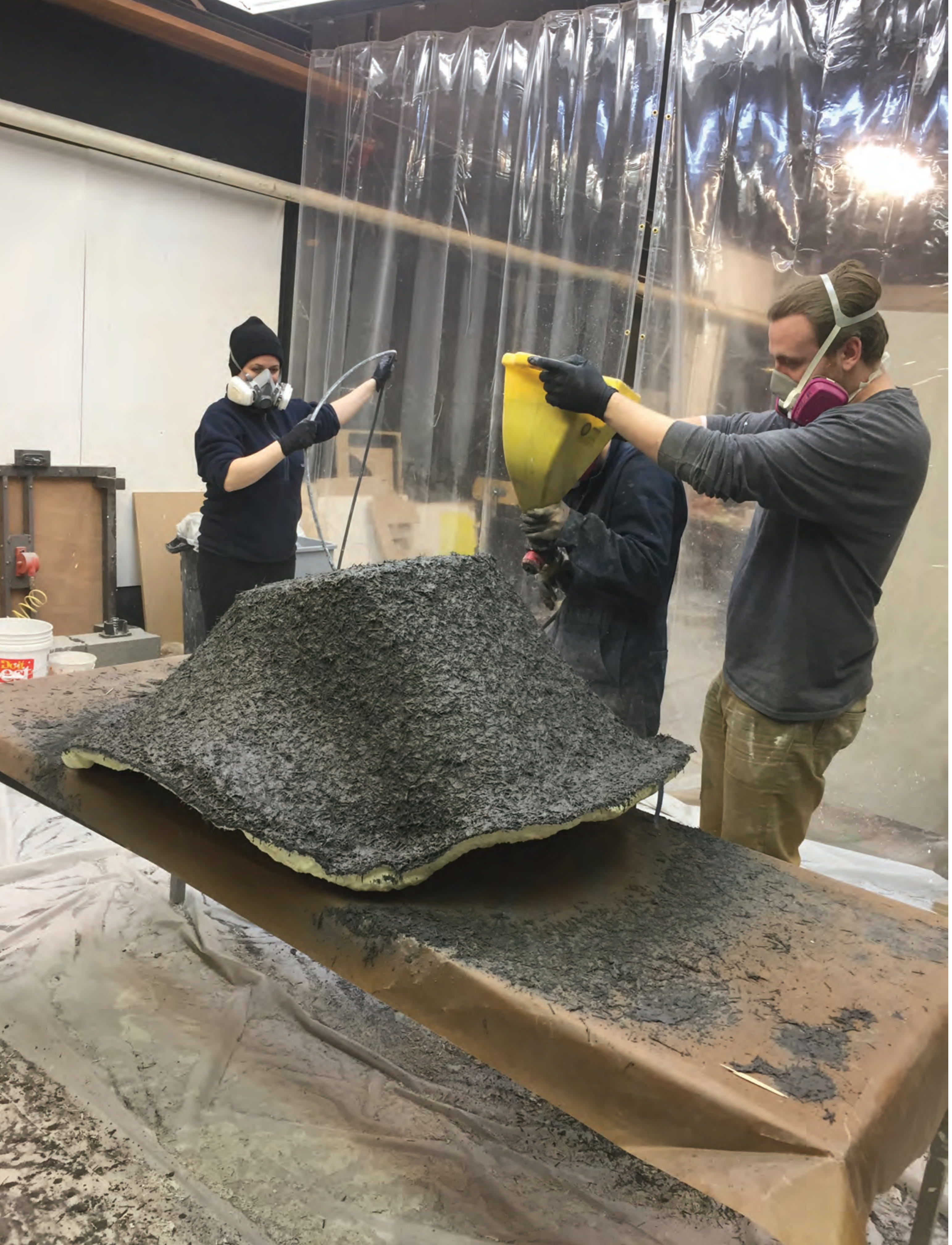

Thermoplastic Concrete Casting

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ABSTRACT
Thermoplastic Concrete Casting explores molding techniques for glass fiber reinforced concrete (GFRC) using non-woven thermoplastic textiles. Casting in concrete typically requires extensive formwork that takes time, material, and a significant amount of labor to produce. This project experiments with a novel way of creating formwork quickly for casting, while eliminating heavy, rigid molds and scaffoldings for support. Incorporating sartorial techniques borrowed from tailoring and patterning in clothing production, the textile is cut and felted together (a process of needle punching where fibers of the textile are entangled together), then heat-stiffened over a rigid frame, ready for GFRC casting.

