Research Article

Prototyping knit tensegrity shells: a design-to-fabrication workflow

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Abstract
This paper describes a design-to-fabrication workflow for knit membrane tensegrity shells, a novel class of tensegrity structures that substitute discrete cables with a continuous machine-knitted membrane as the main tensile element. The workflow integrates (a) a simplified, simulation-driven design method for membrane tensegrity shells, (b) the conversion of the membrane geometry into digital inputs for Computer Numerical Control (CNC) knitting, and (c) the rationalization of the assembly connection details. This workflow begins by iteratively parameterizing reciprocal strut patterns, connecting the strut endpoints to form a mesh to represent the membrane, and implementing a dynamic relaxation algorithm to form-find the tensegrity shell geometry. The digital model then undergoes optimization procedures to negotiate between structural performance and fabrication constraints. Subsequently, the membrane geometry is extracted and converted into machine instructions to be CNC knitted with the following features: (i) integrated pockets to hold compressive struts at intended locations within the membrane, (ii) different types of yarn to create localized stiffer regions in response to stress concentrations imposed by the struts, and (iii) alterations of the shape of the membrane to adhere to the digital geometry. Several physical prototypes, including a 4-meter-diameter pavilion that was exhibited at the International Association for Shell and Spatial Structure's Form&Force Expo 2019, serve as case studies for assessing the fidelity, benefits, and limitations of the proposed workflow.

Keywords Membrane tensegrity · Simulation · Design-to-fabrication workflow · Form finding · CNC knitting

1 Introduction

Tensegrity is a self-supporting structural system that achieves static equilibrium through the distribution of minimal, discontinuous compressive elements within a network of tensile elements [1]. Unlike the current paradigm of stiff, massive, compression-dominated building structures, tensegrity structures maintain structural integrity through a higher dependence on these tension elements. This offers several benefits for this class of structures, including, but not limited to, lightness, material efficiency, deployability, configurability, and scalability [2]. In nature, tensegrity is a technical solution to attain highly adaptable and efficient structures, such as the intricate matrix of filaments and tubules that compose the cell cytoskeleton [3]. Man-made tensegrity structures have often been physically articulated as volumetric components consisting of tensile cables that are interspersed with compressive struts which pretension and transfer loads between their neighboring interconnected cables. Such principles can be seen in Buckminster Fuller's iconic spheres [1], as well as other endeavours [4]

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where tensegrity prisms and columns have been created as proofs-of-concept.

Using classical tensegrity systems as a building structure comes with the challenge of creating covered spatial enclosure. In response to this aspect, several projects have substituted the multiple cables with a singular textile membrane as a continuous tensile element to form *membrane tensegrity* structures. One prominent case study is the MOOM pavilion by C + A Coelacanth and Associates, which consisted of a thin polyester textile mesh that was tensioned uniaxially by a series of alternating aluminium tubes, creating a tunnel-like pavilion measuring 26 m (length) by 8 m (width) [5]. The MOOM pavilion successfully demonstrated scaled implementation of membrane tensegrity with an elastic membrane material and customized membrane-strut connection details. It also presented two opportunities for improvement: firstly, the closed tunnel required external cables for full tensioning, meaning that the forces were not completely resolved to allow for a truly self-supporting structure; and secondly, it was necessary to cut away a part of the membrane to create an opening for the closed space. This prompted the authors of this work to investigate the possibility of deriving fully self-supporting shell forms with large openings premised on this membrane tensegrity typology. This was achieved in a prior research project [6] and denominated *membrane tensegrity shells*, which are formed by coalescing lateral membrane tensegrity arches in a radially symmetric manner. A self-supporting synclastic structure was achieved by a reciprocal patterning of struts arranged as crosses throughout the membrane. These reciprocal patterns are akin to those utilized in efficient compression-based reciprocal frame structures [7], where tessellated unit patterns work as an interconnected network to produce a structural system in equilibrium. For membrane tensegrity systems, these reciprocally patterned strut units are interconnected via the membrane surface and thus do not need to touch. This strut patterning strategy creates numerous regions of localized pretension which provides redundancy within the membrane. By restraining the ends of the perimeter struts on the ground and pushing them closer to each other, the membrane is forced to curve upwards to form a dome-like geometry. This form is sustained by the regions of stiffness from the radial patterning of struts, allowing it to hold up as a synclastic shape.

In this lightweight system, the structural components only occupy the 'skin' of the shell and do not infringe on the interior space. Thus, the use of this system expands the morphological design space for such structures to include a wider range of synclastic geometries with multiple openings. With access to these new forms, therein lies an opportunity to design membrane tensegrity structures for previously unexplored performance criteria like occupant circulation or control of air flow.

This work pushes the investigation of membrane tensegrity shells further by augmenting it with the application of Computer Numerical Control (CNC) knitting, enabling material and geometric variations within the textile that makes the bespoke knitted membrane better suited to be the primary structural element of a membrane tensegrity system. CNC knitting is an advanced additive manufacturing technique in which knitted textiles can be shaped and customized with multiple yarn types and various stitch patterns [8] to form bespoke tensile membranes. This customizability not only influences the membrane form, but also enables the integration of external structural elements. Such strategies can be found in the domain of CNC-knitted membrane installations, as seen in the Hybrid Tower and Isoropia by the Centre for Information Technology and Architecture (CITA) [9, 10]. In these examples, fabric membranes were fully fashioned and integrated with continuous channels. This allowed the textile to house bending-active rods to facilitate the shaping and assembly of these installations. We apply this principle in the context of membrane tensegrity shells, in which the knit membrane was fully fashioned to conform to the digital geometry, while having integrated pockets to house the compressive struts which in turn stretched the membrane. The computerized control of every stitch affords functional grading to the membrane by adding higher tenacity yarn in response to stresses caused by the strut ends being inserted into the pockets of the membrane. For sake of brevity, we refer to such knit membrane tensegrity shells as *knit tensegrity shells*.

