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Soft Structured Knitted Membrane Tensegrity Helix-Tower

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Abstract

This paper explores project-based research approach for using knitted textiles as a participating element in a tensegrity structural system. The design of the tensegrity Helix-Tower takes advantage of the emergent elastic properties of knit material and the self-stress, self-stabilizing characteristics of tensegrity structures. The paper outlines the workflow for working with knit materials, including the feedback loop between small studies, digital models, and simulations, and from small to large prototypes. The resulting prototype is a 2.74-meter (9-foot) helix structured tensegrity tower, which is lightweight, deployable, and at a small architectural scale. The assembly process for the final construction is simple and requires no tools.

The research is novel in its exploration of using knit membranes in tensegrity structures, resulting in a structure that is ultimately more flexible and responsive to movement than traditional tensegrity structures. The design also provides more interactivity with human bodies and the environment. The paper examines the benefits of knitted membrane, including their heterogeneity and uneven stretching. Which provides softness, flexibility, and more movement to the structure. However, questions remain regarding the potential for other environmental factors such as wind or water.

Future work includes exploring the potential and problems of knitted compared to other materials used in tensegrity structures and examining the incorporation of the design into real architectural elements.

Keywords: textile, flexible, structure, tensegrity, knit, membrane.

1. INTRODUCTION

This research explores the potential of knitted textiles as a participating element of tensegrity structural systems through physical and theoretical investigation. Tensegrity is a structural model that balances compression and tension members in harmony, offering unique possibilities for architectural design. This study builds on existing precedents of membrane architecture and tensegrity modules to create a soft, interactive, and responsive structure that reflects the possibility of building with non-rigid materials.

The project described in this paper begins with a base understanding of knit materials, working at a small scale

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and then digitally with simulations and computational design. The design is then scaled up into a full-scale prototype, and which the construction process is detailed through a series of steps that can be easily deployed in a short period. The final prototype is a helix tensegrity tower, which demonstrations the potential of knitted textiles as a participation element in the structure.

Theoretical reflections made about tensegrity and the potential of building with non-rigid materials are a key contribution of this research. Through an exploration of the history of tensions structure and membranes, including the work of Frie Otto and Buckminster Fuller, the study highlights the unique characteristics of knitted textiles and their potential to contribute to contemporary architecture.

By building on the definition and history of tensegrity, this research offers new insights into the possibilities of architectural design and construction, particularly in relation to the use of soft materials. The resulting prototype provides a tangible example of the potentials of knitted textiles in tensegrity structure and offers exciting avenues for further exploration and development in this area.

Figure 1: Completed Helix Tensegrity Tower. Source: Virginia Melnyk 2022.

2. TENSEGRITY

2.1. Definition and History

2.1.1 History of Membrane and Tensile Structure

Tensioned structures are a relatively recent development, made possible due to advancements in building materials. Historically, structures were often built with materials such as stone and bricks that are structurally stable under compression forces. While wood does have some tensile properties, most traditional wooden structure do not rely on the material for its tensile strength alone (Pugh 1976).

In architecture, membranes were traditionally used as skins for enclosure rather than as structural elements. Gottfried Semper, in his *Four Elements of Architecture*, explores the relationships between textile patterns and design and architectural motifs. As well, in his book *Style*, Semper explores a whole chapter on the craft of textiles (Rykwert 1989).

While there are some examples of traditional tensioned structures, such as rope bridges, these structures required significant maintenance and were constructed using natural fibrous materials (Pugh 1976). It is the development of modern steel cables which made it possible to create tensioned structures on larger scale, as the material is very strong and long-lasting.

2.1.2 Tensegrity Definition

Tensegrity was notably developed by three key figures: Richard Buckminster Fuller, David Georges Emmerich, and Kenneth D. Snelson. Although others explored these types of structures earlier, these three individuals are most commonly credited with the development (Gómez-Jáuregui 2010). Buckminster Fuller coined the term “tensegrity”, a contraction of “tensional integrity” (Burkhardt 2008).

Anthony Pugh’s definition of tensegrity from his book *An Introduction to Tensegrity* states:

> 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. (1976, 3)

It is important to note that in this definition Pugh does not refer to struts or cables specifically. While these are often the most common components of tensegrity structures, they are not requirements. In some cases, linear struts could be replaced by planar surfaces or bent members, as well as cables could be replaced by membrane surfaces.

