Concrete Form[ing]work:

Designing and Simulating Parametrically-Patterned Fabric Formwork for Cast Concrete

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Concrete is one of the most widely used construction materials globally, yet its industrial fabrication techniques continue to default to planar formwork and uniform cross sections for the sake of simplicity and predictability. Concrete Form[ing]work evaluates state-of-the-art fabric formwork research and explores the industry's reticence to integrate these novel design approaches. This research has identified two challenges that have significantly hindered the adoption of fabric formwork in architectural design: complex tailoring of parametrically designed forms and the lack of accurate simulation tools for flexible formwork. Concrete Form[ing]work develops methods to address both of these issues, providing an alternative approach to more simply tailor fabric forms and accurately simulate these patterns' response to casting. In doing so, this research has the potential to fundamentally change and streamline how the field of flexible formwork is approached and integrated within architectural design. This paper will present the process of parametrically tailoring non-developable surfaces from single sheets and document the development of these simulation tools.

Keywords: *flexible formwork, concrete, simulation, parametric patterning, smocking*

1 CONTEXT

In the 1960's, designers and engineers such as Miguel Fisac ("Fundación Miguel Fisac" n.d.) began to explore the architectural implications of textile use with cast concrete as an alternative to the costly standard of rigid formwork. This simple, technical reimagining of formwork material brought about research such as Mark West's materially efficient beams (West et al., 2016) and Kenzo Unno's in situ, low-waste houses (Veenendaal et al. 2011). This past research is well documented yet does not address newer technological methods of production.

The advent of digital design and parametric fabrication in recent years has resulted in an era of mass-customization, often directly clashing with fabricability. Consequently, despite considerable advances in the field of fabric formwork, industrial applications of flexible formwork and cast concrete are extremely limited (Concrete Canvas, n.d.; "FASTFOOT Fabric Formed Footings," n.d.). *Concrete Form[ing]work* has

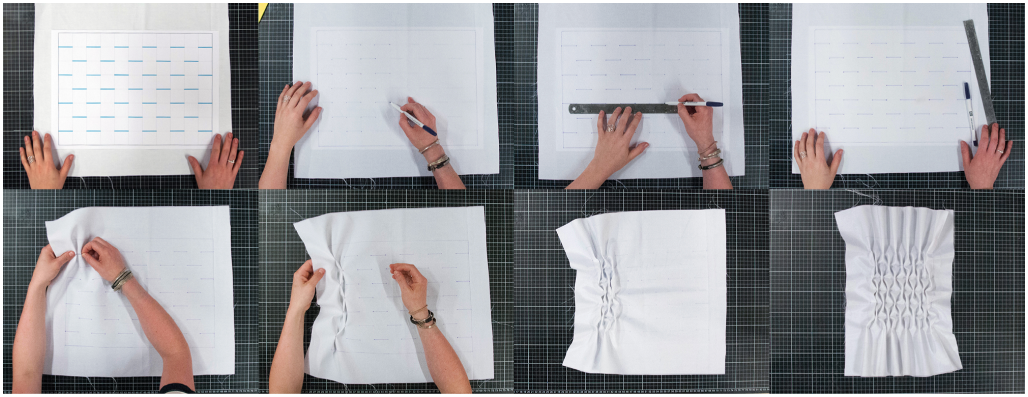


Figure 1
Smocking process of a basic lozenge pattern

surveyed recent architectural research in the field of flexible formwork to understand potential limitations of industrial applications. Projects such as Fatty Shell (Holzwart et al., n.d.) and MARS Pavilion (Sarafian et al., 2017) are prime examples of the vast amount of tailoring that is required to create complex forms from flat sheet material. The large number of components and high degree of fabrication accuracy required in both projects identifies an area that requires further development in order to make flexible formwork more readily accessible to designers.

