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DEPLOYABLE TENSEGRITY STRUCTURES USING PNEUMATIC COMPRESSION MEMBERS

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Abstract

A hybridized structure system is introduced, which extends the principles of active-deployed tensegrity structures through a series of prototypes that use pneumatic compression struts, resulting in a minimum weight deployable structure with maximal global volume change. The design and construction of the prototypes, analytical strategies for the performance of such air-struts under compression, and speculation on material possibilities, and the applications of pneumatic tensegrity structures will be discussed.

Keywords

Tensegrity Structures, Pneumatic Structures, Deployable Structures, Inflatable Tensegrity.

1 Introduction

Tensegrity structures are considered to be optimal because they maintain their stability with the fewest possible number of structural members carrying purely axial forces [1]. Since their introduction in the mid-twentieth century, artists, architects, and engineers have imagined applications for tensegrity structures and several innovative variations to the system have been proposed. This paper presents advancements in a hybridized structure system that extends the principles of active-deployed tensegrity structures through a series of physical prototypes that use pneumatic compression struts. Replacing rigid compression struts traditionally found in tensegrity structures with pneumatic members presents an opportunity to maximize the global volume change of the structure before and after it is deployed, and minimize its overall weight. Though proven to be theoretically possible, no large-scale physical prototypes have been developed. *The research presented in this paper is focused on developing preliminary construction strategies for architectural-scale deployable tensegrity structures that use low-pressure air-struts.* Due to the unique combination of two historic structural systems, this paper will first review the origins, historical context, and applications of pneumatic and tensegrity structures in arch`itecture and give an overview of previous proposals of inflatable tensegrity systems in other fields. Next, theoretical, analytical and design strategies for this hybrid structure system will be described, followed by a discussion of a series of physical inflatable tensegrity prototypes at increasing scale and technological resolution. Finally, this paper will specify next steps in development of large-scale inflatable tensegrity structures, and speculate on the range of material possibilities and applications such structures may have.

2 Historical Overview of Pneumatic and Tensegrity Systems

This section provides a historical context for the system being proposed whereby aspects of two historic systems are being combined. Though distinct in their material strategies, pneumatic and tensegrity systems were not only developed simultaneously in the mid-twentieth century, but also were considered to be conceptually similar because they both isolate matter in a state of compression immersed in matter in a state of tension [2].

2.1 Pneumatic Structures in Architecture

The application of pneumatic, or air-supported structures in engineering and other technical fields far precede their application in architecture. An early example of pneumatic structures being applied to building construction involved spraying concrete onto rubber balloons as formwork [3]. The technology was pioneered by American engineer Wallace Neff in the early 1940's and refined several decades later by systems such as *Domecrete* by Haim Heifetz and later, *Binishells* by Dante Bini [4]. Frei Otto's first volume of *Tensile Structures,* first published in 1962, contained a chapter on pneumatic structures [5], and helped establish an analytical basis for pneumatic structures as a field of building construction. By the end of the 1960's art and design groups such as Archigram, Haus-Rucker-Co, Coop Himmelb(l)au, and Ant Farm proposed and promoted the use of rapidly deployable and materially economic pneumatic environments [6], culminating with the 1970 Expo in Osaka, which featured several pneumatic pavilions. Following the exhibition manuals and handbooks including the Inflato-cookbook [7], a technical handbook by Herzog [3], and a recommendations book by the IASS [8] were published**.** These initiatives to explore and disseminate knowledge of inflatable structures has helped them become a ubiquitous building technology. Advances in materials, design, and fabrication have facilitated their widespread use for many applications and building types. Recent innovations such as the "tensairity" concept [9] use cable-tensioning to give inflatable structures them increased stiffness, bending, or buckling resistance. Like tensegrity systems, the advantage of cable-reinforced inflatables is that states of compression and tension are isolated.

2.2 Tensegrity Structures in Architecture

The history of tensegrity structures is highly controversial as several people have been credited for their invention [2]; all describing identical structural modules comprising of three compression struts and nine tension cables. The name and concept of tensegrity are credited to Buckminster Fuller, whose "tensional integrity" concept dates as far back as the mid 1940's. Kenneth Snelson's 1948 X-Column sculpture is considered to be the first built tensegrity structure [2]. In architecture, 'true' tensegrity structures have scarcely been achieved as the super-structures of buildings due to the difficulty to construct them at building scale. They have most commonly been used for experimental pavilions and sculptures. The nowdemolished Georgia Dome, built in 1992 in Atlanta, Georgia [10] was perhaps the most famous example of a permanent long-span structure that used the concept of tensegrity structures. Although tensegrity-domes are not considered to be 'true' [1] the success in Atlanta helped cultivate fresh enthusiasm for tensegrity research and experimentation. The first building to use a 'real' tensegrity super-structure was built in 2001 at an experimental facility for the University of Tokyo in Chiba, Japan [11]. A current research tread of tensegrity structure research is interested in facilitating their inherent deployment.

