KNITTED TENSILE MEMBRANE TENSEGRITY HELIX-TOWER

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This paper explores the development and research of knitted tensile membranes used within tensegrity structures. The research explores the historical context of tensegrity, as well as contemporary precedent projects. The final design explores a workflow and novel prototype for a tower using bending active helix-shaped rods connected and held in suspension with the knit membranes. This structure explores the possibilities for lightweight deployable construction methods, as well as the resulting structural integrity of tensegrity modules. The process of design and fabrication is a feedback loop between physical and digital models, at each phase scaling larger to create more precision and accuracy in design prediction. Furthermore, through this process designer's intuition and knowledge about working with the materials is developed. The final design is lightweight and generates aesthetic qualities, which are representative of the distribution of forces on the material. The design resultantly creates a large volume and spatial presence for using very few materials.

Keywords: Textile, tensegrity, membrane, structure, knitting.

1. INTRODUCTION

Knitted textiles are not typically used as a performative material. In this case study, knit membranes are explored as a participating part of a tensegrity structure. There are many precedents for tensile membrane architecture, although these examples are typically found as lightweight roofs and building skins. In these cases, the textile membranes create an enclosure and are held up with a combination of a rigid structure or using tensioned steel cables. Meanwhile, tensegrity models are made with linear struts and cables. The load transfers between tension and compression members to create a balanced system where the compression members do not touch one another and are held in constant suspension by the tensioned elements (Pugh 1976).

The objective of the design in this research is to replace the tensioned cables with a knitted tensioned membrane to create a hybrid model of tensegrity and tensile membrane structure. The process throughout this research explores the use of knitted textiles as these tensioned membranes. Resulting in the need to develop a unique workflow that explores a method of feedback from digital design to physical studies, and computational physics simulation. The methods for predicting knit membranes are not very advanced and thus this workflow hopes to overcome these deficits by gradually scaling the design through a multi-phased digital and physical process. At each point in the process, different methods of evaluation inform the next phases of the process creating an informed method of working where the designer develops knowledge and intuition.

The resulting prototype is a 2.74 meters (9 feet) helix structured tensegrity tower. The design explores the possibilities of using membrane tensegrity structures, which are ultimately lightweight, deployable, and at a small architectural scale. The resulting volume of space generated by the design is large in comparison to the volume of raw materials used. The assembly process for the final construction was simple and took no tools to put together. The prototype structure was developed and fabricated while Virginia Melnyk was an artist in residence at Arts Letters and Numbers.

2. TENSEGRITY

2.1. HISTORY

Tensioned structures are for the most part a modern development, made possible due to the advancements in building materials. Historically, many structures were built with stone, and bricks which are only structurally stable under compression forces. Wood is one of the few traditional materials used in architecture that has tensile properties. Although most traditional wood-designed buildings are not using it specifically for their tensile property alone.

A few examples of traditional tensioned structures are those of rope bridges, which often required large amounts of annual maintenance (Pugh 1976). These structures used natural fibrous materials which would degrade over time and have size limitations. Modern steel cables have made tensioned structures a more viable large-scale structural option, as the material is strong and long-lasting.

2.1. DEFINITION

Tensegrity was developed by three key designers, Richard Buckminster Fuller, David Georges Emmerich, and Kenneth D. Snelson. Although there were other designers also exploring these types of structures earlier, the three fore mentioned designers are most commonly credited (Gomez-Juaregui 2010). Also, it is Buckminster Fuller who coined the term tensegrity, a contraction of tensional integrity (Burkhardt 2008).

Anthony Pugh's definition of tensegrity from his book An Introduction to Tensegrity:

> A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space (Pugh 1976, 3).

It is important to note that in this definition Pugh does not refer to struts or cables, which are often found in tensegrity but are not a requirement. As in some cases, struts could be replaced by planar surfaces or bent members, as well as cables could be replaced by membranes. Therefore tensegrity is for the most part a structural system.