The second limitation of current flexible formwork methods is the lack of simulation utilized by current design methods. Varying fabric elasticity, hydrostatic pressures, and tacit material knowledge of concrete are all reasons cited for the difficulty in simulating cast forms. Mark West's research team at C.A.S.T. (West et al., 2016) and Remo Pedreschi's Disruptive Technologies studio (Bush, 2012), both leading researchers in the field of flexible formwork, refrain from using digital modeling, preferring to rely on tacit material knowledge. Fabric patterns are hand-drawn in chalk onto sandwiched sheets of fabric, ultimately designed from material intuition derived from previous experiments. While this is an excellent hands-on approach to research and learning, this technique can hinder the ability of those who have not acquired this knowledge to accurately design, predict or model flexible formwork for cast concrete. Some projects such as Fatty Shell utilize limited 3D modeling, but do so by over-simplifying the formwork as an abstracted, minimal surface mesh. Consequently, this adaptation leads to unanticipated hydrostatic pressure and required ad hoc solutions to keep the formwork in position (Veenendaal and Block, 2012). The crucial link between concrete, parametric tailoring of fabric, and precise simulation is missing, and is a core basis of why flexible formwork has not been more commonly integrated into architectural design and industry. *Concrete Form[ing]work* aims to combine the tacit knowledge of materiality and parametric patterning of formwork within a digital and physical workflow.

2 METHODS

2.1 Smocking

In the context of the current state-of-the art flexible formwork, *Concrete Form[ing]work* investigates alternatives to tailor flexible formwork without the need of several hundred unique components sewn together. The research re-imagines the use of traditional smocking, an embroidery technique used since the middle ages to tailor a laborer's clothing (Cave and Hodges, 1984). The term comes from "*smock*", a farmer's work shirt, and the technique was popularized in the eighteenth and nineteenth cen-

Figure 2
A selection of conventional smocking patterns, sewn fabric and cast counterparts

Figure 3
Column 1 lozenge smocking pattern, fabric formwork, and cast probe

turies as it was possible to more easily tailor flat panels of fabric to the shape of the human body without labor-intensive cutting and sewing of numerous pattern pieces. Hand smocking typically involves marking a regular grid onto the sheet of material to tailor, and connecting the end points of pattern lines where excess material needs to be gathered. The steps of constructing a basic "lozenge" smocking pattern are exhibited in Figure 1.

The potentials of locally detailing flexible formwork with smocking provide new possibilities when combined with cast concrete. During the initial stages of research a series of fifteen hand-sewn smocking patterns were cast to examine the feasibility of casting concrete in smocking, a selection of which are shown in Figure 2. In context of these experiments, a more in-depth investigation was carried out to understand the implications of applying smocking to a fundamental architectural element: the column. The aim of the first column probe was to explore vertical casting in a smocked fabric column formwork and to understand how the pattern would react to hydrostatic pressures and gravity. A simple lozenge pattern was selected and consisted of an alternating series of pattern lines on a 5 cm grid (seen in cyan in Figure 3). The starting fabric width was doubled to accommodate the decrease in size due to gathered detailing. The end points of these lines were connected by hand with industrial-grade thread.

A self-compacting concrete recipe, developed in collaboration with the Swedish Cement and Concrete Research Institute (CBI) at KTH was selected. This mix is characterized by a high fluidity to strength ratio without the addition of excess water, and meets the demand of being self-consolidating (compacting) under its own weight, without vibration. Because vibration is not necessary, this recipe affords ease in fabrication of the prototype, and the fluidity achieved by the super plasticizer (Master Gelenium) allows the concrete to easily permeate the smocking details. While this initial prototype failed in the lower sections due to fabric tearing, the smocking details were easily readable and informed future selection of fabric and smocking patterns in subsequent prototypes. The base detail was unfortunately not clearly distinguished due to the combination of the very elastic material and high hydrostatic pressures at the base of the column, but will be further explored in later mockups.

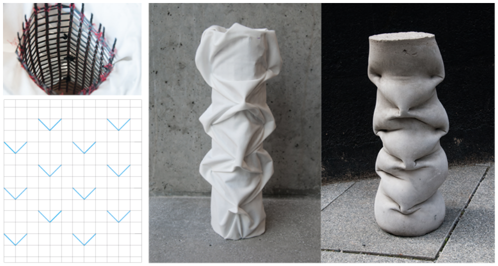


Figure 4
Column 02 basic arrow smocking pattern, formwork, carbon fiber reinforcement grid and cast probe

Column 2 was developed to test multi-directional smocking patterns as well as local anchoring points between the fabric and reinforcement. In response to the learnings from the previous probe, a thicker jersey cotton fabric was used and smocking connections were reinforced to prevent the fabric from tearing. The base was simplified to a circle profile in order to limit the number of new variables introduced. Previous tests determined that the lower limit dimension of a smock detail with this particular fabric and concrete mix is ˜35mm. In order to construct an arrow patterned column with a similar size and radius as column 1, the pre-smocked fabric had to be doubled in both width and height, to correspond to the material loss due to the multi-directional pattern. (Note this scale of prototyping was retained as it results in a cast that can be reasonably transported by one person). A carbon fiber grid was placed inside to achieve two goals: first, it serves as general reinforcement for the cast column. Second, it provides a substructure to anchor the smocking connections, minimizing the global "ballooning" deformation of the column and isolating it to only occur locally between smocks.