Several deployable tensegrity systems have been proposed over the last two decades. One variety of these systems use rigid compression members and use external actuating elements [12; 13]. Another variety builds actuating (prestress) capacity into the tension members [14; 15]. A third variety of deployable tensegrity structures integrate pneumatic actuation directly into the compression members. Such proposals have been made for applications in aerospace engineering, but have only been demonstrated with small-scale models [16; 17]. Others have developed analytical and numerical deployment simulation models for such systems and proved it was possible at large scales, but not physically tested [18; 19]. Recently, Georgia Tech Professor Glaucio Paulino used 3D-printed shape-memory polymers that self-deploy small-scale tensegrity structures by activating and stiffening strut members through changes in water temperature [20]. Paulino's work in producing such impressive shape-changing tensegrity structures has served as inspiration for the research being presented in this paper.

3 Theoretical, Analytical, and Design Considerations

This section describes theoretical, analytical, and design strategies used to develop an ultra-light variety of deployable tensegrity structures that combine the advantages of tensegrity and pneumatic structures. The structural and analytical development of the project are described, followed by a discussion of several built prototypes that expand the field of active-deployed tensegrity structures through their use of pneumatic compression struts.

3.1 Motivation and Theoretical Basis

Tensegrity structures are known to be one of the most efficient forms of construction in terms of span/weight ratio [1] but are only stable under certain combinations of topology, material stiffness, and prestressing. Deployable tensegrity structures such as those demonstrated by Glaucio Paulino [20] can achieve a minimum weight structure with significant global volume change. Replacing rigid struts traditionally found in tensegrity structures with pneumatic compression members presents the opportunity to build an even more optimal structure. Though similar proposals such structures have been made, none have seriously considered their construction at large scale in detail. This project seeks to expand on the concept of self-deploying inflatable tensegrity structures by physically demonstrating the concept at increasing scale and technological resolution. The analytical and design challenges posed by this concept include:

- Achieving a combination of topology and prestress which result in a stable structure.
- Creating a pneumatic compression strut of minimum weight that has both the strength and buckling resistance to sustain imposed loads.
- Selecting materials and components which can be packed into a minimum volume, shipped, assembled, and inflated on site as part of a self-erecting process.

3.1.1 Topology and Prestress

A basic criterion for this research is achieving stable tensegrity structures through an essential combination of precise topology and sufficient prestress in the compression members. In order to demonstrate our concept of large-scale inflatable tensegrity structures, we have chosen to only consider simple and commonly known three and four-strut tensegrity geometries. Testing the proposed concept with a more complex configuration would add unnecessary complications. One advantage to using pneumatic struts is we assume their magnitude of prestress is correlated to the magnitude of air pressure in those members.

3.1.2 Pneumatic Compression Struts

Our research has been focused on developing new material schemas for high-performance, low pressure air-struts. These ultra-lightweight struts are stiffened via air pressure and must have the capacity to be folded or packed into a much smaller volume when deflated. The struts must be air-tight so the structure can be freestanding without the need for continuous air feeds. The struts must be sufficiently strong to handle axial loads imposed on the structure even with low air pressures. Lastly, as the tensegrity structure is loaded, the struts also tend to deform and buckle, so buckling resistance must be accounted for in struts design.

3.1.3 Materials and Components

The prototypes described in this paper were developed using readily available such as polymeric sheeting and tubing. In order maintain their air pressure, the struts require end-caps that permit a certain degree of adjustability, to fine-tune the overall length of the strut. The caps should contain air-intake couplings and any other devices to monitor or enhance the performance of the strut, be lightweight, and made of materials that are compatible with the membrane material. For the tension elements of the tensegrity structure, we assume the use of thin steel cables. The amount of stress in these cables is quite low and dependent on the amount of prestress achieved in the compression strut.