There are several digital and physical challenges to creating knit tensegrity shells. First, there is a noticeable lack of tools for designers to explore potential tensegrity shell geometries borne from the form-active nature and nonlinear behavior of membrane tensegrity structures. For engineers, state-of-the-art finite element analysis (FEA) packages typically cannot accommodate the large deformations associated with the formation of membrane tensegrity structures; in the literature, there exist examples that are able to achieve this feat [2, 11, 12], but the articulations of tensegrity are usually idealized, basic examples that underline the attainment of static equilibrium rather than more elaborate forms. Additionally, CNC knitting software requires specific digital inputs, and thus new software pipelines are required to translate CAD geometry into the appropriate inputs for the knitting software to generate knitting machine instructions. Finally, there are various fabrication constraints associated with the CNC knitting process, such as the number of yarn carriers and needle bed width, that must be included in the design

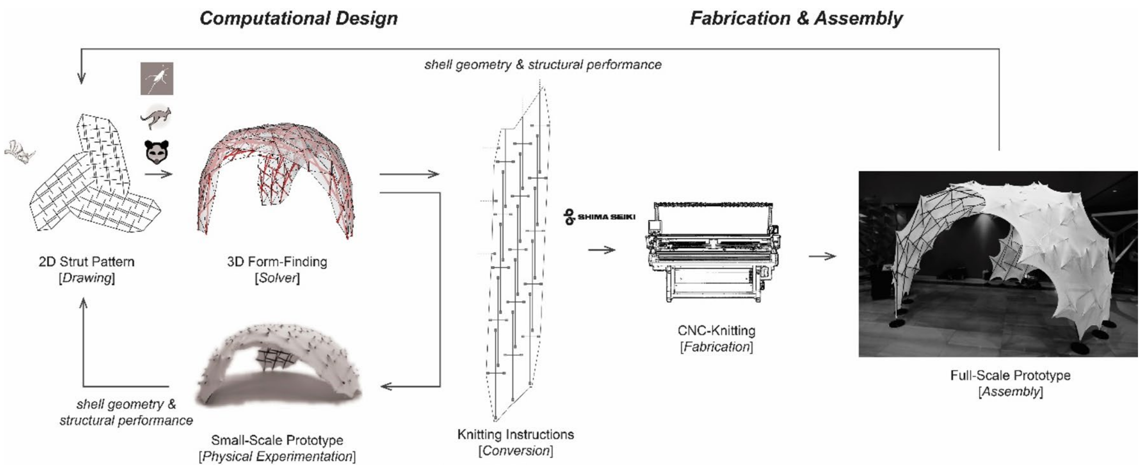

Fig. 1 Design-to-fabrication workflow for prototyping of knit tensegrity shells

phase to ensure that a knit shell structure can be physically realized.

In light of these challenges, this work presents a streamlined design-to-fabrication workflow (Fig. 1) housed digitally in Rhinoceros 3D (CAD) and Shima Seiki KnitPaint (CAM) softwares for producing knit tensegrity shells of diverse forms. This workflow integrates a simulation-driven computational design methodology for designing membrane tensegrity shells (Sect. 2), the conversion of digital membrane geometry into knitting software data for fabrication (Sect. 3), and rationalization of the various assembly connection details (Sect. 4). The design step of the workflow features constant empirical feedback from small-scale and full-scale physical prototypes to inform the strut tessellation pattern, based on evaluating the resultant shell form and its structural stability. The result of implementing this workflow is the successful transfer from digital design to physical prototypes of varying scales that are showcased in the form of various membrane tensegrity shells. The fidelity, benefits, and limitations of the developed workflow will be discussed and concluded.

2 Computational design methodology

2.1 Structural form-finding

The first step in the workflow is to create a digital model of the knit membrane tensegrity shell. Membrane tensegrity structures feature internal tensioning of the membrane through the embedding of compressive struts that stretch localized areas, enabling globally synclastic geometries atypical of traditional membrane structures (which are chiefly characterized by anticlastic geometries [13]) to become plausible. Membrane tensegrity structures are also form-active structures characterized by high degrees of deformation, and their 3D forms are a result of interactions between the struts and the anisotropic non-linear membrane element. This means that traditional top-down, material-agnostic approaches of sculpting membrane forms to adhere to an intended geometry may prove difficult or may not produce accurate results. Form-finding using a computational mechanics approach has been successfully investigated for carefully selected, idealized examples of membrane tensegrity [11, 12]. However, to the authors' knowledge, there exists no accessible, open-ended digital design framework specific to the design exploration of membrane tensegrity shells. To fill this gap, a design method was developed in Rhinoceros 3D and Grasshopper premised on the dynamic relaxation of a particle-spring system using the Kangaroo physics engine. This dynamic relaxation approach was extended from previous research by the authors that studied the form-finding of membrane tensegrity shells [6]. Kangaroo is a suitable platform to form-find membrane tensegrity shells in an interactive interface and is less computationally costly than FEA. Here, the authors use a particle spring system that uses positional dynamics based on Newton's second law. Forces are introduced by native Kangaroo components and the algorithm minimizes the system's internal energy to reach static equilibrium in a nonlinear system [14].

The design process starts with the tessellation of struts in 2D. Struts are modeled as lines in a cross format and reciprocally patterned parametrically using Grasshopper in consideration of their lengths, spacing, angle and quantity within a bounding area which represents the outline of each 'petal' of the membrane (Fig. 2a). Each of these geometric parameters is associated with an adjustable slider so users can flexibly tune these parameters. The struts are