2.3. CHARACTERISTICS AND ADVANTAGES OF TENSEGRITY

Tensegrity structures have many advantages. A few that are integral to this research are that tensegrity is very lightweight. It is also a self-stressing system whereby the higher the stress the more load-bearing the structure will be. This is described in comparison to a balloon. Whereas a balloon inflated fully will react little to external pressure forces, yet a balloon that is half-filled with air can easily be squashed and deformed. Yet, once the force is removed the balloon returns to its stable rounded state (Pugh 1976). This allows for structural resilience as it can flex and again return to its equilibrium state. Meanwhile, the amount of deformation is directly dependent on the amount of force to begin with, the stronger the base force the more stable and resistant to deformation the structure is. As a feature of this characteristic tensegrity modules are sensitive to vibrations and dynamic loading which transfers throughout the structure. Tensegrity modules also are self-stable, meaning they are not dependent on gravitational forces for their structural integrity; meaning they hold their form no matter which orientation they are positioned. Furthermore, elemental tensegrity modules can also be joined and combined together to create larger tensegrity networked structures (Gomes-Juaregui 2010).

2.4. MEMBRANE TENSEGRITY

Although tensegrity is most often seen with struts and cables, as mentioned in the definition of tensegrity, it is not dependent on these elements. It is only the relationship of the compression and tensioned members working together as a system that creates a tensegrity structure. There are some important precedent examples to note of current research exploring tensegrity, membranes, and bending active elements.

The Hybrid Tower developed by CITA, the Center for IT and Architecture at the Royal Danish Academy, explored a bending active Glass Fiber Reinforced Polymer (GFRP) rod structure as well as a knitted textile membrane in this tower design. The structure uses the bent rods as an interconnected network of members, crossed together in a diagonal grid. (Ramsgaard Thomsen 2015). Cables are also used to pull the membrane into tension. The design for the tower expresses a workflow between digital and physical modeling, as well as post-construction analysis.

The Dynamic Assemblies Lab at Singapore University of Technology and Design has explored several structural developments. One recent exploration is a membrane tensegrity pavilion built in 2019. In this structure, a single knitted membrane with linear struts placed in a particular arrangement on the membrane creates a structural shell pavilion (Gupta 2020). This structure uses the tension in the membrane to support the struts and transfer the load.

The BetA pavilion developed by Diane Davis-Sikora and Rui Liu uses bending active compression elements, as well as knitted tensile membranes. Their structure uses bent GFRP rods in the formation of bending active tetrahedrons. The rods are connected at their ends creating the tetrahedron shape, thus the bent members in this case are acting as a network rather than as independent elements. In their design, a triangular knitted textile is connected at the corners. This textile is then used in tension to combine one module to the center of the next creating the tensegrity system in their design (Davis-Sikora 2020).

The final example, using bending active GFRP rods, textile PVC membranes, and polyester belt cables, is the “Form Follows Tension” structure built as part of the 2012 IASS by researchers at Technische Universität München. Their design explores membranes as an active part of the tensegrity module. The structure consisted of four modules, which included two bent rods, one membrane that connects the ends of the rods at opposite corners, and cables connecting the center of the rod to the end of the opposite rod (Schling 2015).

There are of course many other case studies available but not worth mentioning in relation directly to this research. These presidents set up a good basis on to build. Taking the knowledge of how to work with tensegrity with bending active rods as well as knit membranes. In these precedents, the focus was on different features. As well they often included the integration of cables.

3. RESEARCH

3.1. KNIT MATERIAL

With the precedent examples of tensile and tensegrity structures, this research project hypothesized that bending active elements and knit textiles could work together as tensegrity modules. And that two or more of these modules could be combined together to create a larger structure. To develop a design like this, it was necessary to develop an understanding of the materials to be used. To do this several studies were done first at a small scale before they could be further explored at larger scales. This workflow was found to be a successful workflow between material and computational design from the precedents as well as in this project, when working with knitted materials.

Knit material is not typically used for large-scale tensile structures because it has heterogeneous elastic properties. Where the knit material does not stretch evenly across the surface. Most tensile structures use woven materials, which are not as stretchy, and are coated with waterproofing to provide a barrier from the elements. The knit material to be used on this project is very porous since the knit was created on a standard domestic 4.5mm needle gauge machine. The stitch length is also set to 6 and knit with 1 ply cotton yarn. This means that depending on the knit would still have small visible small holes based on the looping structure and would not be water or airtight.

