Tensile Configurations

Exploring Spatial Membrane Tensegrity Shell Structures

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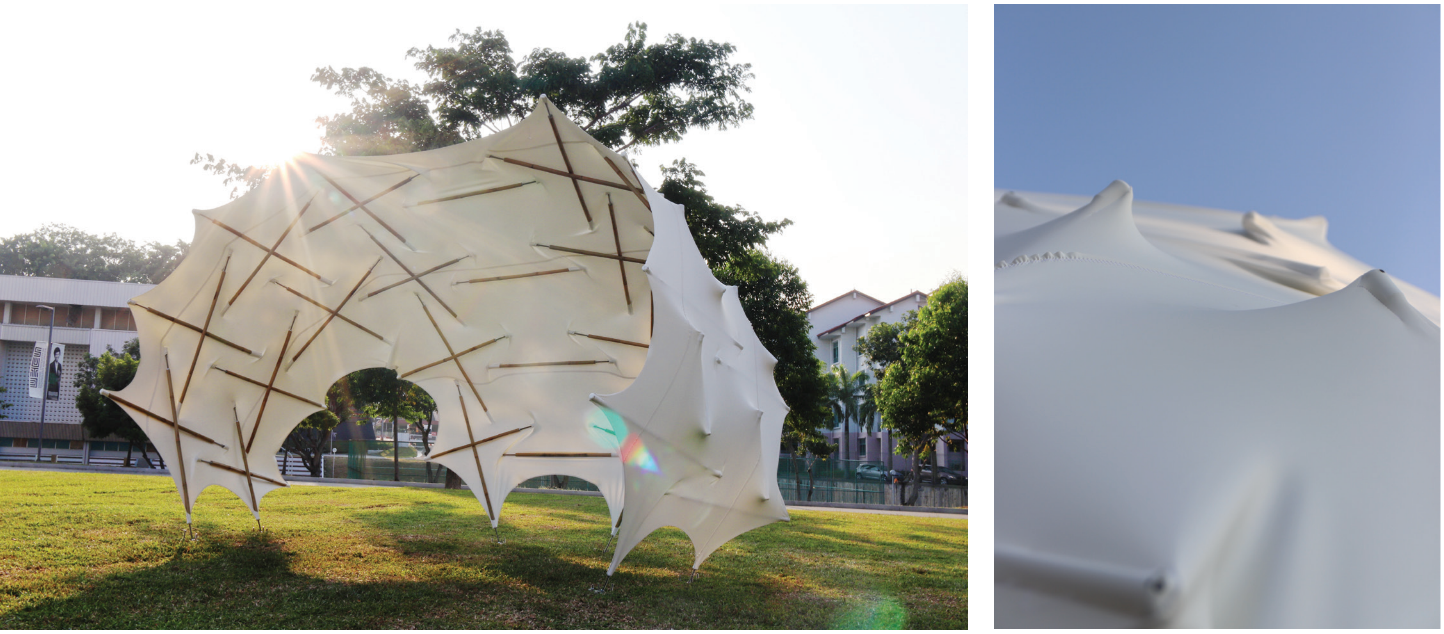

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1 Tensile Configurations studio pavilion

ABSTRACT

Structural membranes exhibit advantages over slab and frame structures, accommodating large deformations while still elegantly combining spatial enclosure with material efficiency. One of the most promising types of membrane structures are membrane tensegrity structures, which are composed of discontinuous struts embedded in a tensile membrane. To date, membrane tensegrity structures are limited to completely closed formations or require extensive tethering, hindering their applicability for diverse architectural contexts.

Here, a design framework is presented for creating self-supporting membrane tensegrity shell structures with spatial openings, enabled by novel reciprocally tessellated strut configurations. Through a combination of heuristic physical prototyping and digital form-finding tools, a library of membrane tensegrity forms has been developed that serves as tangible data for an expanded morphospace. To test the effectiveness of the established methods, a 10 m^2 membrane tensegrity shell pavilion was built as a first large-scale demonstrator. Feedback from this demonstrator led to the development of computational strut tessellation tools that enable the search for informed, performance-driven design space.

INTRODUCTION

Textile membrane structures are renowned for their ability to span wide spaces while remaining incredibly thin, offering lightness of weight and distribution of load solely through tension. However, one recurring challenge to their implementation is that these structural typologies typically require a substantial external support system to tether the membrane, resolve its live loads, and continuously apply sufficient amounts of pretension to maintain its stiffness (Knippers et al. 2013). Creating decomplexified textile membrane structures that do not require such extraneous support can potentially mobilize their widespread adoption. One approach to achieve a self-supporting tensile structure is by instilling tensegritic design principles. Tensegrity (tensile-integrity) structures, as the root of the name suggests, are tension-dominant structures that consist of minimal, discontinuous (non-touching) compression elements connected by an array of continuous tensile elements. In the words of their inventor, the architect and futurist Buckminster Fuller, they can be viewed as "islands of compression in a sea of tension elements" that exhibit high structural efficiency (Fuller 1962). Tensegrity structures are a provocation to the status quo of reliance on mass and thickness: the compressive elements are diminished in size and mass to such an extent that they serve solely as a means of pretensioning and transferring loads to thin, ubiquitous tensile elements, which serve as the primary structure. The compression elements were materialized as struts in the tensegrity structures that were envisioned by Fuller in the 1960s, whereas cables offered tensile capacity. With this choice to use such one-dimensional tension elements came an inherent problem of adding enclosure as a separate layer to the system. The utilization of a membrane—which can be abstracted as the wide-spanning, two-dimensional version of cables—combines structure and enclosure. However, as explained later in the Background section, precedent membrane tensegrity structures have been unable to fully achieve these promised advantages and have been limited to closed forms that struggle to fulfill more advanced architectural programming.

