Tensegrity Structures and their Application to Architecture

Valentín Gómez Jáuregui

"Tandis que les physiciens en sont déjà aux espaces de plusieurs millions de dimensions, l'architecture en est à une figure topologiquement planaire et de plus, éminemment instable –le cube."
D. G. Emmerich

"All structures, properly understood, from the solar system to the atom, are tensegrity structures. Universe is omnitensional integrity."
R.B. Fuller

"I want to build a universe"
K. Snelson

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I. Acknowledgements

In the month of September of 1918, more or less 86 years ago, James Joyce wrote in a letter: “Writing in English is the most ingenious torture ever devised for sins committed in previous lives.” I really do not know what would be his opinion if English was not his mother tongue, which is my case.

In writing this dissertation, I have crossed through diverse difficulties, and the idiomatic problem was just one more. When I was in trouble or when I needed something that I could not achieve by my own, I have been helped and encouraged by several people, and this is the moment to say ‘thank you’ to all of them.

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During all my life, at the point where my own resources failed me, I had the support of my family and friends. “La murria aprieta con juerza”, as is said in my birthplace. Special thanks to Liona for helping me from her computer and sending me all the items that I required. And, especially, many thanks to my mother. For everything. I must sing with Serrat: “Si alguna vez amé, si algún día después de amar amé, fue por tu amor, Lucía”.

Consequently, I must mention Julie. She has been for almost three years a very important part of my life; and for the last months, has helped me with this dissertation; she has been my left hand and, probably, some fingers of the right one. I started this acknowledgment quoting James Joyce, and, thinking of her, I finish with another cite from *Araby*: “My body was like a harp and her words and gestures were like fingers running upon the wires.”

What are tensegrity structures, but beautiful harps in space?

Dhá uair m’aghaidh, uair amháin mo chliabh

II. Abstract

Tensegrity is a relatively new principle (50 years old) based on the use of isolated components in compression inside a net of continuous tension, in such a way that the compressed members (usually bars or struts) do not touch each other and the prestressed tensioned members (usually cables or tendons) delineate the system spatially.

The main aim of this work is to prove that it is possible to find some applications for such an atypical kind of structure, in spite of its particular flexibility and relatively high deflections. With this premise, an in-depth research has been carried out, trying to make the controversial origins clearer, as well as the polemic about the fatherhood of the discovery, the steps that followed the progress of the studies and the evolution until the present day.

Some references about precedent works that have been important for the development of tensegrity structures have also been mentioned. Moreover, the *continuous tension-discontinuous compression* has also been shown to be a basic principle of nature; therefore, this work makes an effort to gather more information from various fields, other than Architecture, and to find out what the derivations of these phenomena are, especially in the so-called *biotensegrity*.

In order to achieve the intended purpose, it is essential to understand the structural principles of *floating compression* or tensegrity, and to define the fundamental forces at play. Once this point is established, the characteristics of these structures are described, as well as their advantages and weakness when applying them to Architecture.

Many experts have been working for the past decades on the subject. Precedent and current works founded on tensegrity are presented in this thesis, distinguishing between false and true tensegrities; the definition is crucial to accept or refuse the legitimacy of using the term. Besides, an intense research on patented works tried to find out more feasible possibilities already invented.

Finally, some proposals designed by the author are shown, as an illustration of the possibilities and potentials of tensegrity structures, rather than detailed drawings proposed for a real project.

When looking at the bibliography, it might be noted that this research has been based on a large number of previous publications. This is because the dissertation also has the aim of serving as a guide to future investigators who could find useful references along with the sources cited.

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Chapter 1

Introduction

Chapter 1. Introduction

Before discussing in any detail the contents of this dissertation, it would be desirable to explain what the topic is about, what the purpose is, why the author wants to deal with this subject and how the research is organised.

1.1. What is Tensegrity?

The definition of this term is essential to the consideration of some structures as real or false tensegrities. During the last two decades, a lot of structures, systems and natural phenomena have been qualified as tensegrity when, actually, they were not. This point is further explained in chapters 2, 3 and 4.

Several definitions have been established by different experts. The author, making an attempt to explain it as simply as possible, suggests that tensegrity is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in such a way that the compressed members (usually bars or struts) do not touch each other and the prestressed tensioned members (usually cables or tendons) delineate the system spatially.

In any case, the best way to understand how a tensegrity system works is to have a look at a model or, even better, to build one. As an illustration, the fig. 1.1 shows a tantalizing sculpture by Kenneth Snelson, the discoverer of the *floating compression*, as he called it. The bars floating in the air, without any contact with a 'solid' support are truly very impressive. People, in general, really like to contemplate such a 'magic' phenomenon that they do not understand.

Fig. 1.1.
"**30' Cantilever**" by Snelson (1967)
Illustration donated by the artist to the author.

