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

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IMAGE CREDITS
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Figure 10. Yogiianman, Christine (2013) Cast Thicket Details. TEX-FAB Exhibition at University of Texas, at Arlington.
Figure 12. Tessmer, Lavender (2014) Detail of ruffled seam tab joinery, St. Louis, MO
Figure 13. Yogiianman, Christine (2014) Full scale prototype of mylar formwork. OPUS 6 Exhibition at Sharjah Art Foundation, UAE.

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