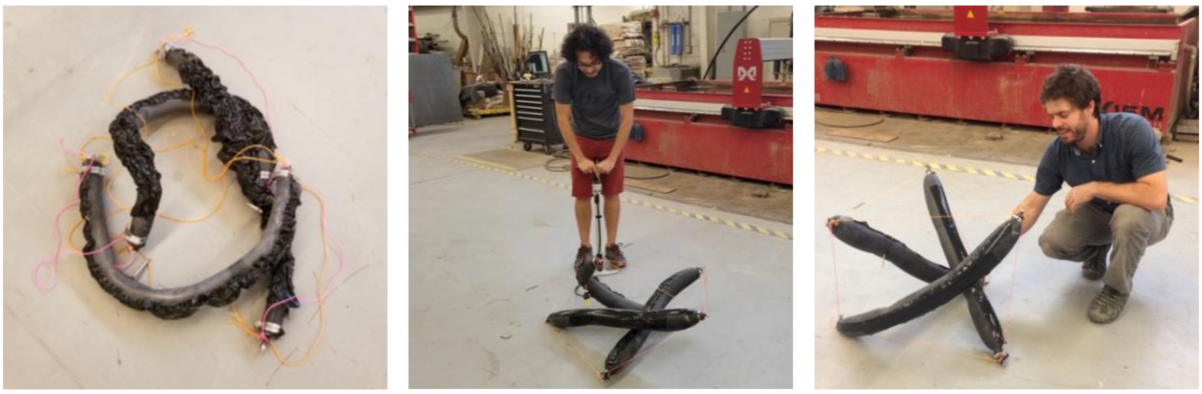

Figure 1: A proof-of-concept prototype for deployable inflatable tensegrity structure.

3.2 Preliminary Physical Prototype

As a proof-of-concept, our investigation started by building a physical model [Figure 1] using basic geometric and intuitive design guidelines [1,2]. This simple three-strut model used inflatable struts made from bicycle innertubes. The tubes were cut to length, capped with wooden dowels at each end, and held in place with epoxy and metal hose clamps. The end-caps were fitted with metal hardware to connect tension members made from braided nylon strings. The rubber tubes satisfied a critical requirement of maintaining inner air pressure, but as they were pumped with air, the synthetic rubber membranes tended to lengthen, expand, deform, and bulge unpredictable ways. As we observed behavior, tape was added to give the membranes additional stiffness. Despite its tactical use of materials and intuitive design concepts, the preliminary prototype proved our basic design criteria could be met; it validates intuitive concepts, and exhibits significant global volume change.

3.3 Structural Analysis

The structural analysis of tensegrity structures is complex. Only certain combinations of topology and prestress are feasible - often resulting in a trial and error analysis process. Additionally, tensegrity structures are geometrically non-linear, which necessitates recursive analytical procedures. Finally, the model must incorporate the non-linear hybrid properties of the air-polymer-steel compression struts.

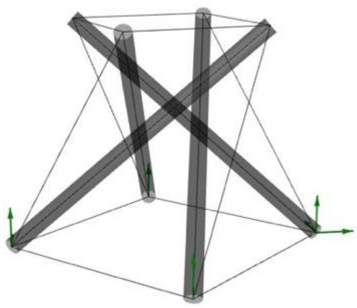

Figure 2. Basic 4-strut Tensegrity

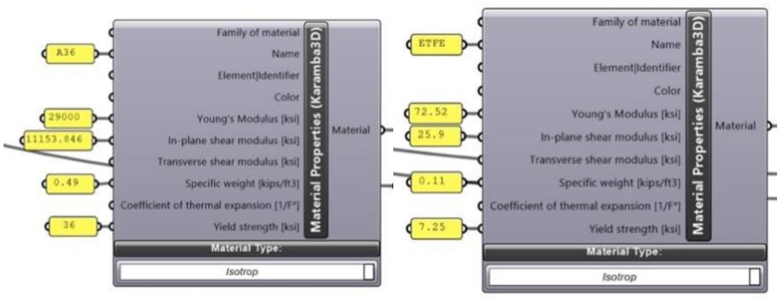

Figure 3. Input parameters for cables and struts.

The four-strut model geometry [Figure 2] was derived from a combination of engineering intuition and analogy to known stable four strut tensegrity topologies [1]. In order to facilitate the design and analysis process, a parametric model was developed using Rhinoceros/Grasshopper [21] linked to Karamba3D [22], which allowed for the viewing of real-time analysis results as input parameters were modified. Input parameters included topology (e.g. number of struts, overall dimensions, angle of rotation, etc.) as well as level of prestress, superimposed loading, and strut/tie properties [Figure 3]. Analysis results [Tables 1 and 2] were based upon incremental loading to capture geometric non-linearity and were reported for two stages: a prestress stage followed by a superimposed loading stage, visualized in Figures 4 and 5 respectively. The final configuration from the computational form-finding and analysis tool was validated using the SAP computer program [23], which confirmed the strength and stability of the proposed configuration and prestress levels.

