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Tensegrity Prototype TG3

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Summary: The purpose of this project was to develop a prototype structure composed of an external tensegrity ring and a central dome that can be used to cover a sports arena or other space requiring a large area free of interior supports. For example: emergency shelters, recreational/educational applications, concert halls, sporting facilities, zoo aviaries, and so on.

The current prototype's key contribution to the field of lightweight structures is that it is the first time a pure-tensegrity ring has been used in place of a compression ring. The prototype formfinding geometry was performed by means of scale models and software. Structural analysis and validation was carried out using WinTess and EasyCAD software, which demonstrated that the structure was in equilibrium.

This project was the result of research conducted in the ILEK Institute at the University of Stuttgart. Several construction alternatives were investigated with the final design determined by the budget, materials, financial, and in-kind assistance received from industrial partners and directly from ILEK.

Keywords: *Tensegrity ring, tensegrity dome, structural equilibrium, flexibility, redundancy.*

1. GEOMETRY

The geometic model was developed as part of a PhD thesis and is based on work by Anthony Pugh, who created a classification of the diverse existing typology. He described three models, or basic patterns, with which tensegrity structures can be constructed: a diamond pattern, a zigzag pattern, and a circuit pattern. The typology is determined by the relative positions of the bars and that the tendons are only attached at their extremes. The current prototype model is based on the diamond pattern. [1]

The tensegrity ring consists of 12 bars (L= 3.00 m) aligned in a double layer, where the bars are located in diagonal position and connected by 48 cables/tendons (L= 1.68 m). This design results in 24 triangle or 12 diamond-shape surfaces. When the final cables are attached to the bars, a closed-tensegrity system balanced by the cable tension is formed. The diamond pattern can be observed in how the 4 cables or tendons come together at the ends of each bar. The top (roof) and bottom (floor) of the structure are in the shape of hexagons.

For the dome geometry, 6 minor mastils (L= 0.60 m) were defined located in a circular position with respect to the central mast (L= 0.80 m). To maintain position in tridimenional space, they were connected by 24 cables (L= 1.14 m) "out" to the tensegrity ring and 12 cables (L= 0.74 m) connected "in" to the central mast. It is important to note that the minor mast position was reinforced by six diagonal cables (L= 0.98 m), which were connect diagonally to the central mast, to reduce vertical displacement.

The prototype geometry (x, y, and z coordinates) was defined in space by 14 dome nodes and 24 ring nodes. These coordinates allow us to draw and test the structure in three dimensions using CAD and/or analysis software.

2. ASSEMBLY PROCESS

2.1 General Features

The final materials cost was approximately 2000€ and was considerably less expensive than the initial estimate

Fig. 01 Tensegrity prototype assembly - ESC_1:10

of 100,000€ for a full, high-tech, detail-rich project. Due to the high design and membrane-manufacturing costs, a more-basic prototype sans membrane was chosen. The structure was built using wood bars and steel cables and accessories, which can be recycled and/or reused. The final structure weight was 48 kg, covered an 8 m^2 area in the minor diameter and 16 m^2 in the major diameter, and had an internal volume of 21.5 m^3. The ring height was 2.10 m and the total height, including the dome, was 2.50 m.

2.2 Details

Twelve 3.00 m x 40 mm beech-wood bars were used to construct the tensegrity ring. The dome was composed of one 0.80 m central-mast bar and six 0.60 m minor-masts bars, also with a diameter of 40 mm. Two protective products, one antibacterial and one UV-inhibiting anti-moisture sealant, were applied to the bars.

In total, 90 (2 mm-diameter) stainless-steel cables were used, 48 (1.68 m) for the tensegrity ring and 24 (1.14 m), 12 (0.74m), and 6 (0.98m) for the central dome. Cables were assembled with 150 carabiners, 150-small and 6-large screw-eyes, 180 simplex wire-rope grips, and 90 cable turnbuckles with zinc-coating or galvanized-steel accessories.

The process and the end result can be observed in the photos (Fig.01)

2.2 Process time

The model was entirely handmade. The final assembly in volved two people and occurred over approximately one week.

Preparing the bars with the antibacterial and sealing liquids took two days. The steel cables were measured, cut, and assembled to the beech-wood bars in three days. The final assembly, which took four hours, involved organizing the bars on the ground in their final configuration and then making the cable connections to the bars. After most of the connections were made, the "open" structure was lifted into position by 4 people. The structure was then "closed" in thirty minutes by attaching the remaining unconnected cables.

Cable tensioning and double checking all measurements took an additional three hours. After the model was assembled, it became apparent that the roof would benefit from additional stiffening and six diagonal cables were added to help and control minor-mast movement. To assemble, attach, and adjust these additional cables took two hours. Four membrane pattern pieces were designed, cut, and sewn over three more days.

Disassembly is estimated to take approximately one-to-two hours and the entire structure can be placed into a 3.10 m x 0.20 m x 0.20 m box.

