THE MORPHOLOGY OF NON-CONVENTIONAL STRUCTURES

Sabah Shawkat

Assoc. Prof., PhD., Academy of Fine Arts and Design in Bratislava, SLOVAKIA, shawkat@vsuv.sk

Abstract

Morphology provides a very interesting approach between artistic expression and structural engineering. Particular task of construction morphology of the non-conventional structures is form finding. Physical models (form-models) are used to describe the power of the variability and beauty of these structures to achieve the fine art of structural morphology of non-traditional structures.

The idea of teaching designers the principles of morphology is the most creative way because it encourages experimentation and makes the relationship between structure and form easily clear.

Working with physical modelling is a very powerful tool for exploration of three-dimensional structural forms and the designers will certainly profit from it. This type of experimentation opens a new space and makes the relationship between structure and form easily comprehensive. Experimentation with small to larger physical modelling is a very important characteristic of this idea.

The objective of this contribution is to show the designers how to create several physical models of non-conventional structures such as tensegrity systems, reciprocal frames, and grid shell structures in a simple and stylish way. The amazing advantage of tensegrity is that we can design various models to demonstrate their structural and physical beauty and at the same time they can have an additional creative function. Our examples of non-conventional structural models serve as beautiful architectural components such as chairs, table lamps, sculptures, tea tables or hammocks designed for interiors or public spaces.

Keywords: Tensegrity Structures, Geodesic Dome, Reciprocal Frames, Grid Shells

1. TENSEGRITY STRUCTURES

The pioneers of tensegrity structures were Karl Mosmann 1920, Richard Buckminster Fuller (1895-1983), Kenneth Snelson 1965, and Rene Motro 2003. The first patented definitions of tensegrity are very general. Fuller described tensegrity systems as "Islands of Compression in a Sea of Tension". Snelson patented the system which he called "Continuous Tension, Discontinuous Compression Structures". Emmerich added the

condition of self-stress state (Snelson,1965, Emmerich,1964, and Fuller,1962). Tensegrity structures consist of struts mounted in such a way that the struts remain physically isolated in a continuous set of cables.

Tensegrity structures consist of compression members (struts) and tensile (cables) components which stabilize each other through pre-stress. A tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components (Snelson,1965). The tensegrity network is a stable, at the same time an adaptable construction. The whole system reacts to an outside force with an adaptive tension distribution.

Tensegrity structures are “internally pre-stressed, free standing pin-jointed networks, in which the cables or tendons are tensioned against a system of struts”. This description introduces the fact that the system is pre-stressed and pin joined. This implies that there are only axial forces present in the system and there is no torque (Motro,1992).

The Tensegrity concept offers a high level of geometrical and structural efficiency, when the external load acting on construction are transmitted to all elements of the structure in the same way. Once the external force is removed the elements will return to their original shape. Vibration in one part of the structure causes vibration in all other parts. Mechanical stability of structures does not depend on the strength of individual parts but on the whole structure distributes and balances mechanical strain.

One of our physical tensegrity models is an amazing chair shown on Fig. 1. We can use it to clarify main ideas of tensegrity and demonstrate the entire concept for educational purposes and at the same time it serves as an unusual chair.

Our experience and way of thinking are conditioning the quality of our proposal. Similarly training conditions are also very important, and common training with other professions may contribute to increase the level of our art of engineering.

Fig. 1. Tensegrity as a Chair (Shawkat, and co-authors 2019)

1.1 Triangular Tensegrity Prism

One of the most elegant tensegrity forms is a three struts T-prism: nine tendons, three struts single layer, twist element that rise to the open space. A triangular tensegrity prism was probably first made either by a Lithuanian artist K. Joganson around 1920 or by a student of R. B. Fuller at the University of North Carolina in the early 1950's named Ted Pope (Snelson, 1965, and Emmerich, 1964). The tension of the cable is applied to each strut (compression) element. As it is a three-dimensional system, at each end of the strut we should have at least three cables in tension

attached to the node to ensure the stability of the entire structure. Based on this principle, we created a triangular tensegrity prism that can serve as a nice hammock for public space which is depicted on Fig. 2.