Fig. 1.2.
"**Mini-Skylon in chess game**"
Sculpture made by the author (2000)

1.2. Why a dissertation about tensegrity structures?

The engineer from Stuttgart Jörg Schlaich, when asked about tensegrity structures, responded in a smart manner: "Food for thought" [1]. At this point, it might be interesting to establish how and when the author's own interest in tensegrity structures started.

In October of 2000, the first exercise in the course of Advanced Calculation of Structures (E.T.S. de Ing. de Caminos de Santander) was a reflection about the equilibrium of the Skylon (cf. fig. 3.5). The Skylon was a sort of sculpture, a symbol erected for the Festival of Britain's South Bank Exhibition, London, in 1951. The atypical and fascinating way it worked motivated the author to discover something more about this structure and about tensile structures in general. In fact, he started building some models of a mini-Skylon made with the two knights of a chess game (fig. 1.2). The co-ordinator of the course, Professor Javier Torres Ruiz,

[1] Personal correspondence: excerpt from a letter to the author, 8 Jul 2004.

not only showed him the sources where to find more information, but also explained to him something else about other similar structures as interesting as the Skylon: tensegrity structures.

Since that moment, a personal exploration of these systems has allowed the writer to better understand their behaviour, and the School of Architecture has permitted him to choose the topic as the central point of this dissertation.

1.3. What are the objectives of this work?

When reading J. Stanley Black's dissertation (1972), the author felt very empathetic with one of his expressions about his own work: "one is 'groping in the dark' with little idea of the final result" (p.4). This reminded him a passage of Seamus Deane's "Reading in the dark":

> "I'd switch off the light, the book open, re-imaging all I had read, the various ways the plot might unravel, the novel opening to endless possibilities in the dark."

The feelings were more or less the same, due to the large amount of resources already read, books to read, methods to choose, possibilities to develop,... Hence, the uncertainty about the final product was present every night in his mind.

Whatever the case may be, the preliminary objectives were adequately defined and very close to the overall aim of this investigation: to find out if it is possible to use tensegrity structures in Architecture and, if that answer is affirmative, to try and understand the best way to do it and suggest proposals (cf. chapter 6 and Appendix H)

Despite the fact that it is an ambitious purpose, some other objectives have been sought. During the research, the author found some incomplete facts about the past, the present and the future of tensegrity that, in his opinion, required clarification. As a result the collateral intention of this investigation is:

- To study the origins of tensegrity, original patents included (cf. Appendix B) and shed light on some polemic aspects about the authorship, enquiring personally to its discoverer, the sculptor Kenneth Snelson (cf. chapter 2).
- To revise the history and progress of this kind of structure, tracing a line of the time and pointing out the most relevant authors, specialists and publications, not only related to Architecture but also to other dissimilar fields, which could serve as a guide for further investigators (cf. chapter 2 & 3).
- To define the structural characteristics and fundamental concepts of the so-called continuous tension-discontinuous compression, describing its properties, highlighting the advantages and indicating as well its weak spots (cf. chapter 4).
- To establish a clear and generally accepted definition of tensegrity (cf. chapter 4) and to set up a general classification for these systems (cf. chapter 5).
- To investigate the use of structures similar to tensegrity in previous studies, works or patents (Appendix C) and compare them to some of the suggested proposals in order to attest the feasibility of their potential (cf. chapter 3 & 6).
- To estimate how widespread the knowledge about tensegrity structures actually is among architects and engineers by means of interviews and questionnaires (cf. chapter 7)

- To achieve a wider professional awareness and encourage consideration of tensegrity structures in Architecture and Engineering, as a feasible application for modern works.

In addition, there are several appendices containing relevant information, but which could be peripheral and could disturb the main theme of the study. Some excerpts of the author's personal correspondence (cf. Appendix D) and some other unpublished works are also included.

It is worthwhile highlighting that at the very beginning some experimental studies and load testing of models were programmed. Unfortunately, the absence of appropriate infrastructures, budget and time suggested abandoning the idea. Instead, the author worked with models in depth (cf. Appendix G) and, once the design was established, an attempt was made to compute the final geometry in more detail.

Chapter 2

Background and History

Chapter 2. Background and History

Tensegrity is a developing and relatively new system (barely more than 50 years old) which creates amazing, lightweight and adaptable figures, giving the impression of a cluster of struts floating in the air. As it will be explained in chapter 7, it is not a commonly known type of structure, so knowledge of its mechanism and physical principles is not very widespread among architects and engineers. However, one of the most curious and peculiar aspects of tensegrity is its origin; controversy and polemic will always be present when arguing about its discovery.