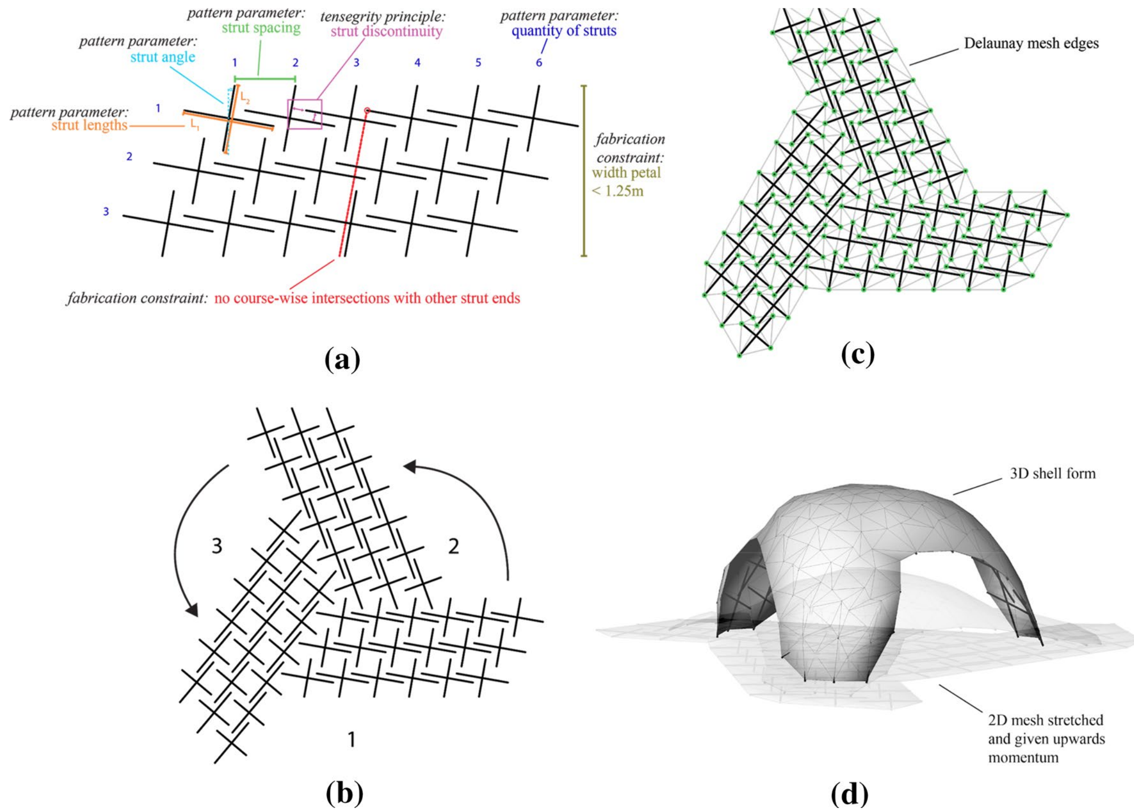

Fig. 2 Strut pattern search and form-finding tool. **a** Strut pattern for one petal is designed according to a variety of parameters such as strut length, angle, spacing, and quantity, in addition to fabrication constraints. **b** The strut pattern for one petal is then arrayed 360° to create the full pattern. **c** A Delaunay mesh is generated using the endpoints of each of the struts as mesh vertices. **d** The struts are then instructed to extend by a predefined amount, and this is coupled with upward 'momentum' to allow the system to converge upon a 3D form

then radially arrayed 360° to form multiple petals that are combined to form the full shell strut layout (Fig. 2b). A Delaunay mesh is generated using the endpoints of each of the lines to model the membrane as a cable net, with the interconnected mesh edges representing internal pathways of tensile forces that occur between neighboring strut ends (Fig. 2c). The Delaunay cable net serves as an approximate model for the membrane since these cables represent the network of force flows within the membrane that receive the most tension and are therefore the most active in generating the membrane form.

The subsequent form-finding step is performed in Kangaroo where a particle-spring system is created using the input mesh (cables) and lines (struts). This involves converting the cables and struts into springs with abstracted material properties. The struts are assigned with a goal to extend to a specified amount (ranging from 1.7 × to 2.4 × in length depending on the prototype), mirroring how the actual struts are physically stretching the membrane to induce tension within the system. The cables are instructed to maintain their lengths, albeit with a lower spring stiffness relative to the struts. This property of the cables causes them to stretch, yet attempt to revert to their original length, exerting a reaction force analogous to a stretched knit attempting to return to its former unstretched dimensions. However, the cables are impeded by the extension of the stiff compressive struts. With this simulated energetic state in place, the system is given a small amount of upward vertical momentum against the direction of gravity to encourage convergence above the ground plane. The result of all these applied forces in the particle-spring system is a 3D shell geometry that reaches a state of equilibrium within 1 min of starting the simulation (Fig. 2d). If the digital model fails to rise, or collapses, this indicates that the strut tessellation needs to be adjusted as it does not tension the membrane sufficiently to allow it to stand. Only with the successful convergence of the form-finding into a self-supporting 3D geometry do we consider the designed structure to be feasible.

In the context of this paper, the authors intend for the knit tensegrity shells to function as a dome-like pavilion where occupants can walk through freely. Thus, the selected performance criteria would be the heights of the openings and the overall structure, as well as the curvature

Fig. 3 Illustrative catalog of various digital shell geometries based on different strut tessellation patterning

of the dome (elaborated in Sect. 4.2 for the development of the IASS Expo pavilion). Once form-found, the simulated geometries are selected with the above criteria in mind. The resultant cable-net can then be processed using Kangaroo into a mesh with a higher resolution for visualization purposes. The parameterization of the strut patterning, coupled with this simplified modeling approach, means that various tessellation patterns, and consequently membrane tensegrity shell designs, can be rapidly explored and empirically validated by the user (Fig. 3).

The strut patterning and form-finding processes were further calibrated by physical models to determine the accuracy of the digital models when compared to their physical counterparts. The Kangaroo form-finding parameters were adjusted using measurements of length, height, and radius of principal curvatures of 3D scans of knit shell physical models with several strut patterns such as those seen in Fig. 4. Another set of experiments was conducted on physical models to test how to increase the principal curvature of the resultant shell along the longitudinal axis. This would allow the shell to achieve a taller height over a smaller footprint, which would contribute to the goal of making a human scale structure with an entrance that is tall enough for head clearance (at least 2.5 m).

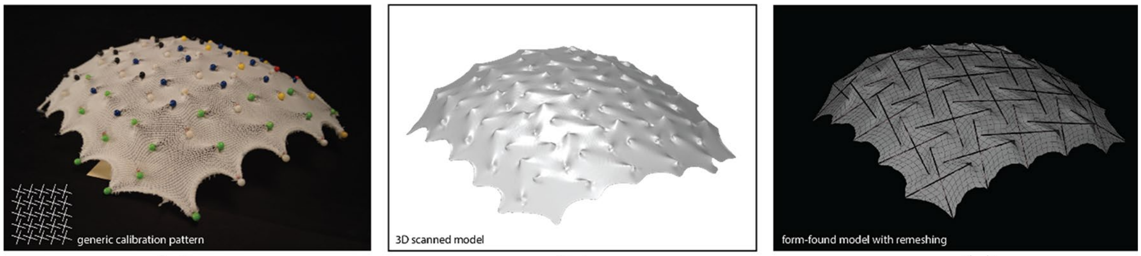

Fig. 4 **a** Physical model and **b** 3D scanned digital model used for form-finding calibration. **c** Form-found calibrated model with remeshing for visualization

Fig. 5 Comparison between two models with the same strut pattern but different amounts of stretching. Left—Top view of membrane stretched 2× along the course-wise axis and 1.75× along the wale-wise axis; Second from left—Top view of membrane stretched 1.75× along the course-wise axis and 2× along the wale-wise axis; Right—Front views of respective membranes. The model that is stretched more along the wale-wise axis is observably taller