Fig. 2. Triangular Tensegrity Prism (Shawkat, and co-authors 2019)

1.2 Triple-X shape

As you can see in Fig. 3, this construction is made of one tensegrity spatial 3D element consisting of six X-shaped modules (six strut elements of equal length and shape). The strut elements are oriented in three mutually perpendicular axes, each having the same length, and eighteen cable elements. Five cables pass through each node. The assemble of triple-X shapes provides structural morphology of tensegrity systems and adding tension cables to the components gives the stability state to the structure therefore preventing a motion of the triple X-shapes out of their own plane. The process is started from a simple system and next, more and more struts and cables are added step by step, however, the strut elements must not touch together. The upper edge of the struts must be connected to the lower edge of the other elements. The properties such as weight, thickness of the elements and the use of the same material in all directions have an influence on the stability, and equilibrium of the structure (Snelson, 1965, and Motro, 2003).

Fig. 3 presents our physical models of triple-X shape tensegrity showing their structural beauty. We have transformed them into interior components, namely table lamps to show some of the other possible functions of this creative tensegrity design.

Fig. 3. Octahedron or Icosahedron Physical Models (Shawkat, 2020)

1.3 Anti-gravity Tensegrity Structures

Our interest in creating elegant and innovative solutions in the field of anti-gravity tensegrity structures led us to design “magical” tea tables (Shawkat, 2021). The structures of our models are constructed of simple materials - wood and aluminium as you can see on Fig. 4. Tensegrity structures, in place of stiffness of the material, derive their resistance from their shape and may therefore be denoted as shape active.

One of the main design steps of tensegrity structures is therefore the design of a shape that is controlled by the required stress state. These floating anti-gravity models represent a nice application of the basic tensegrity structure which are in principle very simple. Anyone can try to create them as it has no special requirements on time, skills or complex materials.

In one category of anti-gravity models that were made as tea tables, the load carrying capacity of the structure is equal to the tensile capacity of the string. It is just a matter of achieving the right tension strings to centre the structure and then connect them in place. The centre string provides tension, and the other strings provide balance. Therefore, all strings are necessary, not just the centre one. By taking any of them out, the whole model falls apart. However, the centre string is the most important and the most elegant one. It seems that the tables fly in the air providing an intriguing sense of freedom. In another type of anti-gravity tea tables, the main element (the centre string) was replaced with two opposite magnets which ensure the stability of the entire system. The resulting models seem to defy gravity and physics. This optical illusion is our favourite demonstration of the charm of physics and the elegance of tensegrity.

Fig. 4. Anti-Gravity Tensegrity Tea Table (Shawkat, 2021)

2. GEODESIC DOME

The term “geodesic” can be understood as the shortest distance between two points (Fuller, 1962). Geodesic structure consists of as many struts of the same length as possible as well as congruent surfaces. It is a network of equal triangles whereby the cross points are always situated on the surface. This triangulation guarantees strength and rigidity of the ball-shaped structure. There is no direct contact between the compression elements as seen on the models in Fig. 5. The struts are combined into triangles, pentagons, or hexagons, whereby each strut is aligned in a way that each connection point is held in a firm position. This guarantees the stability of the whole structure. Tension is distributed equally to all parts of the whole construction. Increased tension in one part provides increased tension in all parts. A global increase of tension is balanced by an increase of tension in various parts. Whilst tension is thus distributed evenly in the whole system, only individual parts are balanced by compression. There is a balance between tension and compression, we can define the system as “stable self-equilibrium”. The tensegrity network is a stable and at the same time an adaptable construction. The whole system reacts to an outside force with an adaptive tension distribution.

Both types of structures depicted in Fig. 5 use separate elements for tension and compression as we can nicely see in this visual example. These tensegrity systems can be defined as spatial structures consisting of compression (struts) and tensile (cables) components which stabilize each other through pre-stress, tension and compression work together to resist the applied load.

Fig. 5. Tensegrity as a Geodesic Dome (Shawkat, 2020, Shawkat, 2021)

3. RECIPROCAL FRAME

The name “reciprocal frame” comes from Graham Brown, who developed this type of structure and used the term “reciprocal” because of the way the beams mutually support each other. A reciprocal frame is a three-dimensional structure with complex geometry, consisting of linear straight members which are mutually supported and interlocking, forming either a flat, horizontal structure or a pitched three-dimensional frame system (Chilton, Choo, and Popovic, 1995).