In light of these current limitations, this paper presents a design framework for realizing self-supporting membrane tensegrity shells of a variety of 3D forms. This work both builds upon and differentiates itself from previous examples of membrane tensegrity by implementing structurally performative reciprocal strut tessellations that are far more effective in achieving the pretension required to maintain structural integrity without being tethered to any external supports, while still allowing for programmatic architectural features such as openings. The undertaken research approach consisted of two coupled design space search methodologies: (1.) intuitive, heuristic, and systematic physical prototyping to understand how the material system can be manipulated to achieve design intent, and (2.) the creation of form-finding tools for digitally exploring the morphospace. The design space search was conducted in the context of the Tensile Configurations undergraduate design studio at the Singapore University of Technology & Design (SUTD), which focused on investigating membrane tensegrity morphologies that invoke optimal air flow conditions in tropical climates. The combination of physical modeling and digital form-finding tools was used to generate a promising pool of shell designs, one of which was selected, scaled, and constructed as a 10 m^2 membrane tensegrity shell demonstrator. This demonstrator provided valuable feedback that led to development of machine learning-based computational design tools for performative strut tessellation. This paper will detail the formulation of these membrane tensegrity shells design methods, highlighting their successes, limitations, and opportunities for further development.

BACKGROUND RESEARCH

Design and Simulation of Membrane Tensegrity

Tensegrity, and specifically membrane tensegrity structures, have been modeled and simulated using a nonlinear finite element method (FEM) approach in the context of computational mechanics for several years (Juan and Mirats Tur 2008; Shigematsu et al. 2008; Yang and Sultan 2016). In contrast to these rigorous structural descriptions, which focus on carefully accepted, idealized examples of membrane tensegrity, to the authors' knowledge there exists no exploratory, open-ended digital design frameworks for membrane tensegrity shells. This is accented by the fact that membrane tensegrity forms with both integrated openings and spatial enclosure have not yet been described, as the structural system instinctively wants to conform into continuous, closed volumetric surfaces to minimize its potential energy (Shigematsu et al. 2008).

Reciprocal Tessellations

Reciprocal patterns consist of mutually-supporting elements arranged within a closed circuit (Song et al. 2013). They are well-regarded for their simplicity in self-similarity, performative redundancy, tectonic appeal, and intrinsic beauty, having been admired and implemented for centuries in compression-based frame structures. Shigematsu et al. (2008) pointed to the success of using reciprocal strut patterning in membrane tensegrity as a means of effectively distributing the membrane pretension, creating strut configurations for physical models of basic membrane forms such as cubes, tubes, and spheres. The method for determining these successful reciprocal patterns is not included in Shigematsu's work but reveals a compelling opportunity to apply computational design and optimization tools to generate performative strut configurations.

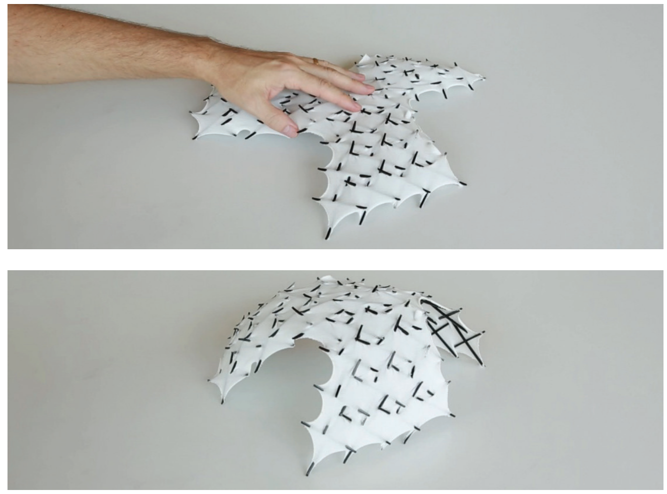
Built Precedents of Membrane Tensegrity

Built architectural examples of membrane tensegrity structural systems are rare, possibly due to lack of awareness of the structural typology given that tensegrity and contemporary textile structures did not gain traction until the 1950s. While there has been active research in the recent decade in constructing bending-active textile hybrid structures (Slabbinck et al. 2017), this is sharply distinguished from membrane tensegrity structures where only pure tension and compression exist. The MOOM Membrane Tensegrity Pavilion—designed and constructed by C+A Coelacanth and Associates and students of the Tokyo University of Science in 2011—is the only full-scale membrane tensegrity structure to date to the authors' knowledge, realized as a 26 m long installation composed of a polyester membrane with aluminum tubular struts inserted (Kojima 2011). While certainly serving as an impressive demonstrator, there are two shortcomings of the MOOM Pavilion that have been identified. Firstly, the structure makes use of external cables in order to be fully pretensioned, so the staggered pattern in which the struts are distributed in the membrane does not internally pretension the structure to the capacity it requires to be standalone: it is not a fully self-supporting structure. Secondly, the pavilion form is essentially a closed funnel with an entrance post-rationalized by cutting a hole into the textile, rather than being a natural opening that is a programmatic feature of the shell form to encourage an open-air experience. These are both areas of improvement which this work aims to address with the established design methods.

