Suspended tensegrity
the anthropomorphic machine

Loh, Paul Ling Leong ; Leggett, David; Bohnenberger, Sascha; Tam, Matthew

Published in:
Integration of Design and Fabrication: Proceedings of the International Association for Shell and Spatial Structures Annual Symposium 2023

Proceedings of the IASS Annual Symposium 2023
Integration of Design and Fabrication
10–14 July 2023, Melbourne, Australia
Y.M. Xie, J. Burry, T.U. Lee and J. Ma (eds.)

Suspended tensegrity: the anthropomorphic machine

Paul LOH[*], David. LEGGETT[a], Sascha BOHNENBERGER[b], Matthew TAM[c]

[*] Bond University
Abedian School of Architecture, Gold Coast, Queensland, 4229, Australia
ploh@bond.edu.au

[a] LLDS Architects | Architectural Research Laboratory
[b] Swinburne University of Technology
[c] Bollinger+Grohmann

Abstract

The paper presents a suspended tensegrity "cloud" structure as an interactive art installation with computer vision. Actuated by 12 pneumatic rubber muscles, the research discusses the design, engineering and fabrication challenges of a dynamic tensegrity "cloud". Through material testing and physical prototyping processes, the design workflow enables a cross-disciplinary approach to the problems with feedback and an iterative static analysis approach. The project demonstrates a cross-disciplinary design collaboration between artists, architects, engineers, and the fabricator towards refinement in the engineering of dynamic structures. Using a pneumatic actuation system combined with tensegrity structures, the project demonstrated a method to develop active, controlled, deployable and form-changing envelopes and structures on a larger scale.

Keywords: tensegrity, fabrication, prototyping, automation, dynamic structure, interactive structure

1. Introduction

A tensegrity structure is typically used for large, spanning self-equilibrium systems composed of continuous prestressed tension cables and individual compression struts, such as the Georgia Dome by Levy [1]. Its use as a dynamic structure to shape space is rare. While there is much speculation about its interactive potential in architecture, typically through a single cell or a spine-like array, to explore transformational (as movements) or collapsible structures as soft robotics [2]. They are usually built as small-scale prototypes as proof of concept [3]. Actuations generally are limited to replacing the tension members to produce movement and are constrained by strut congestion, poor load response, and fabrication complexity.

This paper presents a suspended tensegrity structure actuated by a set of pneumatic muscles driven by a computer vision feedback system. The paper examined the engineering and fabrication of the design with a focus on the tensegrity "cloud". The project, titled the Anthropomorphic Machine, is an interactive art installation, in collaboration with the artist STELARC, that responds to the crowd's behaviour in a gallery setting, see figure 1. The paper outlines the design process balancing structural stability, integrity, and dynamic performance through prototyping. The physical prototyping process incorporates feedback from the system's virtual stress analysis and reaction forces, as well as tensile stress testing of the typical connection joints. The paper concludes with the assembly procedure of the tensegrity structure. It points towards the new potential of using tensegrity structure to modulate spatial experience through automation and machine visions. The project's significance is in demonstrating how to achieve a large-scale dynamic tensegrity structure that is atypical of its use in architecture and engineering.