Thermoplastic Concrete Casting attempts to integrate what otherwise are disparate areas of research — from computational design for developable surfaces using physics-based modeling software (Kangaroo plugin for Rhino/Grasshopper) to formal and performance testing of GFRC, to research and development of molding techniques with non-woven textiles. The prototypes produced are explored at two scales: first, at an object scale, with the reproduction of Eames' molded fiberglass armchair and Saarinen's Womb Chair, both in concrete, and second, at an architectural scale, with the installation of an 11' X 7' wall composed of five modules with an adjoining table surface. The full-scale wall not only tests the structural conditions related to joining discrete panels together without a framing system, but also the formal, spatial, and experiential effects through the design of exaggerated open-ended funnels as apertures through the wall. Beyond proof-of-concept, the project attempts to seamlessly integrate digital design and fabrication processes into textile concrete casting and to challenge typical casting techniques in service of novel design possibilities.

1 INTRODUCTION

Casting concrete is one of the most labor-intensive processes for building, often covering a large portion of the project's overall cost (Lab 2007). Beyond the time, material, and physical labor involved in building the formwork for casting, the formwork itself is already invested with intellectual labor by specialists ranging from structural engineers to concrete technologists that work with mixes, addressing specific applications and loading conditions. As such, the 'craft' of concrete casting is involved on all fronts. While prefabrication has made the use of concrete more cost effective and time efficient, developments in tools and techniques are reconfiguring the ways in which formwork is produced for shaping concrete. This project seeks to form concrete through non-traditional methods by exploring the use of thermoplastic textiles as formwork for casting glass fiber reinforced concrete (GFRC).

Thermoplastic (as opposed to thermoset) polymers undergo a reversible transformation from solid to liquid when heated. The non-woven thermoplastic textile used (trade name Fosshape) comes in two weights: 9 and 18 oz/yd. The textile, similar in texture and thickness to felt fabric, has typically been used for sculptural works or costume design. The material can easily be cut and sewn together like any fabric. But when heated with a steamer or heat gun, it shrinks and stiffens into a three-dimensional form. This unique characteristic of the material (heat-shrinkage) provides opportunities for both manual and digital investigations.

Employing techniques of tailoring and pattern making for clothing production, the project makes use of developable surfaces to transition between 2-D and 3-D to explore complex surface geometries. The cross-disciplinary link between the sartorial process of patterning and architectural modeling/formal investigation is the concept of developable surfaces whereby complex surface geometries could be rationalized to flatten into 2-D patterns. For clothing, patterning address how the 3-D shape of the body, especially a double curved form, could be fattened into patterns for textile cutting. The cut patterns, typically based on formal efficiency (least number of cuts for sewing), is then assembled with different types of seam structuring either based on performance or for aesthetic purposes. For architecture, developable surfaces enable complex geometric surfaces to be unfolded into a flat pattern that could be cut out of sheet material. The cut material could then be assembled, much like clothing production, into 3-D form with seam structuring considerations. *Thermoplastic Concrete Casting* takes advantage of these concepts and techniques for 2-D and 3-D translation in working with the thermoplastic textile. Computational tools are employed through physics-based modeling techniques that simultaneously allow for constraint-based design and analysis, especially in predicting the effects of the shrinkage of the textile as well as seam structuring. Working computationally and heuristically, the project developed through a series of prototypes, testing different techniques and processes for textile formwork making for casting with GFRC.

One of the proposed advantages of this approach is that complex geometries such as double-curved surfaces can be efficiently created, stiffened, and sprayed with GFRC (instead of relying on subtractive processes such as CNC milling or hotwire cutting to achieve complex geometries). The exploration includes not only the development of form-finding techniques in relation to patterning and seams, but also the addition of secondary stiffening material (such as polyurethane foam) to the surface to aid in prepping the mold surface. Felting techniques were employed to join discrete panels of non-woven textiles together. Felting is a binding process whereby barbed needles punch through layers of non-woven material, entangling the fibers together. This process of binding does not require the addition of sewn threads or adhesives. The exploration of *Thermoplastic Concrete Casting* takes advantage of these concepts and techniques as molding processes, enabling the textile formwork to be:

- more lightweight and easier to handle;
- folded up for compact shipping (before the textile is heat treated);
- produced substantially faster than milling or other subtractive processes; and
- produced from significantly less material volume.