These small holes are a result of the weft knitting structure. Weft knitting is the most common form of knitting machine as they use a horizontal bed of needles and draw yarn across the bed creating rows of stitches. The looping structure of the material results in its elastic properties, as the loops permit the yarn to shift and slide between each other creating stretch and tension in the yarn. This slippage of yarn allows for some of the loops to get larger and others to become smaller, creating heterogeneous elasticity across the material (Figure 1). This is more noticeable when tensile forces are applied to the material. The amount of slippage that can occur is dependent on many parameters, such as stitch length, yarn thickness, and yarn fuzziness which causes friction in the yarn material.

Knit material is also quite strong because of this looping structure. When a single yarn is pulled it can easily break. But when it is knitted together the forces are distributed across the material and many strands of yarn, causing it to be able to withstand much more tensile force.

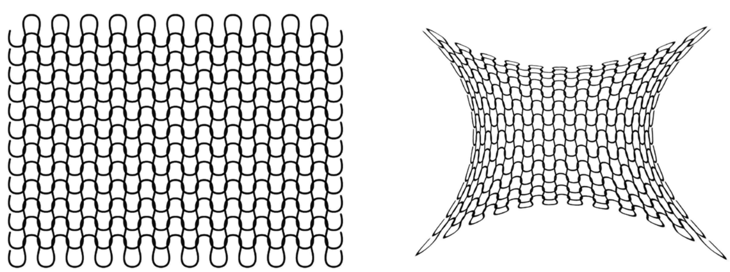

Figure 1: Image of knit structure compared to knit in a tensile state. Source: Author 2022.

3.2. KNIT STUDIES

The initial studies started by exploring the knit material by creating material swatches with different stitch lengths and yarn types (Figure 2). These swatches were generated on a Brother Ameno KH 836E domestic knitting Machine with a 4.5mm needle bed. With these swatches, the designer is able to develop an understanding of the possible materials and different constraints and properties of the resulting textile. The relationship between the designer and the material understanding is an important part of the method and workflow for this research.

It was decided to work with cotton yarn as in the swatch tests, its performance had less elastic properties within the yarn itself, leaving most of the elasticity in the textile to be from the looping structure of the knit. The stitch length used was 6, because it is in the middle range for the domestic Brother knitting machine, which is not too tight or too loose. Tighter stitch lengths caused jamming and breaking of the yarn while loser stitch lengths were prone to dropping the yarn. The middle range stitch length allows for some movement of the yarn between loops, but not too much, allowing the textile to reach tension across the surfaces when stretched, distributing the tensile load.

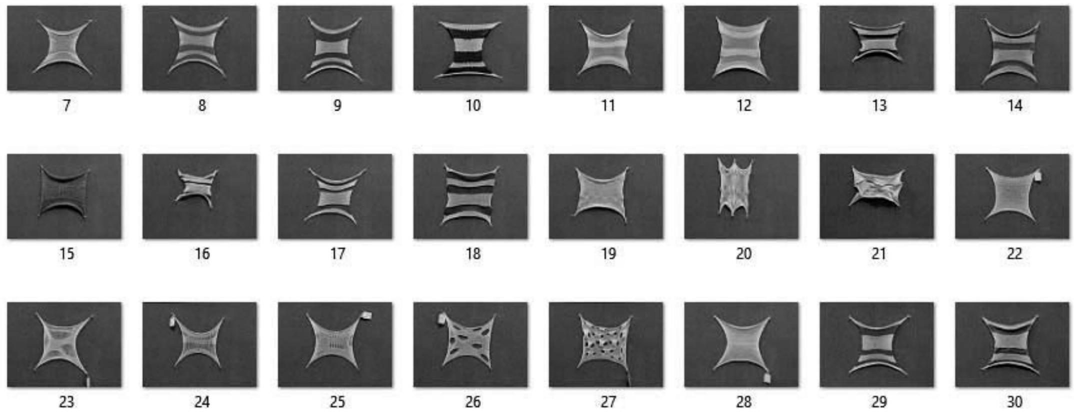

Figure 2: Image of different sample knits in different materials and stitch lengths. Source: Author 2022.

3.3. TENSEGRITY MODULES

The first models with knit tensile tensegrity explored different structural organizations using linear struts and bending active rods, made from PTEG pipes. In these small models, the rods are held in suspension by the membrane and do not touch one another (Figure 3). The forces in these models can be expressed in the membrane in tension and the bent rods in compression. These iterative models proved that a membrane could replace the tension cables that are typically seen in tensegrity modules. As well as the whole surface, not just the edges of the membrane is being tensioned.