2.1. The origins.

Three men have been considered the inventors of tensegrity: Richard Buckminster Fuller, David Georges Emmerich and Kenneth D. Snelson[1]. Although all of the three have claimed to be the first inventor, R. Motro (1987, 2003) mentions that Emmerich (1988) reported that the first proto-tensegrity system, called "Gleichgewichtkonstruktion", was created by a certain Karl Ioganson [2] in 1920 (cf. fig. 2.1). As Emmerich (1988) explains:

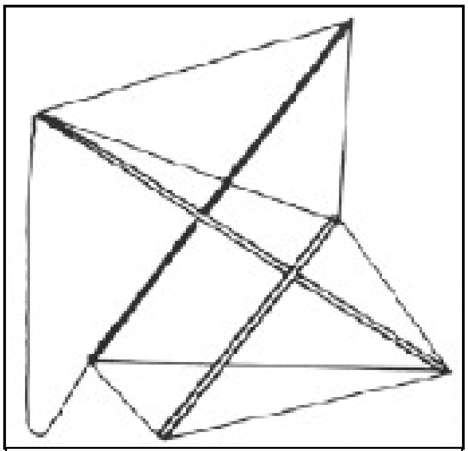

Fig. 2.1.
"**Structure-Sculpture**" by Ioganson.
Illustration taken from Gengnagel (2002)

"Cette curieuse structure, assemblée de trois barres et de sept tirants, était manipulable à l'aide d'un huitième tirant detendu,

[1] As a precaution, these names have been mentioned in chronological order of their granted patents: Fuller-13 Nov 1962; Emmerich-28 Sep 1964; Snelson-16 Feb 1965. (See Appendix B).

[2] It must be contrasted that in Motro (1988) the same author called him Johansen. In order to obtain a further explanation of this sculpture, see Appendix D, where Snelson gives his personal opinion.

l'ensemble étant déformable. Cette configuration labile est très proche de la protoforme autotendante à trois barres et neuf tirants de notre invention."

This means it was a structure consisting of three bars, seven cords and an eighth cable without tension serving to change the configuration of the system, but maintaining its equilibrium. He adds that this configuration was very similar to the proto-system invented by him, the "Elementary Equilibrium", with three struts and nine cables (cf. fig. 2.2). All the same, the absence of pre-stress, which is one of the characteristics of tensegrity systems, does not allow Ioganson's "sculpture-structure" to be considered the first of this kind of structures.

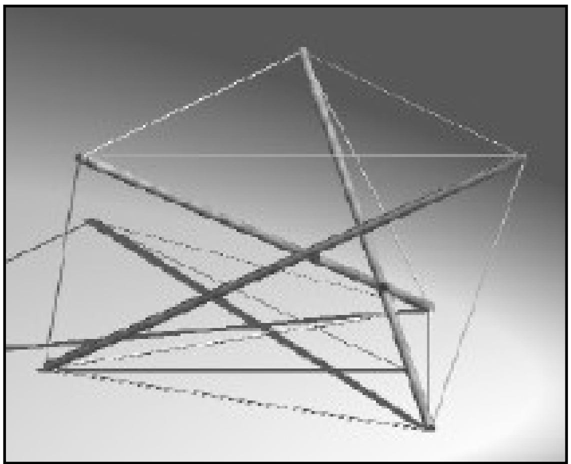

Fig. 2.2.
"**Elementary Equilibrium**" or "**Simplex**"
Illustration drawn by the author.

The most controversial point has been the personal dispute, lasting more than thirty years, between R. B. Fuller (Massachusetts, 1895-1983) and K. D. Snelson (Oregon, 1927). As the latter explains in a letter to R. Motro (see Appendix A), during the summer of 1948, Fuller was a new professor in the Black Mountain College (North Carolina, USA), in addition to being a charismatic and a nonconforming architect, engineer, mathematician, cosmologist, poet and inventor (registering 25 patents during his life). Snelson was an art student who attended his lectures on geometric models, and after that summer, influenced by what he had learnt from Fuller and other professors, he started to study some three-dimensional models, creating different sculptures (see photos #1, #2 and #3 of Appendix A). As the artist explains, he achieved a new kind of sculpture, which can be considered the first tensegrity structure ever designed. When he showed it to Fuller, asking for his opinion, the professor realized that it was the answer to a question that he had been looking for, for so many years. In Fuller's (1961) words:

> "For twenty-one years, before meeting Kenneth Snelson, I had been ransacking the Tensegrity concepts. (…) Despite my discovery, naming and development of both the multi-dimensional vectorial geometry and the three dimensional Tensegrity, I had been unable to integrate them, thus to discover multi-dimensional four, five and six axes symmetrical Tensegrity. [3] "

At the same time, but independently, David Georges Emmerich (Debrecen-Hungary, 1925-1996), probably inspired by Ioganson's structure, started to study different kinds of structures as tensile prisms and more complex tensegrity systems, which he called "structures tendues et autotendants", tensile and self-stressed structures (see fig 2.3). As a result, he defined and patented his "reseaux autotendants" (see Appendix B), which were exactly the same kind of structures that were being studied by Fuller and Snelson (Vesna, 2000).