The defining structural feature of tensegrity is that its geometry is defined by the balance of tensile and compressive forces. It is characterized by a network of discontinuous compression bars balanced by tensed cables. Each node has at least one bar (compression member) and 2 or 3 continuously-tensed cables (tension members) in compression.

Balance is achieved because all the compression and tensile forces are perfectly distributed, that is to say work together, where the structural form is guaranteed because the system is closed and auto-balanced [2]. The current prototype functions in this way.

As shown in the diagram (Fig.02), the greatest tensions are found in the cables that support the upper bars of the ring and the cables that close the upper and lower tensegrity ring. The cable pretension, created by closing each turnbuckle by 2.5 cm, was approximately 0.003 kN or 0.3 kg.

3. STRUCTURAL ANALYSIS

3.1 Structural Balance

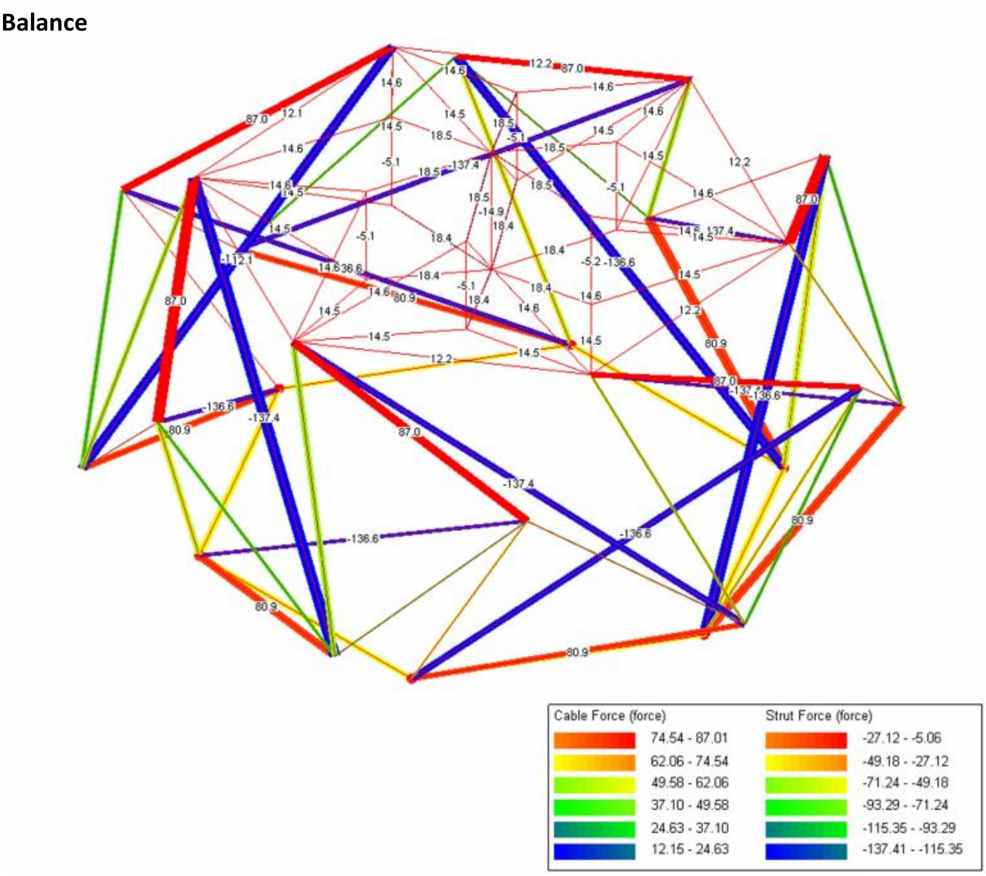

Fig. 02 Tension-Analysis Diagram Using EasyCAD - TechNet.

3.2 Flexibility

The flexibility of the model, taking into account the cable tension and compressive elements, was studied. As can be seen in the ellipse diagram, the largest movements (approximately 11 cm) occur in the free nodes of the tensegrity ring where there is no direct contact with either the dome or ground. The largest movements in the dome (approximately 6 cm) occur in the minor masts (Fig.03).

3.3 Redundancy

Redundancy is especially critical in lightweight tensegrity structures. In some projects, the engineers have created redundancy by using more than one cable when joining the last line of cables to the structural ring so that the structure does not collapse in the case of one cable failing. The current design was tested by disconnecting one of the rings' main cables, which, of course, changed the structure's geometry. The loose bar moved to a horizontal position but the entire structure did not collapse. This can be seen in both the 1:100 and 1:10 scale models (Fig.04).

4. FINAL COMMENTS

4.1 Advantages and Disadvantages

The results were shared with important architects and engineers in the area of lightweight structures. Among them were: Hubertus Pöppinghaus, Peter Singer, Dieter Ströbel, Martin Synold, Alfred Rein, Switbert Greiner, Mike Schlaich, Thomas Ferwagner, and Jonathan Schnepp. These are some selected comments:

- The overall conclusion of the prototype's geometry is interesting for visitors and serves the purpose of being in complete tensegrity. If we compare the example of 12-bar hexagon tensegrity ring (approximate area of 800 m^2 on a model ESC_1:1) with a 20-bar decagon (A= 1200 m^2 approx.) or a 30-bar pentadecagon (A= 1600 m^2 approx), it is important to note that, in the first case, the angle space might be wasted but, in actual project use, it could serve as the structure's eaves, to mark the entry, and/or protect pedestrians from the sun and rain.

