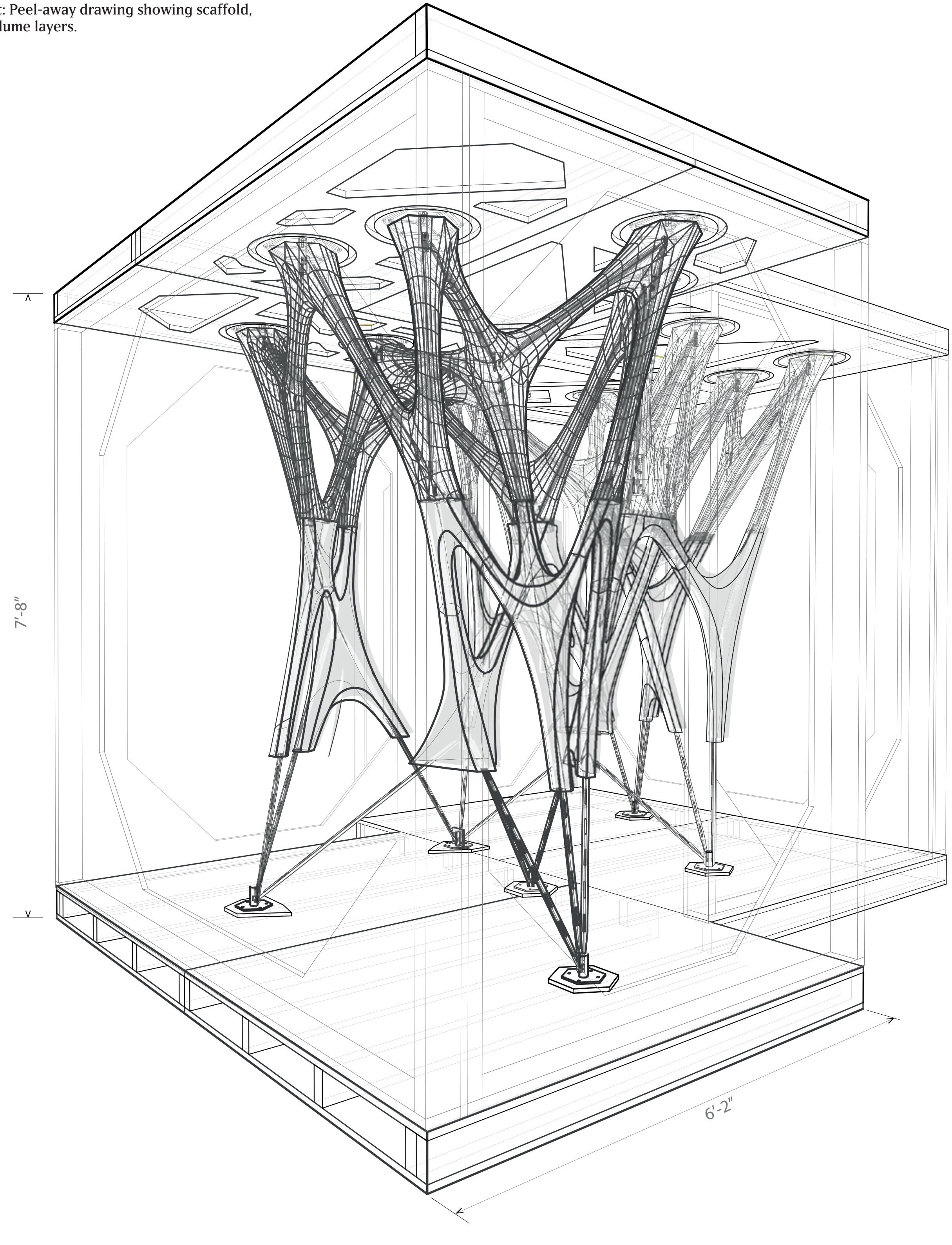
Fig. 1: Cast Thicket: Peel-away drawing showing scaffold, steel, skin and volume layers.