These models were made by hand and the scale of materials was based largely on digital models from Rhinoceros 3D as an estimation of material size and length. Although these Rhinoceros 3D models were only for design and did not simulate elasticity or predict structural performance. As with these models, the number of stitches and length of compression members were measured from the Rhinoceros model as an estimate. This estimate was based on the swatches which measured 50 needles by 50 rows. Thus an estimate could be made as to what the general dimensions should be with the same materials.

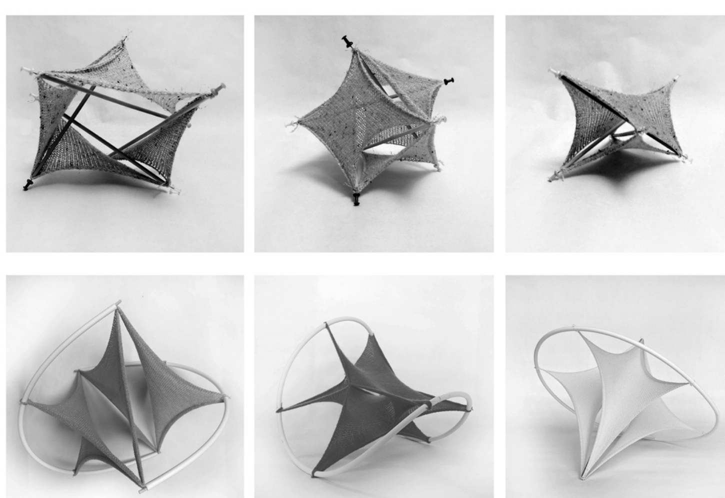

Figure 3: Image of knit tensegrity module studies. Source: Author 2022.

3.4. SIMULATION

The next step in the design process was to create more complex digital simulations of the designs using the Kangaroo2 plugin in Grasshopper for Rhinoceros 3D. For the simulation, a mesh surface is set to have each mesh edge as spring. The mesh is subdivided into inches to allow for an understanding of how much each mesh edge may represent a set amount of knit stitches. From the physical knit swatches it can be known how many stitches would make up a 2.54 cm by 2.54 cm (1 inch by 1 inch) area of knit material given the selected stitch length and material.

Furthermore, the physical swatch samples are used to determine the proportions of elasticity, by measuring the test material in a relaxed state and in a tensioned state. Understanding of how knit stretches are studied here, as knit material reacts differently when tensioned from top to bottom, then from side to side. In this case, the corners of the knit would be used to attach to the structure, and the knit needed to be measured when equally pulled at all four corners. These properties from the sample swatches are measured in a relaxed state and again in a tensioned state. The measurements are then used to help inform the input data for the digital Kangaroo2 model (Figure 4). The mesh edges are organized based on their different directions and location in the material and set to different spring lengths, which mimicked the physical tests. The horizontal mesh edges represent the knit rows or courses and stretch differently than the vertical mesh edges, which represent the interlocking loops or wales of the knit.

Additionally, the top and bottom edges of the knit, which are the cast-on and bind-off, are more constrained than the vertical edges. In the simulation, these are also set as different spring lengths. Moreover, the knit material does not usually scale exactly 1:1. When trying to predict larger models from small swatches, it is important to allow a small factor of variation between scaling the models to larger prediction models. This percent of variation is based on experience and learned knowledge the designer had accumulated through the sampling and testing in this research. Ultimately, the digital simulation allows the mesh to be tensioned by the bent rod members in the design and creates a balanced state of tensegrity. The design is similar to the small studies made with rods and textiles, and can be used to determine dimensions for scaling up the designs into larger models. And further the understanding of the material and design process.

