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Application of the tensegrity principles on tensile textile constructions

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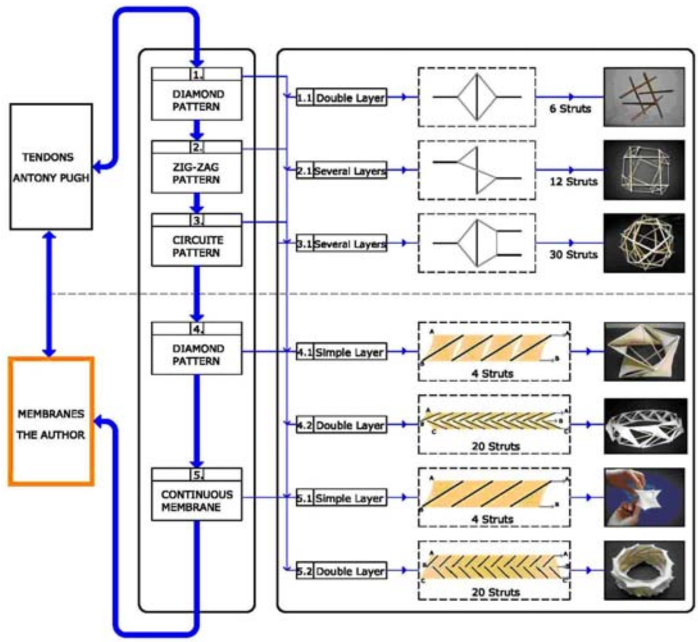
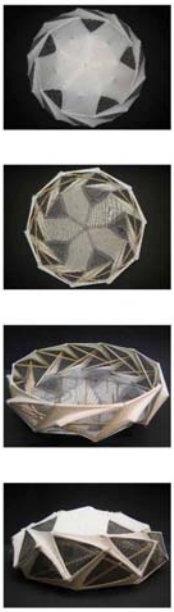
Abstract

This study tries to contribute in a particular way to the application of the tensegrity in architectural spaces, in this case sports spaces through a new proposal that generates an external ring in tensegrity with a central dome, free of any interior support, by formfinding a continuous membrane pattern with discontinuous struts in double layer that find their equilibrium through the tension of the membrane.

In the following examples one can observe that traditional tensegrity tendons are replaced by membranes, which is the main contribution of this work that finds geometry and its constructive method of the different prototypes with the help of software like AutoCAD and WinTess (a software development by Ramón Sastre), which verifies the structural equilibrium.

Keywords: Tensegrity unit, formfinding (continuous membrane pattern and diamond pattern, in simple layer and double layer), constructive method, pretension.





1. Definition of tensegrity

The tensegrity geometry is defined by the equilibrium of tensile and compressive forces. The tensegrity geometry is characterized for having discontinuous compression bars, which remain in equilibrium by tensed cables. The balance is achieved because all the compression and tension forces are perfectly distributed, that is to say work jointly, where the structural form is guaranteed because finally the system is closed and auto-balanced, as Fuller [1] had said "Islands of compression in an ocean of tensions".

2. Precedents

In 1976 Anthony Pugh of the University of California (Berkeley) wrote his book "An Introduction to Tensegrity" where he showed and described different models; in addition he did a classification of the diverse existing typology [2]. He described three models, or basic patterns, with which the tensegrity structures can be constructed: a diamond pattern, a zigzag pattern and a circuit pattern. This classification originates from the relative position of the bars amongst themselves and the ends of the tendons [3]. This work rises from Anthony Pugh's classification of the diamond pattern and the position of the bars aligned in a simple layer or a double layer, and proposes models using a continuous membrane and a diamond pattern.

3. Formfinding by geometry

The tensegrity geometric construction of this study is based on:

- The conception of a basic module or tensegrity unit from polygons and polyhedrons (prisms and anti-prisms), Platonic and Archimedes solids. [4]
- The substitution of geometric components like edges and vertexes by bars, cables and joints by faces in membranes.
- Forming more complex systems from groups and variations of the basic module.

