TEXTILE EFFECTS
SEMI-RIGID CONCRETE FORMWORK

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1 Cast Thicket Installation–TEX-FAB Exhibition at University of Texas, at Arlington (Tessmer, 2013).

ABSTRACT

Tensile concrete formwork offers novel spatial affects, new structural configurations and material efficiency. This paper describes ongoing research in developing thin plastic formwork for multi-story, cast-in-place concrete structures. These techniques build upon Cast Thicket, a previous installation which provides a built example of the system (Figure 1). Continuing the success of Cast Thicket, our current research aims to test the system digitally at a larger scale and refine the formwork details. Future work planned includes further mockups to derive structural information from destructive testing and large-scale structural simulation/analysis.

TENSILE FORMWORK

Architectural use of tensile formwork is not new. Patents date from as early as 1899, and ongoing practitioners continue to develop both practical application and aesthetic expression.[1] Miguel Fisac's work from the late 1960s is arguably the first that leverages both the expressive materiality and practicality of soft molds.[2] Fisac's work consciously expressed the softness of the plastic molds and the fluid materiality of concrete.[3] Inspired by Fisac's buildings Andrew Kudless furthers this research with his P_wall project of 2009.[4] Taking advantage of both stretchy fabric and computational strategies, Kudless creates continuously variable surfaces, modulating both material density and aesthetic intensity. Led by Mark West, The Centre for Architectural Structures and Technology (CAST) in Manitoba indexes the specific materiality of geotextiles to create large-scale, concrete components that optimize structure while using minimal material.[5]

Significant reductions in both concrete and formwork material are possible through thin, tensile materials.[6] Thin materials such as spandex, geotextiles or thin (.04"-.01") plastic sheets are easier to cut, bend, fold and carry than plywood or steel formwork. This ease of workability and material flexibility allows the cross-section and configuration of tensile-cast structures to be optimized without time intensive and costly CNC formwork fabrication.[7] Our current research takes advantage ability of flexible formwork to change sectional area and configuration to create more optimal structural configurations. This formal potential creates opportunities for both spatial and sustainability benefits.

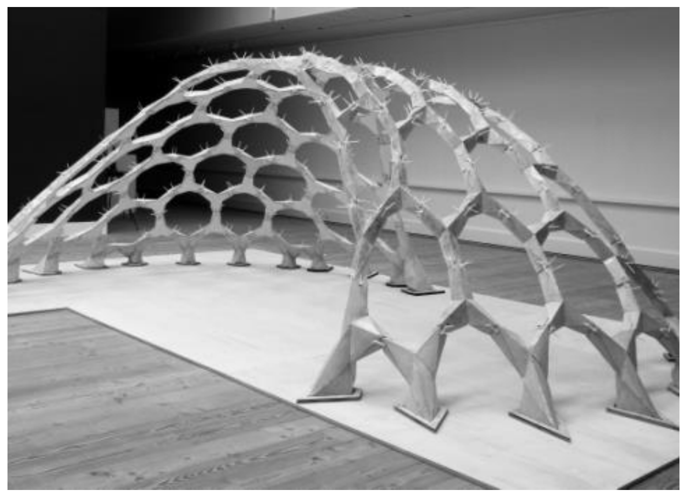
PLASTIC CAST PRECEDENT

The Concrete Gridshell Pavilion by Pigram, Larsen and Padersen provides an example of thin plastic formwork used to create a structural frame. This research presents the benefit of using easily recyclable plastic to create one-off molds as well as the benefits of optimized structure and member configuration (Figure 2). The project uses a parametric catenary system to optimize the configuration of precast concrete tiles into almost pure compression. Design flexibility is inherent in this parametric system which reconfigures to input constraints.

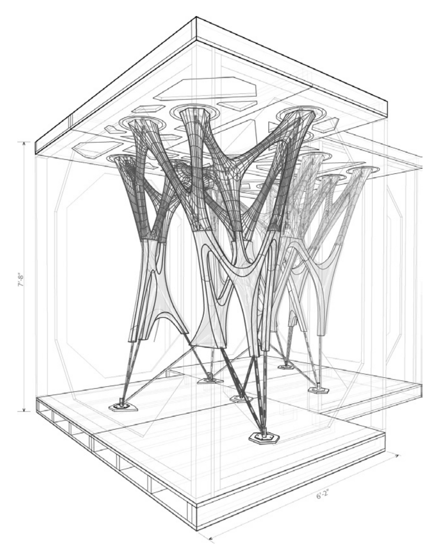
The project demonstrates the integration of digital form-finding techniques and computational file-to-fabrication workflows while synthesizing concrete casting techniques in a practical, affordable and material-efficient manner.[8] Though similar in the assimilation of digital design methodology with file-to-fabrication logistics, our current research targets in-situ, multi-story concrete structures and construction.