As such, this project is an experimental project about formwork making that also aims to further the integration of computational technology (of software and fabrication processes) in building practices that might challenge conventional ways of casting in concrete.

The outcome of this project was tested at two scales: one at object scale, which included a reproduction of the Eames molded fiberglass armchair and Saarinen's Womb Chair, and second, at architectural scale, with the installation of an 11' X 7' wall composed of five modules with an adjoining table surface. Working at the object scale initially enabled a familiarity to be developed in working with the textile. This knowledge was then developed further into a computationally based simulation of the material's characteristics to then design the larger-scale wall system. The following sections of this paper describe the techniques and processes, as well as the final documentation, of the project installed for an exhibition in March 2017 at the Liberty Research Annex Gallery, Ann Arbor (fig. 1).

Figure 1: Overall view of installation with chairs and wall.

2 BACKGROUND

The research and development of *Thermoplastic Concrete Casting* stems from three core areas that are interrelated: fabric formwork and the development of processes for casting concrete; complex geometries of developable surfaces; and non-woven textile manipulation (felting). This unique combination is possible given the alignment of contemporary digital technology available for architectural production and the availability of affordable materials for experimentation, in this case, of thermoplastic textiles and GFRC.

2.1 Textile in Architecture and for Concrete Casting

Textile in architecture is mostly relegated to interior surface applications. It lacks the structural capability that rigid materials offer for building. Soft in nature, textile has generally been explored for its material characteristics to absorb sound, filter light, and, spatially, to divide or articulate boundaries and thresholds (Semper 1989). Softness afforded by textile usually negotiates our body with the environment, be it as flooring treatment or as upholstery for furnishing. Textile's tactile properties dominate its functional role.

The most commonly used textile in the building construction industry is possibly Tyvek, which functions as a moisture barrier within the envelope of the building. This membrane is not rigid and must be fixed onto a stiff surface or frame. A more widely explored field where textile plays a crucial role in architectural production is its use for concrete casting as flexible formwork. This area of investigation for architectural designs has a long history, going as far back as late 19th century with fabric-formed concrete floor slabs, to more contemporary investigations by Mark West through his Center for Architectural Structures and Technology (C.A.S.T.) lab (Veenendaal 2017).

Fabric forming by West highlights the advantages of textile's flexibility, particularly its ability to drape, as a way of integrating structural intelligence (funicular forms) and material performance in concrete's capacity to be molded beyond the rectilinear flatness of typical mass-manufactured materials for building (West 2017). Fabric forming explored by West includes fluid pressurized formwork, as in concrete filling the fabric mold to achieve resultant forms vertically (columns or walls, for instance) and horizontally in open trough molds that are non-pressurized, casting onto textile surfaces. Building components produced include columns, precast panels, beams, and trusses. Beyond elemental components, concrete forming with fabric, for West, features the fluid nature of concrete as a material in its unique ability to mold into expressive, ornamental details. In most of these cases, the ornamentation is generated by the natural stretch and folds of the fabric, not by tailoring it into shape. The limitation of using flat textile was intentional for the sake of construction efficiency, to limit the extensive processing that was typical with conventional means for building.

More recent research on concrete thin-shell structures using flexible fabric forming have been done by the Block Research Group (BRG) at ETH Zurich in Switzerland (Veenendaal & Block, 2014). Their production employed the use of fabric and cable-net as formwork for a large span roof structure. Fabric, in this case, is cut and seamed to achieve anticlastic curvatures to optimize material and structural efficiency. Our exploration in tailoring is to account for either bunching or creasing for more extreme surface bends, or the potential for the textile to rip under stress based on deformation. Thermoplastic Concrete Casting differs in scale and focus primarily in the potential for more extreme design of: 1) anticlastic surfaces (especially in switching directionality) through computational means of working with tailoring processing for the fabric, and 2) pushing GFRC casting to achieve thinness and lightness for novel architectural forms to develop a building system of precast modules.

Figure 2: (clockwise from top left) Paper scaled model for seam and curvature analysis; GFRC tests for thickness, pigmentation, and form; felted seams of patterned non-woven textile; test mold using plywood stretcher showing textile and concrete layer; and early test of GFRC cast showing thinness and curvatures.

Figure 3: (clockwise from top left) Textile formwork for Eames molded fiberglass chair; foam-sprayed backing side of the Womb Chair; both molds prepared and sealed for GFRC casting.