The longitudinal axis in our case corresponds to the wale-wise knitting direction of the fabric, as the limited width of the needle bed (1.25 m) restricts the course-wise fabric dimension. Comparative 1:10 physical models of a single petal were made with varying extents of membrane stretching (1.75 × and 2 ×) by keeping the strut pattern constant and either varying the length of the struts or the position of the strut ends on the membrane. Based on visual observation, the petal that achieved the tallest height (i.e. largest principal curvature due to residual stress in the longitudinal axis) was a petal with greater stretching along the wale-wise axis than along the course-wise axis (Fig. 5). This may occur because knitted fabrics are characterized by anisotropic behavior: due to the geometry of the knitted loops, the knitted fabric is stiffer along its wale-wise axis compared to its course-wise axis. Thus, to achieve an appreciable degree of curvature in the model's longitudinal axis, the principle of stretching the membrane more along the wale-wise axis guided the strut pattern and selection of strut lengths.

2.2 Fabrication-informed patterning optimization

In addition to the structural stability of the generated strut tessellation pattern, two major fabrication constraints based on the knitting machine used in this research had to be factored into the pattern search for human-scale prototypes of knit tensegrity shells. The first was the width of the needle bed. Factoring the shrinkage from the elastic yarn, this amounted to a width constraint of 1.25 m for each petal. Moreover, no more than two strut end pockets could be aligned along the transverse (course-wise) axis of each petal, as this would exceed the number of available yarn carriers needed to knit the pockets. These two issues combined posed a challenging spatial problem given the reciprocal patterning of the orthogonally arranged struts. To overcome this, the Opossum optimization plugin in Grasshopper was used in tandem with the form-finding tool to search for strut patterns that met both fabrication constraints and produced a shell that met the design objectives. Opossum was linked to the numerical sliders dictating the geometric parameters that were used to generate the strut pattern (lengths, spacing, and angle). The plugin operates by being fed a single criterion that it attempts to maximize or minimize in a threshold number of iterations by dynamically adjusting the sliders and reading the resultant criterion value in an iterative fashion. To hasten this search for the desired objective value, Opossum leverages machine learning algorithms from the RBFOpt black box optimization Python library [15]. In this case, this criterion was defined as the sum of the number of intersections between course-wise (pink) lines aligned

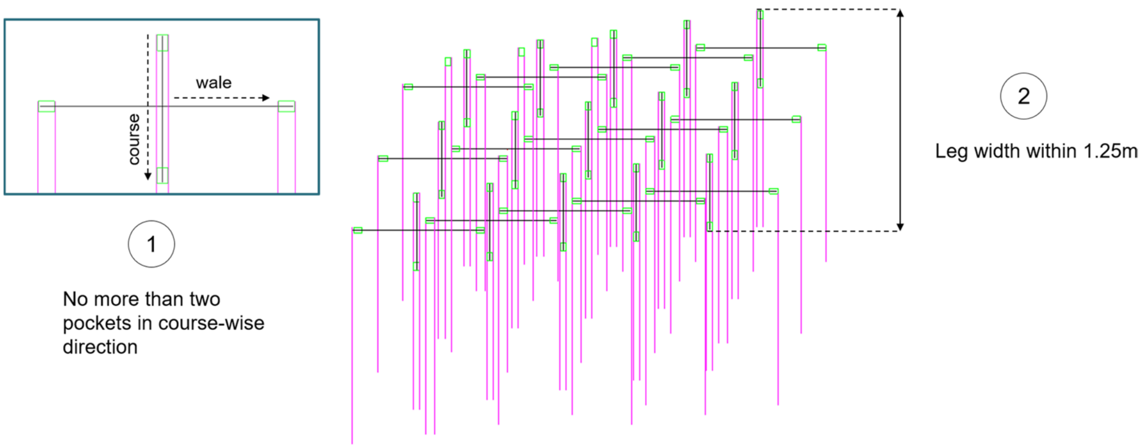

Fig. 6 Strut pattern optimized using Opossum so that the number of course-wise pocket intersections is zero and the petal width falls beneath 1.25 m. The pink lines represent the upper/lower edges of the green pockets (strut pattern is rotated 90° in this figure)

with the upper/lower edges of the pockets (green rectangles) and the deviation in petal width from 1.25 m (Fig. 6). Opossum was instructed to minimize this value (i.e. reach zero intersections and under 1.25 m width). After as little as 300 iterations, Opossum could successfully locate a strut pattern which satisfied these fabrication criteria while producing a desired shell geometry, and this allowed us to proceed to the next step of the workflow.

3 CNC knitting of membrane

To physically realize these knit tensegrity shells, the membranes were knitted on a Shima Seiki MACH2XS computerized, 15-gauge WHOLEGARMENT weft-knitting machine. CNC knitting allows for stitch-by-stitch control of the knitted fabric [8] so that different regions of the membrane can be knitted with different yarns and stitch patterns depending on the functional or aesthetic requirements of each region.

3.1 Yarn material and stitch patterns

In the smaller prototypes, these physical models demonstrated that the areas where the strut ends come into contact with the membrane are at risk of tearing. Therefore, the 1:1 scale prototype was designed with integrated pockets to house the strut ends. These pockets were knitted using 540D UHMWPE-spandex yarn (400D ultra-high-molecular-weight polyethylene, 140D spandex), which helps to prevent material failure when the struts are inserted. UHMWPE filament was chosen for its high breaking tenacity of 25.5 cN/dtex (information provided by material supplier) and significant resistance to abrasion. To form the pockets, the UHMWPE-spandex yarn was knitted using two stitch patterns—single jersey and tubular single jersey (Fig. 7). The single jersey is knitted as a rectangle around a tubular single jersey pocket, acting as an added layer of reinforcement in this region of high stress.

The stiffer pockets were paired with regions of stretchable 550D spandex-polyester yarn. The use of elastic yarns with high elongation (~ 300%) enabled us to stretch the petals to be wider than what is knittable by our machine. To minimize the weight of the membrane, single needle bed stitch patterns (versus double needle bed stitch patterns) were chosen. Piquet lacoste stitch pattern, which is formed by alternating between knit only rows and knit-tuck rows [10] (Fig. 7), was selected because the presence of tucks (as opposed to knit or miss stitches) reduces the course-wise (horizontal) shrinkage after knitting, resulting in a wider piece of fabric compared to other single needle bed stitch patterns. To minimize the amount of cutting and sewing required, the membrane was shaped during the knitting process using two methods. The first method is to add and remove stitches so that selected parts of the fabric become wider, narrower, or skewed. The second method uses a combination of water-soluble yarn and sacrificial waste yarn that are knitted alongside the main membrane body. These are removed by dissolving the water-soluble regions after knitting to form the final shape of the membrane.