PLASTIC-CAST CONCRETE: FABRICATION AS APPLIED RESEARCH

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Cast Thicket is a prototypical installation that furthers earlier research into tensile concrete moulds through the use of plastic formwork and a layered structural network. Leveraging the fluid materiality of 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. Proposed as an application for tall, concrete buildings, the research responds to the 2012 APPLIED: Research through Fabrication competition. Collaboration between Yogiaman Tracy Design, the TEX-FAB fabrication network, the TOPOCAST Lab and Buro Happold Engineering facilitated the project's realisation and expanded the discussion beyond the single installation.

APPLIED: RESEARCH THROUGH FABRICATION

Within the field of architecture, exploration involving computational fabrication is both wide and varied. There is no standard of how the technology is developing and no singular focus on how it is impacting the design process or the construction of buildings. And yet, there is growing evidence that the application is quickly evolving in a variety of unique directions. From novel geometries and innovative structures to improved material and environmental performance, it is clear there is a focused agenda towards a more rigorous implementation of the digital toolset through applied research.

The impetus for this development is coming simultaneously from three positions that collectively provide a critical nexus in the field of computational fabrication: First, the professional demands for buildings to have greater performance capacity, stylistic coherence, and economic efficiency; second, the academic realm where experimentation, research, and theory continue to push technological exploration forward; and third, industry, where innovative development is both an economic imperative and a generative vehicle for technical application and testing.

Cast Thicket is the winning proposal of the two-stage APPLIED: Research through Fabrication competition (fig. 2). The winning

Fig. 2: Cast Thicket: Installation at the TEX-FAB Exhibition at the University of Texas, Arlington. (Photo: Craig Gillam)

team of Yogiaman Tracy Design (yo_cy) along with TEX-FAB, TOPOCAST Lab, and Buro Happold worked to execute the next iterative step in the development of research into tensile concrete moulds through the use of plastic formwork and layered structural network. This collective action demonstrates both the range of innovation being conducted in the field of computational fabrication research and also the capacity for collaborative action to facilitate compelling opportunities for exploration.

CAST THICKET PREMISE

Architectural use of tensile formwork is not new. Patents date from as early as 1899 and ongoing practitioners continue to push the boundaries in terms of practical application and aesthetic expression.[1] Miguel Fisac's work from the late 1960s is arguably the first that leverages the expressive materiality and practicality of soft moulds.[2] Fisac's work consciously expressed the softness of the plastic moulds and the fluid materiality of concrete.[3] Inspired by Fisac's buildings, Andrew Kudless furthered 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 geo-textiles to create large-scale, concrete components that optimise structure while using minimal material.[5]

Cast Thicket continues this work on soft moulds, but is distinct in two ways. First, it uses semi-rigid polypropylene sheets with integrally fabricated seam connections. Second, the overall organisation uses a tensile network of struts and nodes to distribute load and create space. These distinctions yield several technical and spatial advantages. Embedded, prefabricated seams in stiff plastic expand the formal language of tensile moulds allowing for concave ruled-surface geometries as well as convex forms. The seam strategy also allows for the tool-less assembly of seams in 3D space and reduces the need for vertical seam supports. The tensile network formation in conjunction with localised surface optimisation allows the minimal use of mould surface while remaining incrementally variable and spatially responsive to contingent design constraints.

DYNAMIC TENSILE NETWORK

The design of the latest iteration of Cast Thicket used a compressive scaffold as its starting point (fig. 1). The scaffold allows the internal mould to be entirely tensile and serves as a reference for positioning the frame. TOPOCAST Lab additionally developed the scaffold to act as transport bracing and shipping. Fitting the scaffold into the gallery space for the exhibition thus set the preliminary size and weight constraint of the overall piece. Within these constraints, yo_cy developed a tensile network, which became the centreline for both concrete mass and steel reinforcement.