Given these precedents, *Thermoplastic Concrete Casting* deviates from other flexible fabric formwork inquiry by asking: What happens when textile is made rigid, and how might architectural production take advantage of this novel circumstance? In addition, given the advancement of CNC tools and computational software to manage efficiency in streamlining workflow from design to output, could more non-conventional means of textile manipulation be integrated into textile casting for architecture? How might these combinations, of technological and material rethinking, guide and offer innovative ways to reimagine formal, constructive, and experiential designs?

2.2 Typical Molding Techniques for Complex Surfaces

Formworks for the molding of complex geometry are time-, material-, and labor-intensive. They are usually produced subtractively, either milled out of a solid material with a 3 or 5-axis router or hot-wire cut based on ruled surface geometries (or in combination). *Microtherm* by Matter Design and Cagliari Contemporary Arts Centre by Zaha Hadid Architects are good examples (Clifford and McGee 2016; Flöry and Pottmann 2010). *Microtherm* was cast from molds that were first hot-wire cut and then milled out of solid EPS foam, and the geometry of the facade of the Cagliari Contemporary Arts Centre was rationalized based on ruled geometries in order to consider how it could be built. A key advantage of using fabric formwork for complex geometric casting is to reduce the amount of material waste through subtractive processes for the mold's production as well as cut machining time.

Mold making for complex surfaces usually involves a geometric rationalization process. For this project, working with mostly anticlastic surfaces, the geometries are rationalized to be developable or flattened as patterns. The concepts of developable surfaces for manufacturing are shared by designers across a wide range of industries ranging from clothing production to shipbuilding (Clifford 2010). In clothing manufacturing, for instance, tailoring and patterning are fundamental, for giving garments form and more structure or stiffness at the seams, and for material efficiency in cutting from bolts of flat fabric. Such processes are similarly considered in architectural production, especially in shaping complex, non-linear surfaces of synclastic and anticlastic curvatures (Pottman 2007). Computational modeling and physics-based simulation for this project was necessary not only for geometric analysis, but also for incorporating parameters from material tests to inform design and direct CNC fabrication. A major focus of this project was to develop computational approaches for analysis, design, and fabrication as a comprehensive and seamless process.

2.3 Needle Felting for Non-Woven Textiles

Given that non-woven felt material comes in both synthetic (e.g. polyethylene or polypropylene) and natural (e.g. wool or bamboo) fibers of different densities, part of our testing was to understand the material properties and behavior of non-woven textile. Fosshape as an engineered thermoplastic textile has specific shrinkage behaviors. Our goal was to calibrate the shrinkage parameters unique to the material in order to generate a parametric script for design and fabrication.

One advantage of working with non-woven textile is that it does not have the directionality of warp and weft inherent in woven or knitted textiles. For non-woven

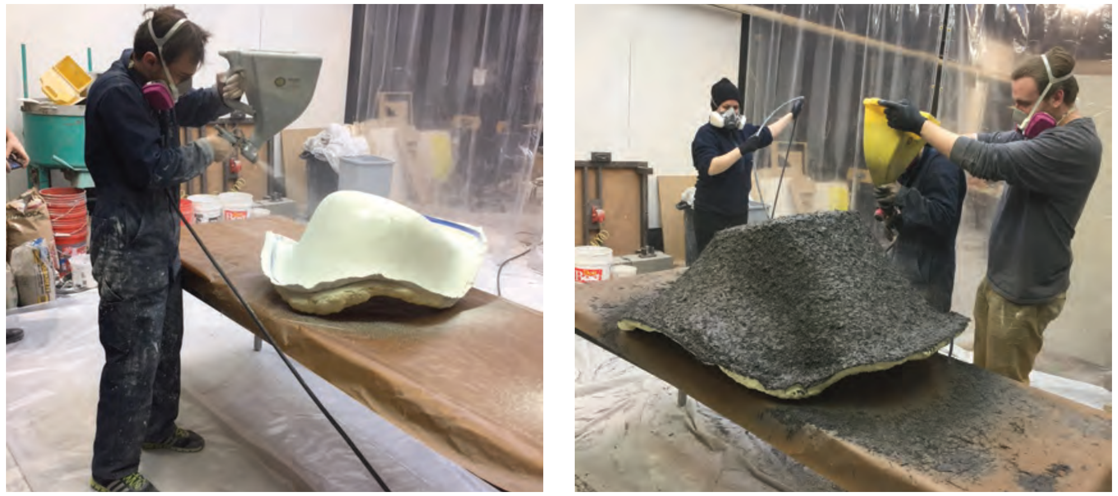

Figure 4: GFRC spraying process for both chairs.

materials, a process called felting was used to seam the patterns together. Felting involves punching with a barbed needle through layers of material and is mainly used for craft-based making. The advantage of felting is the actual meshing of fibers together to become a uniform whole, eliminating seams and producing an extremely strong connection without the use of binding agents such as adhesives or sewn threads. Typically, felting is done by hand in a repetitive motion with a single needle or a few needles bundled. Mechanical felting is achieved with a felter similar to the scale of a sewing machine. Given the size of our textile patterns, a mechanical felter was used to felt the 2D patterns together.