2.2. Characteristics and Advantages of Tensegrity

Tensegrity structures have many advantages and disadvantages. A few characteristics in particular are integral to this research. One characteristic is that tensegrity is very lightweight, using very little material for large overall volume (Pugh 1976). This provides easy assembly and are easily transported by individual humans.

Tensegrity modules are self-stressing systems whereby the higher the stress, the more load bearing the structure will be. This allows for structural resilience as it can flex and transform. Yet, once forces are removed, it will return to its equilibrium state (Pugh 1976). Another feature of tensegrity modules is that they are sensitive to vibrations and dynamic loading which transfers throughout the structure, creating reverberation (Gómez-Jáuregui 2010).

Tensegrity modules also are self-stable; they are not dependent on gravitational forces for their structural integrity, which means they hold their form no matter their orientation or position (Pugh 1976). They are also not dependent on foundations or anchor points, as the structure will find balance within its own form.

Finally, individual tensegrity module elements can be joined together to create larger structures and networks (Gómez-Jáuregui 2010). These aggregations allow tensegrity structures to expand in size and scale without modules themselves scaling.

These key traits are directly relevant to the research in this project. The design for the Kitted Helix tower emphasizes the use of soft materials such as elastic knit material and PVC rods, which are very flexible; allowing the structure to have less load-bearing strength and more flexibility. This flexibility and transformation within the self-stressing of the tensegrity system is crucial (Pugh 1976). When the forces are removed, the structure returns to its stable equilibrium state (Pugh 1976). Secondly, the structure is built by one person and is assembled laying on its side, making the lightweight quality of tensegrity crucial to make this possible, compared to other structural systems that rely on gravitational forces and anchor points to be structural (Pugh 1976). Finally, the design for the Helix tower developed from taking an individual tensegrity module and stacking a second one on top of it, taking advantage of the unique characteristics of tensegrity’s structural properties.

2.3. Membrane Tensegrity Precedents

In order to explore the potential of using tensegrity with membranes, several important precedent examples were studied. Bending elements were also explored to gain a better understanding of the possibilities. These precedents helped to identify knowledge gaps and build upon existing knowledge in the field.

The Dynamic Assemblies Lab at Singapore University of Technology and Design has explored various structural developments using membrane tensegrity design. One recent exploration is a membrane tensegrity pavilion built in 2019. This pavilion features a single knitted membrane with linear struts arranged in a specific pattern to create a structural shell pavilion (Gupta et al. 2020). The design takes advantage of the unique properties of knit material to help with strut placement.

The BetA pavilion, developed by Diane Davis-Sikora and Rui Liu, explores bending active tensegrity logics as well as knitted textile membranes. The structure uses several bent Glass Fiber Reinforced Polymer (GFRP) rods to create bending active tetrahedrons. The rods are connected at their ends, forming a network instead of independent elements (Davis-Sikora, Liu, and Ohrn-McDaniel 2020).

The Hybrid Tower, designed by CITA, combines bending active compression members and a knitted textile membrane in a tower design. The structure includes bent GFRP rods, knitted membranes, and tensioned wires (Thomsen et al. 2015). Post-study analysis was performed to evaluate the movement and stability of the tower design.

The “Form Follows Tension” structure, built as part of the 2012 IASS by researchers at Technische Universität München, explores membranes as an active component of the tensegrity module. The structure consists of four modules, including two bent rods, a 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 et al. 2015).

These precedent examples provide valuable insights into potential workflows and methods for building, as well as ways to work with knit material for tensioned design modules. However, a knowledge gap exists in using the flexibility of knit material and the resonance found in tensegrity as a design advantage, rather than a disadvantage. Most architectural structures strive for rigidity, which contrasts with the elastic and heterogeneous nature of knit materials.

3. RESEARCH

3.1. Knit Material

This research project hypothesizes that bending elements and knit textiles could work together to create a soft tensegrity module that is more precarious and flexible. This allows for responsiveness to human and environmental interaction while still maintaining a balanced state when external forces are removed. To gain an understanding of the knit materials used in the design, it was necessary to develop these designs at a small scale before prototyping them at a larger scale. This workflow was found to be successful in many of the precedent studies. Furthermore, a working process between physical material and computational design when working with knitted materials was also found to be a common practice. Current simulation tools need to be informed by the material and feedback loops are necessary at different stages and scales.