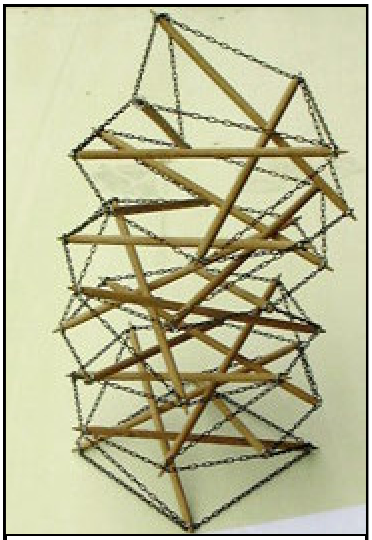

Fig. 2.3.
"**Z3-1 mat prismatique 4B racemique**" by Emmerich
Illustration taken from frenchculture.org

2.2. The controversy

Even though at the beginning Fuller mentioned Snelson as the author of the discovery, after some time he started to consider it as "my Tensegrity". Actually, he coined this term in 1955 as a contraction of "Tensional-Integrity", so by calling these structures with the denomination he chose, he let people think that it was his invention. "*Creating this strange name was his strategy for appropriating the idea as*

[3] In contrast to other authors, and serving as an illustration of how important it was considered, he always wrote "Tensegrity" starting with a capital T.

his own", quotes Snelson in various publications (Coplans, 1967; Schneider, 1977; Snelson, 2004).

Obviously, his art student was certainly confused; at the end of 1949 Fuller wrote to Snelson saying that his name would be noted in history (see Appendix A), but some years later he changed his mind, asking his student to remain anonymous for some time. This situation pushed Snelson to insist on acknowledgement during an exposition of Fuller's work in 1959, at the Museum of Modern Art (MOMA) in New York. Therefore his contribution to tensegrity was credit and recognized publicly.

A couple of years later, Fuller (1961) referred to Snelson again:

> "(…) an extraordinary intuitive assist at an important moment in my exploration of the thus discovered discontinuous-compression, continuous-tension structures was given me by a colleague, Kenneth Snelson, and must be officially mentioned in my formal recital of my "Tensegrity" discovering thoughts."

However, he always thought that if he had not catalyzed Snelson's discovery, Tensegrity would have never been invented as a new structure. In fact, he never mentioned Snelson in one of his most important and renowned books about tensegrity, "Synergetics" and failed to do so again in his correspondence with Burkhardt (see both references in Bibliography).

The *accuracy in reporting* [4] by both men continued furthermore, when in 1980 Fuller wrote a 28-page letter to Snelson, in answer to a Snelson's one-page letter. According to Vesna (2000), in those letters they tried to clarify the authorship of the discovery, and not the inventor, because Fuller affirmed that inventors can't invent the eternal principles-cosmic laws of the universe. Paradoxically, he had patented those universal laws in 1962.

[4] Expression suggested by Snelson instead of *battle of egos*. (See Appendix D)

Who invented tensegrity? It is *evident* that the answer is not *evident*. In the author's opinion, the *synergy* (a word so often used by Fuller) created by both the student and professor, resulted in the origin of tensegrity. As quoted by Stephen Kurtz's:

"If Fuller acknowledges his debt to Snelson for the invention of the tensegrity principle, Snelson likewise acknowledges his own debt to Fuller's visionary work" (1968).

Although acknowledgement is very important for the two of them, especially for Snelson (the only one still alive), perhaps it would be better to pay more attention to the possibilities of these structures than to the past controversy.

2.3.The evolution.

After the brief moment of acknowledgment in the MOMA, Snelson was once again keen to continue working with tensegrity as an essential part of his sculptures, which he has been creating until the present day. Even though he commenced studying the fundamental concepts of tensegrity, gathered and summarised in his web page [5], he focused his work on the sculptural and aesthetic aspect. He avoided very deep physical and mathematical approaches, due to his artistic background and his opinion in relation to the difficult application of tensegrity systems. This process provided him the facility to develop very different configurations, asymmetrical and non conventional,

Fig. 2.4.
"**Dragon**" by K. Snelson
Illustration taken from Snelson (2004)

[5] See Keneth Snelson's web page (www.kennethsnelson.net)

applying his intuitive knowledge and achieving impressive sculptures that are spread all over the world (cf. fig. 2.4). Moreover, the construction of tensegrity systems requires a fine and delicate technique that he has been improving over the years. The actual process whereby Snelson erects his works is a science and an art in itself; actually, as it is stated by Fox (1981), he is the only person capable of engineering his constructions.

On the other hand, Fuller and Emmerich took a different approach, studying the different possible typologies of tensegrity, mainly spherical and one-dimensional systems: masts (cf. figs.2.3 & 2.5). They did it using models and empiric experiments as their main tools, and in contrast to Snelson, they looked for possible applications to architecture and engineering.

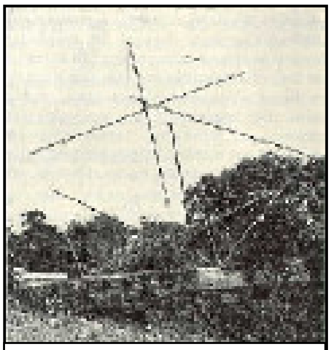

Fig. 2.5.
"**Monument à la forme futile**" by Emmerich.
Rambouillet (France)
Illustration taken from Emmerich, 1966.