3 PROCESS, TESTING, AND FABRICATION

Our initial approach to the project was to develop models both digitally and physically to analyze complex curvatures. Using Kangaroo and explicit modeling in Rhino, we began with the development of a workflow that would enable analysis, design, and output for CNC fabrication of component parts. The modeling process was a way to analyze seam structure in relation to form for patterning. There were two branches of material testing that took place. The first was GFRC spraying processes, taking into account mix composition, thickness-to-strength ratio, pigmentation, and quality of final surface finish. The second was the felting processes for the non-woven textile. This includes not only needle felting to test seam strength but also deciphering shrink rate when the material is subjected to heat for stiffening. We found that the thermoplastic textile has a shrink rate of approximately 5–10%, depending on the extent of the heating process and the thickness of the material (as it is not absolutely uniform due to the textile's manufacturing process). A plywood stretcher was devised to hold the edges of the textile in place for the heat stiffening process. The non-woven textile is simply stapled to the edges of the stretcher before heating. After heating, the texture of the fabric was smoothed with a fairing compound, prepared, and sealed from moisture for concrete casting (fig. 2).

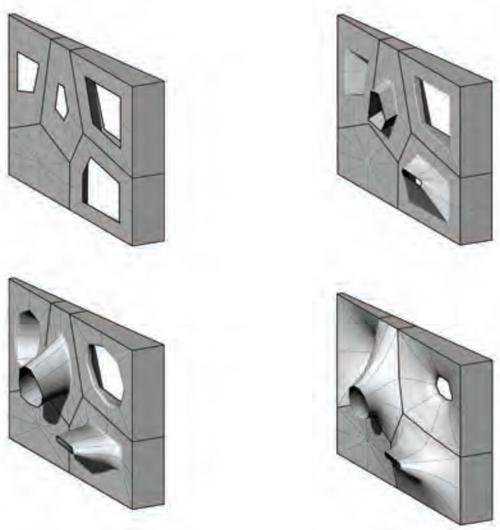

Figure 5: Progressive relaxation of mesh shown in different stages, from flat to double curve.

3.1 Concrete Chairs

At the object scale, using Eames' fiberglass molded chair and Saarinen's Womb Chair with complex curvatures, we developed the patterns by strategically locating the seams and unrolling the curve surfaces (by approximation). The patterns were then knife cut using the 4-axis CNC cutter. For the molded chair, the scale enabled the seamed textile to mold against the original chair. For the Womb Chair, since we did not have one available to mold against, we created a stretcher to wrap the textile on to heat stiffen. Once the textile for the chairs was stiffened, we found that, while it holds it shape, the mold would probably deform during the GFRC spraying process. The weight of the wet concrete would be enough to change the textile formwork's shape. To give the molds extra rigidity, we