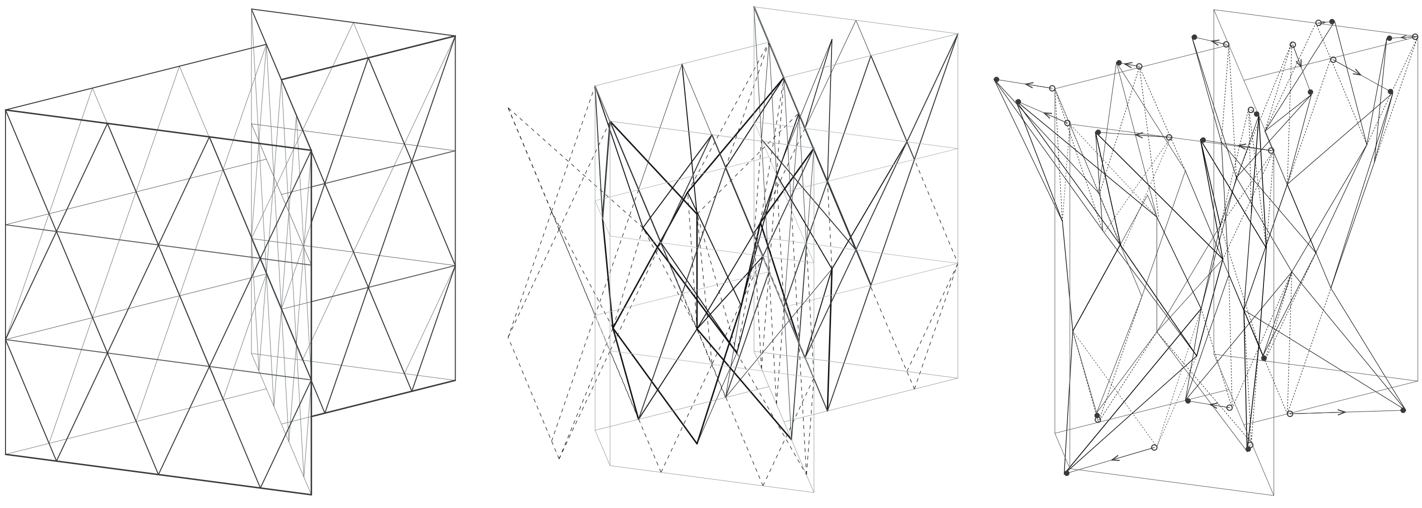

Fig. 3: Massing strategy diagrams: (from left) Equilateral triangles with three levels of vertical diagrid, truncated massing grid with simplified interior branching members, and base points spread out for stability.

Starting from an initial grid converted to virtual springs in Kangaroo, yo_cy set up an optimisation scheme similar the game cat's cradle (fig. 3). Played out over a series of iterations, the virtual spring simulation is trained into an optimised, interlaced network. Using 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. This nuanced, haptic design process allows yo_cy to interface with and adjust to the structural concerns from Buro Happold while creating a formation that demonstrates the maximum flexibility of the system.

STRUCTURAL ANALYSIS

The computational approach used by yo_cy in developing the form allowed a fluid exchange between the design and analysis models. The embedded centreline skeleton is the primary interface for design iterations. The iterative simulation allowed the design and fabrication team to make decisions about member lengths, cantilever spans, and the required bracing during construction.

To prevent the concrete from cracking, the final geometric configuration must satisfy the imposed loads without failure or signs of stress. The neuron-like formation of the piece, though inherently stable, does not provide direct vertical load paths and its upper, cantilevered branches resulted in some high nodal moments. These constraints on the structure, once analysed, confirmed the original strategy of relying on a steel reinforcement frame for tensile support. To ensure that the concrete does not show signs of stress, the underlying steel is designed to do the primary structural work, not relying on the concrete for stability, while minimising deflections in both the pre- and post-cast conditions.

STEEL REINFORCING FRAME

Cast Thicket's internal steel frame replaces typical steel rebars. Using both flat-cut and radial laser cutters, the system leverages CNC technology and parametrically variable connections to create a smooth fabrication workflow and to insure precise positioning within the slender moulds (fig. 4). The system uses T-section struts and vertical pipe connectors to overlay the tensile network's spans and nodes. Organising the welding workflow in stages allows small node components to be tack welded so the frame can be cold assembled and positioned before the final structural welds are made.

