Tension Structures in ”Fifty years of progress for shell and spatial Structures”

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Chapter 8: Tension Structures

Section 8.3: Tensegrity Structures

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Tensegrity Structures are nowadays very popular even if, until now, there are very few full scale true tensegrity projects. Since the concept enounced by Richard Buckminster Fuller, and the first sculptures by Kenneth Snelson at Black Mountain College in 1948, they were the object of an increasing number of studies. The main applications are not all in the field of Architecture and Civil Constructions, many other fields take advantage of this fascinating and surprising structural composition. It also inspired other efficient structural systems.

8.3.1. Tensegrity Structures: initial comments

The literature about Tensegrity principle, tensegrity structures, and tensegrity state is increasing day after day, and looks like a tangle of definitions and explanations, even if the available texts are all derived from early ones and among them from the initial patents. This section does not aim at providing an exhaustive explanation of Tensegrity Structures; it is only the place to give some "keys" for their understanding. Roughly speaking literature is appearing in three main periods: the early works in the forties and fifties, the first publications relating theoretical and experimental studies (from sixties to early nineties), and an increasing amount of publications since twenty years combining important books, papers of great interest, and appropriation of the "tensegrity" concept without a recognized pertinence

8.3.2. The pioneers

From the concept to its materialization

There is no doubt that three names are always quoted when people want to know more on the emergence of Tensegrity Structures: Richard Buckminster Fuller, Kenneth Snelson and David Georges Emmerich. All three applied for a patent with different wordings, and for a better understanding of their personal contribution to the field, interested readers may consult a special Issue of the International Journal of Space Structures [8.3.1]. David Georges Emmerich was very popular in France, where he taught in a school of architecture. His text books were appreciated, and so was his paper published at the second International Conference on Space Structures [8.3.2]. Even if the title "Réseaux" is not explicitly indicating the topic of the paper, this was a matter of fact that it was dealing with tensegrity systems, even if David Georges Emmerich called them "Systèmes autotendants" ("Selfstressing Systems"). His studies very mainly geometrical and despite his collaboration with academic people like J. Tardiveau and R. Siestrunck [8.3.3], he could not overcome the drawbacks of this single side approach for systems characterized by self stress geometries.

Richard Buckminster Fuller is another major pioneer in the field, It is him who expresses the concept associated to these systems and he creates the word “tensegrity” by contraction of the words “tensile” and “integrity”. He will then animate many workshops with students, and incites them to build models at different scales. He would have hoped to build the “Biosphere” in Montreal (1967) using tensegrity systems, but it was too early both for computation and realization issues. Nevertheless some people do believe that this geodesic dome is a tensegrity system, and this is not true.

Photo: Richard Buckminster Fuller in Black Mountain college

R. Buckminster Fuller

(1895-1983)

Milton, Massachusetts, Fuller taught at Black Mountain College in North Carolina (1948-1949), serving as its Summer Institute director in 1949. Throughout the course of his life Fuller held 28 patents, authored 28 books, received 47 honorary degrees. His most well known artifact, the geodesic dome, has been produced over 300,000 times worldwide. The best-known is the US exhibition pavilion for the EXPO 67 in Montreal. Very creative actor in many fields, from dwelling to transportation, and urban proposals, his designs were qualified with the word “Dymaxion” (a contraction of the three words Dynamic, Maximum, Ion). His name is also associated with Tensegrity. Dedicating his life to making the world work for all of humanity, Fuller operated as a practical philosopher and visionary who demonstrated his ideas as inventions that he called “artifacts.” Fuller did not limit himself to one field but worked as a 'comprehensive anticipatory design scientist' to solve global problems surrounding housing, shelter, transportation, education, energy, ecological destruction, and poverty.

He received the Gold Medal award from the American Institute of Architects in 1970. Many associations, mainly in USA, still organize meetings in order to disseminate his futuristic studies (Buckminster Fuller Institute http://www.bfi.org/).

Some of his most notable projects and innovations are described in this chapter as well as in Chapters [additional chapter numbers to be inserted by Editors].