Knit material is not typically used for large-scale tensile structures because it has heterogeneous elastic properties. Knit textiles are fabricated by creating rows of slipknots, where one strand of yarn looped across the next. In this case, the knit material was fabricated on a domestic Brother knitting machine with a 4.5mm gauge bed of 200 needles. The looping structure of knit material is what results in its elastic properties, as the loops permit the yarn to shift and slide between each other creating relaxation across the material. This creates variation of stretch and tension in the yarn across the surface. This slippage of yarn allows some of the loops to get larger while others become smaller and tighter, creating a non-uniformity across the material. The amount of slippage that can occur is dependent on many parameters, such as stitch length, yarn thickness, and yarn “floofiness” which causes friction as the yarn slides (Roberts 2019).

These elastic properties of knit material can be utilized to create tension in the module, contributing to its overall stability. Previous studies have explored the use of knit material in tensioned structures. However, a knowledge gap was identified in utilizing the flexibility of the knit and resonance found in tensegrity as a design positive rather than negative. This approach is different from traditional architectural structures that attempt to achieve rigidity, and further research is necessary to explore the potential of soft tensegrity modules.

3.3. Tensegrity Modules

The early prototype models with the knit tensile tensegrity explored different structural organizations using bending active rods, made from PTEG pipes. In these small modules, the pipe is bent into compressive state held by a tensioned knit membrane. The rods in these modules are held in suspension by the membrane and do not touch one another (see Figure 3). These models were constructed by hand and the size and lengths of the materials were estimated from digital models from Rhinoceros 3D. The rod lengths were adjusted by trimming them on the fly, while the knit material was knit to exact size. Since the knit material is made of a single looping yarn, it must be made with precision as adjusting it afterward by cutting would cause the material to unravel.

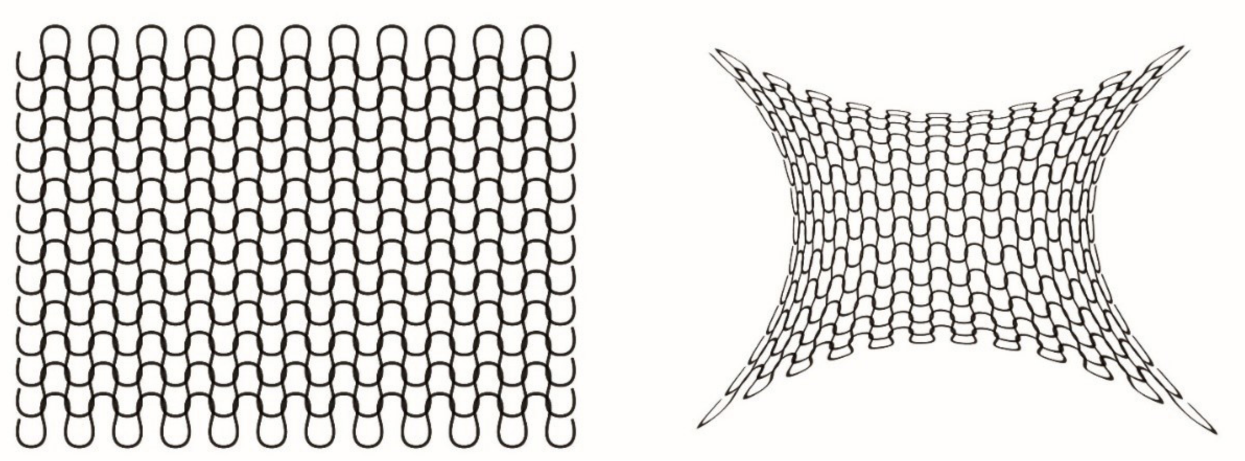

Figure 2: Image of knit structure compared to knit in a tensile state.

Figure 3: Image of knit tensegrity module studies.