Centred at each node, vertical pipes act as the primary positioning element of the assembly. Indexing the azimuth angle of each connection, these slotted pipes receive the hooked tenons of the vertical component of the T-sections. Each strut is fabricated from three flat-cut parts. Registering the altitude angles of each connection, the vertical portion of the 'T' is bisected so each side can be pre-welded to its corresponding node-pipe (fig. 5). Working with TEX-FAB, yo_cy designed

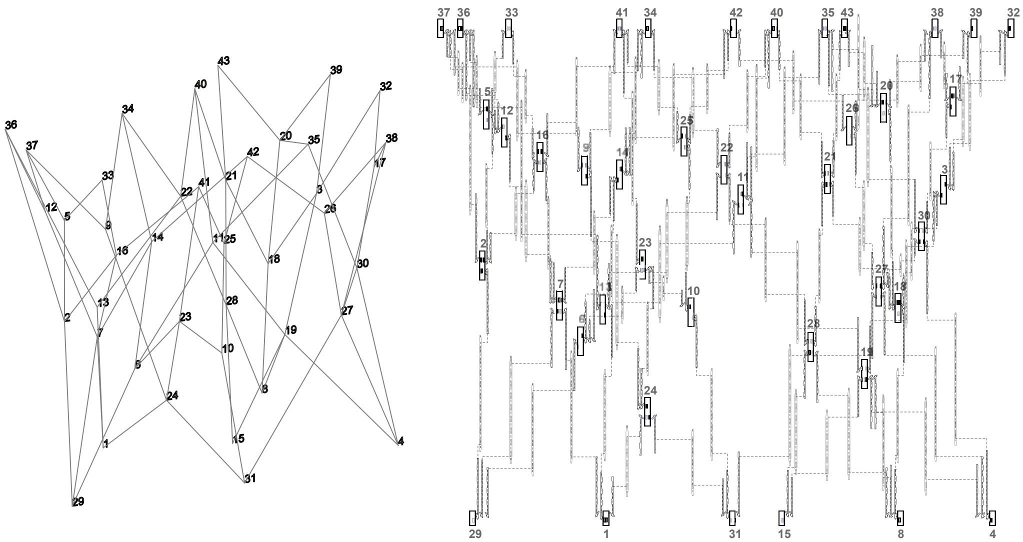

Fig. 4: Cast Thicket: Diagram showing relationship of steel components.

a system of CNC cut angle-finding jigs to precisely locate and weld the vertical strut components to the node-pipes (fig. 6). A notched, horizontal T-component spans the full length of each strut, precisely aligning to the tenons of each pair of bisected verticals. This three-part connection system allows pre-welded, branching nodes to be 'stitched' together and temporarily secured with zip ties. Using a system developed by TOPOCAST, the zip-tied assembly is precisely located relative to a template in the base of the scaffold and then welded in place.