Kenneth Snelson who is always very active was the keynote speaker of recent videoconference during the 2010 IASS symposium in Shanghai. After listening to Richard Buckminster Fuller in Black Mountain College (1948), he elaborated three main sculptures “One to Another”, “One to the Next” and “Double X” that describe the way from the concept enounced by Richard Buckminster Fuller to the its materialization. He explains this in the appendix of the author’s book [8.3.4].

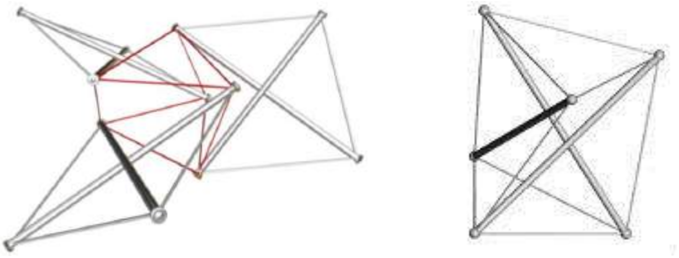


Figure 8.3.1: Simplex generation by assembly of three “X” components © Author

In his patent delivered in 1967, [8.3.5] Kenneth Snelson described precisely his design process beginning with “X-shapes” and ending in the three dimensional tensegrity unit, called “simplex” by many people..

 *http://www.kennethsnelson.net/icons/struc.htm*	**Kenneth Snelson** 1927- Born in Pendleton, Oregon, U.S.A, he studied fine arts in many places : University of Oregon. Black Mountain College, Chicago Institute of Design, and with Fernand Leger in Paris. “His art is concerned with nature in its primary aspect, the patterns of physical forces in three dimensional space” Since 1966 to date his works were exhibited in more than thirty international one man shows and as numerous collective shows. He authored ten books and fifteen papers. His tensegrity sculptures were built in many international places demonstrating his artistic skills and mastering knowledge of forms and forces coupling, arousing surprise and fascination. He received the most prestigious honors and awards from international institutions (and particularly in **1985** the Honorary Doctorate, Arts and Humane Letters from Rensselaer Polytechnic Institute). His achievements are present in many collections in USA, Europe, Asia and Australia. Some of his most notable projects and innovations are described in this chapter as well as in Chapters [additional chapter numbers to be inserted by Editors].

Forces made visible

In 2009 Snelson had an exhibition in Marlborough Gallery, Chelsea, New York. The title was “Kenneth Snelson Forces Made Visible, and this is also the title of the book edited for this opportunity (Hartney [8.3.6]).

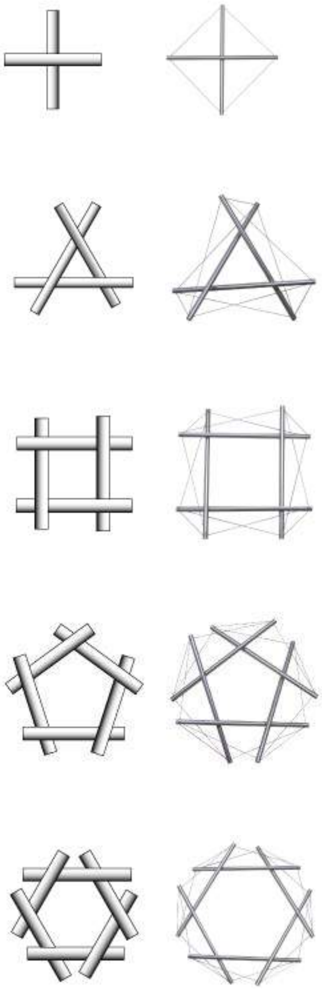
Figure 8.3.2: A *Easy Landing* 1977 stainless steel 10 x 25 x 20 m Collection: City of Baltimore, Baltimore, Md– B *E.C. Tower* 2006aluminum and stainless steel 15 x 4 x 4m © K. Snelson

This was the best possible title for the work of this artist who is able to make forces visible. Engineers who want to size their structures need to know the forces inside, and they are by nature invisible, and this why mechanical models are used. On the other hand forms are visible and measurable, and they are the product of the artistic process. This aspect has been developed in a recent scientific meeting ([8.3.7]). It can be said that the artistic work by Snelson obliges the structural engineers to question their structural approach, and to enrich it.