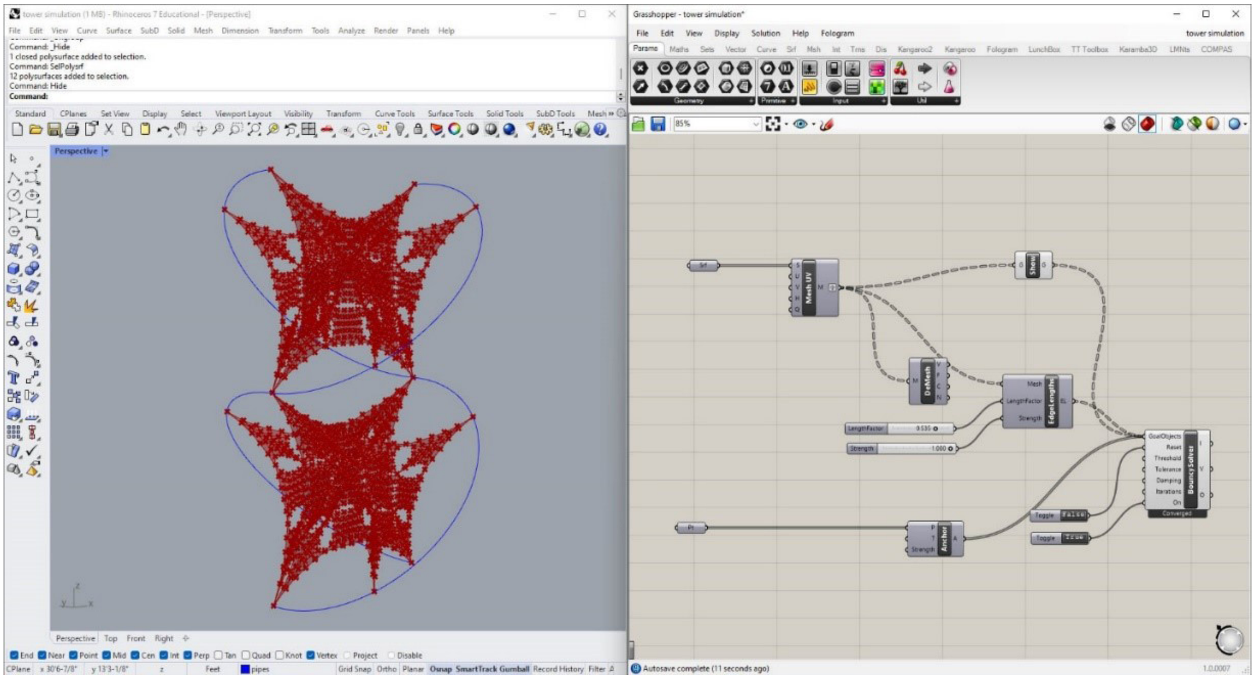

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Figure 4: Image Grasshopper Rhino Simulation.

3.4. Simulation

The design process progressed to developing computational simulations of the designs using the Kangaroo2 plugin for Grasshopper and Rhinoceros 3D. Developed by Daniel Piker, the Kangaroo plugin allows for physics simulations of materials and forces. These simulations were necessary to provide information for the creation of knit material to the precise dimensions and size required. In the simulation, a 3D mesh surface was set to have each of the mesh edges as a so-called spring. These springs enabled the material to shrink and stretch and simulate how the knit material would react when forces were applied.

The mesh was subdivided into square inches in the model, with each mesh edge equal to one inch. Sample materials were tested at one inch of stretch to see how the physical knit material reacted to different forces. This information informed the dimensions and proportions applied as input for the springs and forces in the simulation. Based on this prediction, recalculation was used to estimate the number of stitches per inch needed to make up a 2.54 cm by 2.54 cm (1 inch by 1 inch) area of knit material to achieve the desired amount of stretch and support for the design. (Refer to Figure 4) The rate of elasticity was physically measured with sample material by testing it using a spring scale and pulling on it in both the warp and weft direction to determine elasticity in both directions of the knit at given forces. Since the design was intended to be at low stress, a minimum amount of force was required to determine the rate.

4. HELIX-TOWER

4.1. Hypothesis

The hypothesis behind this design is to create a unique tensegrity structure that utilizes the flexibility of bending active PVC pipes and knitted tensile textile. The goal is to create a lightweight and visually engaging structure in the form of a vertical helix. The use of textiles allows for a larger surface area and creates an enclosure that is visually appealing. This approach differs from traditional tensegrity structures that use cables, as the membrane surfaces serve as the sole tensile elements. The structure is designed to be less rigid, utilizing the elastic properties of the materials to generate possibilities for flexible and transformable structures.

4.2. Scale and Design

The proposed design consists of two modules stacked on top of each other, standing at a height of 2.74 meters (9 feet). The scale of the structure is based on the available off-the-shelf PVC pipes, which consist of four 3.048 meter (10 foot) pipes connected with a coupling fastener end-to-end. The Rhino 3D simulation was scaled to this size to predict the necessary amount of material needed to knit the membrane dimensions.

The digital simulation predicted that the knit membrane would need to be 396 by 264 stitches for the required

Figure 5: Time-lapse video stills of the construction process.

dimensions of the design. However, this would be too large to knit on a domestic Brother knitting machine as a single material. Therefore, the design was subdivided into nine smaller pieces that were attached together to make the larger membrane. To avoid affecting the elasticity of the knit material when sewing the panels together, they were only attached at the corners and not along all the edges. The subdivision design used nine pieces to create the panels for the structure.