Reciprocal frames and structures similar to them have been built by many cultures throughout history. Villard de Honnecourt provides us with information on how to deal with the problem of beams shorter than the span, but he gives no information on the spans. His solution to this problem was a planar grillage and it adopts similar principles to the reciprocal frames, for spanning long distances with shorter beams (Chilton, Choo, and Yu, 1994).

Generally, it is always useful to begin with physical models, because it is the best way to understand the complexity of the design with all implied parameters. Here we try to present some of the opportunities the reciprocal frame offers, however, like any structural form, the reciprocal frame structure has its limitations too.

On Fig. 6 is depicted a small-scale physical model of Leonardo da Vinci's proposal for temporary bridges. The arched form is created by using short timber elements of simply supported interlocking beams.

Fig. 6. Physical Model of Temporary Bridges, (Shawkat, 2021)

Fig. 7 shows nine different morphology forms of classical self-supporting structures (reciprocal frames). All these physical models are made of one type of wooden rectangular beam with the length 30 cm. Traditionally, reciprocal frames were used as roofs but due to their beauty we can consider them also as art.

Fig. 7. Self-Supporting Structures - Reciprocal Frames (Shawkat,2021)

3.1 Hyperbolic Paraboloid Model - Grid Shell Structure

As we know from mathematical diagrams, the hyperbolic paraboloid is a ruled surface, which means that we can create it using only straight lines even though it is curved. Fig. 8 shows our model of a hyperbolic paraboloid made of fifteen straight 30cm long wood elements. First, we created an equilateral triangle using three elements of our straight timbers. Then we used this triangle as a template to form two skewers into a 60-degree angle, completing 2/3 of another equilateral triangle. Connecting the first triangle by one skewer to the second triangle, created together as a regular tetrahedron shape. Further, we marked the edges of the tetrahedron in regular 4 cm intervals to connect the skewers between the marks. Then we connected a skewer to the first marks on each of the edges. In another step, we created another layer of skewers so that they would overlap. We kept connecting skewers by moving one interval mark on each edge. The overlap got greater each time. To reach the goal we had to use two of the other edges to form the other ruling lines.

Fig. 8. Hyperbolic Paraboloid Model (Shawkat, 2021).

REFERENCE LIST

- Snelson, K. (1965). Continuous Tension, Discontinuous Compression Structures. U.S. Patent 3,169,611, 16 February 1965.
- Emmerich, D.G. (1964). Construction de Reseaux Autotendants. French Patent 1,377,290, 28 September 1964.
- Fuller, R.B. (1962). Tensile-Integrity Structures. U.S. Patent 3,063,521, 13 November 1962.
- Shawkat, S. and co-authors (2019). The Art and Engineering of Lightweight Structures, Tribun EU, pp. 308.
- Shawkat, S. (2020). Art in /of Nature, Tribun EU, pp. 209.
- Shawkat, S. (2021). Time Space Existence 2021, European Cultural Centre, Grafiche Veneziane Venice, Italy, pp. 550.
- Shawkat, S. (2021). Structural icons for architects, Tribun EU, pp. 840.
- Motro, R. (1992). Tensegrity systems. The state of the art. *Int. J. Space Struct.* **1992**, 7, 75–83.
- Motro, R. (2003). *Tensegrity. Structural Systems for the Future*; London, UK. Imprint: Butterworth-Heinemann, ISBN: 9780080542348
- Zienkiewicz, O.C. (2000) and Taylor, R.L. *The Finite Element Method. Vol. 1. The Basis*; Elsevier Butterworth-Heinemann: London, UK.
- Pugh, A. (1976). *An Introduction to Tensegrity*; University of California Press: Berkeley, CA, USA.
- Chilton, J. C., Choo, B. C. and Yu, J. (1994). Morphology of reciprocal frame 3-dimensional grillage structures. In *Spatial Lattice and Tension Structures, Proceedings IASS-ASCE* (Abel, J. F., Leonard, J.W. and Penalba, C. U., eds), Atlanta, GA, pp. 1065–1072.
- Chilton, J.C., Choo, B. S. and Popovic, O. (1995). Reciprocal frames past, present and future. In *Proceedings of the International Conference in Lightweight Structures in Civil Engineering* (Obrebski, J. B., ed.), Warsaw, Poland, September, pp. 26–29. Magat-Magdalena Burska, Warsaw, Poland.