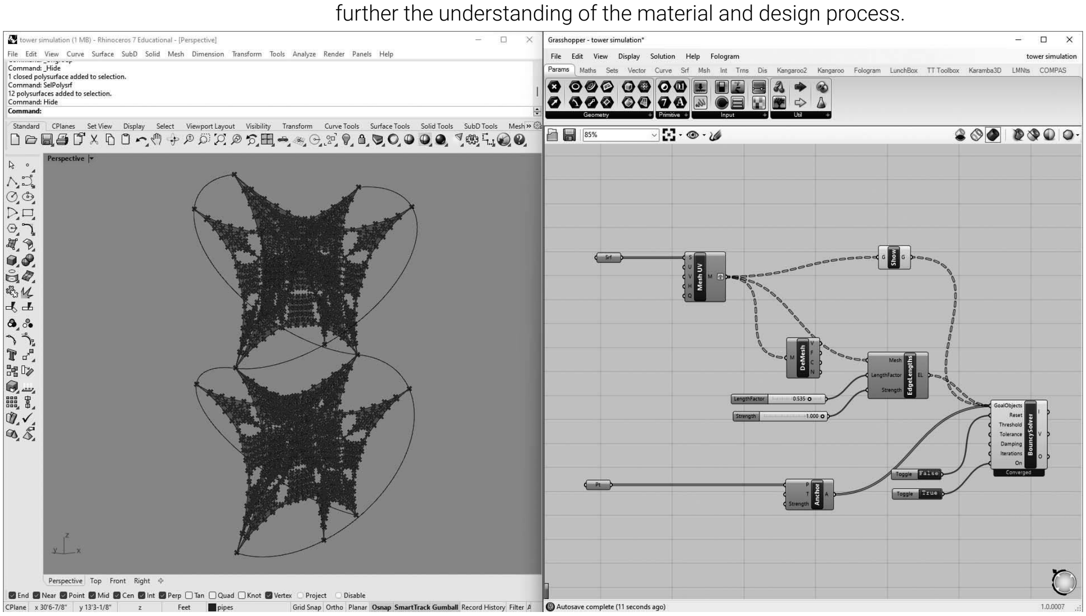

Figure 4: Image Grasshopper Rhino Simulation. Source: Author 2022.

3.5. LARGER MODEL

After the digital simulations of a larger-scale proposal were made, a physical phase of testing was necessary to determine the accuracy of the digital predictions. The predictions were used to take the information from the smaller scale models and determine the possible sizes and dimensions for the larger design. The next model would be around twice the size of the original model. Based on the scaling of the proportions and simulation in Grasshopper, an understanding of how many courses and wales would need to be knit to produce material so that it would stretch to the desired size. The resulting sample consisted of three knit panels that were 160 needles by 120 rows and the bent rods would be two 1.22 meters (4 feet) PETEG pipes.

The result showed that the design was able to somewhat successfully estimate the necessary sizes and material properties when scaled up to a larger size. Although some important observations took place. At a larger scale, the flexibility of the PETEG rod was too much and it did not create enough bending compression force to make the structure stable. Resulting in it being too flexible and not rigid enough to pull the textile into full tension. This determined that the bending rods would need to at least be more rigid, and later were replaced with PVC rods. Since the knit was not pulled fully into tension it was also noticeable where slack areas and tighter areas would occur across the membrane. This allowed for some assessment and information on how to adjust the design to provide better performance across the material. The simulation was adjusted to make the knit even slightly smaller than the original prediction. Ultimately the module was supporting its weight and was able to successfully transfer load between the membrane and the compression members creating a tensegrity module.

4. HELIX-TOWER

4.1. HYPOTHESIS

The objective for the final structure was to make a tower by stacking multiple of the previously studied and designed tensegrity modules together to create a vertical tower-like structure. The hypothesis is to use the bending active tensile textile and tensegrity to create a large structure using very few raw materials. By using textiles the material is lightweight and expands creating a large surface area and visual enclosure to the volume. This structural organization is novel as it is using no cables, and the membrane surfaces act as tensile elements. Although when attaching the two modules together, the bending active members are connected end to end. This although does not break the tensegrity module as the members are now acting as two compression members in a spiral rather than four “C” shaped members.

4.2. SCALE AND DESIGN

For the final structure, the goal was to create a 4.5 meter (13.5 foot) tall tower by stacking three of the modules on top of one another. Unfortunately, due to the height limitations of the available space and time constraints for the fabrication and construction, the design would end up being only two modules stacked and would be 2.74 meters (9 feet) tall.