Weaving and tensegrity

Snelson's long research into tensegrity led him to conclude that it was a form of weaving, he writes “Weaving and tensegrity share the same grounding principle." And with authorization it is useful to quote some sentences of his website ([8.3.8])

> Weaving and tensegrity share the same grounding principle of alternating helical directions; of left to right; of bypasses clockwise and counterclockwise. In these figures, the column on the left shows the primary weave cells.
>
> To their right are the equivalent basic tensegrity modules. By transposing each weave filament to become a strut (stick, tube or rod) the cells transform into arrays of two, three, four, etc. compression members. They retain their original form and helical direction.
>
> Individual tension lines (strings, wires or rope) are attached to the ends of the struts as shown so that each assembly comprises a closed system of tension and compression parts. Each tension line connects individually to the ends of two struts; they do not thread through like strings of beads. The lines are made taut so that they bind the struts, pressing on them as a continuous tension network. The forces introduced by the tightening is permanently stored in the structure, a state known as prestressing. In tensegrity structures complete triangulation in the tension network is highly important for it decides whether the structure is firm or flaccid. Only the cross with its two struts (and four tension members) and the three-way prism among these primitive figures have total triangulation. The square, the pentagon and the hexagon do not. They can be stabilized with additional lines but the supplemental lines necessarily will be selective in directions that will distort the form.
>
> The transformed weave cell has now become an endoskeletal structure, mammal-like in that its muscles are external to the bones. Uniquely in tensegrity, the compression struts are separated one from another; non-touching within their tension envelope. The exception is the two-strut cross unit which lacks forces in the “Z” direction needed to separate the two struts. The cross figure is the same as a common kite frame in which the two sticks press on one another at their intersection. This simple form known as an “X” module, is the preeminent key to all extended tensegrity structures.



8.3.3. Tensegrity Structures, a new structural composition

A sub class of tension structures

Tensegrity Structures are generally classified as “Tension Structures” and they are since they share some main features of this class:

- Some components have a unilateral rigidity (cables and sometimes membranes) and can only be subject to traction.
- There are pre-stressed.

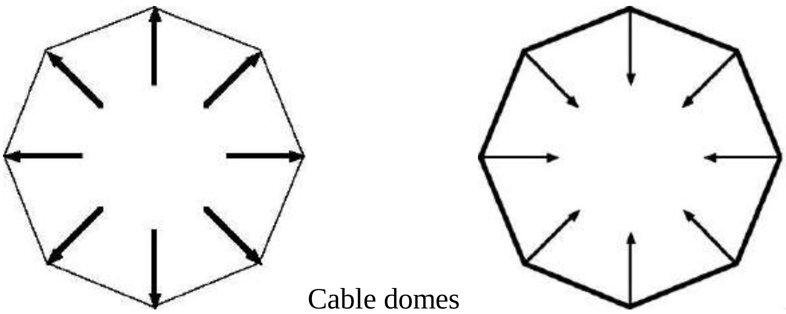
But they have some other topological and mechanical characteristics

- There are self-stressed (independently of any boundary conditions), and this state is stable, with the mechanical meaning attached to this word.
- Compressed components (namely the struts for the first examples) do not touch each other and constitute a discontinuous set.
- So called “tensile components” constitute a continuum set.
- The set of compressed components is in any case “inside” the set of tensile components.

Consequently the struts seem to “fly” in the air and people who understand compressed columns as a direct transmission way of load to the ground are surprised and fascinated. Moreover they cannot understand immediately how this structural system is working.

But it is important to understand clearly that, even if flying masts and/or cables are present in other tension structures, it is not sufficient to include them in the sub class of tensegrity structures. As examples we can quote the Skylon, the Kurilpa Bridge and the cable domes. They are evoked in a website about tensegrity [8.3.9].

The “Kurilpa Bridge” is a pedestrian bridge in Brisbane. Structurally speaking this is a multi mast cable-stay bridge and the designers underlined some flying masts. In 1951, a temporary structure called the **Skylon** was designed by architects Powell and Moya. A simple analysis is sufficient to understand that this huge flying column is equilibrated thanks to cables that are anchored in foundations. These are tension structures, but not tensegrity structures, and this is also true for cable domes: these very efficient tension structures were inspired by tensegrity concept, but their mechanical behavior is quite different. They are stabilized and tensioned on a peripheral compressed ring. Tensegrity structures can be compared to discrete pneumatic structures (struts and cable corresponding respectively to air pressure and tensioned envelope). Their mechanical behaviors are dual (Figure 8.3.3).