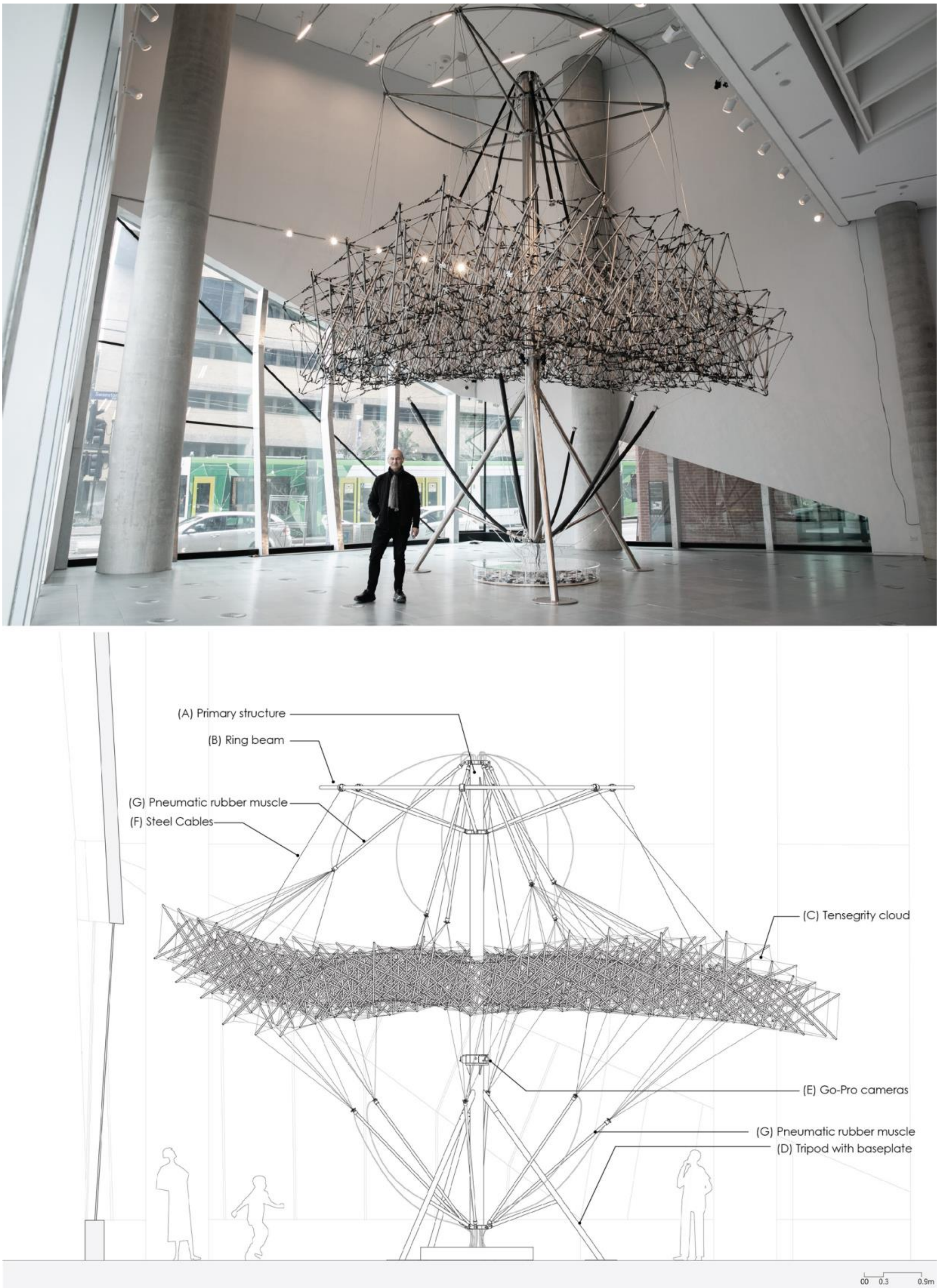

Figure 1. The 8-meter tall Anthropomorphic Machine installation in an art gallery with an actuated suspended tensegrity "cloud".

2. Background

The Anthropomorphic Machine is an interactive art installation presented as part of the Swarm exhibition at the Science Gallery Melbourne. The research was a two-year collaborative project with multiple contributors, as acknowledged at the end of the paper. Led by LLDS architects in collaboration with the artist STELARC, the structure analysis was performed by Bollinger+Grohmann engineers with the cooperation of the fabricator, Pelican Studio. The fabrication team was given a 5-month period to fabricate the structure. The installation needed to be operational 24 hours, seven days a week, as the installation was also linked to a proposed web interface that allows remote interaction. The project was intended to be in the Gallery for three months, and this was extended to 12 months post-installation.

2.1. Design of the anthropomorphic machine

The project consists of an 8-meter-tall stainless-steel primary structure with a circular ring boom and supporting struts at the top from which the tensegrity "cloud" is suspended, figure 1A, B and C. The structure sits on the raised floor of the Gallery on a tripod support structure with baseplates, figure 1D. The tensegrity "cloud" is 8 meters in diameter and consists of 204 tensegrity cells. It is suspended 4 meters off the ground using 5mm diameter stainless-steel cables, see figure 1F. Twelve pneumatic rubber muscles actuate the "cloud", each 2.5m long, that take advantage of the dynamic quality of the tensegrity to create a set of choreographed movements, see figure 1G.

2.2. Problems with tensegrity structures

A tensegrity system consists of a set of discontinuous compression components (struts) interacting with continuous tensile members (cable or cords) to define a stable 3-dimensional form. Buckminster Fuller first used the term in his 1959 patent on "Tensile-Integrity Structures" [4]. Its geometries (in various configurations) and mathematics have since been widely studied. However, the design and fabrication of tensegrity structure remain challenging. Burkhardt [5] highlighted the four obstacles in the design and fabrication of a tensegrity structure, namely: (1) strut congestion, (2) poor load response (with high deflection), (3) fabrication complexity and (4) inadequate design tools. This research utilised the high deflection of the system to produce an interactive artwork. The strut congestion becomes part of the design intent – designing opportunities for the stainless-steel struts to generate sound as they strike each other when actuated. The later section will discuss the fabrication complexity, primarily around the dynamic behaviour and connection details. As the system are difficult to predict [1], the research team develops prototypes throughout the build process to test and counteract issues around fabrication, assembly, and installation. Typically, tensegrity is designed as either a single cell (with unique arrangement) or part of dome geometry (either as a higher frequency sphere or double-layer system); a planar array is limited in its configuration [5].

3. Suspending tensegrity for interaction

The early concept of the Anthropomorphic Machine took inspiration from Loren Carpenter's Audience Participation project based on his Cinematrix Interactive Entertainment System presented at the 18th Annual Conference on Computer Graphics and Interactive Techniques [6]. Carpenter pioneered the deployment of computer vision, moving from bi-directional one-on-one interaction between a human and a computer towards multiple audience participation using images captured with a conventional camera and a computer to process the image as data [7]. In SIGGRAPH 1991, the system was tested on an audience of participants, each provided with a green and red paddle to collectively play the classic computer game, Pong [8].