3.1 Model types – Membrane patterns (contribution of the author)

a. Diamond membrane pattern and struts in a simple layer

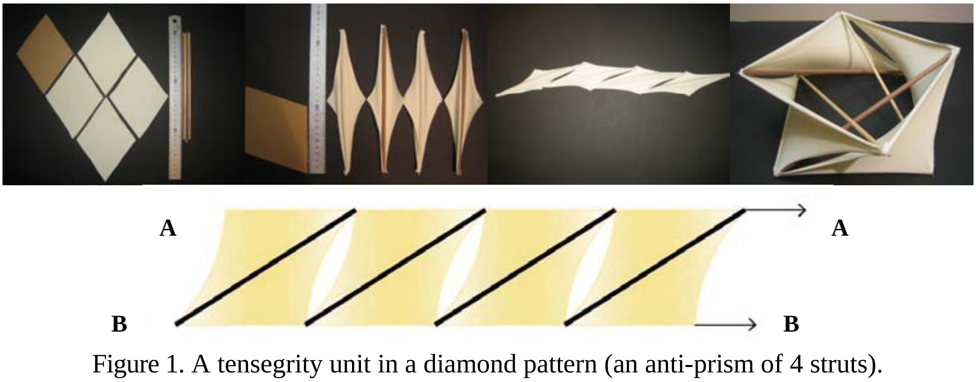


Figure 1. A tensegrity unit in a diamond pattern (an anti-prism of 4 struts).

The process is generated by cutting textile membrane, rhombus or diamond shape patterns, for the basic anti-prism unit of four bars, which are arranged in an oblique direction or diagonal position. The bars are joined to the end points of the membrane as shown in Fig. 1. The bars are tied to the adjacent pattern on one of its vertexes, and so on. The tied up units can be closed by joining the first bar and the last membrane pattern. The final anti-prism form has four paraboloids surfaces constructed from a flat rhombus. The initial position of the bars in this case is a simple layer.

b. Continuous membrane pattern and struts in a simple layer

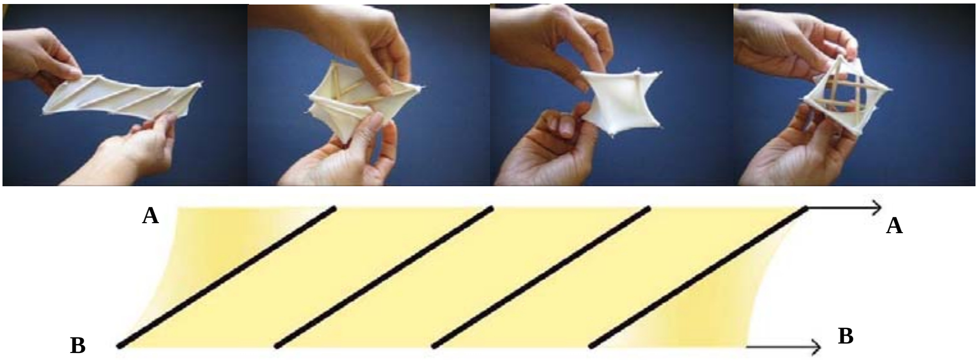


Figure 2. A tensegrity unit formed by continuous membrane patterns (an anti-prism of 4 struts).

One can depart from the previously described process, and use a continuous rectangular membrane pattern to find the form. The bars arranged in a simple layer and joined to the end points of the membrane as shown in Fig. 2. Finally the system is closed by joining the first bar and the last corner of the membrane. The equilibrium of this unit tensegrity anti-prism with four bars and continuous membrane pattern is achieved through the tension of the membrane. The final form is a continuum of four paraboloids.

c. Continuous membrane pattern with twenty struts in a double layer

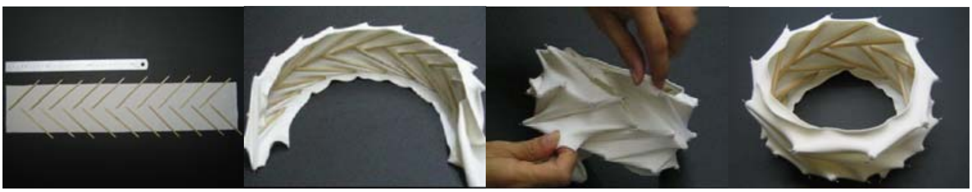


Figure 3. A tensegrity ring with a continuous membrane and 20 struts.