Table 1: Member Forces.

	After Applying Initial Prestress (Lbf)	**After Applying Superimposed Loads on the Structure (Lbf)**
Struts	-18.08 (Compression)	-158.16
Top Cables	8.47	74.57
Bottom Cables	5.57	60.38
Ties	13.9	76.16

Table 2: Displacement of an upper compression node.

	After Applying Initial Prestress (in)	After Applying Superimposed Loads on the Structure (in)
dX	4.42	0.76
dY	-3.00	-0.45
dZ	3.07	0.54

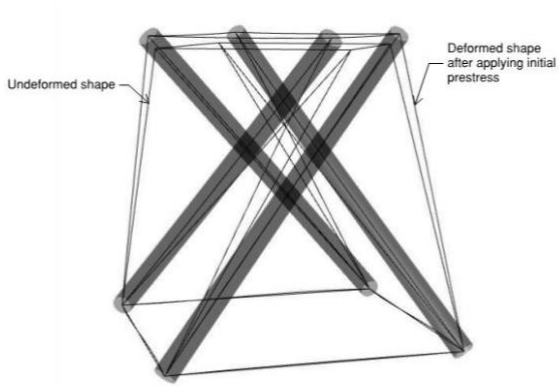

Figure 4. Deformed Shape After Prestress

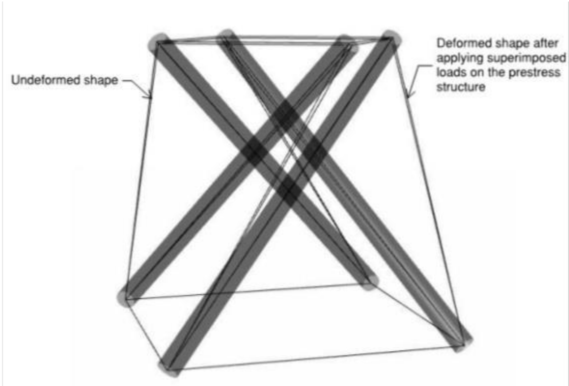

Figure 5. Deformed Shape After Superimposed Loading

4 Inflatable Tensegrity Prototypes

Following the preliminary prototype, two prototypes were built to test our scaler limits and validate the computational structural analysis methods described above. In this section two physical prototypes of deployable tensegrity structures are presented. Their common design details will be described, followed by brief discussions of each structure.

4.1 Design Details and Materials

The preliminary prototype revealed several important design considerations that were addressed in these next prototypes. The rubber membrane material lacked stiffness and was highly prone to deformations and deflections. Seeking to maintain our criterion of using commonly available materials, the two prototypes used high-density polyethylene (HDPE) tubing. Somewhat stiffer than rubber, our assumption was HDPE would provide a stiffer membrane that could handle higher air pressures and would tend to buckle less. This was proved to be particularly true when several layers of plastic tubing were used together to make a thicker membrane. The development of new endcaps to correspond with the new membrane material was another important area of focus. The caps [Figure 6] are made from polyvinyl (PVC) plumbing ends with steel hose clamps and synthetic-rubber casketing to provide an airtight seal in the HDPE membrane. Affixed at the center of each cap, a threaded rod around which the braided steel tension cables of the were looped around. Pairs of hex nuts were used to fix the cables to the cap and by moving them up or down the treaded rod, offered a small degree of adjustability to the length of each strut. Installed in one of every two PVC caps were brass pneumatic air couplings and valves that make it possible to inflate the assembly and let the struts maintain their air pressure.

Figure 6. End-cap and valve detail with tension cables. Shown with 2 layers of HDPE tubing.

4.2 Three-Strut Inflatable Tensegrity Prototype

The three-strut prototype [Figure 7] sought to deploy the most basic tensegrity unit at maximal scale. The geometry was intended to be a scaled-up iteration of the preliminary prototype and thus, still based on intuitive design concepts. The inflatable struts neared three meters in length and 10 centimeters in diameter. They were designed with two-layers of HDPE membranes, which provided a higher capacity for internal air pressure and were far stiffer than the synthetic rubber tubes. Despite monumental improvements compared to the preliminary prototype, the three-strut prototype did not fully satisfy our structural design criteria. The overall topology of the structure was not accurate enough, causing to struts to nearly touch. More significantly, the construction and detailing of the struts were improved, but for the strut length attempted in this second prototype, the membranes neither had enough stiffness to counter buckling tendencies, nor could they hand air-pressure need to supply enough prestress to the structure.