2.2 Digital Prototyping & Casting Simulation of Flexible Formwork

Simulation in the field of flexible formwork is relatively unexplored, due to the complexities of modeling the stretch of the fabric and hydrostatic pressures. Researchers prefer to rely on hand-drawn patterns and material intuition, or simple minimal surface abstractions. The lack of predictability and ease of replication are the main hindrances that deters industry's enthusiastic adoption of flexible formwork. This

Figure 5
Simulation tool development & design variations

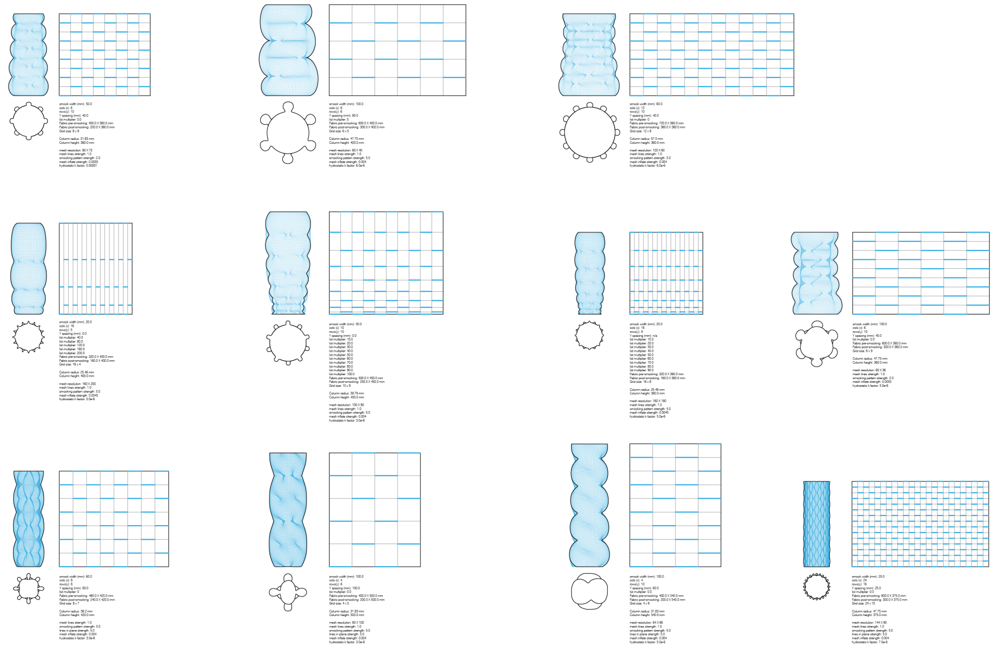
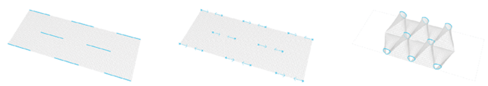


Figure 6
Basic smocking kangaroo simulation



research seeks to understand the accuracy possible with accessible tools to architects, such as Grasshopper, Python, and Kangaroo 2. *Concrete Form[ing]work* uses these tools to develop a parametric workflow for pattern generation, as well as simulating the smocking process and resultant cast geometries of the patterned formwork. With complex parametric patterning, it becomes critical to negotiate a digital workflow of simulation, fabrication, and calibration to anticipate flexible formwork's response to hydrostatic pressure. The first parametric design studies of varying patterns of columns are seen in Figure 5 and Figure 6. Their correlation will be discussed in a later section.