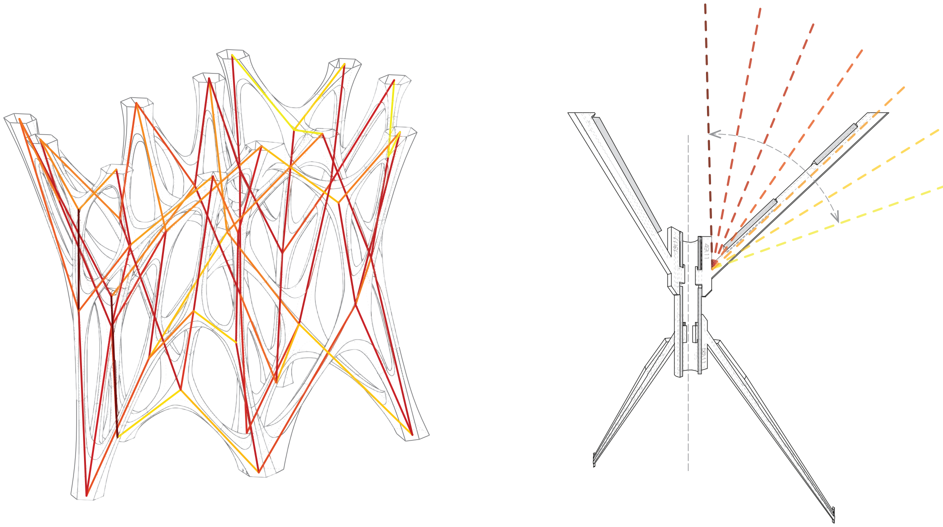

Fig. 5: Steel assembly diagrams: Variety of vertical steel connection angles, range of vertical angles accommodated by steel pipe detail.

MOULD SURFACE OPTIMISATION

Again using the spring network as a centreline, the mould patchwork starts from a piped, hexagonal profile. 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 (fig. 7). Relaxation dynamically simulates the behaviour of a stretchy, tensioned skin morphing the straight, longitudinal profiles towards minimal arcs. Several parameters were at play in formally defining the final surfaces. Increasing mesh subdivision prior to relaxation greatly decreased the volume of the final mesh creating a more linear formation, while decreasing subdivisions spreads the struts into more continuous surfaces. The intensity of the relaxation can be varied through using more or fewer iterations. Each iteration brings the struts closer to a true catenary profile, thus reducing their surface area. Limiting this variation is crucial, as it tends to create a bottleneck for concrete when the profile area at the centre 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.

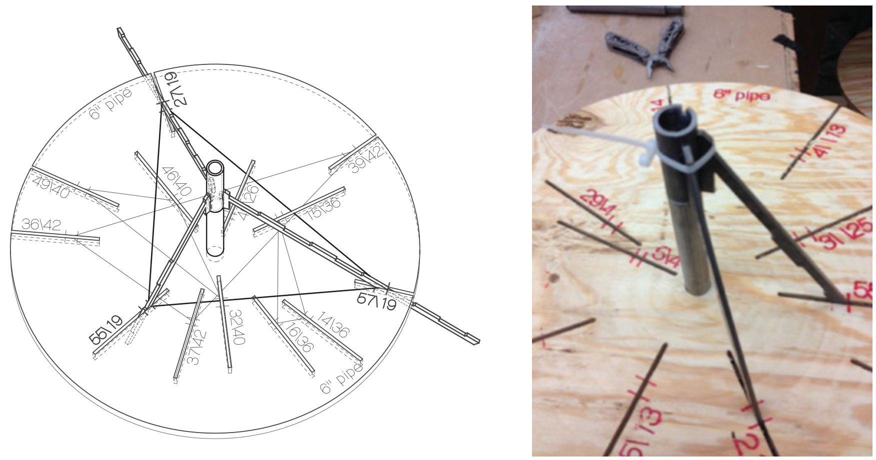

Fig. 6: Steel assembly process: Precise horizontal angles registered by angle-finder welding jig. Radially-cut steel pipe, flat-cut steel struts, and plywood angle-finder jig. (Photo: Brad Bell)

PLASTIC FORMWORK

Integrally fabricated parametric tabs are used to lace or tie the tensile plastic patches together. Seam curvature indexes the relaxation of the mesh. This same curvature guides the distribution of the tabs, which increase in density to correspond with reduced curve radii (fig. 8). This non-uniform distribution of tabs allows for stronger, more redundant connections at nodal joints where most tension occurs during the casting process.

Designed to be assembled exclusively from the exterior of the formwork, the tabs leave a smooth tensioned seam on the interior of the mould surface. Calibrated to the dexterity of the hand, a single hole in each tab creates a finger-sized handle to allow incremental manual lacing of the seams. Sequenced after the final welding of the steel frame, the external tabs allow the skins to be partially pre-laced in groups that correspond to nodes and then wrapped around the steel to form the moulds (fig. 9). This strategy organises the skin assembly so several nodes can be assembled simultaneously (fig. 10).