CAST THICKET

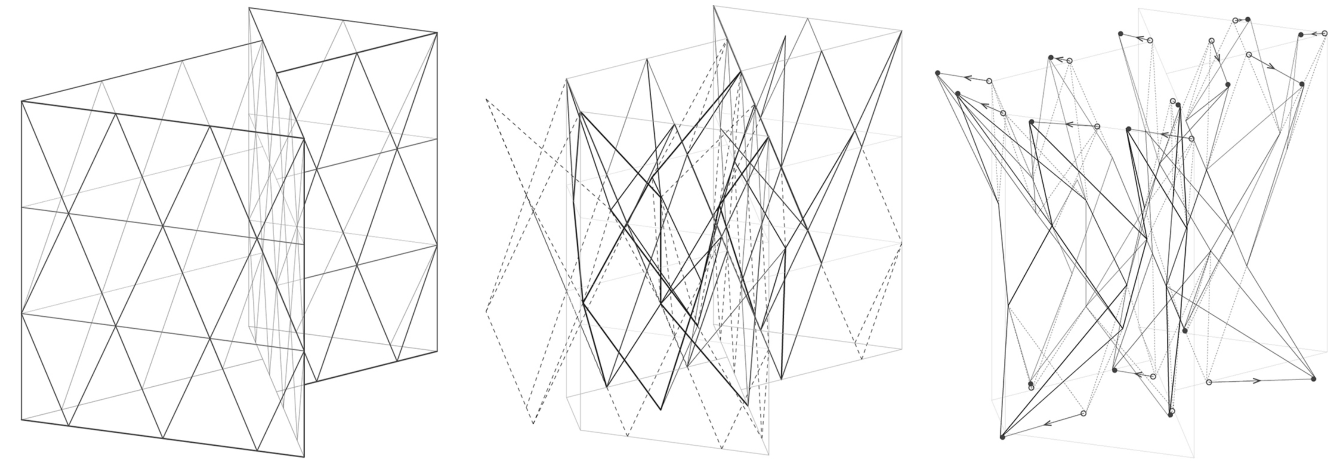
Completed in March of 2013, Cast Thicket is a prototypical installation utilizing plastic formwork and a layered structural network. Leveraging the fluid materiality of low-viscosity concrete and the machinability of polypropylene, Cast Thicket creates a lacy network of thin members that disperse and coalesce to address structural and spatial needs. To realize the project, two material and physical systems were simultaneously developed. The first was the plastic mold made from semi-rigid polypropylene sheets with integrally fabricated seam connections. Second was an overall organization using a tensile network of struts and nodes to distribute load and create space. Both systems used a series of parametric *Grasshopper* definitions, including the *Kangaroo* physics engine used in the simulation of tensile network. The seam details and fabrication were refined through iterative physical tests.



2 Concrete Grid-Shell Pavilion by Pigram, Larsen and Padersen (Pigram 2011)

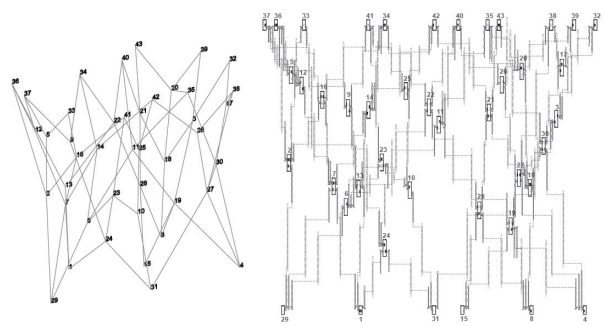


3 Cast Thicket–Peel-away drawing showing scaffold, steel, skin and concrete volume



A. B. C.

4 Tensile Network–(from left) Base grid of equilateral triangles with three levels of vertical diagrid, truncated massing grid with simplified interior branching members, base nodes repositioned to spread out for stability