DESIGN METHODS

Physical Prototyping

Physical prototyping of membrane tensegrity structures occurred at both the small scale and the 1:1 scale, with the latter imparting knowledge for the construction of the full-scale demonstrator. Due to speed and ease of production, systematic study of small-scale hand models of membrane tensegrity shells (fitting within an approximately 250 cm^2 area) was the main strategy to empirically understand the working principles of the structural system. The hand models were produced by simply arranging thin acrylic sticks within flat pieces of elastomeric textile. By designing them with barbed ends, the sticks could hook around the textile threads, causing the elastic material to stretch. The stretched membrane's natural tendency to shrink inwards to its original size is opposed by the attachment of



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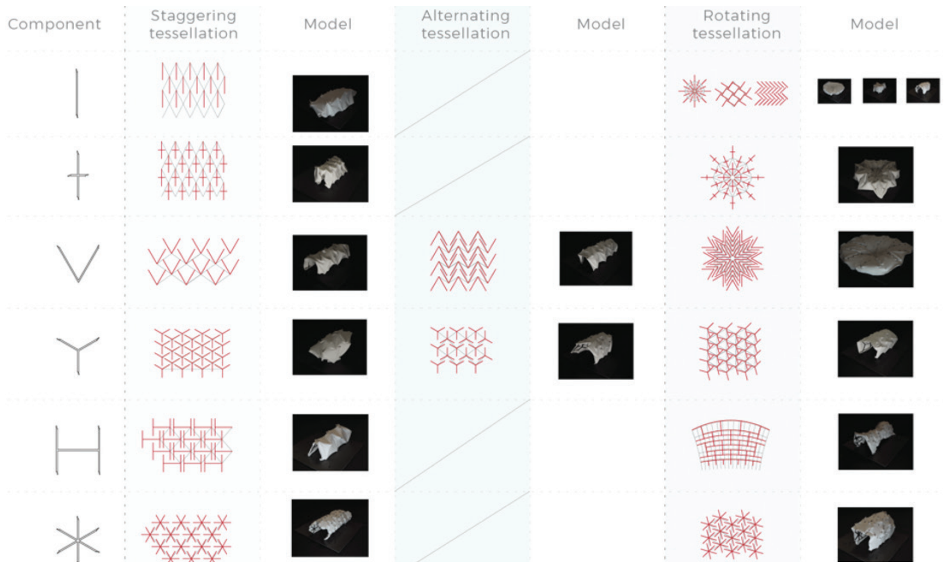
axially-stiff struts to the membrane, resulting in an energetic frustration that is released by the textile assembly rising into a 3D form (Figure 2). This 3D form is dependent on the tessellation of struts in the plane of the membrane and the initial shape and material properties of the textile.

In this study, different strut tessellations were explored: staggering, alternating, and rotating, as well as a variety of strut geometry such as linear, crosses (Vs, Ys, and Hs), and asterisks; these parameters were combined in pairs to make a design space matrix, as seen in Figure 3. This investigation was first carried out with the membrane cut as a simple rectangle to produce a tunnel form once activated by struts. The tunnel typology served as a control in the pursuit of more open and expressive morphologies, while also enabling comparison to predecessor membrane tensegrity structures, i.e. the MOOM Pavilion. After conducting these experiments on tunnels to establish the physical prototyping workflow, new design primitives such as funnels, saddles, and domes were brought forth as potential typologies. These primitive forms emerged in anticipation of their ability to feature multiple entry points and airfoil-inspired membrane walls for enhanced air flow. By manipulating all of these parameters—strut geometry, strut tessellation pattern, and choice of design primitive—in an iterative, trial-and-error fashion, a design space to explore membrane tensegrity shells was conceived (Figure 4).

During the course of this investigation, a crucial finding was that by combining the staggering and rotational strut tessellation patterns, sound and redundant distribution of prestress was induced. This was characterized as reciprocal patterning, with one reciprocal tessellation tile consisting of four strut units whose ends pull the section of membrane which they surround in a circuit-like fashion



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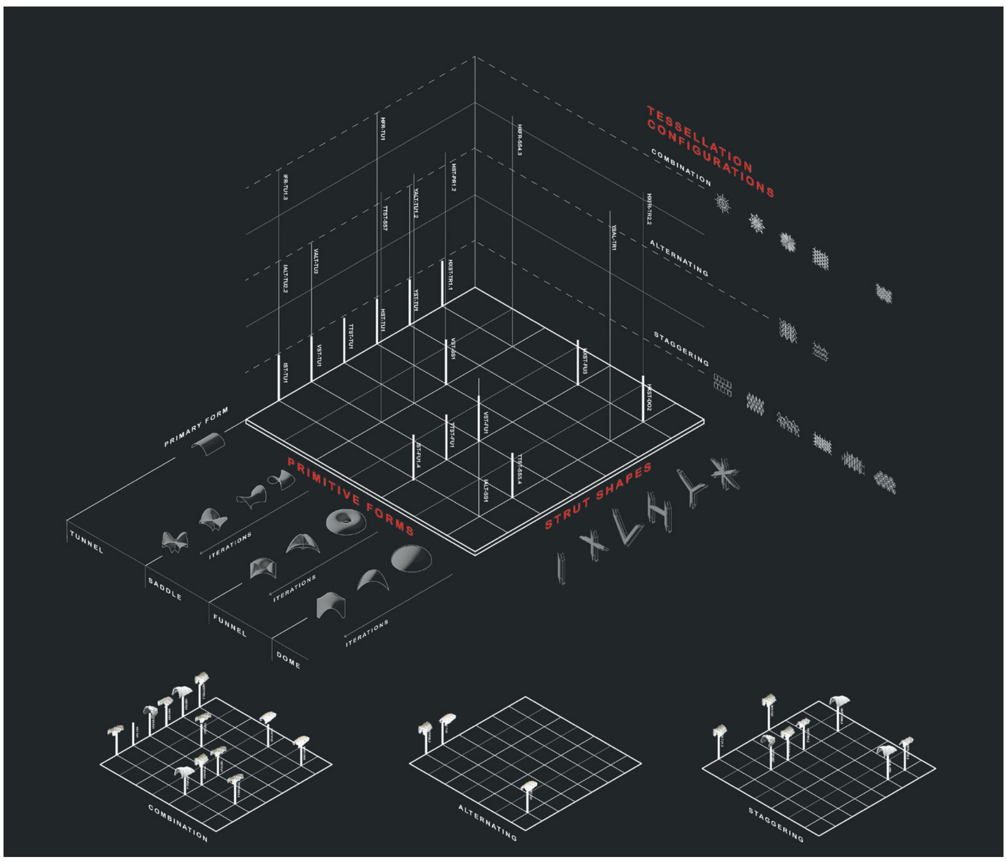