Just after viewing Snelson's sculpture, the inventor from Massachusetts studied some simple compositions, and produced a family of four Tensegrity masts characterised by vertical side-faces of three, four, five and six each, respectively (Fuller 1961). He also discovered the "six-islanded-strut icosahedron Tensegrity" (expanded octahedron)[6] . Subsequently, this work was developed by other people, creating such Tensegrity systems as the "vector equilibrium" (cubo-octahedron), the "thirty-islanded Tensegrity sphere" (icosahedron), the "six-islanded Tensegrity tetrahedron" (truncated tetrahedron) and the "three-islanded octa-Tensegrity". Consequently, a hierarchy of premier Tensegrity structures was created and the comprehensive laws of universal tensegrity structuring were completed.

[6] In quotation marks, Fuller's denominations.

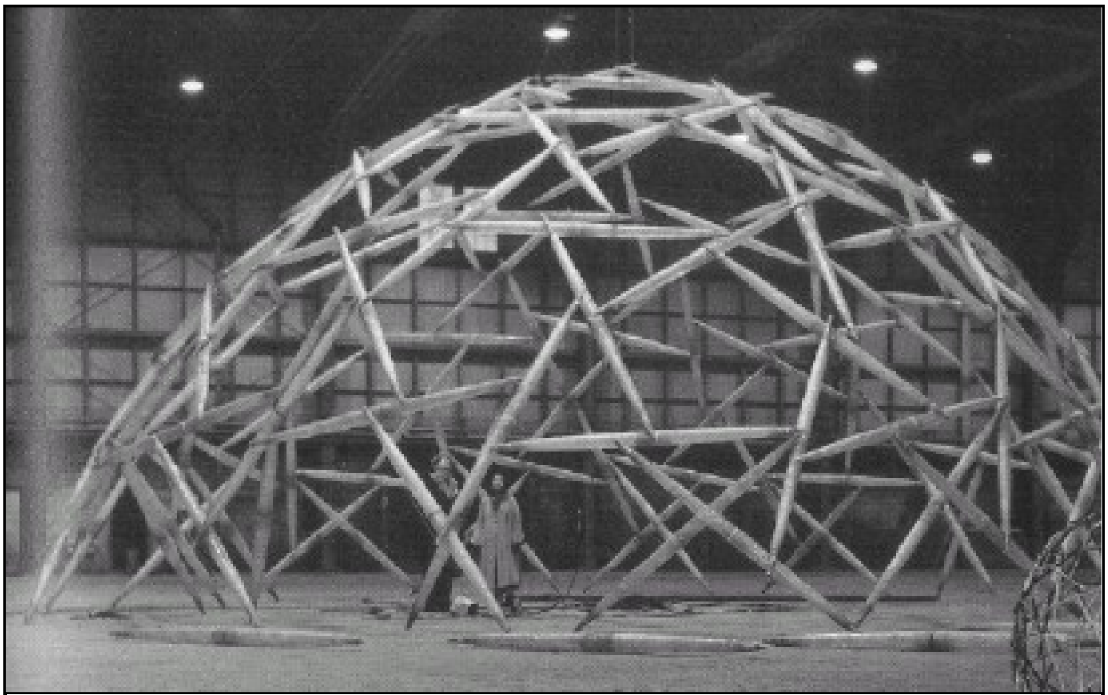

Fig. 2.6.
"**Geodesic Tensegrity Dome**" by Fuller in 1953.
Illustration taken from Gengnagel (2002)

Thus, Bucky (as Buckminster Fuller was also known), kept on looking for new designs, applications and methods of construction. He made several attempts to design geodesic tensegrity domes (cf. fig. 2.6) (although they lacked of stability due to the absence of triangulation), and patented [7] some of his works connected to this subject (Fuller, 1967, 1975a). However, the final application of Tensegrity was not as successful as he thought it would be; he was never able to produce the Tensegrity dome which could cover a whole city, as he intended; and, in addition, he was forced to build the Montreal bubble at Expo '67 (cf. figs. 2.7 & 2.8) as a geodesic dome but without using Tensegrity principles due to time and budget reasons.

Henceforth, some people who were influenced by Fuller's work, started to explore this new structural system, looking for any application to architecture and

[7] By coincidence, while Fuller patented his "Geodesic Domes" in 1954 (US 2,682,235), Emmerich patented the "Stereometric Domes" in 1967 (US 3,341,989).