Once assembled around the steel, the plastic formwork is further tuned using techniques developed by TOPOCAST Lab.

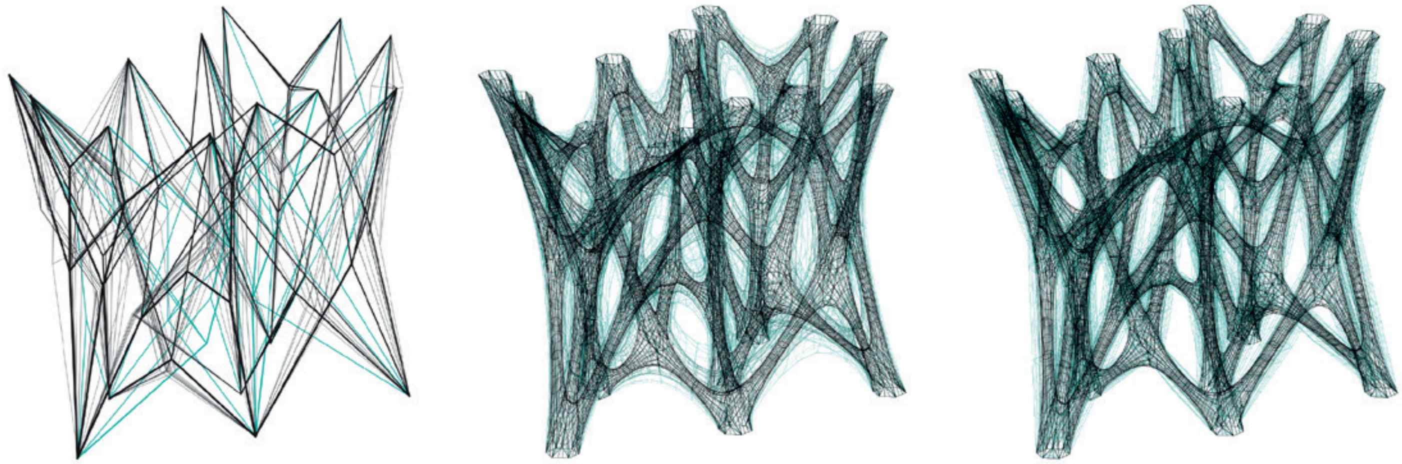

Fig. 7: Form-finding and optimisation diagrams: (from left) Tensile network optimisation, mesh subdivision form-finding resulting in varying porosity, and mesh relaxation varying iterations.

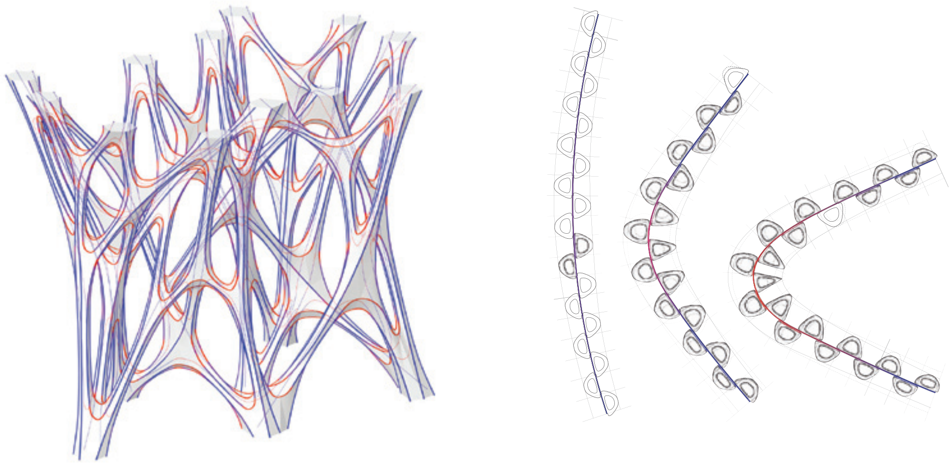

Fig. 8: Plastic formwork detail diagrams: Seam curvature analysis, tab density increases with increased curvature.