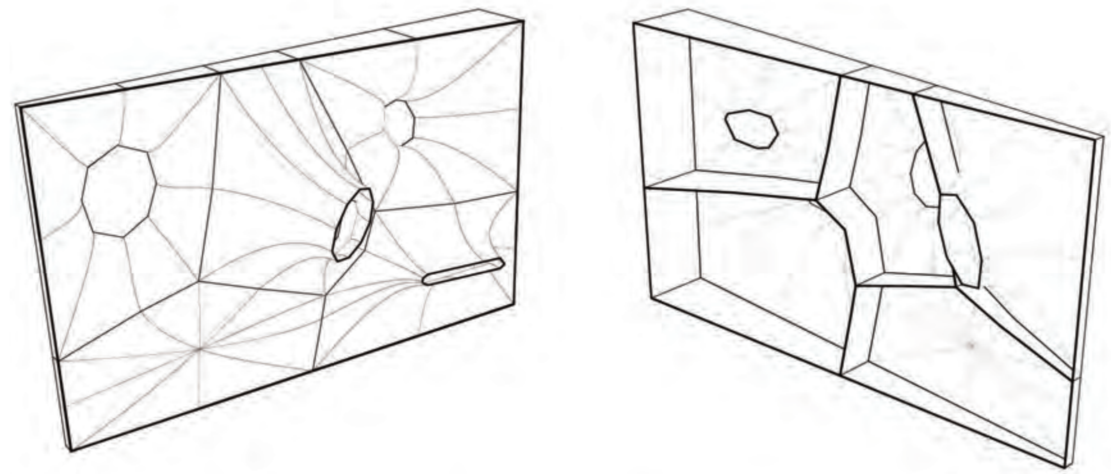

Figure 6: Variable-depth flanges are added to stabilize the wall and allow for the joining of discrete modules.

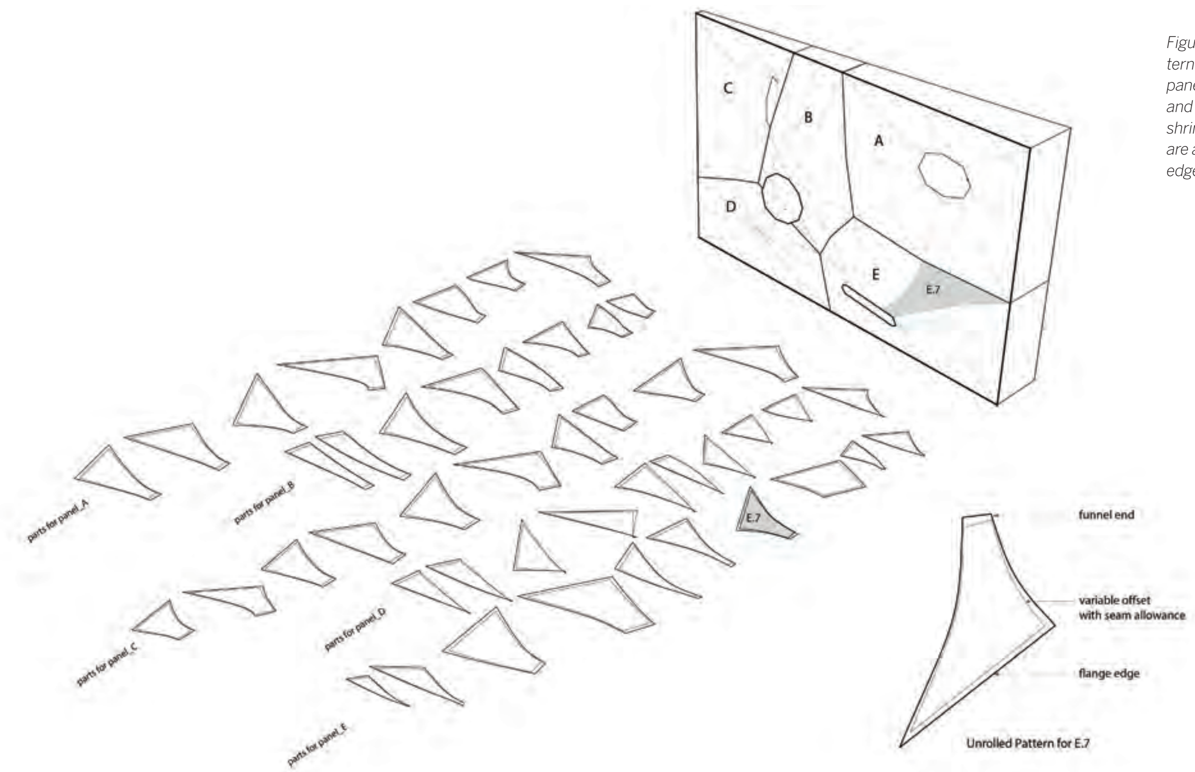

Figure 7: Once patterned, the individual panels are unrolled, and seam offsets and shrinkage allowances are added to each edge.

Figure 8: Each of the five individual molds consists of a plywood stretcher assembly, which is joined to the assembled textile surface. The material is heat-stiffened, backed with polyurethane spray foam, and then surfaced for casting.