The scale of the proposed structure was based on available materials. Using off-the-shelf PVC rods, so as not to create any waste material keeping them at the original size. The structure would use four, 3.048-meter (10-foot) rods, which would be connected with a coupling fastener end to end. The Rhino 3D simulation was then scaled to fit these size dimensions and proportions. Creating a prediction of how much knit material would be needed to fit the proposed design. The PVC rods would also be pre-measured at the connection points for the material and marked with eye hooks for attachment. This would help streamline the assembly process.

The textile when scaled in the digital simulation predicted that the knit would need to be 396 by 264 for the necessary stitch count for the design. This would be too large to be knit on the domestic Brother knitting machine. Therefore the design subdivided the membrane into nine smaller pieces that would be attached together to make the larger necessary pieces. Given the understanding of the material and its variation in elasticity, the information learned from the large-scale model was used to adjust the simulation for the final. This also helped predict the new necessary sizes of the smaller subdivided knit pieces. To avoid issues of sewing the panels together affecting the elasticity in the knit material, the proposal was to only attach the panels at the corners and not along all the edges. Expecting that the load would still transfer through the material along the X, Y, and diagonal axis. The new subdivided design used nine smaller pieces to create the panels that would provide the tensile membranes for the structure. When the material of these panels stretches openings are created as they are not sewn edge to edge and this creates an even more dynamic and porous membrane expressing the forces of elasticity in the material.

In the simulation, each knit panel responded differently to forces formed by slightly different geometries. As the edge panels would stretch more than the center panels. The panels that are located to either side in relation to the bending active member, tended to stretch into a diamond shape. Which led to the sizes of the panels slightly varying to respond to these different measurements found in the simulation. The smallest panel resultantly was 108 needles by 72 rows. The middle size is 120 needles by 80 rows. And the largest panels which would be used for the center membrane and arranged on a diagonal of the side membranes were 132 by 88 rows. This variation in panel sizes was arranged to help emphasize and support the natural form of the elasticity of the material. The pieces needed to be attached facing the same way so that the orientation represented the direction of stretch that was previously studied and designed in the simulation.

4.3. CONSTRUCTION

All fifty-four panels of textile were knit and attached at the corners to make the final six panels needed for the design. The corners were marked with small tags noting which corner of the structure to attach to. Since the panels were not symmetric and their orientation was dependent on the direction of the stretch in previously studies. This was important since this variation in knit direction and panel size is not visible to the naked eye.

The final construction of the tower took less than 30 minutes, from start to finish. The first two textiles are attached to the first bent rod. Then the middle textile and the third textile are attached to the second rod. Once they are attached, what was a small amount of material pops up to fill the space and form the first module. The second PVC rods are attached to the ends of the first module with the PVC coupling. While the module is laying on its side the next three pieces of textile are connected to the new rods bending them into place. Since tensegrity structures are a self-stable system gravity, they can be built on its side and do not affect the structural integrity of the modules. Once fully attached the structure is lightweight enough that an individual can pick it up and rotate it into the desired vertical position. The weight of the overall construction is 8.9 kilograms (17.6 pounds). The final structure stands on the two ends of the rods and the three bottom edges of the textile membranes (Figure 5).


Figure 5 time-lapse video stills of the construction process: Author 2022.

4.4. RESULTS

The final structure stands on its own although, the weight of the material forces the rods to compress at the base more than at the top. This was not accurate in the prediction models but was obvious in the final physical construct. Although this deformation did provide a larger edge for resting place on the two rods which touch the ground, making the structure more balanced (Figure 6).

Resultantly the structure is also still a bit flexible since the knit material is not held fully tensioned. The material visually deforms resembling the movement of forces across the surface. Making the center portions of the knit remain softer and somewhat flexible, which is different from the precedents of typical tensioned membrane structures, which pull the whole membrane is tensioned to such an extent that it becomes almost rigid. This allows for the softness of the structure, which can be pushed and manipulated by visitors. Having similar residual effects to the balloon example described earlier in the paper. However, as with all tensegrity structures, they are self-stressing and their stiffness depends on the material proprieties as well as the level of tensioned stress. Thus this structure does hold its geometry and will recoil back to its equilibrium state. The PVC pipes used are not as sturdy as they are needed for a more rigid structure to be in full bending force. This is not necessarily a design flaw as a change in material and the amount of tension applied could create a more rigid structure. Yet the dynamism of tensegrity in this model's structure allows for these dynamic reactions to be part of the design result and its return to a predetermined form proves that the structure does have stability.