3.1. Computer vision for interaction

In this project, we used an open-source software called OpenPose connected to three go-pro cameras to provide a 360 degrees vision of the Gallery, see figure 1E. OpenPose is a real-time multi-person human pose detection library [9]. The interactivity in the Gallery was based on the overall dynamic of the human crowd movement; their speed and density (number of people) were mapped to four pre-defined sets of choreographed performances. Each set of performances creates a seamless behaviour that changes the cloud shapes and form, with a typical play length varying from 10s to 15s. The performance was caused by actuating the pneumatic rubber muscles at different speeds and frequencies. Six pneumatic muscles hung from the top to actuate the top surface of the cloud, and a further six pneumatic muscles were located below the "cloud". Aside from its self-weight, the tensegrity "cloud" must withstand the dynamic forces resulting from the performances. The design of the performance and actuation sequences are outside the scope of this paper.

3.2. Actuation system

Early experiments with students at the Melbourne School of Design explored using OpenPose to trigger a pneumatic rubber muscle - a single-action actuator which contracts up to 25% of its nominal length, actuated using compressed air (typically at 6 bar pressure) regulated by valves with no mechanical system. Figure 2 illustrates early prototypes that explored the actuation of a one-cell and 12-cell tensegrity prototype. The positioning of the pneumatic muscles is critical in maximising the dynamic effect of the cloud. When the actuator replaces one of the tension cords, the movement is precise, but its impact is minimal as a network. When the pneumatic muscle is located outside the system, its action is amplified across the network. The latter is used in the gallery installation; each muscle has a set of 2mm diameter steel cables (called tendons with 6 to 12 arrays) that connect the "cloud" as a network. The initial test also identified that all the tension members should be elastic as this help to amplify the movement; we used an industrial multi-strands shock (or bungee) cord for the installation.

Figure 2. Left, pneumatic muscle interaction with OpenPose. Right, the 12-cell tensegrity prototype actuated through OpenPose.

The final installation used twelve 2.5 meters long, 40mm diameter pneumatic muscles, with a 250 kg freely suspended additional load capacity. Each weighs 2kg with wrought aluminium alloy press-fitted connections.

3.3. Detailing of the T-prism cell

As discussed in 2.2, the tensegrity structure has several fabrication limitations and constraints. With five months to engineer and fabricate the steel structure and the 204 tensegrity cells, the design and detailing of the cell were critical to the success of the project. The design team developed a system where the individual cell was prefabricated and joined together to form a planar assembly on site.

The design team proposed using a tensegrity prism (also known as the T-Prism) as the primary cell for the planar assembly. The planar arrangement repeats rows of T-Prism with a half-cell offset; see figure 3-left. Each cell comprises of three 22.2mm diameter stainless-steel tubes acting as the compression struts (figure 3A). Two end connectors are fitted to both ends of the struts (figure 3B). The tension cables are 8mm diameter multi-strand industrial shock cords (figure 3C) with hooked connector fixtures to both ends (figure 3D). The hook is connected to the end connectors enabling the fabricator to pre-assemble the unit. A triangular arrangement of cords is on the top and bottom planes of the cell (figure 3E). These triangular cords are connected with temporary connectors (figure 3F), allowing neighbouring cells to attach and expand as an array. Once the neighbouring cells are added, the triangular cord forms part of the tensegrity network. Figure 3-right illustrates the prefabrication of a three cells cluster. With dynamic forces acting on the connectors and the cords (figure 3B, C and D), these components were tested to satisfy the dynamic load of the system, see 4.2.