5 Cast Thicket–internal steel frame fabrication files indexing the nodal system of the tensile network

TENSILE NETWORK

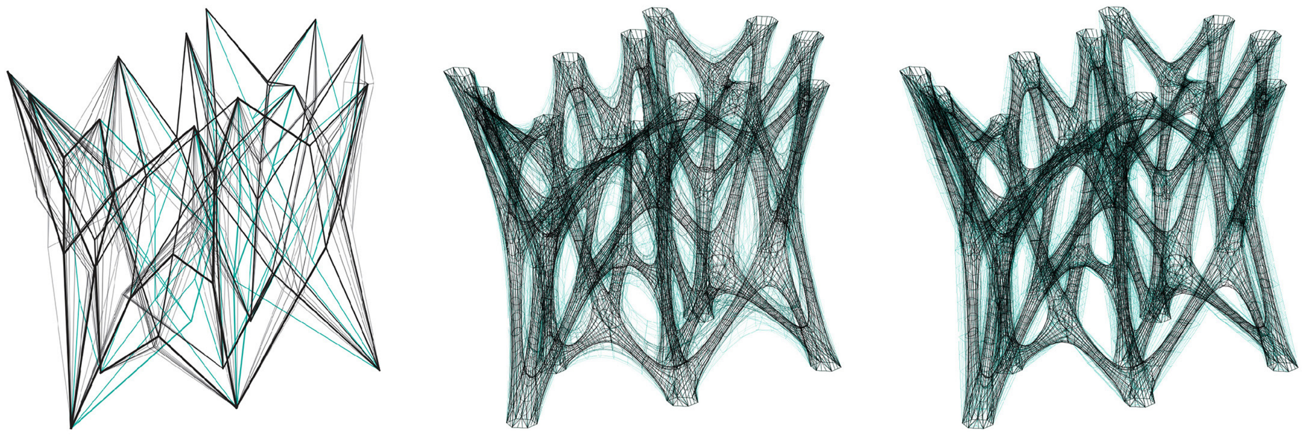
Borrowing from the stacking logic of most multi-story buildings, Cast Thicket used a rectangular compressive scaffold as its starting point (Figure 3). The scaffold allows the internal mold to be entirely in tension and serves as a reference for positioning the frame. Within these constraints, an initial grid is converted to virtual springs in *Kangaroo*. Played out over a series of iterations, the virtual spring simulation is trained into an optimized, interlaced network. Using The use of two types of nodes, fixed and dynamic, allows the framework to be moved either directly by positioning fixed nodes or more subtly by changing the tension on the springs (Figure 4). This nuanced, haptic design process allows for adjustments related to both intuitive design decisions and specific project constraints.

The tensile network is used as the primary interface for structural analysis and fabrication centerlines, allowing for a fluid exchange between design, fabrication and structural analysis. Parametric definitions were developed to overlay Cast Thicket's internal steel frame and its concrete volume onto the structurally analyzed tensile network (Figure 5). This workflow provides seamless design-to-fabrication and assembly logistics that enable flexibility of working with this tensile network system.

MOLD SURFACE OPTIMIZATION

The process of optimization of the mold surface bridges between the large scale of the structural network and the small scale of the seam details. This system for deriving the mold skin patterns starts by piping (reference) a uniform hexagonal profile along the network centerlines. The hexagonal profile accommodates many nodal relationships including 1:1 or bypassing conditions, 1:2 bifurcating conditions, up to 3:3 nodes and all permutations in between. This rough, tubular form is topologically refined through mesh relaxation (Figure 6).

Relaxation dynamically simulates the behavior of a stretchy, tensioned skin morphing the straight, longitudinal profiles towards minimal arcs. The intensity of the relaxation can be varied using more or fewer iterations. Each iteration brings the struts closer to a true catenary profile reducing their surface area. Limiting this variation is crucial, as it tends to create a bottleneck for concrete when the profile area at the center point is decreased. Once a balanced volume is achieved, the initial profile edges are extracted from the mesh and lofted to form developable, ruled-surface patches. These patches are combined and unrolled to form the initial patterns for the polypropylene formwork.