4.5. NEXT STEPS

Although the size of the design did have to be reduced based on space and time constraints, further exploration into larger prototypes and stacking more modules together is the next desired phase of research. Furthermore, advancements can be made to use GFRP rods, similar to many of the precedent examples, which would have more bending resistance and be more stable, avoiding the extra flex seen in the results of this prototype. As well as more precision in the material could be developed, to achieve more overall balanced tension across the membrane. A denser knit material could also be useful by using CNC knitted membrane to provide more specificity and control in the design rather than the single jersey knit that was created for this prototype on a domestic knitting machine.

The overall process of starting with small studies, and using this information to inform the digital simulations through measurement and visual study also worked successfully. Although there was also some added information from experience such as when scaling up the proportions would not be 1:1, and those

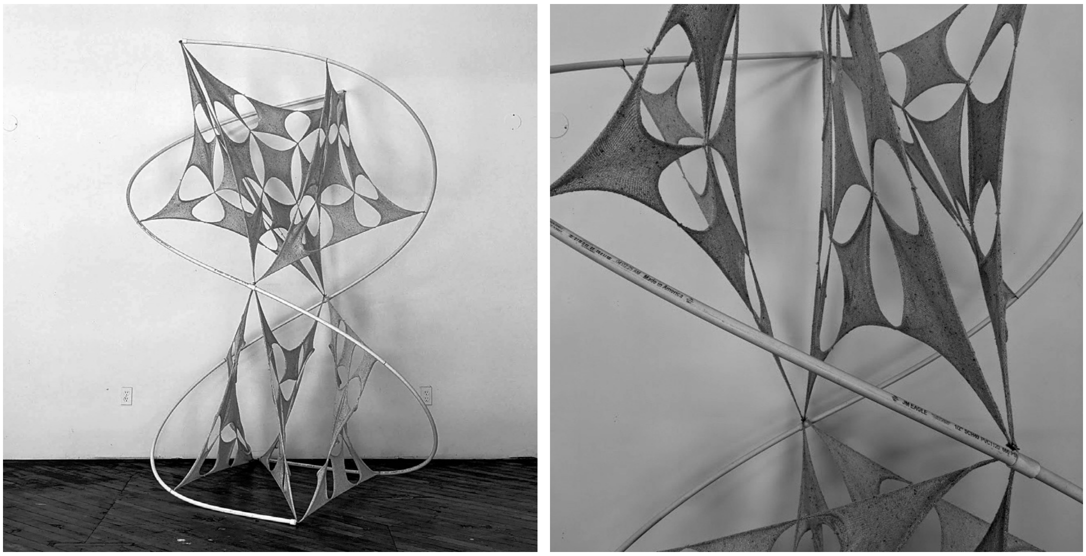

Figure 6: Images of the final structure. Source: Author 2022.

intuitive minor adjustments had to be taken into consideration. The consecutive scaling up from small-scale models to a medium-scale mock-up, before the construction of the final, was also successful as different material and physical information was learned at each phase and able to be applied to the final design.

CONCLUSION

The overall proposal to create a new structural design that uses bending active and membrane tensegrity modules stacked together to create a helix-tower structure was successful. The design hypothesized that using lightweight materials could produce visual and spatial impact with very low material resources. The prototype design resultantly is quick and easy to assemble and can be done by an individual person.

The developed workflow also proved to be successful. Through this process, not only is the data implemented into the computer but also there is natural learned information through the experience that the designer generates as they work closely with the materials. The process also involved consecutive scaling up from material swatches to small-scale models to medium-scale mock-ups, before proceeding with the construction of the final. This process also involved several points to adjust information in the computer as well as physically.

Although, space and the size of the knitting machine were ultimately constraints. They eventually provided opportunities to explore different aspects of the design such as breaking down the membranes into smaller panels. In conclusion, the structure did produce the desired objectives. The exploration of creating a new knitted membrane tensile tensegrity model did generate an easily deployable structure that provided a large volume with minimal material usage and was very lightweight. This provides a strong impact on how we build with these materials and structural systems. Creating new possible design methods as well as construction fabrication methods for these lightweight structures. Ultimately, there is more to be explored and developed to make these models viable at larger architectural and building scales.

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