In this tensegrity ring, formfinding is generated by means of a continuous membrane pattern, which has an initial rectangular form. For this model of twenty bars in a double layer, the bars arrange in oblique direction or diagonal position, in alternate form and are joined to the end points of the membrane like shown in Fig. 3, and resemble the veins of a leaf. Finally the system is closed by joining the first bars and the last corners of the membrane. The initial location of the bars was determined by an orthogonal mesh, whose distance was defined by the elasticity of the membrane regarding the length of the diagonal bar. The final form is a continuum of ten paraboloids above and ten paraboloids below.

d. Diamond membrane pattern and mesh with twenty struts in a double layer

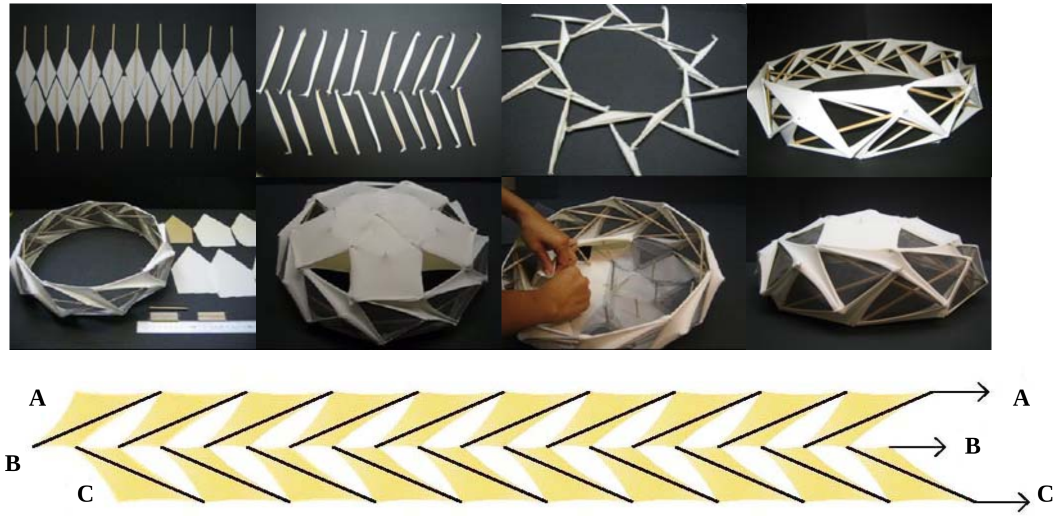


Figure 4. A tensegrity ring with a central dome and a diamond membrane pattern with 20 struts.

Formfinding is generated by means of a diamond membrane pattern. This model is formed by two layers of twenty bars, which are arranged in an oblique direction or diagonal position. The bars are tied to the end points of the membrane as shown in Fig.4. Then the bars are joined to the adjacent pattern at one of the remaining free end points. The procedure is repeated with the adjacent pieces, which include the alternate ones of the lower level that are joined to the top bars at the adequate place of the pattern continuum. The last two bars close the system.

The final ring form is a continuum of ten paraboloids (on the upper level) and ten paraboloids (on the lower level). To cover the upper ring a supported central dome is proposed that creates an internal free space. The central dome is formed by a central mast and several minor masts placed in a circular form, which are held by the tension of the membrane. At the same time, the membrane helps to balance the system and joins the top dome with the tensegrity ring.

In this case, the top part of the model uses a textile membrane and the lower part uses a mesh with which it is possible to observe the location of the masts and the bars in inside the structure.

Finally a 40 cm. in diameter tensegrity structure has been completely constructed. To achieve a larger diameter, the number of bars would have to increase, but this must be proportional to the elasticity of the used membrane.

If one compares the model in Fig. 4 with the continuous membrane in Fig. 3 it can be observed that though they have the same number of bars, the diameter of model in Fig. 4 is larger, approximately double, and for this reason the diamond pattern model was selected to continue with the structural analysis by means of WinTess software.