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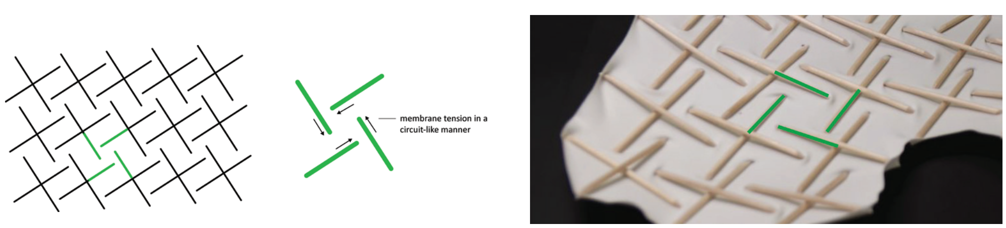

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2 Physical interaction between compressive struts and elastic membrane causes a transfer from potential to kinetic energy that allows an initially flat tensegrity structure to rise into a 3D form

3 Exploration matrix of strut shape and tessellation patterns; note that alternating tessellation patterns did not apply to strut shapes with bilateral symmetry

4 Representation of design space that emerges when exploring strut shape, tessellation pattern, and choice of design primitive

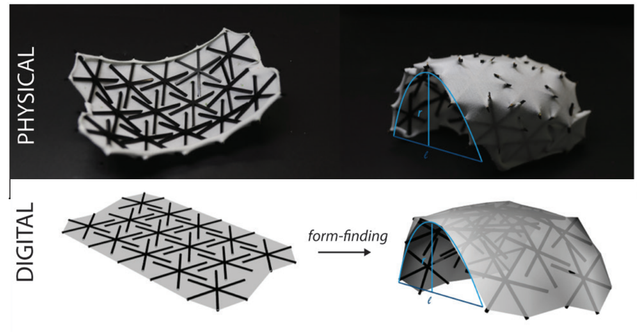
5 Reciprocal strut patterning is used to tension the membrane in a circuit-like fasion

(Figure 5). By introducing these periodic lines of pretension in a repeating pattern across the surface across the membrane, pretension of high degree and uniformity could be achieved, producing improved stiffness and smooth curvature. Thus, from its point of discovery onwards, this reciprocal tessellation patterning was implemented.

Digital Form-Finding

With enormous morphospace of unknown dimensions, a need arose to rapidly iterate through various strut configurations and evaluate the stability of membrane tensegrity shell designs without investing the time to physically model every single one. Thus, to supplement the physical exploration, a means of modeling and simulating membrane tensegrity shells was required. A nonlinear FEM approach as per the literature precedents was nontrivial and out of the scope of the design studio. Instead, a more accessible digital modeling framework was established in the CAD software Rhinoceros with its visual programming plugin Grasshopper. Because membrane tensegrity structures are form-active systems, a form-finding approach to model the structures using positional dynamics in the Kangaroo physics engine was implemented. An overview of the form-finding workflow can be seen in Figure 7.

First, a strut configuration was manually drawn as linear curves, from which a Delaunay mesh was generated with the 'Delaunay mesh' Grasshopper component to model the membrane as a cable net using the strut endpoints as vertices. Although the actual membrane's mesh of textile fibers was far denser than that of the digital mesh resolution, the Delaunay cable net mesh nonetheless served as an approximate model given that the primary lines of pretension between struts is represented by the Delaunay mesh edges. These mesh edges were designated as linear springs using the 'Length' Kangaroo component and were given a 15% shrinkage in length to simulate prestress, mirroring the physical reality of the struts stretching the elastic membrane. The curves representing the struts were attributed as springs with high stiffness relative to the membrane mesh edges, reflecting the physical struts' rigidity. With this energetic frustration in place due to the interaction between the shrinking mesh and stiff struts, the system was finally given a tiny amount of momentum in the upwards direction using the 'Floor' component to encourage the structure to find its 3D conformation above the ground plane (Figure 6). Four corner points of the mesh were constrained to the ground to mimic the structure resting on a surface. If the shell model failed to rise, or collapsed, this indicated that the strut configuration was not structurally performative and must be adjusted. The settings of the simulation were tuned using the dimensions



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of the physical models, using an arc of heights, *r,* and length, *l,* as references until satisfactory visual fidelity between the two was achieved. Upon calibration, this digital form-finding methodology enabled rapid, indicative testing throughout the membrane tensegrity design space.

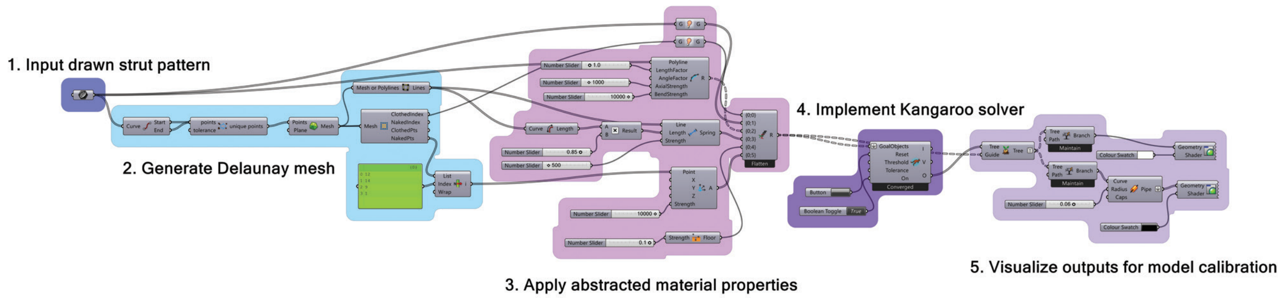
Digital-to-Physical Workflow

After having form-found geometries that showed structural promise, physical models could be produced in a more selective manner. The digital model was used as a production template to coordinate the physical material system, specifically the shape of the membrane in its unstretched state, the positions of the strut ends, and the lengths of the struts. The initial membrane shape was provided by the outer boundary of the Delaunay mesh model and could be cut with a digital cutting system. This outline was segmented into patches based on the size constraints of the cutter and the locations of the strut ends, which determined the placement of sewn pockets in which struts could be inserted to attach to the membrane. The locations of these pockets were manually marked on the membrane in its flat state according to the initial positions of the strut ends in the digital model, and the strut lengths were directly provided by their digital counterparts. With this digital-to-physical workflow implemented, realization of the material assembly based on a digital design was feasible.