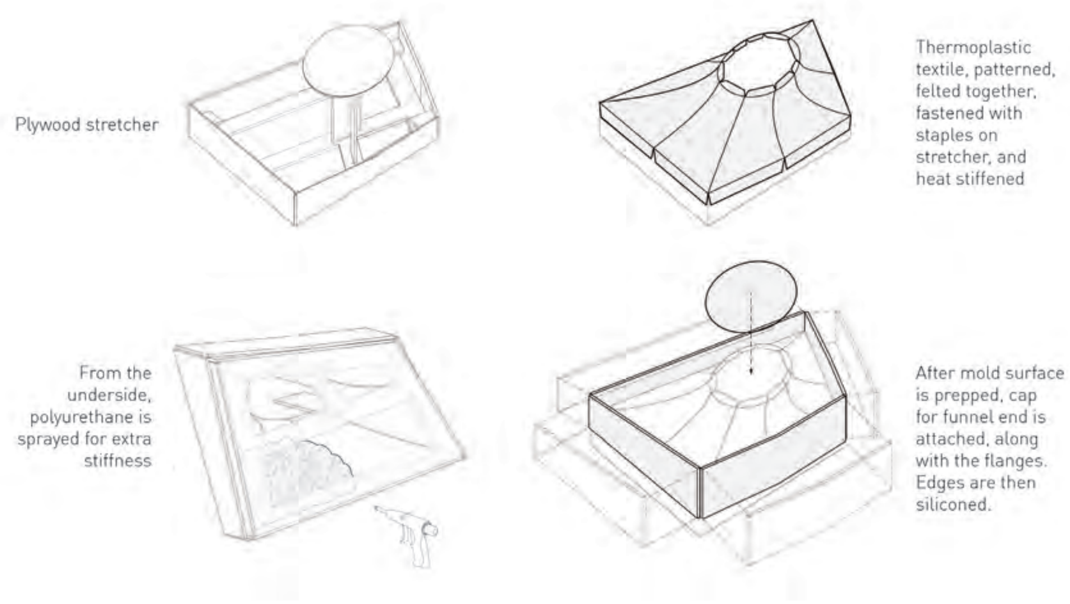

Figure 9: (clockwise from top left) Patterned non-woven thermoplastic textile; heat shrinking on stretcher; prepared mold with flanges attached—edges are silicone; underside of stretcher with thermoplastic stiffened on top.

sprayed polyurethane foam to the underside of the mold as a rigid substrate. While the heat generated during the curing process for the spray foam might further deform thermoplastic textiles such as those that are plastic sheets with a thickness of 4 or 6 ml, Fosshape, because it is a thicker felt material, could withstand the curing process with minimal global deformation. Small local deformations do occur, but the surface preparation process for casting smooths out the surface (figs. 3 and 4).

3.2 Concrete Wall with Funnel Apertures

Using physics-based modeling, the design of a 7' X 11' wall mesh was dynamically relaxed with real-time manipulation. The mesh is relaxed with differential warp/weft stiffness, combined with planarization constraints to force individual panels to remain developable (fig. 5).

The breakdown of the wall panels utilized a Voronoi diagram, each with a funnel center that is controlled with a varying protrusion depth and direction. The constraints are used to control orientation of funnels to produce site-specific views. The design of the wall accounts for balance with the modules' weight in compression, tapering from 18 in. from one side to 2 ½ in. at the other. This thickness is made possible by adding flanges (in plywood) to the sides of the stretcher after the thermoplastic has been heat-stiffened. The flanges for the GFRC modules also serve as coplanar surfaces to mechanically bolt the panels together (fig. 6).

Following a similar rationalization approach to working with developable surfaces through ruled geometry by Flöry and Pottmann (2010), our design and analysis of complex surfaces was derived through formal and construction logic. Each funnel was patterned using ruled surfaces to develop the geometry. While the rationalization of the curved surfaces is an approximation (one could infinitely segment to ever smaller panels for more accurate ruled surface development), the manual process of heat shrinking the textile against a stretcher enables the physical making to resemble the mesh design with reasonable accuracy. A script was written to automate the process for generating the unrolled patterns, including seam offsets and variable shrinkage allowances depending on directionality of the pattern's edge (funnel end versus flange edge) (fig. 7). The patterns were CNC cut, felted together, and pulled over a plywood stretcher. The stretchers for each module were CNC routed and assembled as a frame, enabling simultaneous fabrication with the textile surface.