6 Refinement through iterative mesh relaxation, to achieve volume with optimal profile for concrete flow

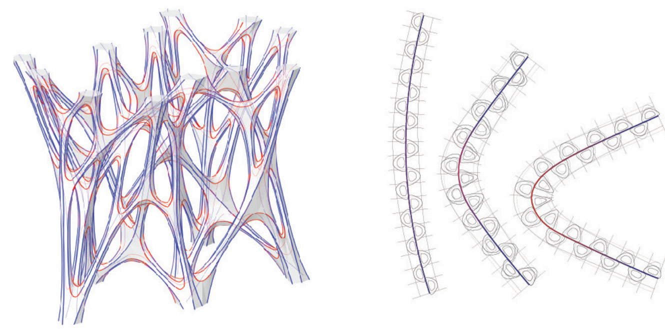
SEAM TECTONIC

The extracted profile edges of the relaxed mesh directly translate to the seam curvatures that calibrate the small scale seam details. The curvature guides the distribution of tabs which increase in density to correspond with reduced curve radii (Figure 7). This non-uniform distribution of tabs allows for stronger, more redundant connections at nodal joints where most tension occurs during the casting process. Integrally fabricated, these parametric tabs stitch the ruled-surface plastic patches together. Calibrated to the dexterity of the hand, a single hole in each tab creates a finger-sized handle to allow incremental manual "stitching" of the seams. The prefabricated seams expand the formal language of tensile molds allowing for concave ruled-surface geometries as well as convex forms.

Assembled exclusively from the exterior of the formwork, the tabs leave a smooth, tensioned seam on the interior of the mold surface. Sequenced after the assembly of the steel frame, the external tabbing allows for the skins to be partially pre-stitched in groups that correspond to nodes and then wrapped around the steel. This strategy stages the skin assembly so that several nodes can be assembled simultaneously. The final assembly of tensile polypropylene formwork is then filled with low-viscosity fluid concrete mixture and cast into its final installation formation (Figure 8).

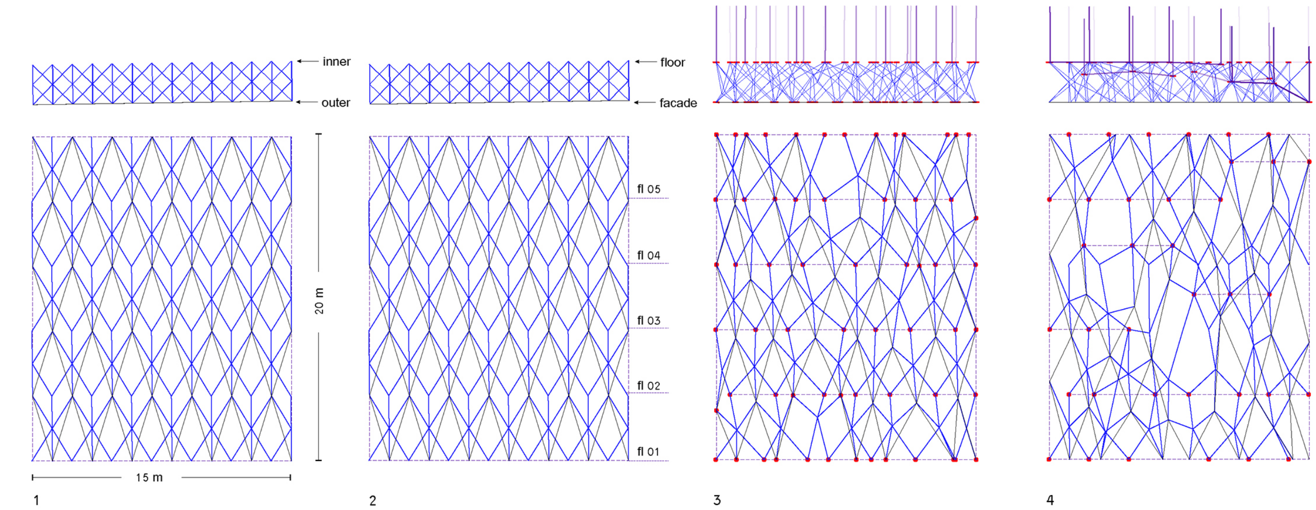
CURRENT RESEARCH

Current investigations into the potential of thin plastic formwork for medium size buildings have been undertaken. This phase of the work involves refinements to both the parametric tools and details for fabrication. The next phase of this investigation will involve destructive testing of structural members and the use this testing data to structurally analyze the system at the scale of a medium sized building.



7 Seam Curvature Analysis–tab density increases with increased curvature

8 Top. Plastic Formwork Assembly Process–(from left)Assembled steel frame, plastic formwork being wrapped around steel frame, and fully assembled plastic formwork. Bottom: Casting Process. (from left) Assembled polypropylene formwork, formwork after casting, unwrapped concrete (Bell 2013).