3.2 Formfinding by AutoCAD and WinTess software

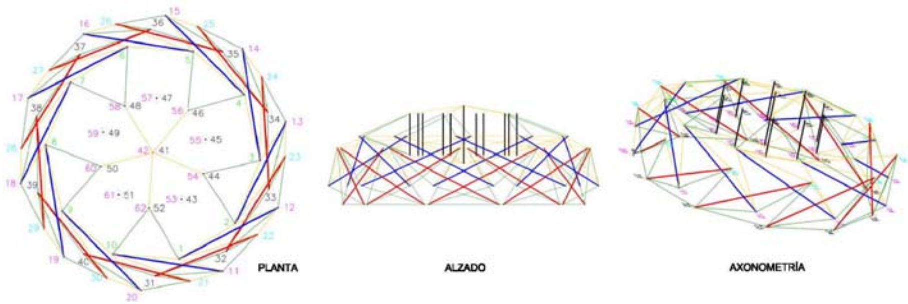


Figure 5. A tensegrity ring with a central dome constructed by AutoCAD.

Formfinding is generated using the AutoCAD and WinTess software [5]. First, an orthogonal 40 point mesh was constructed where the coordinates (x, y, z) came from the chosen model (Fig. 4). After introducing the coordinates and defining the bars like: membranes, border cables, external cables, tubes, etc. with their respective structural characteristics and proper weight; a static equilibrium analysis of the prestressed membrane structure was performed. The balance is achieved because all the compression and tension forces are perfectly distributed, that is to say they work jointly, where the structural form is guaranteed, because finally the system is closed and auto-balanced.

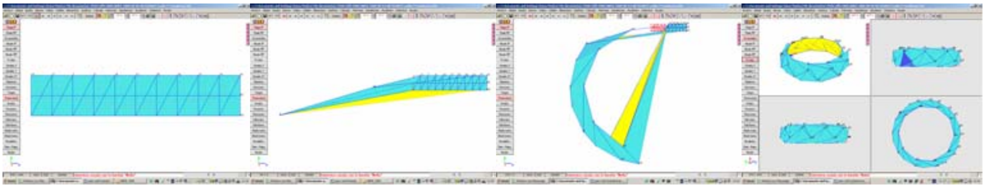


Figure 6. A tensegrity ring generated by WinTess.

4. Structural analysis

Tensegrity structures are characterized because of their: [6]

- Discontinuous elements that work under compression,
- Prestressed structure,
- Auto-balanced structure.

In the following analysis the model is tested for external loads, first for wind at 170 km/h, and then for 50 kg/m^2 of snow. The tensegrity ring has sufficient stiffness to withstand the wind, however the major horizontal displacement is of 1143 mm, therefore the central dome moves also, hence it is necessary to use external elements to prevent the displacement and probably the collapse of the structure.
Pressure changes, depending on the direction of the wind over the membrane, and deforms and creates points of suction (dynamic pressure for 150 km/h wind over the membrane is 100 kg/m^2 approximately). In case of snow, the central dome has a vertical displacement of 800 mm at the membrane where the maximum stress is located.
Exterior tubes are proposed to prevent these exceptional displacements. The exterior tubes are placed surrounding the ring so that they continue in the direction of the forces coming from the top membrane dome. The pretension cables can then increase the stiffness of the structure, and contribute to support the balance of the system.

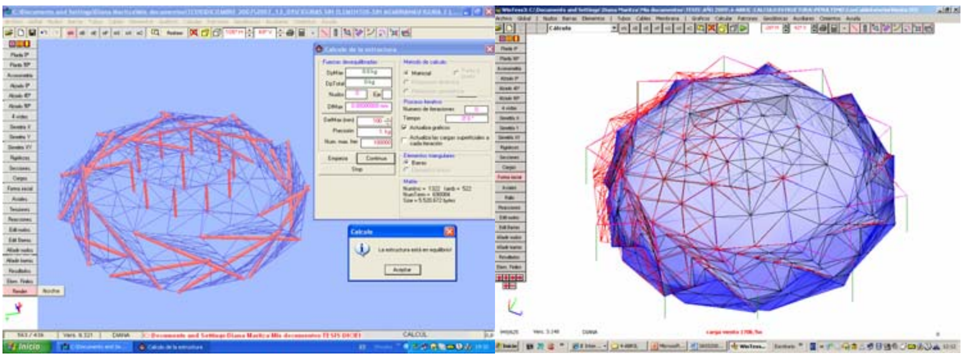


Figure 7. The structural analysis considering self weight (left), and external loads like wind and snow (right).