3 DESIGN RESEARCH DEVELOPMENT

3.1 Parametric Patterning of Non-Developable Surfaces with Smocking

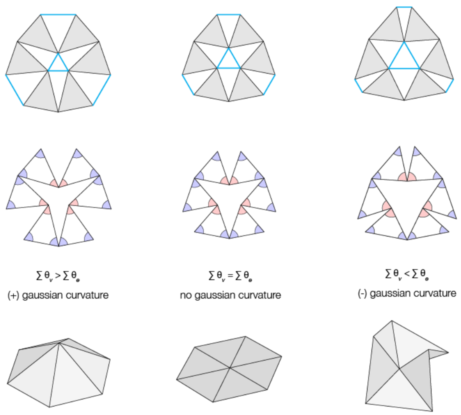


Figure 7
Programming patterns with Gaussian curvature

Until this step in the research, only manipulation of 2D patterns was possible and relied heavily on intuition gained from working with smocking. The next series of probes investigated the deconstruction of non-developable, tessellated meshes into flat smocking patterns. In order to re-imagine the complex tailoring of parametrically patterned fabric formwork, *Concrete Form[ing]work* synthesizes a variety of research fields that address the task of programming curvature within flat sheet material. It builds upon geometric principles of Ron Resch patterns ("The Works of Ron Resch," n.d.), Tomohiro Tachi's Origamizer (Tachi, 2010), auxetic materials (Konaković-Luković et al., 2018) and kirigami (Castle et al., 2016), (Scherer, 2015) and applies these geometric findings to smocking. The underlying principles of these research topics include tessellation and programmed curvature. Similar to kirigami (a variation of origami with cuts), or programmed auxetic materials, a smocking pattern can be abstracted as a mesh. The "cuts" or "holes" of these precedents can be re-imagined as smocks or "tucks." A computationally-designed smock, in a similar manner as a Ron Resch pattern, gathers excess material at specified vertices, to follow the changing relative angles and mesh curvature. This principle is illustrated in Figure 7. By changing the relation between the sum of the interior angles (θv) shown in red and the exterior angles (θe) shown in blue, it is possible to program zero, positive, or negative Gaussian curvature in a folded material or fabric.

Deconstructing a 3D mesh to a smock pattern. Figure 8 details the principles behind generating a smocking pattern from a 3D mesh. (1) The desired 3D shape is tessellated with mesh triangles and the circumcenters (point where three perpendicular bisectors of the triangle meet) are calculated and connected (dual graph). In (2), the triangles (with same edge lengths and relative positioning as their 3D counterparts) are laid out on a flat hexagonal grid, which is a scaled and flattened version of the 3D mesh dual. In order to achieve an arrow smocking pattern, alternating inside and outside vertices of the triangles are identified to anchor together in Kangaroo (3). The simulation is run (4) and the specified vertices snap together, all the while retaining the same mesh edge lengths as the 3D configuration. Finally, the vertices of the "gaps" are connected (5, seen in cyan), and are the smocking pattern connection points.

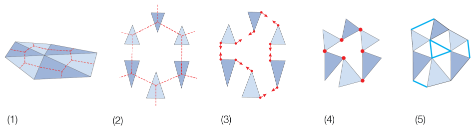


Figure 8
Deconstructing a double-curved surface into a smocking pattern, based on Ron Resch's origami pattern

Column 3.1 Demonstrator. This deconstruction process was applied to a one-sheet hyperboloid with negative Gaussian curvature to create a non-developable surface from a single sheet of material. Figure 9 shows the (1) triangle mesh tessellation, (2) circumcenter mesh dual found to retain tiling structure when unrolling (3) scaling of the mesh dual and placement of corresponding mesh triangles in the XY plane (4) connecting alternating triangle vertices to

Figure 9
Smocking pattern generation from a tessellated one-sheet hyperboloid with negative Gaussian curvature