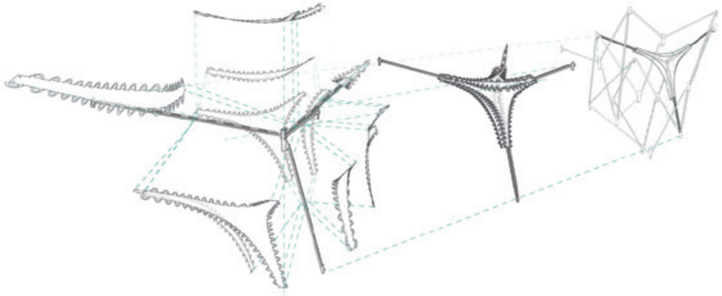

Fig. 9: Cast Thicket: Exploded axonometric drawing describing assembly process.

The tabs play an important role at this stage providing an anchoring device for seam reinforcement and positioning the mould relative to the scaffold. Nylon string is laced through the tabs and reinforces the mould at the bottom nodes and in other areas of high pressure (fig. 11). Further reinforcing can be achieved locally through the use of zip ties during pouring. Though empirically determined, these techniques evidence the tensile nature of the mould and the materiality of the polypropylene by piggybacking on the optimised connection system.

Fig. 10: Plastic formwork assembly process: Assembled steel frame, plastic formwork being tied around steel frame, and fully assembled plastic formwork. (Photo: Brad Bell)

Fig. 11: Nylon string laced through tabs in plastic formwork. (Photo: Ken Tracy)

CONCRETE COMPOSITION

The final material component of Cast Thicket is a custom formulated mix of high strength, low-viscosity white concrete. Several substitutions and admixtures were made to create a mix that is light-weight and facilitates pouring into the complex, slender moulds. Using Poraver®[6] expanded glass to replace sand as a fine aggregate is the most significant deviation from typical concrete. This ultra-light, air-filled aggregate reduces the overall weight of the mix by 22%, allowing a significantly larger construction and enabling manual positioning inside the gallery. Polypropylene fibres reduce small cracks that may occur during movement, and set retarders and plasticisers increase workability time and liquidity. Along with precisely screened large aggregate, these admixtures allow the concrete to flow into small gaps and enable larger quantities of concrete to be poured incrementally into the intricate moulds (fig. 12).

CONCLUSION

Borrowing from earlier research, Cast Thicket provides a proof-of-concept, which has both significant challenges and shows potential advantages over other tensile mould typologies. While successful at this scale, the simulation of both structure and mould deflection remains overly simple, and does not account for buckling. Scalability remains a challenge both in terms of labour management and seam strength. Integral seams do allow for variation, but testing on larger scale components and less relaxed components would significantly add to the variation and the instrumentalisation of the process. Integration between Cast Thicket's concrete formulation, seam details, steel assembly and the overall surface optimisation are registered by small varying deflections in the final surface. This effect and the range of responses to contingent constraints within the small space of the installation, exhibit potential spatial opportunities as well as the success of Cast Thicket's implementation. Adding concave surface variation and flexible spatial configurations into the mix of soft mould typology provides both designers and researchers with a glimpse into one potential future for architectural form.

NOTES

1 Diederik Veenendaal, Mark West, and Philippe Block, 'History and overview of fabric formwork: Using fabrics for concrete casting', *Structural Concrete* 12, no. 3 (2011), p. 165.

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

3 Luis Fernández-Galiano, 'Miguel Fisac', *AV Monographs* 101 (2003).

4 Andrew Kudless, *Bodies in Formation*, p. 102 (See note 2).

5 Veenendaal, West and Block 2011 (see note 1), p. 172.

6 Poraver® is a registered trademark of the Canadian firm Poraver North America Inc.

Fig. 12: Casting process: Assembled polypropylene formwork, formwork after casting, and unwrapped concrete. (Photos: Craig Gillam)