RESULTS AND REFLECTION

Expanded Membrane Tensegrity Morphospace

Figures 8 & 9 show the evolution of membrane shells from closed to open forms over the course of the research. The initial tunnel-like forms that were used to better understand the structural system blossomed into "transitional forms" that represented an intermediary stage before achieving more performance-based morphologies. The primitive forms that next resulted—funnel, saddle, and dome, with the tunnel remaining as a control—developed from expectations of their optimal air flow performance due to their varied openings and airfoil-inspired walls. Finally, the proposal forms showed the most promising structural



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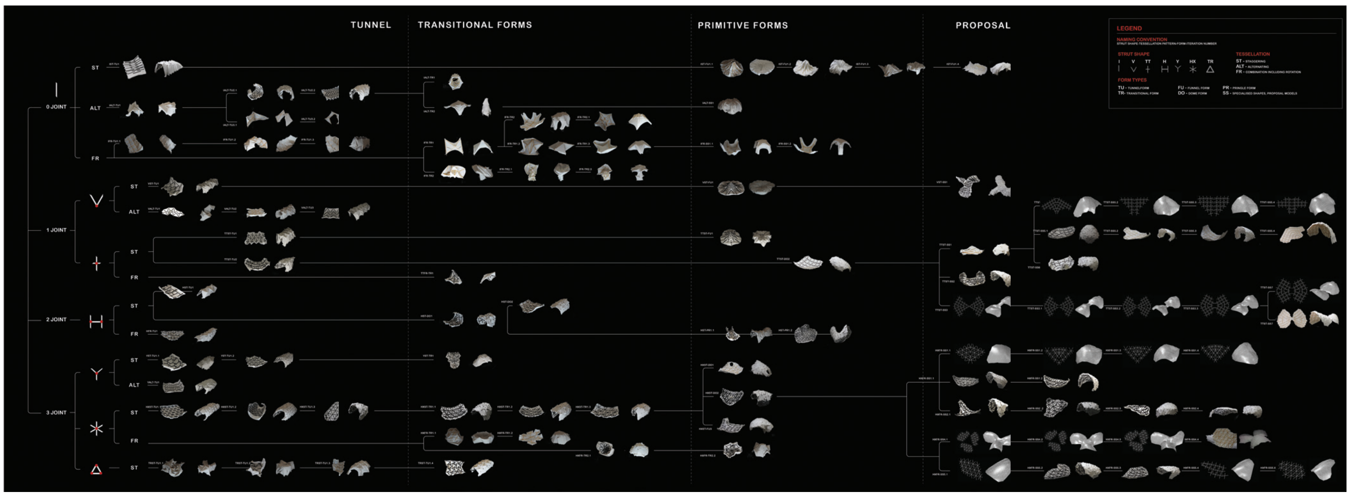

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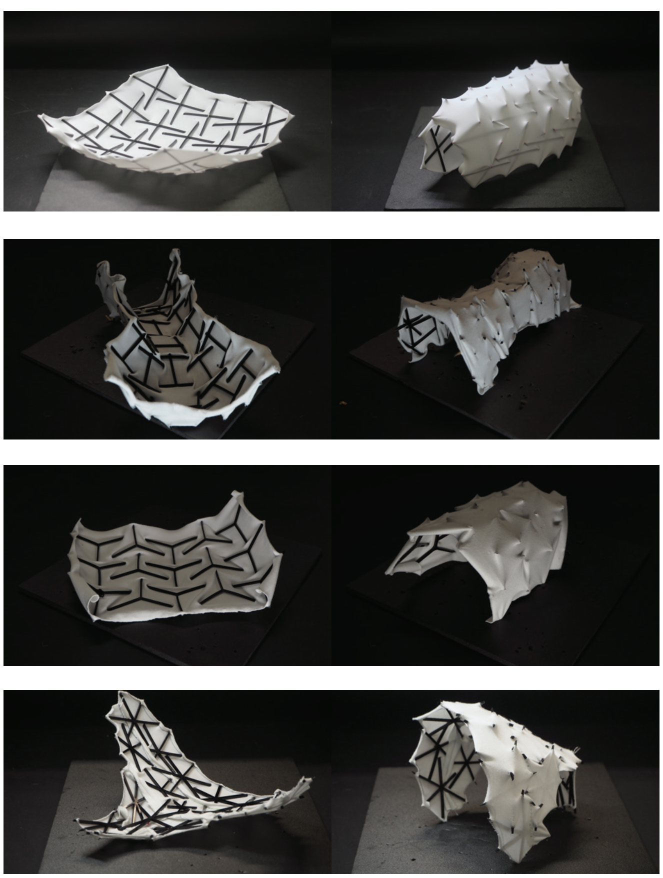