Tensegrity

Cable domes

Figure 8.3.3 : Dual structural principles

Definitions

One of the first definitions was provided by Anthony Pugh [8.3.10], and I discussed this definition [8.3.4], introducing the term of “compressed component”, since the so-called tensegrity masts previously designed either by Richard Buckminster Fuller or by Kenneth Snelson contained a four-strut compressed component. It seems that nowadays a consensus was reached classifying tensegrity structures in several classes: for class I the compressed components are single struts, with class II several struts are contiguous. Besides his tensegrity mast Kenneth Snelson built mainly class I Tensegrity Structures that are also qualified as “pure” tensegrity structures. This is the case for “Easy land” (Figure 8.3.2).

It is worthy to note that mathematicians are interested by this topic, and we have to quote their definition [8.3.11] :

> The mathematical definition of a tensegrity, according to Connelly and Terrell, is a finite configuration of points, the nodes, in space or the plane where some pairs of the nodes are designated cables, constrained not to get further apart, and some pairs are designated struts, constrained not to get closer together.

Some of the mathematical results are of great interest mainly those related to stability and rigidity of tensegrity structures.

A new structural composition

Many of the known structural innovations in the two previous centuries were characterized by new materials. Stone and wood were the basic ones, but step by step iron, steel, reinforced concrete, pre stressed concrete, steel cables, technical textiles, composites offered the possibility of new designs. The pre stress concept was also a major improvement: thanks to Eugène Freyssinet it was mainly used for concrete in the first part of the nineteenth century, but also for other materials in the second part of this century, and particularly for tension structures. Even if tensegrity structures are a subclass of tension structures, they are more than that, they constitute a new structural composition, which is so surprising that even the engineers do not understand immediately “how it works”. Such an innovation is very rare in the history of structures; it can perhaps be compared to the apparition of arches solving some limits of the classic beam and columns solutions. Designers cannot imitate the forms of the preceding structures, they have to deeply understand this new structural composition, and the scientific works that have been undertaken since the late seventies are useful for them, helping to go further to “fascination” and “surprise” stages. It will take time to design pertinent projects based on this new structural composition.

8.3.4. Understanding of Tensegrity Structures

Introduction

It is out of the scope of this section to provide precise analysis and to explain the results that have been obtained mainly by researchers in the last twenty five years of the previous century. Only some fundamental characteristics are addressed in this paragraph helping to understand tensegrity structures.

Forms and Forces coupling

As it was the case for other tension structures like cable nets and membranes, the shapes of tensegrity structures are closely related to their self stress states. Beyond the geometrical models, beyond the simple static considerations for simple cases, it was necessary to develop form finding processes. The first attempts used dynamic relaxation [8.3.13] and force density methods [8.3.14].

Mechanisms and self stress states

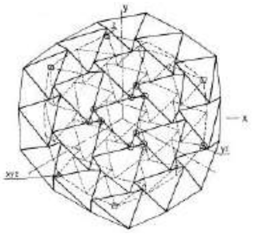
There exist infinitesimal mechanisms and self stress states in tensegrity structures, and it is necessary to identify them. The order of these mechanisms is important, and designers have if the self stress states are stabilizing or not these mechanisms [8.3.15]. This was possible thanks to previous works [8.3.16] on statically and cinematically indeterminate reticulate systems. Moreover the self stress states have to be compatible with unilateral rigidity of cables. But besides very simple cases, the number of self stress states prevents form global collapse when a cable or a strut is out of service. The corresponding effects are local.

Mechanical behavior and stiffness

As every tension structures, tensegrity structures have a non linear behavior, as I could experiment with a full scale model for the simplex containing nine cables and three struts (Figure 8.3.4: Simplex under vertical loading (1982) © Figure 8.3.4.) [8.3.17].

Figure 8.3.4: Simplex under vertical loading (1982) © Author

Ariel Hanaor has devoted many studies to tensegrity systems in form of double layer grids [8.3.18], and of domes [8.3.19]. He concludes on the excessive flexibility of these structures. This is certainly resulting from the studied class 1 tensegrity systems for which compressed components are reduced to single isolate struts.