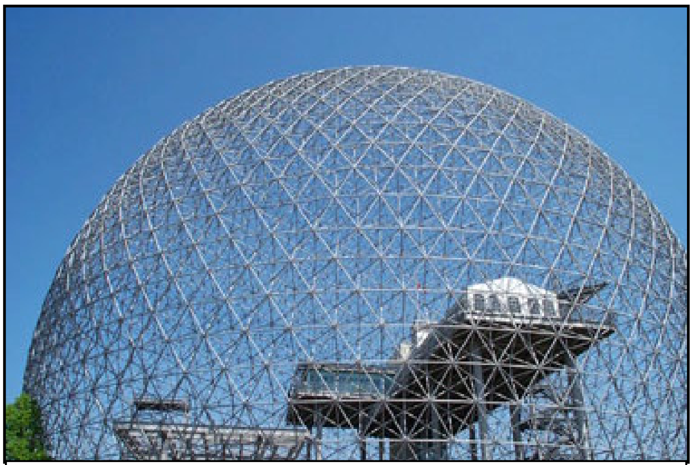

Fig. 2.7.
"**U.S. Pavilion for Expo '67**" by Fuller in 1967.
Illustration taken from CISC (2003)

Fig. 2.8.
"**U.S. Pavilion for Expo '67**"
Illustration taken from CISC (2003)

engineering [8]. For instance, J. Stanley Black (1972) wrote an unpublished study which tried to recall the main concepts known at that time and to figure out some possible systems and configurations. Although it was a good attempt, the basis of tensegrity were not very clear at that moment, and his final design was not a reflection of a true tensegrity system, but something more similar to Levy and Geiger's works (Geiger, 1988; Goosen et al., 1997; Setzer, 1992). It will be explained in the next chapter that after some first attempts of tent-shaped structures by Frei Otto during the 60s, tensile structures became more popular in the 1970s, e.g. the Olympic Stadium of Munich by Fritz Leonhardt, Frei Otto and Jörg Schlaich in 1972.

René Motro, probably one of the most important specialists in tensegrity at present, started to publish his studies on the subject in 1973: *Topologie des structures discrètes. Incidence sur leur comportement mécanique. Autotendant icosaédrique*. It was an internal note for the Laboratory of Civil Engineering of the University of Montpelier (France) about the mechanical behaviour of this kind of

[8] See Appendix I, Extended Bibliography by subjects, to have a more complete perspective of the different aspects of tensegrity in terms of publications and studies.

structure. From this time forth, this laboratory and engineer became a reference in terms of tensegrity research.

Some years later, in 1976, Anthony Pugh and Hugh Kenner (see bibliography), both from the University of California (Berkeley), continued this work with different lines of attack. On the one hand, Pugh wrote the "Introduction to Tensegrity", which is interesting for the variety of models that it outlines and his strict classification and typology. On the other hand, Kenner developed the useful "Geodesic Math and How to Use It", which shows how to calculate "to any degree of accuracy" the pertinent details of geodesic and tensegrity regular structure's geometry (lengths and angles of the framing system), and explores their potentials. Even though the latter work is more explicit in geometric and mathematic subjects, it also lacks the treatment of behaviour of tensegrity under load. Nevertheless, both of the authors realized that, apart from some of Fuller's writings (see Bibliography), little reliable information had been published on the subject. It is important to note that there is conflicting information in both books: Kenner affirms that Snelson's work was "unknown to Tony" (pg. xi), while Anthony Pugh refers to Snelson in several paragraphs of his book (pgs. ix, 3,…).

During the 1980s, some authors made an effort to develop the field opened by their predecessors. Robert Burkhardt started an in-depth investigation and maintained a correspondence with Fuller (1982) in order to obtain more details about the geometry and mathematics of tensegrity.

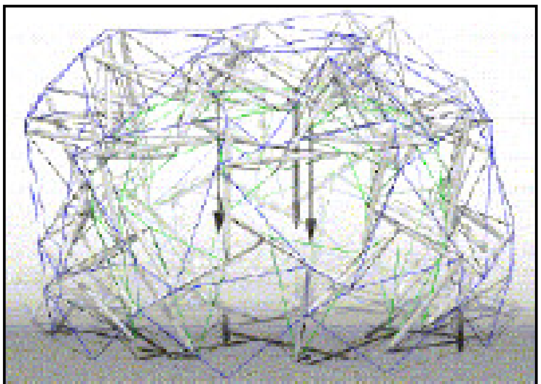

Fig. 2.9.
"**T-Octahedron Dome**" Positions and effects of exogenous loads.
Illustration taken from Burkhardt (1994-2004)

The final result, 20 years later, is a very complete, useful and continuously revised *Practical Guide to Tensegrity Design* (Burkhardt, 1994-2004). Other important investigators have been Ariel Hanaor (1987, 1992), who defined the main bi-dimensional assemblies of elementary self-equilibrated cells and Nestorovic (1987) with his proposal of a metallic integrally tensioned cupola.

Recently, several works have been adding to the body of knowledge. Since it is not always possible to read all the publications that are appearing in relation to a specific field, only the most relevant will be pointed out in the next paragraphs.

Connelly and Back (1998a, 1998b) have aimed to find a proper three-dimensional generalization for tensegrities. Using the mathematical tools of group theory and representation theory and the capabilities of computers, they have drawn up a complete catalogue of tensegrities with detailed prescribed types of stability and symmetry, including some that have never been seen before.