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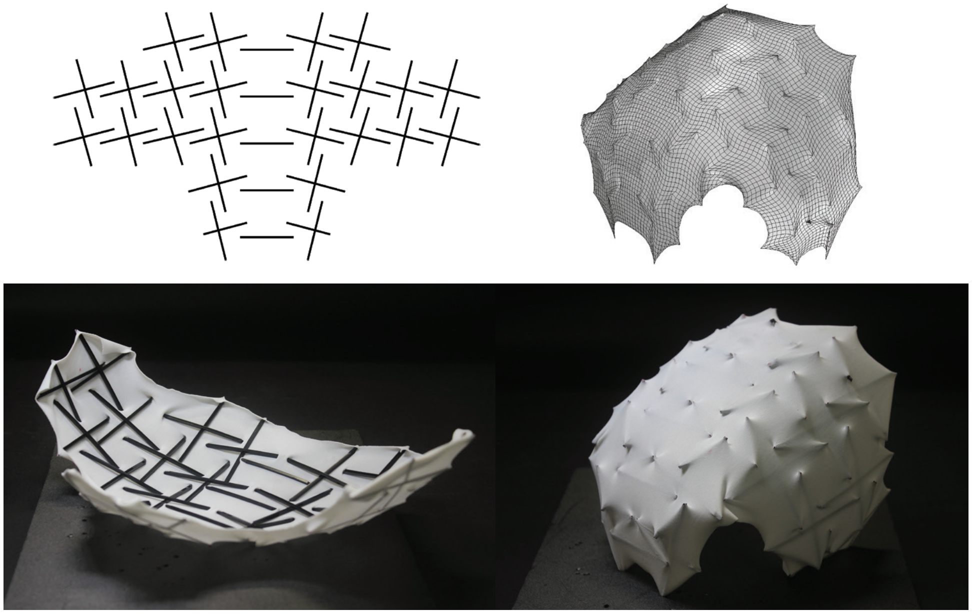
6 Example of results of form-finding simulations of a planar strut pattern to digitize the 3D physical models; the digital models were then calibrated by the curvature of basic physical models until satisfactory fidelity was achieved

7 Form-finding workflow

8 Generational timeline of membrane tensegrity open shell forms

9 The formal exploration transitioned from closed tunnel forms (top) to more open forms (bottom) that attempted to maximize the size of openings

performance in both the digital and physical realm. The reciprocal strut configurations enhanced structural capacity of these membranes to allow them to handle more intense structural scenarios, resting upon fewer support points to permit large openings. However, it was concluded that the asymmetrical strut shapes (Vs and Ys) did not produce consistent pretension distribution and thus were discarded. Rapid prototyping, which was possible due to both the speed of the physical modeling and computation-driven form-finding, enabled design space searches of breadth and depth that illuminated previously unexplored areas of the membrane tensegrity morphospace. These experiments served as tangible data that was compiled into a library of rationalizable membrane tensegrity shell forms. Those forms seen at the rightmost end of the generational timeline were considered as candidates for the full-scale demonstrator.



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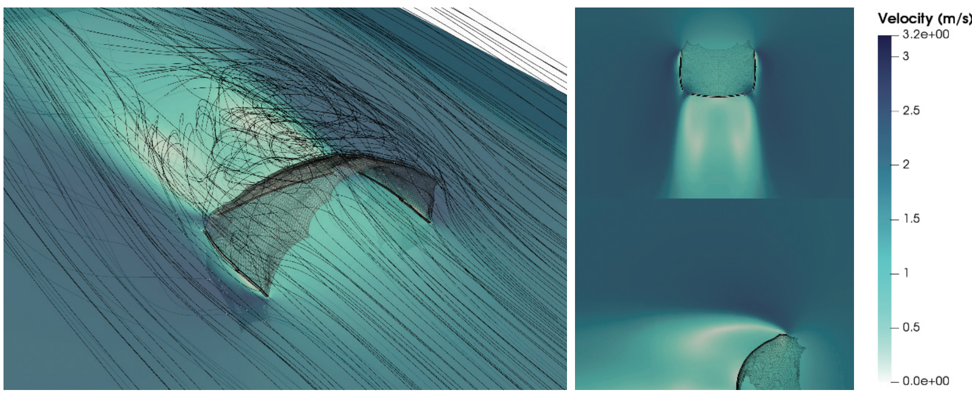

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10 (Left) Digital and physical final strut pattern consisted of two halves or reciprocally pattern cross struts and a spine of linear struts; (right) digital and physical final shell design

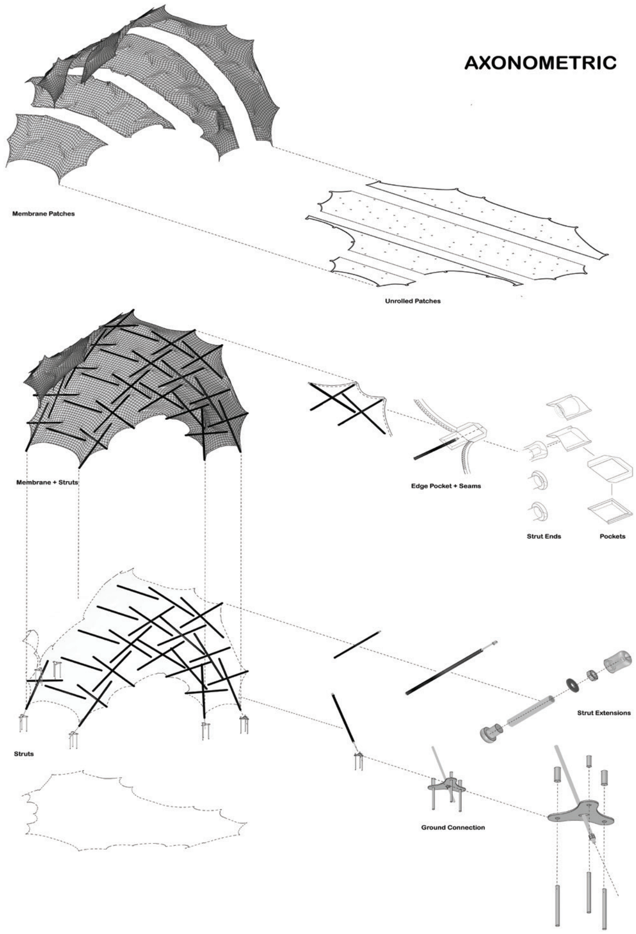
11 CFD analysis guided the design of the final membrane tensegrity form: the results are displayed with a linear color gradient from low (light) to high (dark) wind speeds. The simulations were run using OpenFOAM and visualized in ParaView. Steady state was assumed and The case setup the membrane shells in air were: (a) steady state (b) 2m/s velocity North-South winds from +Y-direction (average wind condition), (c) fixed initial pressure in -Y-direction and (d) assigned slip symmetry to remaining walls of test region