3.2 CAD geometry to knitting instructions

Yarn and stitch patterns are implemented within the physical knitted membrane by converting the digital model into knitting machine instructions. Once the desired shell geometry is obtained from the form-finding simulations and validated for fabricability, the flattened membrane geometry of a single petal is scaled in Grasshopper to

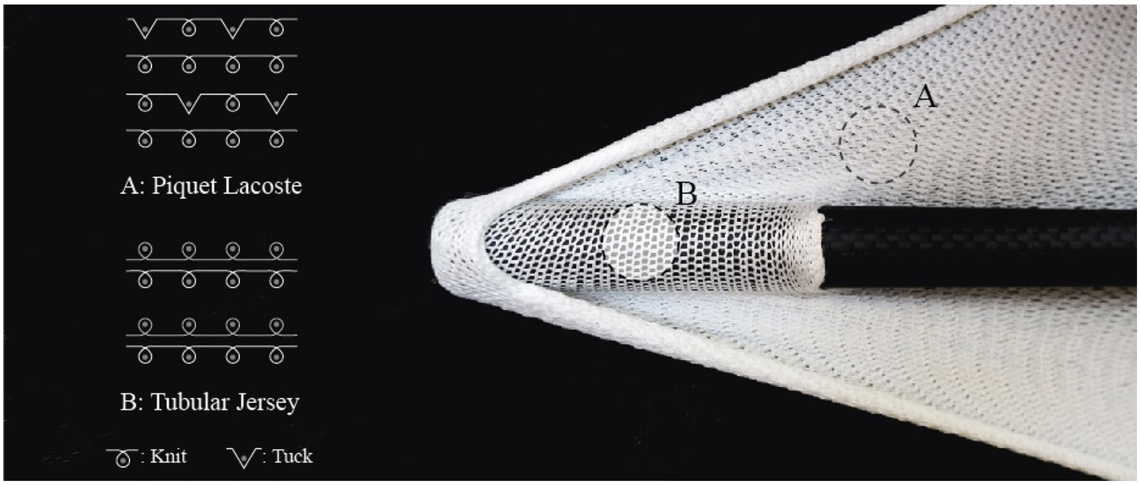

Fig. 7 Left—Knit notation for piquet lacoste (main body) and tubular single jersey (pockets); Right—Pocket with carbon fiber strut end inserted inside

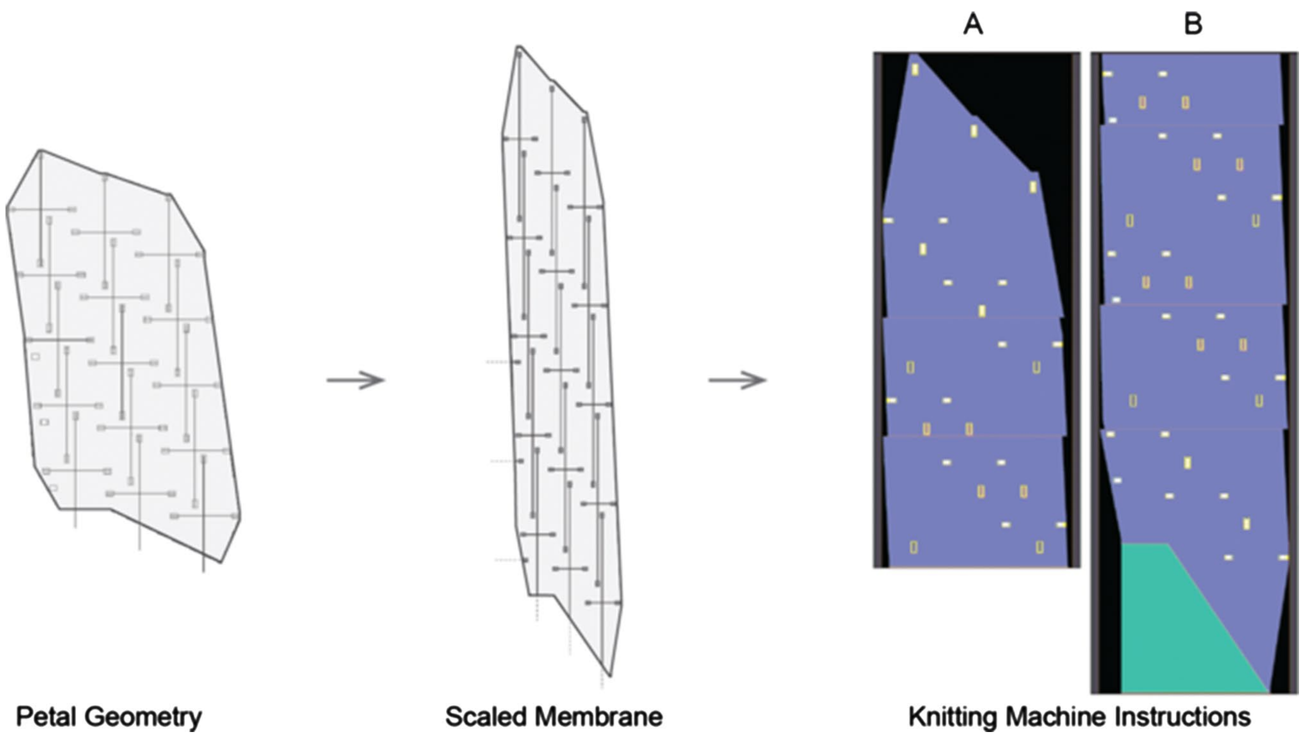

Fig. 8 Conversion from Rhino petal geometry to knitting machine instructions

Fig. 9 Design variations of the knit tensegrity shell, expressed in 1:10 scale models and full-scale prototypes