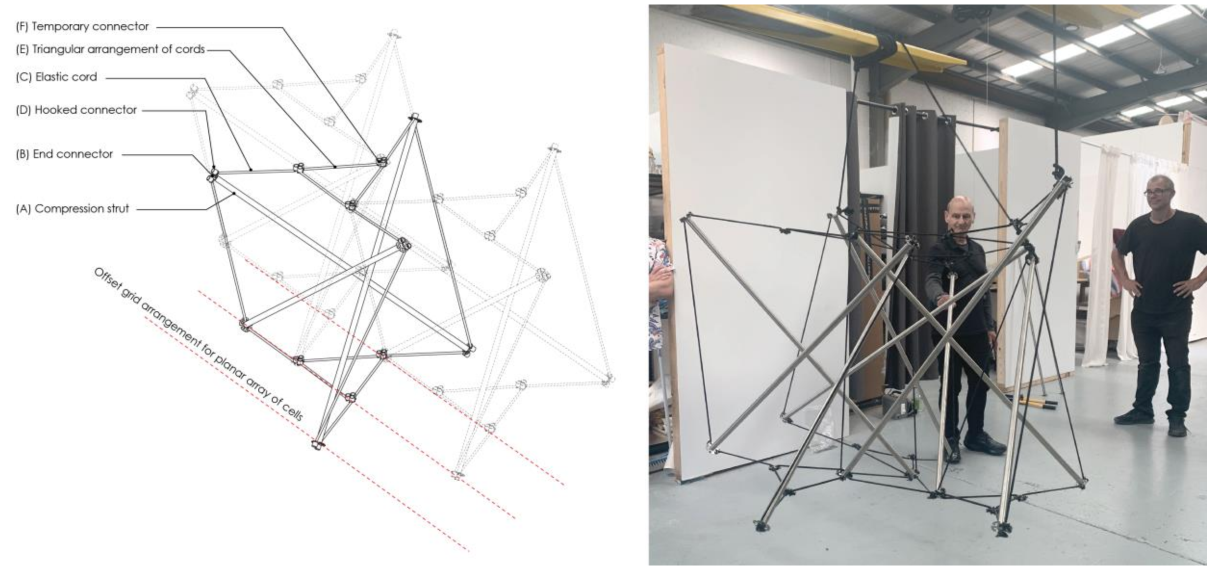

Figure 3. Left, Single T-Prism and planar arrangement of the "cloud". Right, the 3-cell cluster prototype at Pelican Studio.

4. Engineering dynamic system

This section focuses on designing and engineering the tensegrity "cloud". It comprised 204 prefabricated T-Prism cells with 612 struts, each 1340mm long. There were 1400 meters of 8mm diameter multi-stands industrial elastic (shock) cord cables that acted as tension members. In addition, 50 meters of 5mm diameter stainless-steel wire cables supported the "cloud" structure. A further 50 meters of 2mm diameter steel (tendon) wires spread the linear actuation force from the pneumatic muscle to the tensegrity network. The tensegrity "cloud" weighs 780kg. The dynamic performance of the tensegrity "cloud" posed challenges in structural evaluation. Critically, much of the materials used to fabricate the T-Prism were non-standard or unknown, particularly the elastic cord and connectors.

4.1. Testing material and connection details

The first author conducted three sets of tensile strength tests at the mechanical lab at the University of Melbourne using an Instron 5569A electromechanical Universal Testing Machine – (1) industrial elastic cord, see figure 4A, (2) strut's end connectors, see figure 4B, and (3) hooked connector fixtures to the elastic cord, see figure 4C & 4D. The data collected in the tests inform the design of the connection details and engineering analysis.