5. Application

There exists a need for roof structures that can cover big surfaces and spaces, but free of any interior supports. After doing the pertinent calculations, a tensegrity ring is proposed with a central dome, using diamond membrane patterns with twenty struts in a double layer, to cover a 40m diameter sports arena, which has a surface of 1.200 m^2 and may be occupied by 626 persons, approximately.

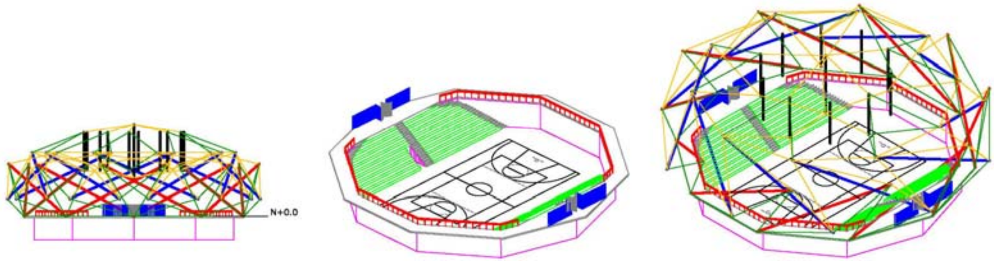


Figure 8. Application of the tensegrity ring to cover a sports arena.

6. Conclusions

This methodology allows this conclusions:

- Tensegrity is not a conventional structure.
- The balance is solved by formfinding, constructive methods and pretension possibilities, where models of continuous membranes and diamond patterns, with bars in a simple layer or double layer are proposed.
- It is essential to know the initial state system (pretension and stiffness of the elements that compose it) and its behaviour when it is subjected to external actions.
- Tensegrity structures are kinematically weak and need geometrical stiffening elements, such as tension elements [7].
- The analysis of the forces in the components is important, considering endogenous factors, like the internal prestress of the structure and exogenous factors, such as external loads, points of support, anchorages, etc.
- The major stress distribution given by the WinTess software shows the importance of property selection in the elements (to define dimensions). In addition it is observed that a safety coefficient to take account for the calculation.
- The difficulty of these systems lies in the fact that though they are auto-balanced, with external loads such as wind and snow, it is necessary to increase the stiffness of the elements and moreover they should be reinforced by external tubes, which help to prevent a collapse of the system in particular conditions.
- The system stiffness is achieved through the membrane prestress and auxiliary external elements such as tubes.

- These systems are flexible in the Z axis, which it is possible to take advantage like elements or folding and unfolding systems. [8]
- To verify the hypotheses that here propose, a major scale prototype to be constructed and a wind tunnel test will be realized.

References

[1] Fuller, R. B., *Synergetics*, MacMillan, New York, 1975.

[2] Pugh, A., *An Introduction to Tensegrity*, University of California Press, Berkeley, 1976.

[3] Jáuregui, V., *Tensegrity Structures and their Application to Architecture*, Master Thesis in Architecture, Queen's University Belfast -UK., 2004.

[4] Pérez, N., *Folding Closed Tensegrity*, Thesis in Architecture, University National of Colombia, Bogotá, 2003.

[5] Sastre, R., *Disseny i Càlcul d'Estructures de Barres Totalment Articulades amb Grans Deformacions,* Ph.D. Thesis, Department of Architectural Tecnology I - UPC, Barcelona, 1981.

[6] Llorens, J., García Ch. y Pöppinghaus H., *Tensegrity Structures for Textile Roofs*, Textile Composites and Inflatable structures, E. Oñate and B. Kröplin (Eds.), Cimne, Barcelona, 2003.

[7] Wagner, R., *Tensegrity and Cable Domes*, The Seventh International Workshop on the Desing and Practical Realisation of Architectural Membranes, Berlin, 2002.

[8] Motro, R., and Smaili, A., *Foldable/Unfoldable Curved Tensegrity Systems by Finite Mechanism Activation*, Journal of The International Association For Shell and Spatial of Structures, Vol. 48, No. 3, Dec n.155, 2007.