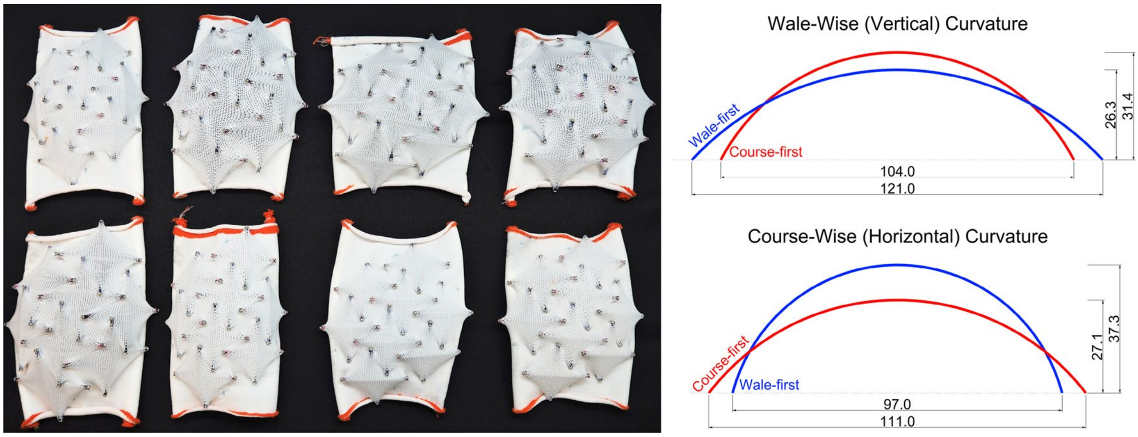

Fig. 10 Left—8-strut-unit models; Right—Diagrams showing curvature of two models with the same stitch pattern (piquet lacoste) and strut length (60 mm), but with either wale-wise struts inserted first (blue lines) or course-wise struts inserted first (red lines). Unit: mm

match the exact number of stitches/pixels in the knitting machine's software that will correspond to the required physical dimensions, where 1 mm = 1 pixel (Fig. 8). Next, 2D points that specify the outline of the flattened membrane and positions of the strut ends are extracted and converted into the shaped membrane's main body and pockets respectively. This is implemented via a Clojure script which generates a *compressed pattern* that is readable by the knitting machine's proprietary software. The compressed pattern specifies the stitch pattern and input yarn materials for every part of the knitted fabric, and then the compressed pattern is combined with a library of instructions (*package base patterns*) that are written by this paper's authors to generate the knitting machine instructions. This computer-assisted conversion of the CAD geometry into knitting software data allowed for multiple full-scale prototypes of different design variations to be created within the short span of a few months (Fig. 9).

4 Shell assembly

4.1 Assembly logic

After knitting, the tensegrity shell is assembled by inserting the struts into the membrane. The assembly process was first prototyped at smaller scales. Small 1:20 scale study models consisting of 8 strut units made from laser-cut acrylic sheets were made to investigate the effect of several variables such as stitch pattern, strut length, and strut insertion order on the curvature of the shell at this scale (Fig. 10). On the assumption that the shell's curvature approximates an arc, the curvature was calculated from chord and height measurements along the course-wise and wale-wise axes. Among the variables tested, only strut insertion order showed a consistent effect on the curvature of the model. For each strut unit, either the wale-wise or the course-wise strut is inserted first and is thus positioned closer to the membrane. Along a given axis, the shell curvature is greater when the strut perpendicular to the axis is inserted first. A possible cause for this phenomenon is that inserting the perpendicular strut first prevents the second strut from touching the membrane except at its ends, causing the second strut to stretch the membrane into an arc dependent on the cross section of the first strut. Since a greater curvature along the wale-wise axis would help the pavilion achieve a greater height over a smaller footprint, the course-wise struts were inserted first to maximize the wale-wise curvature.

4.2 IASS Form&Force Expo 2019 pavilion

To showcase the performance of the design-to-fabrication workflow at human scale, a pavilion measuring approximately 4 m in diameter and 3 m in height was exhibited at the International Association of Shell and Spatial Structure's Form&Force Expo 2019 [16, 17]. The shell design comprises three radially symmetrical petals patterned with 15 strut units each (Fig. 11). The criteria driving this design were structural equilibrium as derived from Kangaroo form-finding approach, a maximization of opening size for human entry (including a minimum height of 2.5 m), adherence to the knitting fabrication constraints, and aesthetic appeal. Because the

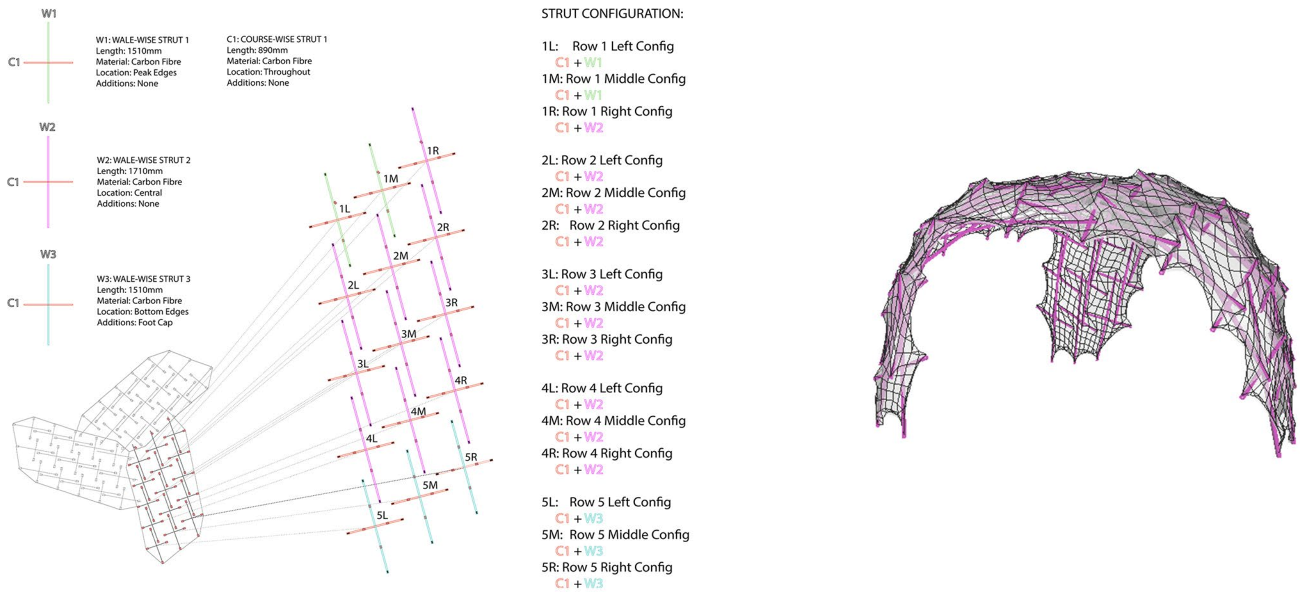

Fig. 11 Left—Form&Force Expo pavilion strut pattern; Right—Form-found digital model. Mesh resolution of the digital model was increased for visualization purposes

combined size of the 3 petals of the pavilion exceeded the knitting machine's width, and the length of a single petal exceeded the machine's data input limit, each petal was split into an upper and lower section for knitting. The 6 sections were knitted using approximately 30 h of machine time. This was followed by washing, drying, and finally sewing to join the 6 sections into a single membrane.