4.3 Four-Strut Inflatable Tensegrity Prototype

The four-strut prototype [Figure 8] attempted to test the geometry that was described and analysed in section 3.3. This prototype used the same end-caps from the three-strut prototype but made some measured adjustments. Once again, the membranes consisted two layers of 10 cm diameter HDPE tubing. Thanks to the integrated computational form-finding and structural analysis tools, the overall geometry of this third prototype was far more precise. The struts were a stiffer than before, likely due to the fact that they were shorter (close to two meters in length) and had less of a tendency to buckle due to prestress. When any part of the structure was externally loaded, the struts would buckle nearly immediately. Numerous modifications are needed to address several aspects of the pneumatic struts. Though we initially had a desire to use cheap, “off the shelf” materials, the

HDPE membranes are ultimately too weak on their own for a large-scale application such as this. With a higher-performance plastic membrane such as PVC, the inflated portion would be stiff enough to resist higher internal pressures.

Figure 7. Three-Strut Prototype.

Figure 8. Four-strut Prototype.

5 Toward Buckling-Resistant Compression Air-Struts

The tensegrity prototypes described above indicated compression strut stability issues. Although inflation pressures were theoretically adequate to maintain structural integrity, premature buckling caused by weak membrane materials was an issue. As the tensegrity prototype was loaded, the struts tended to deform and buckle, which in turn caused the HDPE membrane to permanently yield into a deformed shape. This shifted the focus of our investigation toward developing new material schemas for low-pressure, buckling-resistant compression air-struts - a process that is ongoing. Our initial strategy involves using a steel cable reinforcing system in a manner similar to the “tensairity” concept [10], which offer increased stiffness to low-pressure pneumatic tubes through cable-reinforcement. Though tensairity has been proven to provide buckling stiffness to inflated members in bending, very little work has been done to develop reinforcing strategies for an air-strut in compression.

Conceptually, the inflatable tube serves mainly to provide prestressing to steel cables of sufficient strength and stiffness to sustain imposed loads. This is analogous to the effect of tendons in prestressed concrete construction. A computer model of a hybrid strut consisting of a polymer tube reinforced with steel cables was developed. Simultaneously to these computational studies, a new strut prototype was built [Figure 9], which began addressing several of the problems identified before. Through our experience working with these polymer-membrane struts, we found that the strut tended to shorten slightly as it gained more internal pressure. The caps were modified to include several points of adjustability to adjust the length of each cable. An added advantage to this was the ability to ‘true’ or straighten the compression strut. A delicate balance had to be observed: while the steel cables (along with the plastic hoops) have the potential to increase buckling resistance in the strut, one could also imagine causing premature buckling in the membrane, simply by tightening the tension cables too much. This would be analogous to putting too much post-tensioning in a concrete beam and exploding the concrete in compression.

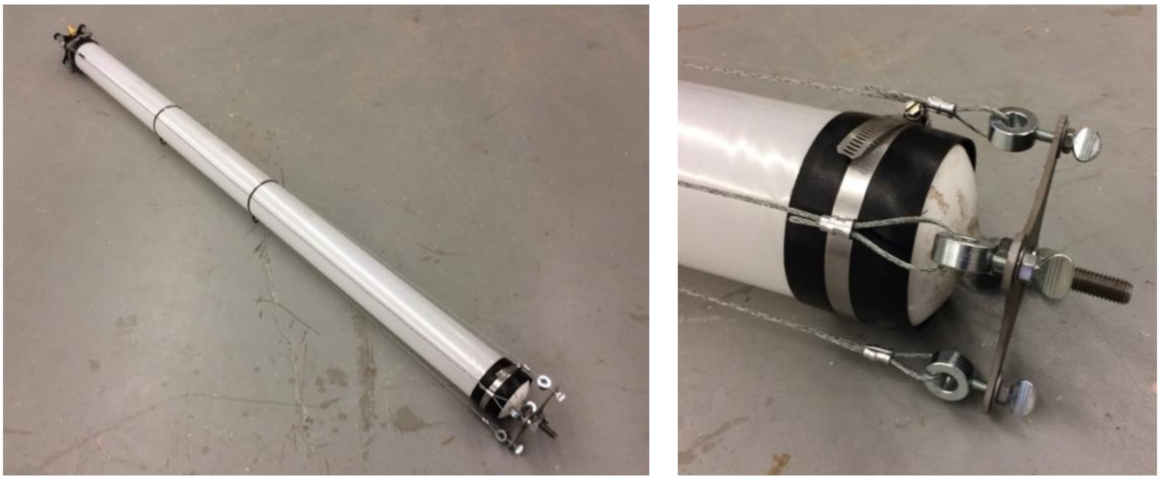

Figure 9. Cable-Reinforced Air-Strut Prototype.