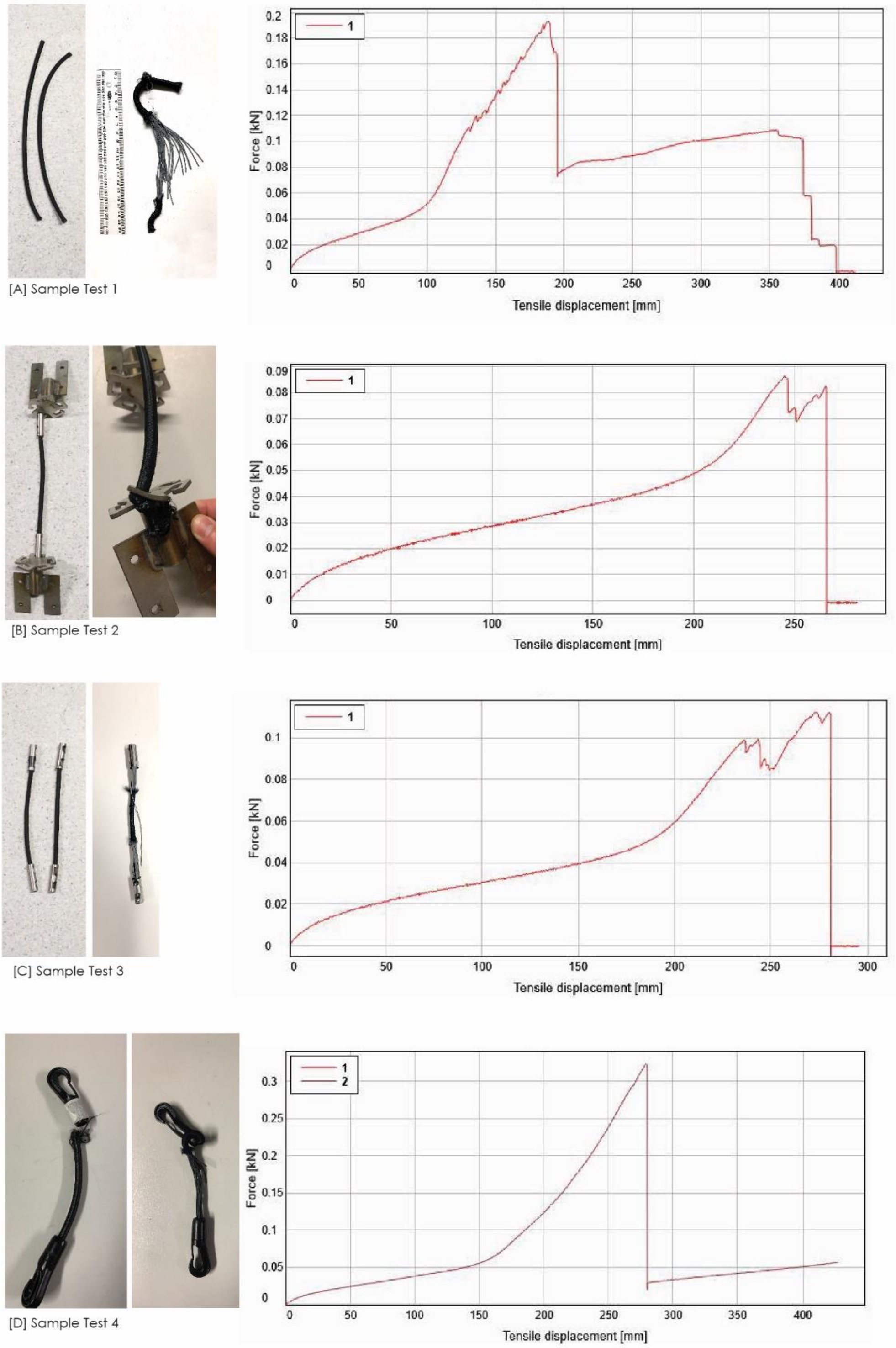

Figure 4. Ultimate Tensile Strength testing of connectors and elastic cords.

4.1.1 Tensile tests of elastic cord

The shock cord manufacturer cannot provide the material's tensile strength. The research team conducted two-sample tests; both samples were 8mm diameter industrial elastic cords with a rest length of 95mm. Sample 1 yields an Ultimate Tensile Strength (UTS) of 3.6MPA and elongation of 200.5%.

Sample 2 produces a UTS of 3.3MPA, and elongation of 183%, see figure 4A. Both samples have similar break patterns—for example, in Sample 1, the outer shell fabric tears at 190.46mm displacement at the clamps. Between 350-375mm, the individual strain of rubber breaks one at a time. In the final displacement calculation of the structure, a typical elongation of 140% was permitted, with the maximum permissible elongation of 200%.

4.1.2 Tensile tests of connecting fixtures.

The initial design for both ends of the compression struts consisted of a bespoke end connector using a 3mm laser-cut steel profile, see figure 4B. The open hook end was to connect the tensile cords. The steel distorted at 0.65kN and released the elastic cord at 0.89kN when displacement reached 455mm.

The weakness came when we tested the fixture to the tensile cord's ends. Figure 4C illustrates the initial design with a 6mm diameter stainless steel tube and a crimp joint to the end of the cord. It yielded a UTS of 1.7MPA and elongation of 152%. The worst-case scenario illustrated that the crimp connection is half as effective as the elastic cord itself. The fabricator and the architects need to reconsider the detail.

The fabricator required a quick-to-assemble solution and proposed a proprietary PET plastic hooded fixture with a compression-fit as a solution, see figure 4D. It yielded a UTS of 6.1MPA and elongation of 280%. In Sample 1, we observed the outer fabric of the elastic cord failed at the claws of the clamp. In Sample 4, the fabric failed at the compression-fit joint; we suspect this explains the higher UTS and elongation.

4.2. Structure evaluation

Typically tensegrity structures are categorised as non-linear structures. For a large arrangement of cables and struts, it is computationally complex to find its equilibrium state, especially if it is a kinematic-driven and controlled shape in continuous flux. Therefore we decided to apply a static analysis approach at various critical positions of the different shapes. The evaluation was concerned with finding the maximum internal stresses of the tension cables, compression forces in the struts to its dimension and suitable material thickness for the cables.

The overall behaviour of the different states also governed the dimensions and design of the supporting stainless steel column with its tripod legs and circular boom structure for the suspended cables. The five different states were as follows:

- Static (figure 5A). None of the muscles is activated. All the tendons (cables) are loose and should not receive any force. The main structural cables (figure 1F) support the tensegrity structure.
- Dynamic All (figure 5B): all the muscles are activated, and the tendons receive various forces.
- Dynamic V1 (figure 5C): some muscles are activated, and some tendons receive various forces.
- Dynamic V2 (figure 5D): some muscles are activated, and some tendons receive various forces.
- Dynamic V3 (figure 5E): some muscles are activated, and some tendons receive various forces.

The simulation considered a maximum of 200% elongation for the multi-strand elastic cord. The results showed the highest reaction forces nearest the "cloud" centre at 9kN. The highest displacement of the structure came from the splicing of the support legs, resulting in a maximum deformation of 40mm. The stainless steel support structure reached a maximum of 60% utilisation, and the support cables had a maximum normal force of 1.6 kN. The analysis showed that some suspension cables would fail under tension forces during dynamic behaviour. However, due to the redundancy in the system, the structure was always predicted to be stable.