 *Double layer tensegrity dome © A. Hanaor*	**Ariel Hanaor** 1943- Born in Israel, he received his first and second degrees in structural engineering from the Technion, and PhD from the University if Melbourne, Australia. He has wide ranging industrial and academic experience as a structural engineer in four continents. Dr Hanaor has published extensively in the technical literature and is a member of editorial boards of International Journals of Space Structures, as well as of several professional institutions. Special interests include research into the design and behavior of space structures, and the teaching of structural design. He devoted many studies to tensegrity structures evaluating their structural stiffness as well as submitting folding policies

Tensegrity structures as deployable structures

According to Tibert [8.3.20]

> "Deployable structures are capable of large configuration changes in an autonomous way. Most common is that the configuration changes from a packaged, compact state to a deployed, large state. Usually, these structures are used for easy storage and transportation. When required, they are deployed into their service configuration."

There exist many kinds of deployable structures in the field of Shell and Spatial Structures. Among them the “scissor” based systems were popularized by Emilio Perez Piñero, and then by Felix Escrig. But tensegrity systems offer a new possibility: when playing on the length of its components, it possible either to deploy them and at the end to rigidify them, or to fold these structures by introducing finite mechanisms and applying activation forces [8.3.21].

This is exemplified for the tensegrity ring derived from a single circuit tensegrity cell [8.3.22].

Figure 8.3.5: Folding a tensegrity ring ©N.A. Dung

Ongoing research is still very active for this field which is very promising for tensegrity structures [8.3.23].

Active control of tensegrity structures

This deployability property opened a wide field of research and applications in Civil Engineering, and also in robotics (for parallel robots). One of the characteristics of tensegrity structures is related to their self stress states. When submitting his ideas of pre stress for concrete, Eugène Freyssinet (after more than twenty five years of work!) anticipated the effect of external loadings so as to prevent cracks in concrete. An important program of research is in progress on this theme in the EPFL[8.3.24] and [8.3.25].

When robots are concerned it is necessary to find a single kinematic foldable process, and to control the robot. Robert Skelton devoted a great deal of work in this field with his colleagues since more than ten years [8.3.26].

Tensegrity as paradigm

Since now more several years tensegrity appeared as a paradigm in many, but sometimes without any relevance. Among the fields that used it the following can be quoted: cellular biology, languages, mathematics, anatomy, philosophy…The most popular is certainly the first one beginning with Donald Ingber [8.3.27].

8.3.5. Projects

Introduction

As soon mentioned there are still few projects based on tensegrity structures. Some are inspired by its characteristics as cable-domes. Some are historically derived from tensegrity principles like “Tensairity Structures”[8.3.28]. With tensegrity structures a wide gap has been opened in the structural composition itself, it will take time to design structures meeting the cost requirements but some projects arouse soon.

Double layer tensegrity grids

Besides the theoretical studies on double layer grids, a full scale double grid was realized in 2000 inside the so called “Tensarch” project. This grid covers an 84 m^2 area resting on rectangular boundary[8.3.29]. His design is based on the “woven grids” principle [8.3.30]. The goal was to prove the feasibility of a tensegrity grid meeting the Eurocode rules in terms of external actions and limit states requirements. No optimization was achieved for the size of the mesh which can be described as a cubic one, with adapted boundary cells. It was not also the goal to optimize the cross-sections and the material itself.

Figure 8.3.6: “Tensarch project” © Author

Warnow Tower

The tower was designed by Mike Schaich, and engineered by MERO Structures, Incorporated and erected at the 2003 Gardening Fair in Rostock, Germany. It is also evoked in chapter 6 of this Jubilee Book.

Figure 8.3.7: Warnow Tower- Assembly of twist elements and node details ©Mero

The tower was raised in only ten days time. According to the BauNetz Online Architect's service:

> The tower had a diameter of 5 meters. It was composed of 6 3-strut t-prisms, called "twist elements" by the firm. Each prism, being 8.3 meters tall. was composed of three steel-tube compression members, three heavy-duty diagonal cables and three thin horizontal cables. Each stacked prism in turn was rotated by 30 degrees. To enable the tower to achieve an even greater height, the architects added a stainless steel needle, hung by ropes from the top prism, adding an additional 12.50 m to the tower. The tower was founded on a concrete base and foundation piles with a diameter of 8 meters.