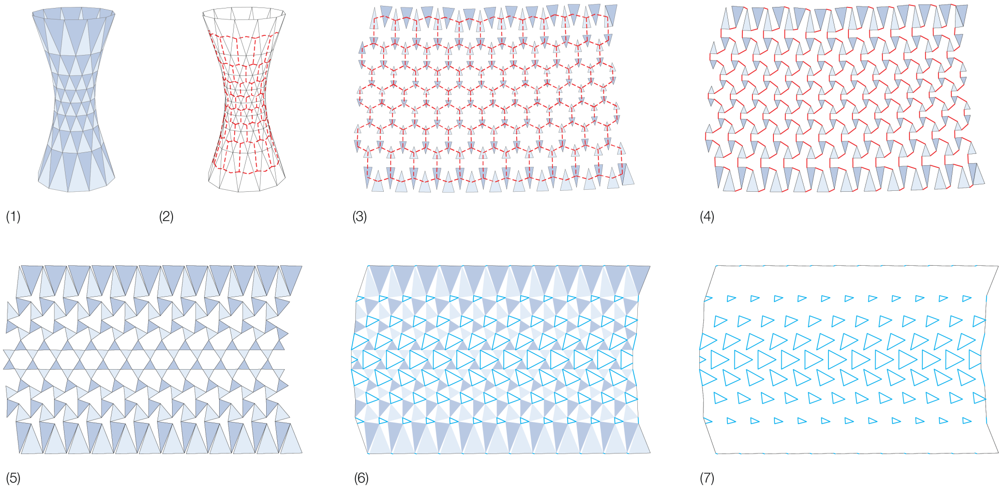


Figure 10
Column 3.1 demonstrator of a one-sheet hyperboloid fabricated from a single sheet of material

snap together (5) running the Kangaroo simulation, retaining mesh edge lengths while snapping appropriate triangle vertices together (6) connecting resulting "gaps" with smocking pattern lines and finally (7) producing the fabrication pattern. The size of the smocks in column 3.1 do not meet the minimum requirements for concrete to correctly flow into the details, and the demonstrator was fabricated solely as a geometrical proof of concept (Figure 10). A lower resolution version of this pattern was cast (column 3.2) and is detailed in Figure 12.

Concrete Forming[work] has successfully developed a tool in which a desired shape can be input by the user and outputs a Ron Resch-based smocking pattern to apply to the fabric in order to achieve the desired curvature. This research investigates the parameterization of smocked patterns and showcases its possibilities for programming both local and global articulation in a single piece of fabric, eliminating the need to sew hundreds of individual components together.

3.2 Correlation with Cast Probes

The concrete industry today is hesitant to integrate non-planar fabrication methods, citing a lack of accurate simulation tools and repeatability with flexible formwork. In addition to constructing parametric patterns to tailor formwork into non-developable surfaces, this research also acknowledges the vital development of digital models in parallel with material testing. Results from physical probes must inform simulation tools, and in turn, computational models must be verified by correlation to realized prototypes. This feedback loop is relatively undeveloped in flexible formwork research today, and is critical to establish to successfully integrate flexible formwork at an industrial level.

Column 2 Simulation & Correlation. *Concrete Form[ing]work* has developed a Kangaroo simulation in parallel with fabrication of physical probes. This tool provides valuable fabrication information to the user such as starting fabric size, smocking pattern, simulated fabric tensile stresses and a detailed calculation of the concrete mixture. Column 2 was scanned and correlated and the point cloud was colorized based on deviation from the simulation (Figure 11). The maximum deviation of the simulation from the point cloud was between -21 to 12.8 mm. The main source of this error was that the column twisted slightly during fabrication, due to the elasticity of the fabric.