12 Axonometric view of the components that composed the tensegrity membrane assembly

13 (a) Parameters for reciprocal patterning which the Opossum optimization solver can vary; (b) Strut configuration for a shell design optimized for minimum variation in positive Gaussian curvature; (c) Form-found result for a shell design optimized for minimum variation in positive Gaussian curvature

Full-Scale Demonstrator

One shell design was selected to test this structural system at full scale as well as demonstrate its potential as a textile architecture typology. Utilizing the developed methods, the authors and students set about designing and constructing a 10 m^2 self-supporting membrane tensegrity pavilion. The shell design was required to feature structural stability in its physical model, and reciprocal strut tessellations with crosses and linear strut units were preferred due to their ease of fabrication compared to units with more struts. To underline the capacity of such structures to create an open-air spatial experience, the pavilion required three features: (1.) a large entrance, (2.) a central venue for gathering, and (3.) openings that promoted wind flow. The most promising shell form that catered to the desired programme can be seen in Figure 10. To confirm this design's environmental performance, the membrane geometry underwent computational fluid dynamics (CFD) studies using OpenFoam—an open source software for CFD. The associated wind velocity results from this design are displayed in Figure 11 with a linear color gradient from low (light) to high (dark) wind speeds. Although two openings through the back of the pavilion were designed to be non-obstructive, the formation of a pocket of vorticity within the pavilion became a buffer that reduced the speed of approaching winds. However, the large frontal opening of the pavilion exposed the occupants to more air movement relative to a completely closed volume. It was also notable that greater velocity was observed within the structure than in its wake region, which supported the design decision. With the pavilion design confirmed, the digital-to-physical workflow was implemented to rationalize the production of the material components seen in Figure 12. This demonstrator consisted of a polyester-based membrane material and bamboo tubes retrofit with an aluminum extension mechanism for the struts. The digital model revealed that in order to span an area of 10 m^2, the membrane had a total unstretched size of 20.9 m^2.



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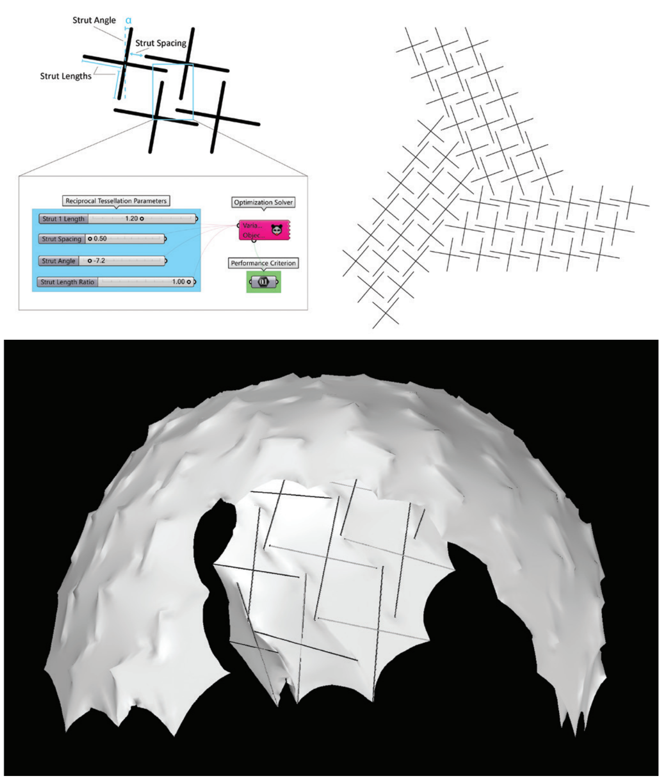