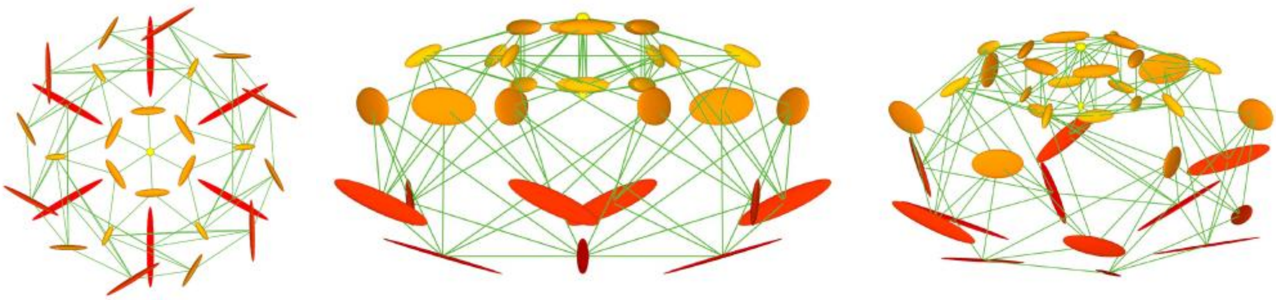

Fig. 03 Plan, Elevation, and Axonometric Views using EasyCAD - TechNet.

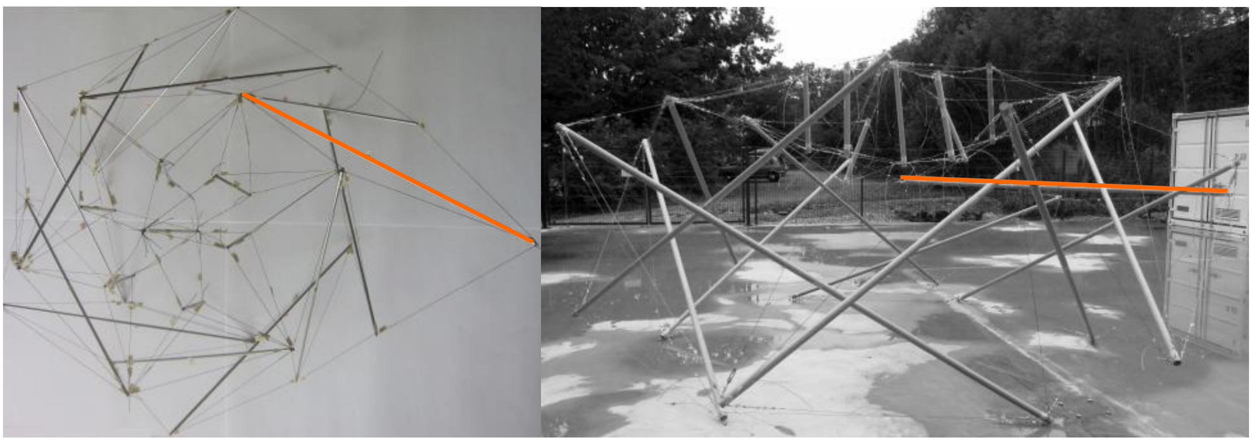

Fig. 04 Model Scale 1:100 Plan View (left) – Model Scale 1:10 Elevation View (right).

- Regarding the structural behavior, the structure works well as can be observed in the model. For some engineers, movement is an integral part of a flexible structure's behavior, which can be seen as an advantage or disadvantage depending on the point of view. It is comparable to the behavior of pneumatic structures, where the structure moves in response to external forces but then returns to its initial position. Some structures require external devices to handle flexibility but in this case, it is inherent in the structure itself.

- It should be noted that it is necessary to perform dynamic wind tests to analyze the effects of vibration in the structure. A specialist in this area would be required. Also, regarding redundancy, the ability for the structure to have loosened cables resulting in changed geometry and still not collapse is important.

- As for the structure's cost, we do not have an actual figure on the difference between a tensegrity ring and a compression ring, which would be an important point when considering its use in a real-world project. The standard used when costing a lightweight structure per m^2 is, on average, 1000€ for high technology, 700€ for mid, and 300€ for more basic structures. The total cost of the current prototype, as mentioned above, was 2000€, or approximately 250€ per m^2.

- In terms of sustainability, it is important for a structure to be easily assembled and disassembled, recycled, relocated, and be flexible in how it is used. The current structure meets many of these requirements and also is relatively low cost.

- It should also be noted that industry support is essential if the continued development and use of this type of tensegrity structure is to be realized.

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