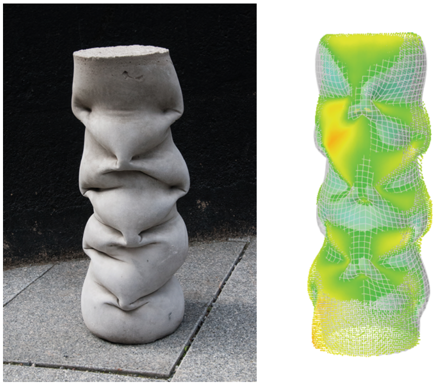


Figure 11
Column 2 cast probe and simulation correlation

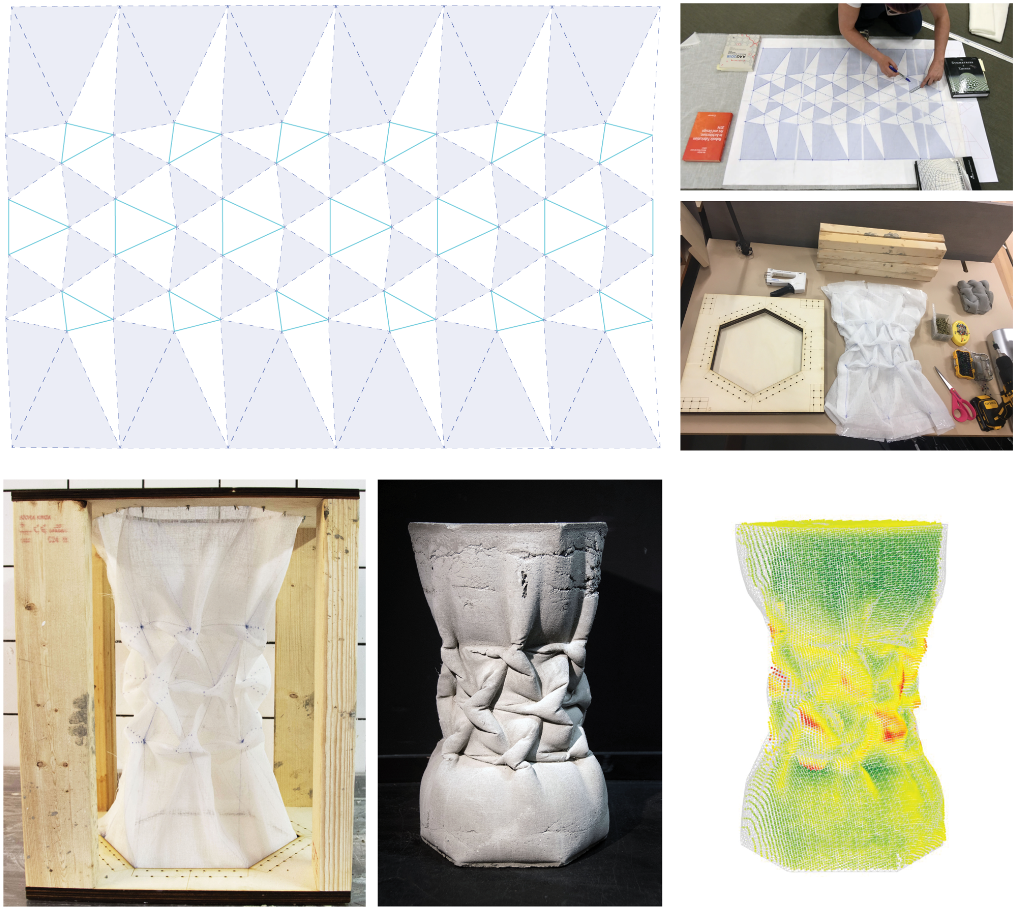
Column 3.2 Simulation & Correlation. In order to test the applications of the parametric patterning findings in the previous section, a lower-resolution version of column 3.1 was produced. These smocks meet the minimum requirements to be appropriately filled with concrete without overlapping, thus allowing the fabric to be more easily removed after casting. The same patterning methods as Figure 9 were used, but based on a more simplified mesh triangulation. The linen fabric was laid out and marked, and an additional string tension ring was added to maintain column section dimensions. The fabrication steps, including the smocking pattern, formwork sewing, casting and correlation can be seen in Figure 12. While a mixer malfunction during the last phase of casting unfortunately caused some separation in the upper section of the column, the cast probe still correlated to the simulation model with a -26.2 to 22.5 mm deviation. This appears to be caused by some smocking details being less filled by the concrete mix than others, and a closer look into mixture ratios and minimum smocking size will be included in future probes.

CONCLUSION

In conclusion, this series of prototypes details Concrete Forming[work]'s ability to parametrically pattern non-developable formwork for cast concrete and fabricate demonstrators that accurately correlate with their corresponding simulations. Learnings from these tests such as fabric selection, minimum smocking size, and base detailing will be further developed in future probes. The next step is a series of larger investigations, as it is critical to address smocking connections and fabric type at at full-scale.

Concrete Form[ing]work synthesizes hand-craft construction technologies with computational design and simulation to address gaps in current state-of-the-art flexible formwork research. This project achieves parametric patterning of doubly curved surfaces with smocking, eliminating the need for complex tailoring of individual elements and provides development of interactive, accurate, and accessible

Figure 12
Column 3.2 pattern, fabrication, cast probe and simulation correlation



design and simulation tools. Because it is possible to accurately simulate flexible formwork under the hydrostatic pressures of cast concrete, this tool opens the possibility for designers with no previous flexible formwork or casting experience to utilize these techniques, without having to first acquire tacit material knowledge. It is situated within current architectural design and expands upon the field by combining a centuries-old sewing technique with computational design. The integration of such techniques is a relatively unexplored topic in current fabric formwork research, and the tools developed within this project aim to increase the accessibility and reliability of flexible formwork, narrowing the existing gap in fabrication processes today.

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