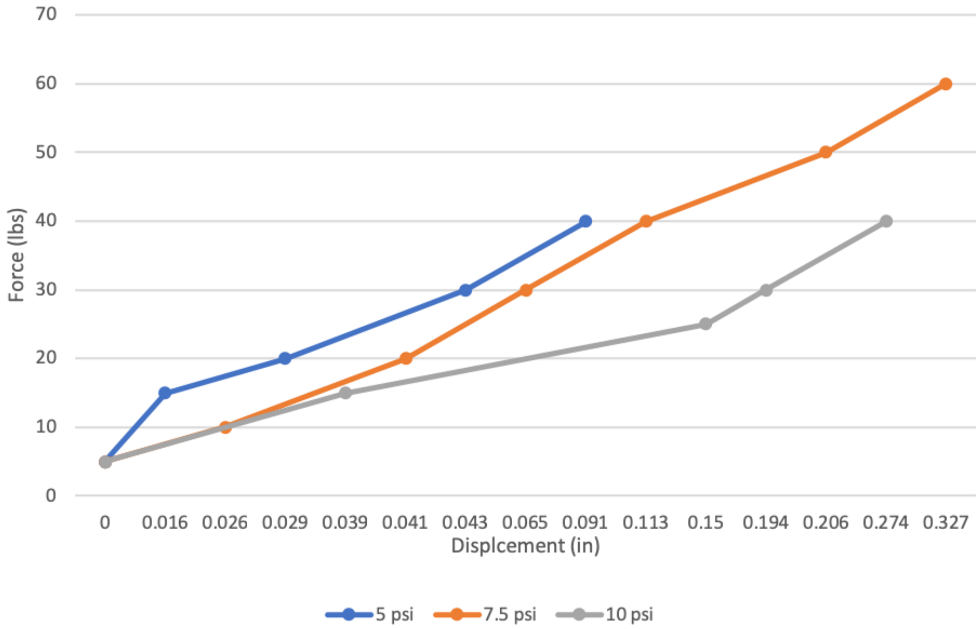

Figure 10. Force-Displacement Graph of Cable-Reinforced Air-strut Prototype.

To confirm our analytical results, the new strut was load tested at different air-pressures. These initial tests resulted in strut capacities far lower than those indicated by the analysis. The graph [Figure 10] shows the highest loading did not correlate with highest internal pressure. Significantly, the tests revealed that as the strut was loaded externally, the diameter of the membrane increased, in turn causing the length of the strut to shorten – which we attribute to a Poisson's ratio effect caused by insufficient hoop stress capacity in the plastic. The shortened strut caused the cables to lose their tension in turn caused the strut to buckle prematurely. Using a stiffer membrane material and reconfigured tension cable scheme would help reduce this effect. Our team is currently improving the design for retesting.

6 Conclusion

The research presented in this paper has focused on developing preliminary construction strategies for architectural-scale deployable tensegrity structures that use low-pressure air-struts. Replacing rigid compression struts traditionally found in tensegrity structures with pneumatic members presents an opportunity to maximize the global volume change of the structure, and minimize its overall weight. Though proven to be theoretically possible at large scale, previous inflatable tensegrity systems have only been physically developed at small scale. This paper has presented advancements in the concept of active-deployed tensegrity structures through a series of physical prototypes that use pneumatic compression struts. The prototypes demonstrate that inflatable tensegrity structures are possible at large scale - particularly if high performance materials were to be used. With continued development of buckling resistance strategies, there is even greater potential for expanding the material and performative schemata for the struts. This is significant because it expands the potential for this technology to be applied in several contexts and scales. As performative and aesthetic concerns are considered, a wide range of design possibilities arise. At architectural scale, such deployable structures could be designed to be self-supporting or work as a part of a larger superstructure. Depending on the application, the design of the compression air-struts and the materials used could differ drastically.

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