1. **Base grid** : interlaced inner and outer surface of structural frame
2. **Fixed and Dynamic Nodal assignemtns** : in relation to facade and floor
3. **Spring Relaxation** : constraint to node properties and perimeter edges
4. **Reconfigured Tensile Network** : **Spring Relaxation** with nouanced design contingence

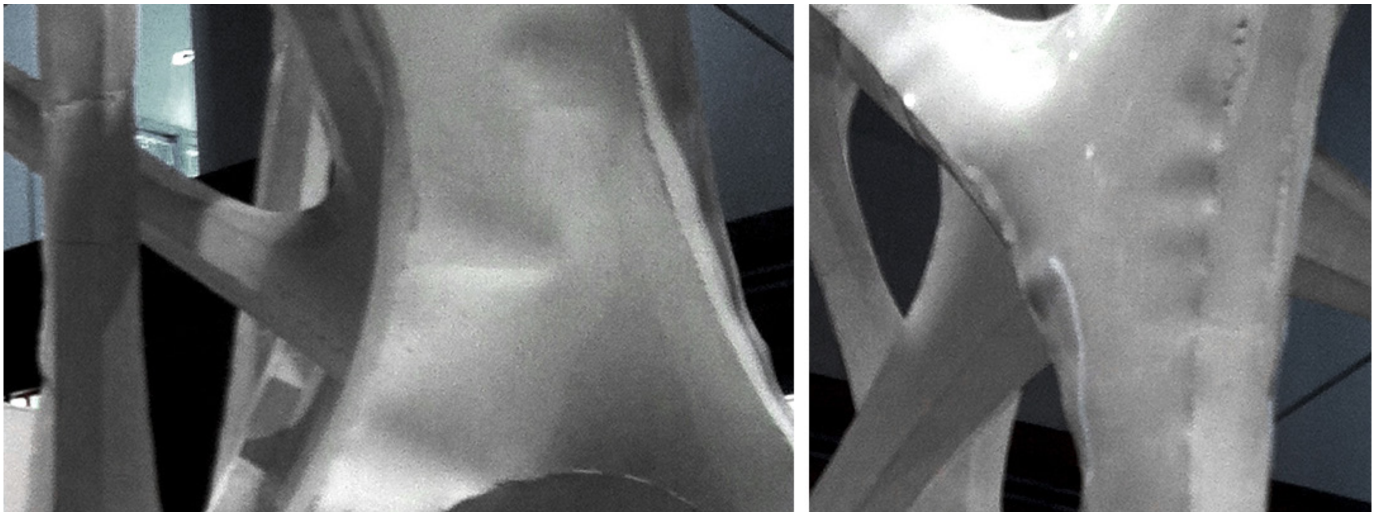
9 Working Sample in Large-Scale Tensile Network

This paper describes the first phase of work that particularly concerns the modeling and simulation of a larger-scale tensile network and the refinement of the seam geometry and details. The bulk of this work involves iterative creation of workflows relating *grasshopper* definitions to physics simulation in *kangaroo* and physical tests of seam details.

LARGE-SCALE TENSILE NETWORK

Initial work on large-scale tensile network uses a small number of building floors to simulate a tensile grid that can adjust to changes in the constraining floors. Conceived from potentials for the system to be a perimeter structural frame in a medium height concrete building, an initial sample of a base grid of nodes covering an elevation area of fifteen meters by twenty meters is used. This initial base grid interlaces between the outer and the inner surface of the structural frame at a depth of two meters. The nodes in this initial grid are assigned with variable fixed and dynamic properties based on their relationship to the façade and floors. The nodes intersecting the floor datum in the inner surface of the structural frame are constrained to move only along the edge of the floor plates, connecting directly to a horizontal beam network. This contrasts with the nodes on the outer surface of the structural frame that are dynamically constrained to movements within the vertical plane of the façade. The remaining nodes in between the inner and outer surface of the structural frame are assigned as dynamic. With these assignments of nodal properties, an initial spring relaxation is applied to simulate a distribution of tensile network (Figure 9).

This initial workflow to obtain the tensile network can be implemented to speculate variable floor placement and respond to the structural analysis model. Nodes that connect floor plates on the inner surface of the structural frame are moved and placed to allow for nuanced control of spatial contingents in a design process. The network of assigned-variable fixed and dynamic nodes reconfigures to a tensile network that reflect this imposed constraints (Figure 9). The ability for the interlaced network to reconfigure and absorb alternation allows potential for future structural analysis models to identify and eliminate underused load paths and their corresponding members within the tensile network system.