> Tensegrity towers of this scale are exposed to significant wind shear and stress. The Rostock fair ground in particular is exposed to strong winds accelerated by pressure systems over the Baltic Sea coast. MERO's engineers added a "push rod contact" to increase the systems pre-stress, and also used high-strength materials such as full locked coil ropes normally deployed only in cable-stay (suspension) bridges.

Blur Building by Diller & Scofidio

Thanks to the engineering work by Mauro Pedretti[8.3.32], and his investment in tensegrity structures applications, Diller & Scofidio designed a true tensegrity structure.

> The Blur Building was a media pavilion built for Swiss Expo 2002 at the base of Lake Neuchatel in Yverdon-les-Bains, Switzerland. From piles in the water, a system of rectilinear struts and diagonal rods cantilevers out over the lake. Ramps and walkways weave through the system, some of them providing a counterweight for the structure. "It was an exhibition pavilion with nothing on display, except for our cultural dependency on vision," said Diller.[8.3.9]

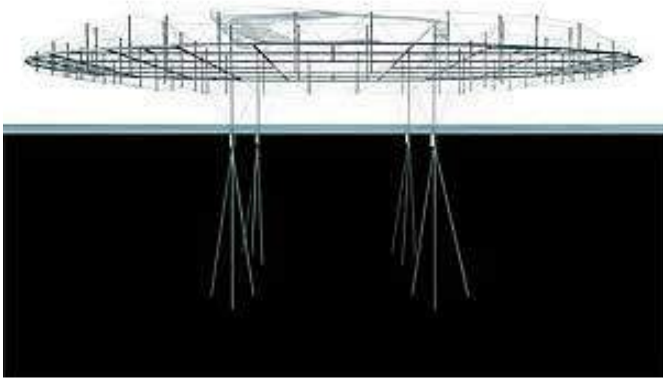


Figure 8.3.8 Blur Building, by Diller and Scofidio© Diller and Scofidio

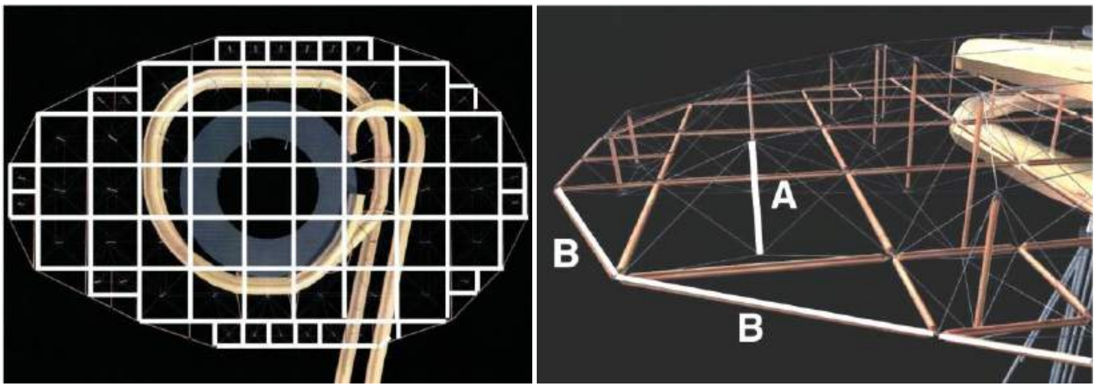


Figure 8.3.9: Blur Building virtual representations ©Passera-Pedretti

8.3.6. Conclusion

Since more than sixty years, tensegrity structures fascinate and surprise people, and even, perhaps more, architects and engineers. They constitute a true innovation in terms of structural composition inducing several design possibilities: active control, lightness, deployability among others. After a phase of pioneering works, followed by theoretical and experimental studies the way is opened for projects. Their complexity can be overcome by the actual numerical tools, and the designers need to find their pertinent application field, as did their predecessors for other innovative structural solutions. It needs time, it needs training of designers. It needs also to work with contractors and companies to invent the economic ways for building these structures that offer a new structural “grammar”.

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