Other authors (S. Pellegrino, A.G. Tibert, A.M. Watt, W.O. Williams, D. Williamson, R.E. Skelton, Y. Kono, Passera, M. Pedretti, etc.) have also studied the physics, mathematics (from geometrical, topological and algebraical points of view) and mechanics of tensegrity structures. However, apart from the authors mentioned above, and Motro and his group in Montpellier, there have not been many works seeking to apply this new knowledge to any field in particular. The most recent works will be referred to again in chapter 6.

2.4. Divergences

Nevertheless, Buckminster Fuller, the resourceful and charismatic inventor, looked for something else, something more universal and abstract, more generic, something that would be able to achieve a major universal law. Although he never refused to apply tensegrity to technical fields, in his opinion tensegrity was the base of the Universe: both, macrocosm and microcosm, the solar systems and the atoms, were structured following the tensegrity principles. In his book *Synergetics*, he wrote:

> "All structures, properly understood, from the solar system to the atom, are tensegrity structures. Universe is omnitensional integrity" (Fuller, 1975b, 700.04)
>
> "This structural scheme of islanded spheres of compression, which are only mass-attractively cohered, also characterizes the atomic nucleus's structural integrities. Tensegrity discoveries introduce new and very different kinds of structural principles which seem to be those governing all structuring of Universe, both macrocosmic and microcosmic." (ibid, 713.08)
>
> "I simply found that the Universe is compressionally discontinuous and only tensionally continuous. The structural integrity of Universe is tensional as Kepler discovered. I gave this phenomena the name "tensegrity." (Fuller, 1982)

Therefore, convinced about the advantages and basic principles of tensegrity, Fuller extrapolated this phenomenon to the total Universe, making a rather complicated metaphor. He was not very readable; it serves as an illustration that, after Fuller was deceased, Edmonson (1987) wrote her *Fuller explanation*, while Applewhite (1986) prepared the *Synergetics dictionary: the mind of Buckminster Fuller;* both of them tried to make the ideas of such a hectic inventor clearer. In these publications, it is explained, following the ideas exposed in *Synergetics*, how compression obliges the components of a structure to become thicker in order to avoid buckling, until the point of considering the sphere as the best shape to support compression loads. Contrary, elements under tension don't need a great deal of matter, especially with the discovery of new materials which are resilient and strong, and support enormous amounts of tension with very narrow sections (cf. fig. 2.10). Fuller (1975b) thought that there is no limit ratio in tension, so we could have very great lengths and no section at all; this is the game that the

Universe is playing: Gravity. In this way, the Earth and the Moon are invisibly cohered and, generally speaking, this is the manner in which the solar system coheres.

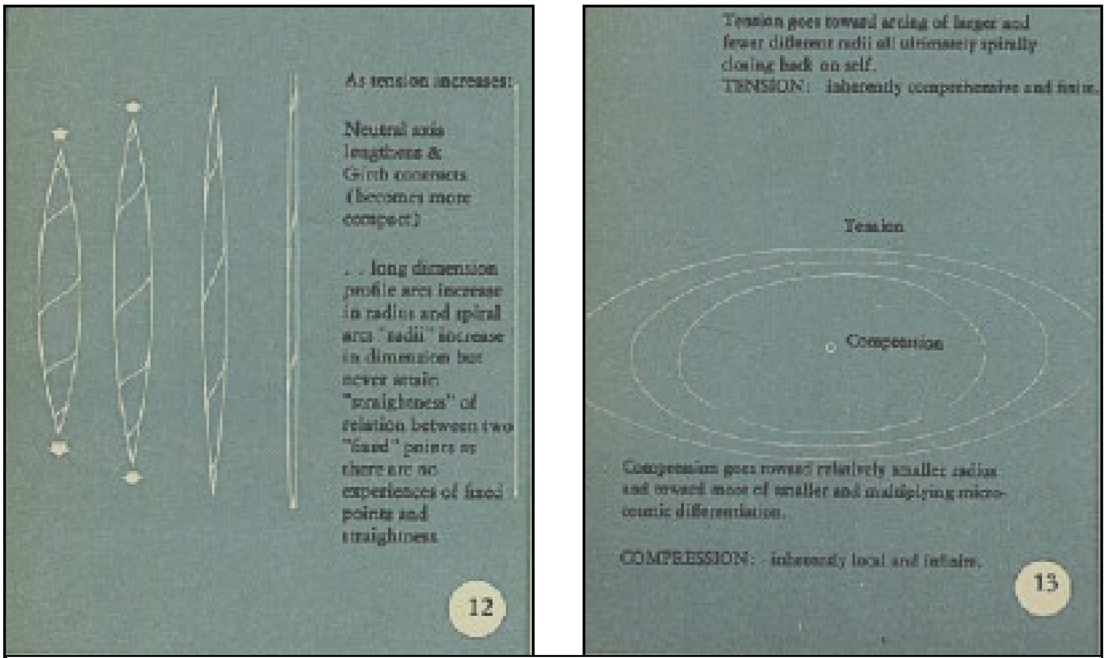

Fig. 2.10.
Fuller's figures.
Illustrations taken from Fuller (1961)