4.3. Construction

Fifty-four pieces were knit and attached at the corners to create the final six panels needed for the structure. The final construction of the tower took less than 30 minutes from start to finish. Since tensegrity structures are self-stable systems, the tower can be built on its side, making it easier to access without a ladder. Building it on its side does not affect the structural integrity of the modules. Once fully assembled, the structure is lightweight enough for an individual to pick it up and rotate it into the desired vertical position. The overall weight of the construction is 8.9 kilograms (17.6 pounds). The final structure stands on the ends of the rods and the bottom edges of the textile membranes (see Figure 5).

The use of flexible materials and textiles in this design offers a unique and visually striking approach to tensegrity structures. The combination of bending active PVC pipes and knitted tensile textile allows for the creation of a lightweight and transformable structure that can be easily assembled and disassembled. The use of computational simulations played a critical role in predicting the necessary materials and dimensions required for the final design. Overall, this design showcases the possibilities of utilizing flexible materials and computational tools in architectural design.

4.4. Results

The final structure was able to stand on its own, but due to the weight of the materials, the rods compressed more at the base than at the top. This deformation was not predicted in the simulation models but was observed in the physical construct. However, this deformation did provide a larger edge for resting the structure on the two rods that touch the ground (see Figure 5). Overall, the structure remained flexible since the knit material was only held in tight tension at the edges, and the center portions of the material remained softer and flexible. This design differs from the precedent examples researched for tensioned membrane structures and allows for a balance between structural stability and responsiveness to those who engage with it.

4.4.1 Flexibility

The resultant structure is also still flexible since the knit material is only held into fully tight tension at the edges. The center portions of the material remain softer and flexible which is different from the precedent examples researched for tensioned membrane structures. This design allows for the softness of the structure, to provide a precarious balance between structural stability and responsiveness to those who engage with it. Similar to the definition of tensegrity and how the lightly filled balloon reacts to deformation. This does provide a possibility that with more stable materials pulled at full force it could become stronger. However, in this research the desired design to have flexibility and use the soft knit and PVC was a choice, to provide a more kinematic soft structural design.

Furthermore, this flexibility of the structure allowed for an interactive and performative aspect, exploring the relationship between bodies, space, and movement. Guests were invited to gently touch and interact with the structure, and it softly responded and bounced back, reverberating with each interaction where a push on one side flexed through the structure responding to the others (see Figure 6).

This aspect begins to reflect on the meaning of structures and stability in architecture. Can architectural environment be more buoyant? Structural systems, which are more flexible but self-stabilizing properties of tensegrity offer opportunities for more unique possibilities of engagement in architecture. How do our architectural environments respond to the human condition and how might we change and adapt our environments to fit our needs and desires? These questions respond to the possibilities of working with soft materials for soft structures and begin to develop new methodologies of working beyond the rigid building structures.

Figure 6: Image of the final structure.

5. CONCLUSION

In conclusion, this research project successfully achieved its objective of creating a soft structural design using bending active and knitted membrane tensegrity modules to form a helix-tower structure. The use of lightweight, flexible materials allowed for the creation of a tensegrity structure that was soft yet self-stabilizing and responsive to vibrations and movement.

The workflow developed for this research proved to be successful, allowing for consecutive scaling up and feedback between digital and physical modeling, leading to minimal waste production and exact fabrication of materials. The final structure generated an easily deployable design that provided a large volume with minimal material usage and was quick and easy to assemble by a singular individual.

However, while the knitting machine size was a constraint, it also provided certain advantages. The small size of the machine allowed for easy transportation and setup, and the use of a computerized design system made it easy to create complex designs quickly. Moreover, the knitting process allowed for the production of a continuous, seamless material that could be stretched and shaped to fit the desired form, leading to minimal waste and precise material usage.

The exploration of building with soft materials raises important questions about the potential advantages of creating reflexive and responsive structures that engage with human bodies and their environments. By using soft materials, architects and designers can create structures that respond to the human condition in unique and novel ways. The continued development of soft structures and integration of non-rigid building typologies will allow for the creation of buildings that can adapt and change in response to the needs and desires of their users.

The soft structural design presented in this research is a promising example of the possibilities of building with flexible materials. While there are still many questions to be answered and challenges to be faced, this research project contributes to the ongoing conversation about the future of architecture and the potential for more responsive and engaging built environments.

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