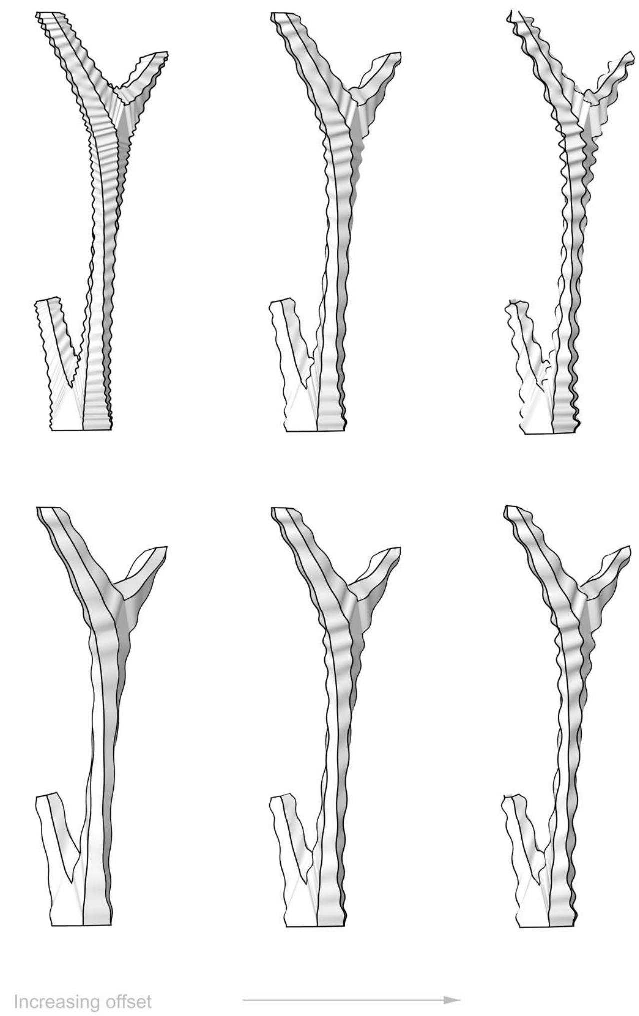


10 Localized patterned buckling of cast concrete installation (Yogiaman 2013)

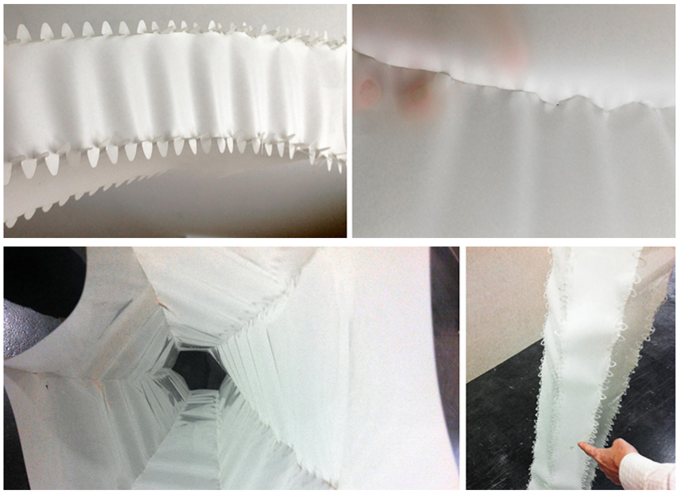
RIPPLED SEAMS

Along with the network optimization, another concurrent vein of continuing research addresses the geometry of the formwork panels in order to improve the behavior of the plastic against the pressure of the liquid concrete during casting. A series of tools are being developed that deploy targeted surface deformations in the formwork, adding a variation of the seam geometry that creates surface ripples that mimic and augment the localized uncontrolled buckling inherent in the plastic mold system. The added deflections are proposed to both increase the visual intensity of the seam buckling and direct the buckling into a more predictable pattern.