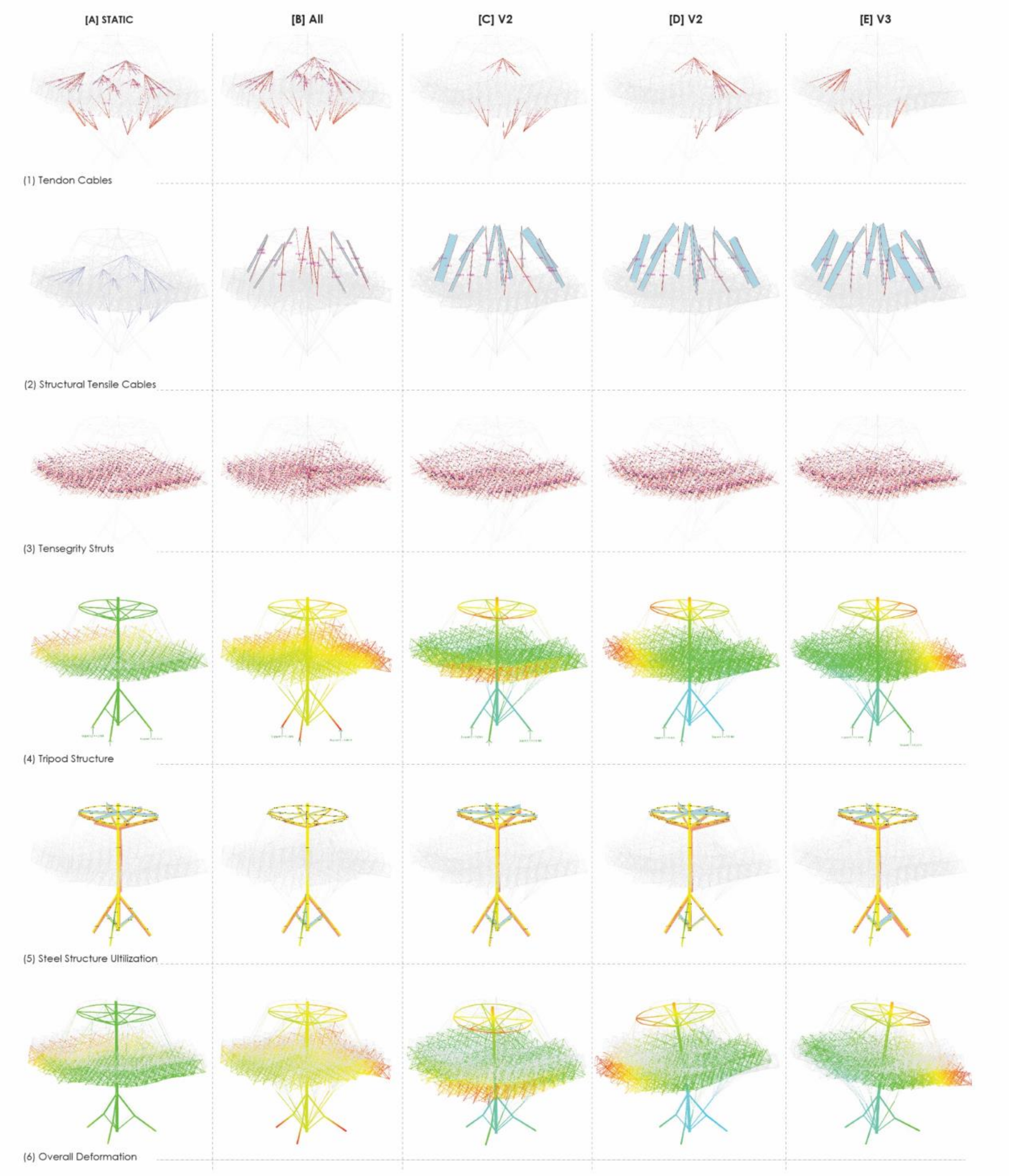

Figure 5. Matrix of static analysis across the five different states. (1) Forces on tendon cables caused by pneumatic muscle actuation. (2) Maximum internal stresses of the tension cables at the various states. (3) Compression forces in the tensegrity struts. (4) Forces on the tripod support structure and its impact on the raised gallery floor. (5) Steel utilisation of the primary structure. (6) Overall deformation at the various states.

5. Assembly of the tensegrity cloud

The primary frame was erected in the Gallery in two parts. Figure 6 illustrates the assembly of the tensegrity "cloud". The design of an individual cell allowed all the parts to be prefabricated off-site and assembled in the Gallery. As the cells were assembled, parallel lines denoting the row alignments were set out on site. Rows of tensegrity were built and then connected together. Once the cloud was completed on the ground, it was lifted 300mm higher than its final position and suspended with 12 steel cables connected to the circular ring boom. This allowed the installer to slowly adjust the "cloud" into position after installing the pneumatic muscles. The pneumatic muscles must remain in a "relaxed" position and not take the tensegrity load until it is inflated with air. The bunching of the tensegrity cell was challenging for the installation when it was suspended. The configuration is unpredictable, despite the best effect to simulate it in Grasshopper 3D. It resulted in an uneven load distribution across the 12 supporting steel cables, causing them to twist and tangle. The suspension cables and the positioning of the wires were manually adjusted; this amplified the human error affecting the "relaxed" state of the "cloud". These effects are hard to predict and simulate, and as Knippers stated, physical prototypes are necessary when engaging with new materials and material systems [10]. Therefore, during the installation phase, the engineer checked and worked with the installer to adjust the cable positions to ensure an evenly distributed load. The installation took over five days, followed by one week of testing with the dynamic performance.