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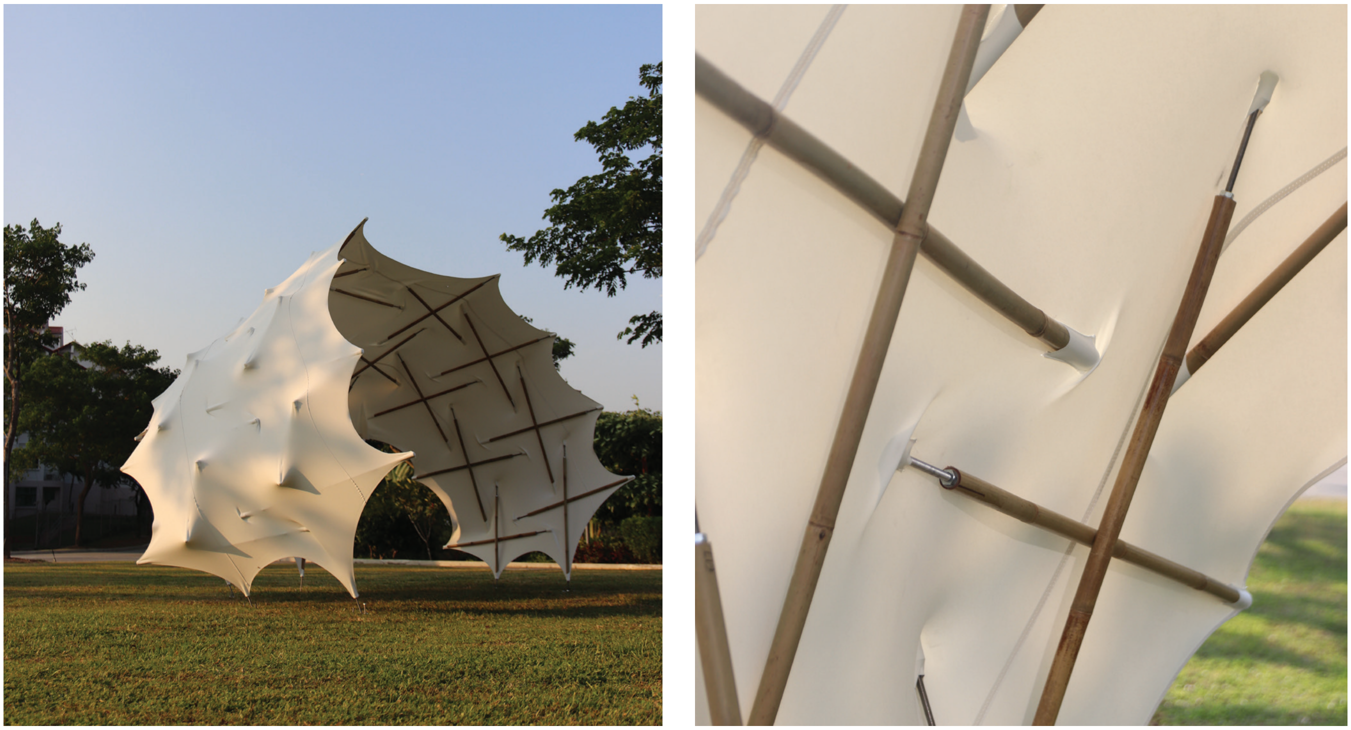
This profile was discretized into four patches which were cut on the digital cutter, sewn on an industrial sewing machine, and manually marked with the pocket locations. The 52 struts of length 1.2 m and 1 m were cut and successfully cast with the extension mechanism. After insertion into the membrane pockets, they were extended in an iterative process to slowly enable the structure to stand. The erected 10 m^2 demonstrator can be seen in Figure 14. The pockets and ground connection details fared well, showing no signs of failure and maintaining consolidation of the material assembly. The built artefact showed a high degree of visual semblance to the digital model, which provided feedback on the validity of the form-finding process. However, the pavilion exhibited structural problems: while the pavilion successfully withstood its self-weight for the several weeks during which it was on display, it was noticeably vulnerable to wind loading from different directions, swaying slightly even with the struts elongated to their full capacity. These load conditions were not present in the digital simulation and therefore not accounted for. To counteract these loads, the membrane required further pretension, which lay in improving the strut configuration. This led to a choice to further develop the strut tessellation methods.

Computational Strut Tessellation

While the trial-and-error process of testing various strut tessellation was effective in providing a more empirical understanding of how the structural system functions, this method was limited in considering the overwhelming number of geometric patterning parameters available that could influence the membrane tensegrity form. This is augmented by the inherent complexities of dealing with a nonlinear material system. For this reason, a computational strut tessellation optimization tool was developed in Grasshopper to converge upon reciprocal strut configurations that attain a definable performance criterion for the form-found model. The optimization is introduced by integrating the plugin Opossum, which leverages machine learning algorithms in the RBFOpt library to achieve solutions in a smaller number of iterations compared to other optimization solvers in Grasshopper (Wortmann 2017). Because no reciprocal tessellation tool for discontinuous elements exists to the author's knowledge, the computational tool starts with a framework for modeling the struts given three geometric parameters: lengths, spacing, and angles, which together form the basis of a reciprocal tessellation unit that can be repeated as many times as desired (Figure 13a). The form-finding process is identical to that discussed in the previous section (Digital Form-Finding), with the only change being the computationally generated struts input. The choice of performance criterion



14 Tensile Configurations studio pavilion

for the form-found membrane and whether it is maximized or minimized is dependent on the user. Criteria can include height, curvature, deflection, etc., assuming that the desired evaluations can be linked to the form-found geometry. For example, Figures 13b-c shows the optimized results for a membrane tensegrity structure where minimization of variation in positive Gaussian curvature of the mesh is the objective value in the pursuit of creating a perfect dome. This computational tessellation tool fleshes out the design framework, enabling exponentially larger exploration of membrane tensegrity forms that can be rationalized using the established physical methods.

CONCLUSION

In conclusion, a design framework for realizing self-supporting membrane tensegrity shells of a variety of 3D forms was established. Physical prototyping and digital form-finding were synthesized in an integrated design space search that resulted in a rich library of morphological data from which a novel membrane tensegrity form was generated. This virtual form was rationalized using a digital-to-physical workflow to build a physical full-scale demonstrator, which served as a proof-of-concept of the effectiveness of the developed methodologies in creating an ultralightweight structure. Feedback from this demonstrator led to further investigation of computational strut tessellation methods using machine learning to generate optimized forms.

There are several areas of further research that can be immediately envisioned to build upon this work. A robust structural analysis tool should be developed to predict the behavior of these structures and include the orthotropic, nonlinear material properties of the membrane. This could be paired with the developed optimization tools to maximize stiffness, which would be crucial for load-bearing ability at scales higher than that explored in this first demonstrator. In terms of fabrication, one current avenue of research is to additively manufacture a membrane using CNC knitting technology, which would allow gradation of stiffness and compliance in accordance with concentrations of loads provided by the struts.

The method developed in this work of post-tensioning the membrane could be also made easier, as significant manual effort was required to elongate the struts; an automated means of extending the struts would be ideal. Building on this concept would be the ability to automate the strut lengthening according to integrated sensor data, potentially making a dynamic structure that can produce subtle real-time changes in shape in response to air flow. Deploying this actuated membrane tensegrity structure as a modular system at different sites would be a compelling way of pushing lightweight textile membrane structures deeper into performance-driven architectural terrain.

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