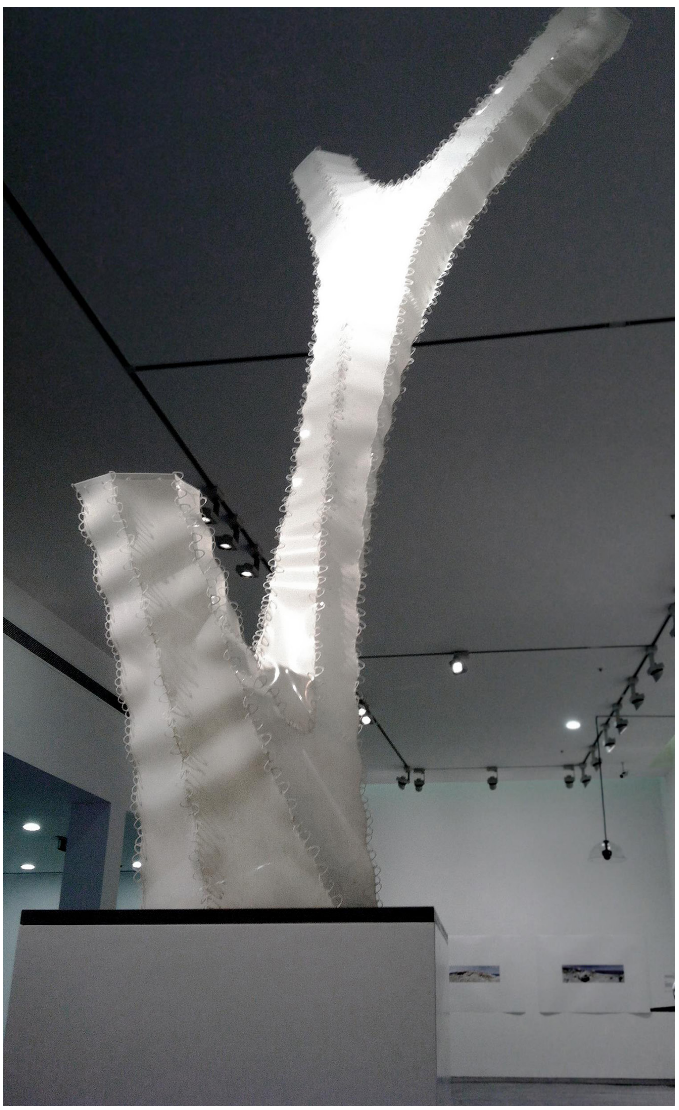
This work was instigated through observation of localized and patterned buckling in the Cast Thicket installation. Patterned ripples occurred regularly along the seams varying in length and size. This pattern evidences the uneven connection strength created by gaps between tabs and the inability of the plastic to stretch when the cross section is pushed outward, deviating in their ruled surface geometry from the double curved, minimal surface mesh from which they are derived. This discrepancy also creates individual local buckling. Surface buckling frequently occurs where the final panelized form deviates most significantly from the original optimized mesh primarily near the nodes where the panels are the largest and need to accommodate the largest volume of concrete (Figure 10). The new rippled surfaces alleviate the need for precise prediction of the behavior of the formwork with the forces of internal pressure. In addition to allowing more controlled buckling, the ripples have potential to add rigidity to the formwork panels.



11 Variations in depth and frequence of rippling along seam curvatures



12 Detail of rippled seam tab joinery (Tessmer 2014)



13 Full scale prototype of mylar formwork with rippled seams

A parametric model allows experimentation with different depths and frequencies of rippling in the formwork and enables subtle adjustments in the distribution of the ripples between nodes and struts (Figure 11). Achieved by producing a surface that interpolates between two offset versions of the original relaxed mesh, the variation in amplitude of the offset can be controlled as a function of distance from node centers. This potentially enables a non-uniform distribution of ripples throughout the network, allowing the rippling to be localized to where buckling occurs most, whether at the nodes or along the struts.

Physical tests examine the depth and frequency of ripples and refined tab joinery detail (Figure 12). The prototype molds explore ways of introducing variable rippling frequency and depth between each of the nodes and adjacent struts. In a full-scale prototype of a single node and strut combination, .02" Mylar replaces the original .03" polypropylene previously used in the Cast Thicket. Along with the extra rigidity of the Mylar, the added strength of the rippled panels will allow the possibility of further reduction in the necessary material thickness.

Adjusted to suit the Mylar material, the new tabs are slightly smaller to accommodate finer detail and higher degree of curvature caused by the presence of the ripples. With the smaller scale tabs, surface curvature and buckling patterns can be controlled more precisely. Future casting tests are planned to determine the effects of the refined seams on final cast elements (Figure 13). This testing will help assess both potential aesthetic and performative attributes of the rippled seams.

CONCLUSION

Taking advantage of current parametric tools, mesh relaxation, physics simulation and file-to-fabrication workflows this work bridges between digital fabrication and building technologies. The Cast Thicket installation as well as other similar work in plastic and fabric formwork provides encouraging evidence supporting their use. These developments could radically change the paradigm of concrete architecture both practically and spatially. Plastic-cast concrete offers new flexibility in terms of creating both a workflow and structural paradigm, which can change to accommodate building constraints. Additionally, the work is promising in the potential to reduce the weight of concrete formwork, the need for standardized/repetitive molds and the creation of structures that respond more specifically to structural demand.