During the testing phase, three shock cords broke, resulting from the actuated movement. The congested struts, predominantly around the central column of the primary structure, caused some of the elastic cords to rub against the steel connectors and tear its outer fabric. Additional stay cables were introduced to pull the tensegrity away from the column. Three inner cells were also removed during the testing process.

5.1. Discussions

When actuated, the Anthropomorphic Machine produces a variety of dynamic performances. The most compelling is the slow inhalation and exhaustion of air mimicking 'breathing'. This results in the 'cloud' animating slowly above the visitors, changing the experience of the space. Since installation, prominent Australian dancers, artists and musicians have created performances interacting with the structure.

There are several key lessons learnt in this project. First, the project could only be possible through interdisciplinary knowledge and collaboration. The architects have also taken on a significant role in prototyping the design and developing the actuation system – this interdisciplinary bridge is critical. Second, the project results from design and engineering research through testing and prototyping. The knowledge gained through the fabrication process informed the final design. Last, the project demonstrates a refinement in engineering towards dynamic structural design. The use of pneumatic elements in combination with tensegrity structures illustrates a method to develop active, controlled, deployable and form-changing envelopes and structures on a larger scale. However, the system still requires a level of maintenance (visual inspection and replacing shock cords). The shock cords seem to rapture in an irregular pattern while the Machine is operational. The team believes this might be because the dynamic load on the cord and the increased state of change in elongation (cycling through the different performance modes) are causing the cords to break faster than expected. Further on-site testing and investigation, especially into the shock cord layout and material composition, should be conducted to identify the issues and to be able to suggest improvements to extend the life expectations of the structure.