This human-scale pavilion required additional design considerations for the struts. The struts were built from 14 mm-diameter carbon fiber tubes that were cut into two segments to allow the strut segments to be inserted into the pockets without needing to stretch the membrane, thereby easing the insertion process. The strut segments were then pulled apart and slotted together as guided by an inner sleeve joint. A total of 90 struts were used, with the course-wise struts being 890 mm long and the wale-wise struts being either 1510 mm or 1710 mm long. 3D-printed end caps were added to both ends of the carbon fiber tubes to create an even contact surface between the ends of the tubes and the knitted pockets. Lastly, the entire installation was anchored to the ground at nine strut ends by 3D-printed conical base footings. These bases were further weighted down to secure the structure and resist accidental lateral forces on the pavilion. These details can be seen in Fig. 12.

During assembly, the membrane was placed flat on the ground and the struts were inserted starting with the innermost strut units and ending with the outermost strut units that interface with the base footings. Once all the struts were inserted, the entire membrane was flipped over and the nine struts at the edges were inserted into the base footings. The strut insertion took approximately 40 min with 8 people working simultaneously. The entire assembly process can be completed in 2 h (Online Resource 1).[1]

The design-to-fabrication workflow for the Knit Tensegrity Shell was successful in terms of creating a lightweight, self-supporting spatial enclosure. Broadly speaking, the digital form-found model from Fig. 10 approximates the curvature of the physical pavilion (Fig. 13), but there are discrepancies between the two, particularly in the angles at which the lateral arches rest on the ground and join one another. This is most likely due to the choice of using a single idealized cable net as the digital modeling approach, and not breaking it into segments like its physical counterpart. In addition, the exact material properties of the knitted textile are not directly taken into consideration in this form-finding process, but rather its general

[1] See https://youtu.be/3OdlximOgnI (Online Resource 1: Timelapse of the pavilion assembly).

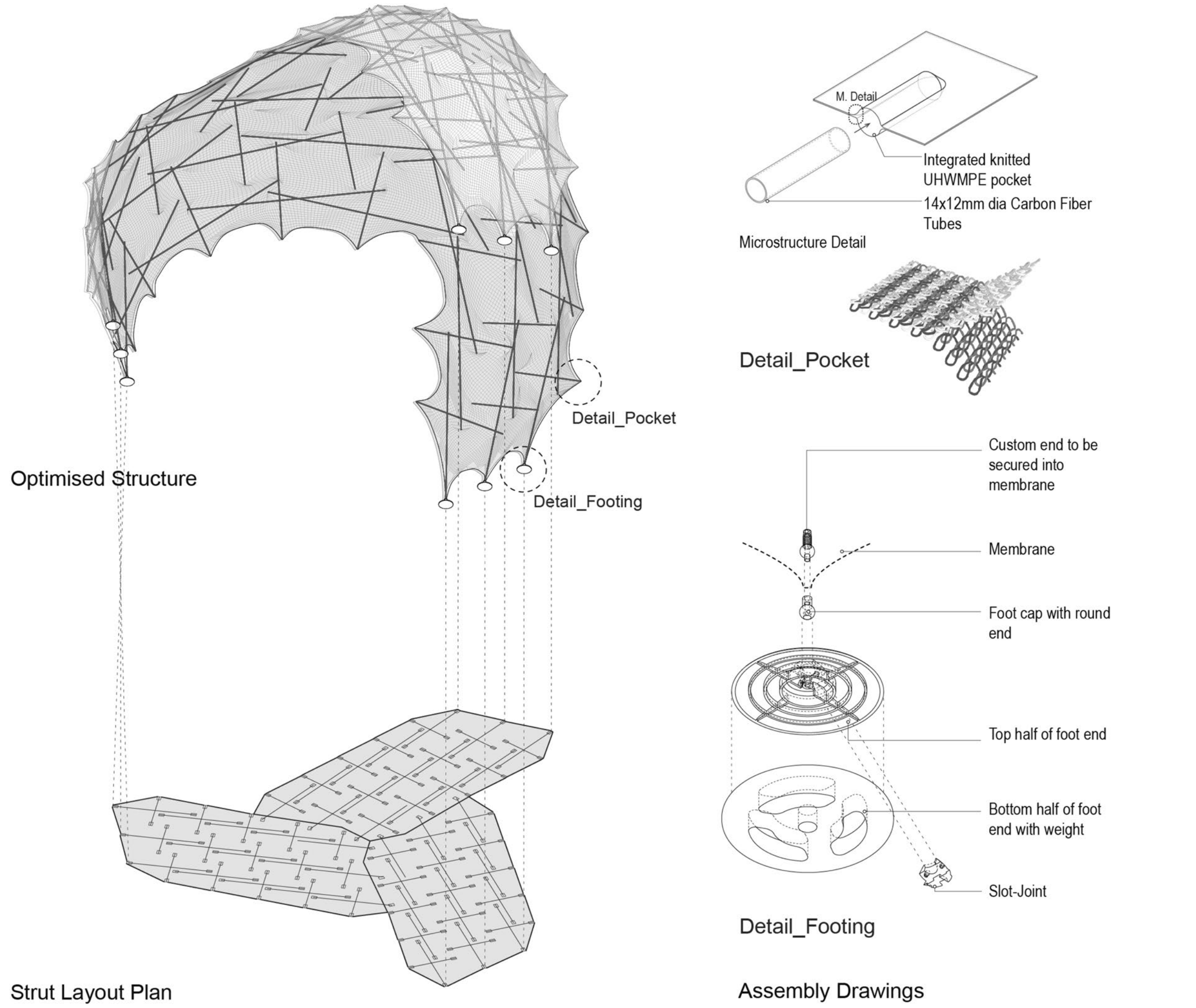

Fig. 12 Worm's eye axonometric and details of the IASS Form&Force Expo 2019 pavilion assembly

ability to expand. Despite these shortcomings, this modeling approach allowed for rapid formal exploration of knit tensegrity shells without specialist knowledge. The dome-like geometry and required entrance height were achieved, which were crucial performance criteria that created the desired spatial effect. Finally, no failure or breakage of any the assembly components was observed during the exhibition period, providing informative physical benchmarks about the performance of this structural typology.