Once the stretcher is assembled, the thermoplastic textile is stapled and stretched, heat-stiffened, then backed with polyurethane spray foam, ready for water-based fairing compound and sealant. Edges inside the mold are silicone sealed, and the entire surface is sprayed with a mold release agent (figs. 8 and 9) The GFRC spraying process includes a thin mist coat and a backer glass fiber reinforcement coat—where thickness of GFRC is built up by applying multiple layers of backer coat. This thickness ranges from 3/8" to 5/8", depending on whether it is a surface or an edge condition. Slightly thicker or rounded edges provide for extra structural stiffness for the GFRC panel. After the casts are demolded and fully cured, each of the panels weighs anywhere between 200 and 250 lbs. and can be lifted by two people for installation. During installation, the panels are clamped in place at the flanges, drilled to receive bolting hardware (fig. 10).

Figure 10: (clockwise from top left) Spraying process for panel; demolding process; bolting panels together; panel transport.

4 RESULTS

The intention for the funnel openings at eye level is to direct one's view through the wall. One of the funnel ends (at the base) is constrained to meet the end of a table, testing the variability of shaping curvatures with extreme sectional quality (figs. 11 and 12). With the directional switch of the funnels, the continuity of the mesh surface from one panel to the next highlights the fidelity of the initial mesh design in relation to the built construct as the curvature smoothly matches adjacent panels (fig. 13). When a viewer walks from the smooth (front) side to the back, the thinness of the GFRC casts is revealed.

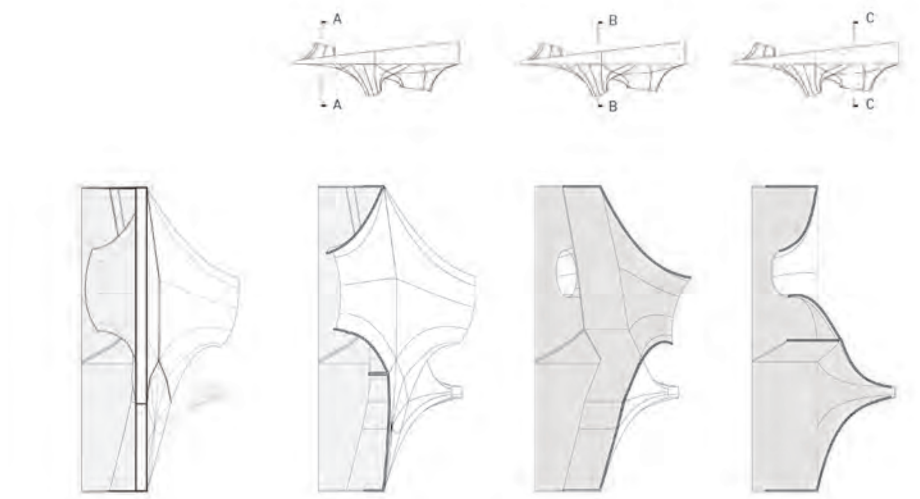

Figure 11: (left to right) Side elevation from 2 ½" side, with section A, B, and C through center of funnels.

Figure 12: Plan view showing the final subdivision of individual mesh faces. A balance is struck between accuracy of the unrolled geometry (higher-resolution meshes) and responsiveness of the parametric model.

While the panels were able to hold their own weight without extra support, given enough resources and time, it would be beneficial to analyze the wall system as a whole so that future designs and adjustments could be based off of quantitative data. This includes ratios of overall wall depth to height, panel size to GFRC thickness, and funnel opening size and protrusion depth in relation to surface stiffness.

To further reduce labor involved in the formwork preparation, the surfaces of the non-woven textile could be sprayed with multiple layers of polyester coating with light sanding in between. The spray coating process would eliminate manual surfacing with fairing compound and heavy sanding in between layers, as well as the final layers of polyurethane coating necessary for water sealing.

5 CONCLUSION

Thermoplastic Concrete Casting aims to challenge typical processes for formwork making for complex geometries, offering an integrated process for computational design, fabrication, and construction. While other fabric molding processes have invariably been explored especially for material and structural performance, this exploration tests more extreme designs that are often difficult to achieve given their complex geometries. The project comingles sartorial techniques with architectural processes to address construction challenges—one that is not limited by the orthogonal flatness of normative building material and techniques. Through a discursive process of full-scale prototyping and computational design, the project links digital technology with heuristic knowledge of building. The latter includes certain types of skilled crafting, such as heating techniques for the Fosshape, as well as GFRC mixing and spraying. In being able to control the entire process from ideation to construction, tolerances are controlled, offering more precision in what otherwise could be a loose process for concrete construction. Ultimately, *Thermoplastic Concrete Casting* attempted to challenge conventional casting techniques for forming complex curved surfaces with less time, material, and labor.

Figure 13: View of cast panels composed.

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