and control panel.

Next steps in the research would be to establish the following issues:

- Batch Production: Utilizing the current Test Two configuration a larger surface will be cast to demonstrate and test viability using the current system. Surface deviation will be measured in order to more clearly under stand limitations of the current system
- Silicone Sleeve: Additional testing will be done to produce alternatives of the silicone interface, as well as potentially alternate strategies, between the 3d printed surface and the cast surface.
- Scalability: The current 3D printed surface will be printed in modular parts instead of a single surface. This will be done in anticipation of scaling up the surface for larger panel production prototyping. Distribution of the stepper motors and load capacity will factor into current parameters for next phase testing.

Figure 15: Test Two preliminary fiberglass resin panel test.

6 Conclusion

Substantial energy in both industry and academia is now being leveraged towards the means by which complex panel geometries with double-curved surfaces might be manufactured. Combined with potential to also incorporate structural capacity, these surfaces are hybridizing functionality while expanding the geometric possibilities. However, what is ultimately at stake is the precision of fabrication. Standard tolerances no longer apply when dealing with complex surface geometry or even more so if incorporating structural performance (Bechthold 2007). The pursuit of a digitally reconfigurable surface for casting, challenges existing manufacturing technologies but is potentially not so removed from market application. Specifically, the digitization of the precast and composites industries reveal an awareness that customization within component production can provide a broader range of design applications and opportunities. The use of prototypes such as the ones presented in this preliminary research to examine the technical performance of the surface suggests a potential for applied research outcomes to lead to innovative breakthroughs that will provide viable manufacturing options for non-repetitive double curved panelized surfaces.

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Endnotes

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[1] Additional information on TailorCrete and the industry/academic partnerships association with it can be found at www.tailorcrete.com & www.superpool.org/index.php/tailorcrete

[2] Primary site explaining the ADAPA technology is www.adapa.dk

[3] www.npl.co.uk/science-technology/mass-and-force/hardness/rubber-hardness

[4] More information on Richard Beckett's work intelligent fabrics can be found at Beckett, Richard. "Stereolithographic Fabrics." N.p., n.d. Web. 20 April 2014. http://www.richard-beckett.com/?page_id=52

[5] Additional technical information on the 3D printer used for this researchwww.stratasys.com/3d-printers/design-series/precision/objet-connex500