5 Conclusion

This paper presented the development of a design-to-fabrication workflow for prototyping a new class of lightweight structure: knit membrane tensegrity shells. The workflow consists of (a) a simplified, simulation-driven design method for membrane tensegrity shells, (b) computer-assisted conversion of CAD geometry into knitting software data, and (c) the rationalization of the assembly connection details. This workflow enabled flexible

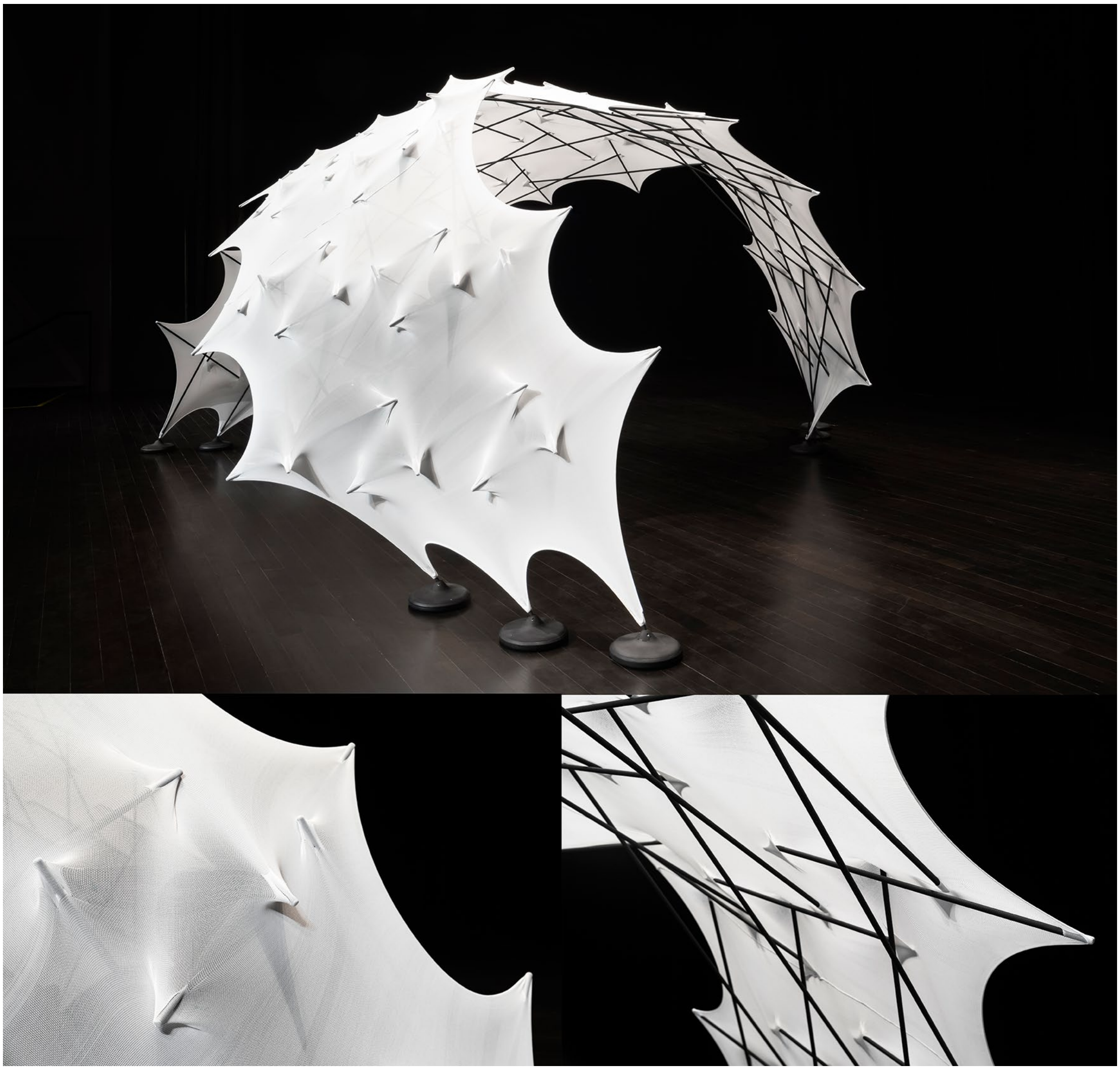

Fig. 13 Knit tensegrity shell at the IASS Form&Force Expo 2019. Photo Credit: Katariina Träskelin

exploration of membrane tensegrity shell structures with a relatively quick and smooth transition from digital model to physical product. Its efficacy was demonstrated in the successful completion of a human scale knit tensegrity shell pavilion.

Building upon this research can take several directions. Innovations in CNC knitting technology and its associated software packages will enable a wider array of gradation capabilities than those demonstrated in this work. Preliminary explorations with scale models suggest that knitting a membrane with more extreme and complex variations of stiffness and elasticity has potential to optimize the material consumption and achieve smooth, dome-like curvature of the shell. Similarly, more nuanced variation of strut lengths or shapes across the membrane can be explored. Both forms of gradation can be applied in the pursuit of non-trivial or unconventional target geometries. In the digital realm, the simulation tools can be upgraded to include post-form-finding FEA, assuming that the nonlinear deformation characteristics of the knitted textile can be approximated and input into FEA plugins such as K2 Engineering. Furthermore, future work investigates implementing multi-objective optimization tools. This allows structural performance to be negotiated with other performance criteria like wind flow to evaluate the size and arrangement of openings in the shell. Deploying such structures and testing their behavior at different sites would be a compelling way of pushing knit tensegrity shells deeper into the territory of performance-driven membrane structures.

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Compliance with ethical standards

Conflict of interest Sachin Sean GUPTA declares that he has no conflict of interest. Ying Yi TAN declares that he has no conflict of interest. Pei Zhi CHIA declares that she has no conflict of interest. Christyasto P. PAMBUDI declares that he has no conflict of interest. Yu Han QUEK declares that he has no conflict of interest. Christine YOGIAMAN declares that she has no conflict of interest. Kenneth TRACY has received research grants from Singapore University of Technology and Design through the Digital Manufacturing and Design Centre.

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