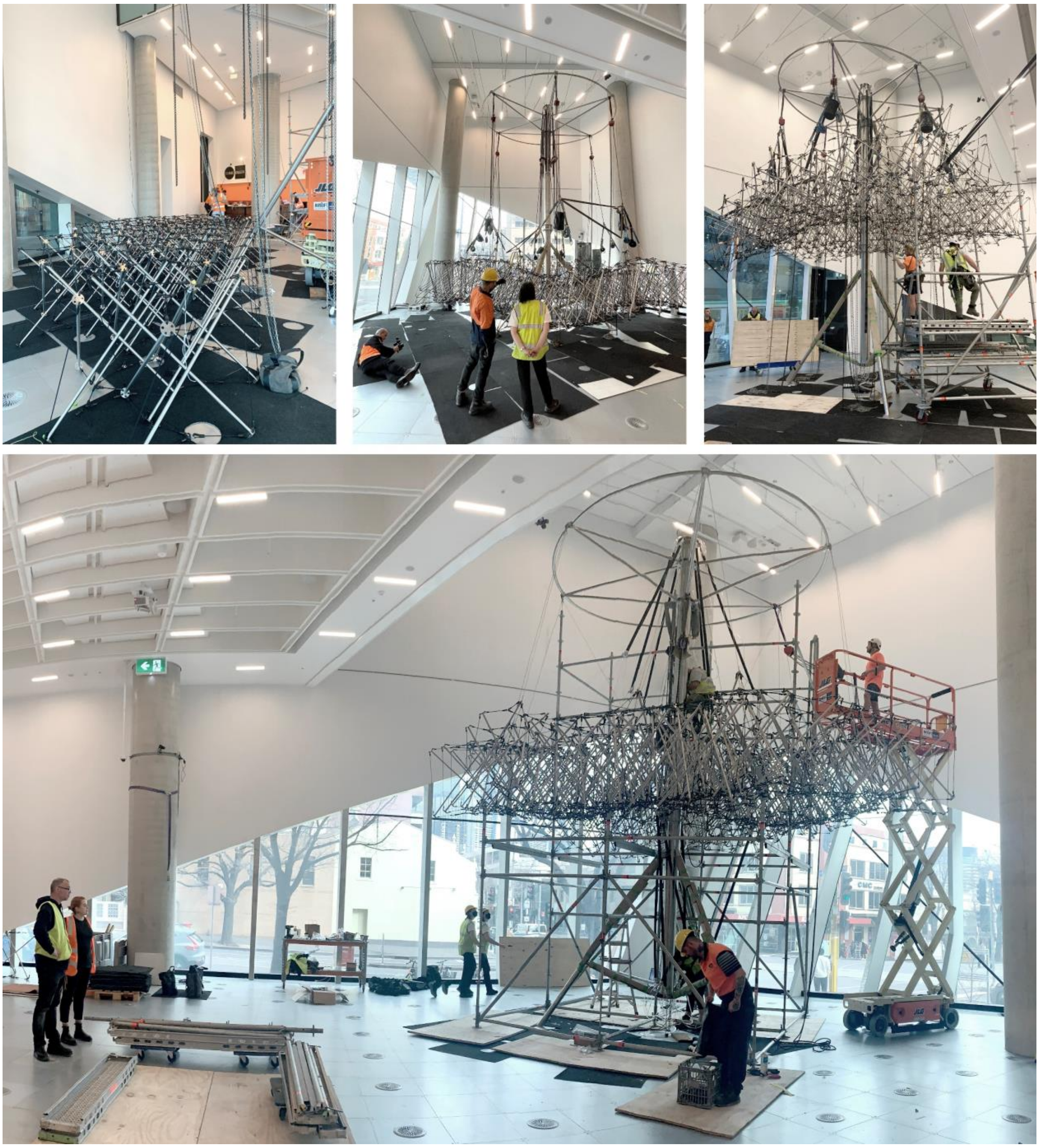

Figure 6. Top left, setting up of T-Prism planar array for the tensegrity cloud. Top centre, Suspension of tensegrity cloud. Top right, lifting of tensegrity cloud into position. Bottom, adjustment to tension cable to distribute the load evenly. Pneumatic muscles are in relaxed mode without air inflation.

6. Conclusion

The paper presents an unconventional use of tensegrity structure as a suspended and dynamic interactive installation. The high deflection of the tensegrity is maximised as part of the performance design, which creates challenges in the system's design, prototyping, fabrication and installation. The design and fabrication of the tensegrity were refined through material testing, and data was used to evaluate its dynamic behaviour through an iterative static analysis approach. The project illustrated a method of assembling T-Prism tensegrity cells into a planar arrangement and discussed the challenges of the assembly process. It demonstrates a successful cross-disciplinary design collaboration between artists, architects, engineers, installers and fabricators.

Acknowledgements

The project acknowledges the generous commission of Science Gallery Melbourne with support from Festo, Melbourne School of Design and School of Computing and Information Systems, the University of Melbourne. Special thanks to Dr Jeffrey Ryan, Elise Brokensha and Philippa Brumby for coordinating and making the project possible. Design and Pneumatic system: Paul Loh, David Leggett, Psyche Hou. Model Making: Haoyu Chen. Electrical and Electronic Engineering: Dr Eric Schoof. Computing and Information Systems: Dr Eduardo Velloso, Qiushi Zhou and Gabriele Marini. The Architectural Association Visiting School Melbourne 2021, led by Paul Loh, David Leggett and Psyche Hou with students Mason Mo, Ying Lee, Lu Bai, Mingjia Shi and Yichen Sheng.

References

[1] F. Fu, *Design and Analysis of Tall and Complex Structures*. Saint Louis, UK: Elsevier Science & Technology, 2018. [Online]. Available: http://ebookcentral.proquest.com/lib/bond/detail.action?docID=5257306

[2] A. Musaffar and A. Agogino, "Scalability and Design of Six Rod Tensegrity Soft Robotic Structure," 2021. [Online]. Available: https://ntrs.nasa.gov/api/citations/20210014844/downloads/AgoginoTensScale.pdf

[3] J. Won, M. Silverio, J. Llubia, A. Markopoulou, A. Chronis, and A. Dubor, "Remembrane: A Shape Changing Adaptive Structure," 2017.

[4] R. B. Fuller, "Tensile-integrity structures," 3,063,521, 1962 [Online]. Available: https://patentimages.storage.googleapis.com/ab/cb/74/362b8cd8c7b88b/US3063521.pdf

[5] Robert William Burkhardt, *A Practical Guide to Tensegrity Design*, 2nd ed. Cambridge, Massachusetts, 2008. [Online]. Available: https://www.angelfire.com/ma4/bob_wb/tenseg.pdf

[6] SIGGRAPH, "'Audience Participation' by Carpenter," *ACM SIGGRAPH Infomration and Artifacts History*, 1991. https://history.siggraph.org/animation-video-pod/audience-participation-by-carpenter/ (accessed Mar. 25, 2023).

[7] L. Carpenter, "Cinematrix, Video Imaging Method and Apparatus for Audience Participation," US Patents #5210604, 1994

[8] D. Maynes-Aminzade, R. Pausch, and S. Seitz, "Techniques for interactive audience participation," in *ACM SIGGRAPH 2002 conference abstracts and applications*, Jul. 2002, pp. 257–257. doi: 10.1145/1242073.1242270.

[9] B. Gaudenz, "The Complete Guide to OpenPose in 2023 Read more at: https://viso.ai/deep-learning/openpose/," *viso.ai*, 2023. https://viso.ai/deep-learning/openpose/ (accessed Mar. 24, 2023).

[10] J. Knippers, "The Limits of Simulation: Towards a New Culture of Architectural Engineering," *Technol. + Des.*, vol. 1, no. 2, pp. 155–162, Nov. 2017, doi: 10.1080/24751448.2017.1354610.