Initial work already shows some of the spatial and aesthetic potential of the system. Continuing work planned to address structural and logistical issues will continue to use a series of various computational tools, proven so far to both allow design flexibility and create spatial intensity linked directly to practical outcomes. This synthesis between materials, structural and spatial testing offers a glimpse into the potential of materially-responsive, computational paradigms in architecture.

NOTES

1. Diederik Veenendaal, Mark West and Philippe Block, ‘History and overview of fabric formwork: using fabrics for concrete casting’, Structural Concrete Volume 12, issue 3 (2011), p.165

2. Andrew Kudless, ‘Bodies in Formation: The material evolution of flexible formworks’, ACADIA 11: Integration through Computation (Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture 2011), p. 101

3. Fernández-Galiano, L, ‘Miguel Fisac’ AV Monographs, no101 (2003),p 3

4. Kudless, ‘Bodies in Formation’, p.102

5. Veenendaal/West/Block ‘History and overview of fabric formwork’, p.172

6. See discussion on the reduction of concrete used in soft versus prismatic formwork Orr, J. J., Darby, A. P., Ibell, T. J., Evernden, M. C. and Otlet, M., 2011. Concrete structures using fabric formwork. The Structural Engineer, 89 (8), pp. 21.

7. See comparison of fabric and CNC formwork Orr, J. J., Darby, A. P., Ibell, T. J., Evernden, M. C. and Otlet, M., 2011. Concrete structures using fabric formwork. p24

8. Niels Martin Larsen,<f/ Ole Egholm Pedersen and Dave Pigram, ‘A Method for the Realization of Complex Concrete Gridshell Structures in Pre-Cast Concrete’, ACADIA 12: Synthetic Digital Ecologies [Proceedings of the 32nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) San Francisco 18-21 October, 2012), p. 209

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IMAGE CREDITS

Figure 1. Tessmer, Lavender (2013) Cast Thicket Installation. TEX-FAB Exhibition at University of Texas, at Arlington.

Figure 2. Pigram, Dave (2011) Concrete gridshell pavilion. Aarhus School of Architecture.

Figure 8. Bell, Brad (2013) Cast Thicket assembly sequence. TEX-FAB Exhibition at University of Texas, at Arlington.

Figure 10. Yogiaman, Christine (2013) Cast Thicket Details. TEX-FAB Exhibition at University of Texas, at Arlington.

Figure 12. Tessmer, Lavender (2014) Detail of rippled seam tab joinery. St Louis, MO

Figure 13. Yogiaman, Christine (2014) Full scale prototype of mylar formwork. OPUS 6 Exhibition at Sharjah Art Foundation, UAE.

KENNETH TRACY teaches architectural design at the American University of Sharjah where he is an Assistant Professor of Architecture. Tracy has taught at the Pratt Institute, Columbia University, the New Jersey Institute of Technology, as well as Washington University where in 2009 he established the Digital Initiative CNC Research Lab. Tracy holds a Master of Architecture Degree from Columbia University and Bachelor of Design Degree from the University of Florida. In 2005 Kenneth co-founded Associated Fabrication, a digital fabrication shop in Brooklyn, New York. Currently Tracy co-directs Yogiaman Tracy Design whose research includes designs, lectures and writing related to digital techniques and culturally resonant craft practices.

CHRISTINE YOGIAMAN is an Assistant Professor at the American University of Sharjah, where she teaches architectural design. Focused on digital technologies in early architecture design education, Christine has coordinated the Graduate Core studio sequence in conjunction with her development of a digital curriculum at Washington University in St. Louis. Christine directs Yogiaman Tracy Design, currently designing projects in Indonesia that focus the utilization of digital technologies techniques along with contextual influences to create culturally embedded, affective work. She has received third place for 2012 Steedman Fellowship international design competition, and has won the 2012 TEX-FAB APPLIED: Research through Fabrication competition.

LAVENDER TESSMER, a designer, fabricator and material researcher, is currently a lecturer at Washington University in Saint Louis, where she has taught courses in architectural representation and digital fabrication since completing her MArch at the school in 2011. Specializing in parametric design, material testing, connection design and visualization, Lavender has worked for three years with Yogiaman Tracy Design (yo_cy) on both residential and commercial projects, as well as a variety of architectural installations. The firm won first place at the 2012 TEX-FAB international design and fabrication competition, with their entry, “Cast Thicket,” which was installed at the University of Texas/Arlington in 2013.