On another scale, he was convinced that the atomic attraction (especially the invisible interaction between atoms, nuclei and electrons) is another type of tensegrity, where compression and tension are always separated, and always coexist.[9]

Finally, it is curious how he tried to explain everything making use of tensegrity principles. The following example, which is applied to the human race, is a good illustration:

> "I also then point out to you the difference between the male and the female. The male then becomes discontinuous. He becomes islanded. He is a hunter. The female and her young and so forth are the great continuity of that family, but the male goes off to be the hunter and the fighter. He is the island. She is central. This is really very fundamental in social behaviour. Now, I just, personally find then that the woman is tensive. Just fundamentally. Just the sex act. She pulls in. And a man is compressive. He thrusts, she pulls. And it's just very fundamental. What we call being female is to pull—to walk away, to attract. I find the male tending to do this—to punch. She does the other way." (Fuller, 1981)

---

[9] Perhaps it is a coincidence, but Snelson, like Fuller, also tried to obtain an atomic configuration, a "portrait" of the atom, but his approach was from an artistic and geometrical perspective (Snelson, 1989)

In contrast to this opinion, Snelson is very clear:

> "Yes, Fuller declared that everything in the universe was tensegrity. Tensegrity structures are endoskeletal prestressed structures -- and that restriction leaves out endless numbers of items. As I've also said elsewhere, if everything is tensegrity then tensegrity is nothing of any particular sort; so what's the point in using that word?" [10]

Following Bucky's line of thinking, other authors (Wilken, 2001) compared this "push and pull" strategy to living organisms in Nature (including vegetables and plants) to describe the three possible classes of life looking for tensegrities: in photosynthesis-radiation, where sun pushes and plants pull; in prey-predator, where female is continuously attracting and males are discontinuously pushing; and finally in student-teacher, where the first is pulling in new knowledge while the latter one is pushing out information to someone else.

In the next chapter, other examples of tensegrity in Nature are shown: cell structures and their behaviours (Ingber 1993, 1998, 2003), internal structure of the radiolaria (marine protozoa), support system of the spine and some other components of the skeleton (Levin 1982).

Another good example of the extension of the term tensegrity to other fields was the participation of René Motro in a seminar at the Collège International de Philosophie of Paris. The course was dedicated to, and named as, "Tensegrity", and had the contribution of biologists, historians and Hellenists.

In conclusion, it is possible to affirm that depending on the definition of the word "tensegrity", it is feasible to involve these kinds of principles to a wide range of phenomena. Structures, systems, sculptures, anatomic organisms, relationships and interactions between diverse elements in the environment can be considered as tensegrity, so it is necessary to have a clear and concise definition that avoids confusion. This will be the aim of chapter 4.

[10] Kenneth Snelson: excerpt from an e-mail to the author, 3 Aug 2004. (See Appendix D)

Chapter 3

Precedents and Key Studies

Chapter 3. Precedents and Key Studies

3.1. Introduction.

Despite the fact that the origins of tensegrity were exposed in the previous chapter, its evolution and development are strongly connected to other events and circumstances. This chapter will attempt to explain how it is possible to achieve such a modern and contemporary structure from its more original beginning.

3.2. Materials and tension

Due to the fact that the main support of these structures is the continuum tension, the investigation of materials suitable for traction efforts has been crucial. Efficient "push-and-pull" structures would have been inconceivable before the 18th Century due to the incapability to obtain effective behaviour of material under tension. Edmonson (1985) states that, until that moment, only the tensile strength of wood had been exploited (mainly in ships' construction), but its 10,000 psi [1] in traction was not comparable with the 50,000 psi in compression of stone masonry.

However, the first mass production of steel, in 1851, changed this situation greatly. That steel was able to reach 50,000 psi, in both compression and traction, resulted in many new possibilities and, according to Edmonson (ibid), the building of the Brooklyn Bridge opened an innovative era of tensional design. "Tension is a very new thing", said Fuller (ibid).

[1] psi = pounds per square inch. (1 psi = 0.069 bar = 6.89 KPa = 0.068 Atm)

From the author's point of view, this statement is not completely accurate. It should not be forgotten that the first suspension bridges, based on a tensile structural concept, were invented many centuries ago. Although they were made from rope and wood, and their load-bearing capacity was incapable of supporting heavy loads, they were probably the first system that took advantage of tensile properties of materials. An example is the An-Lan Bridge, in Kuanshien (China), which is the oldest suspension bridge in use (app. 300 A.D.). It is made of bamboo rope cables, which hang from seven piers; six out of hardwood and the centre one out of granite (cf. fig. 3.1).

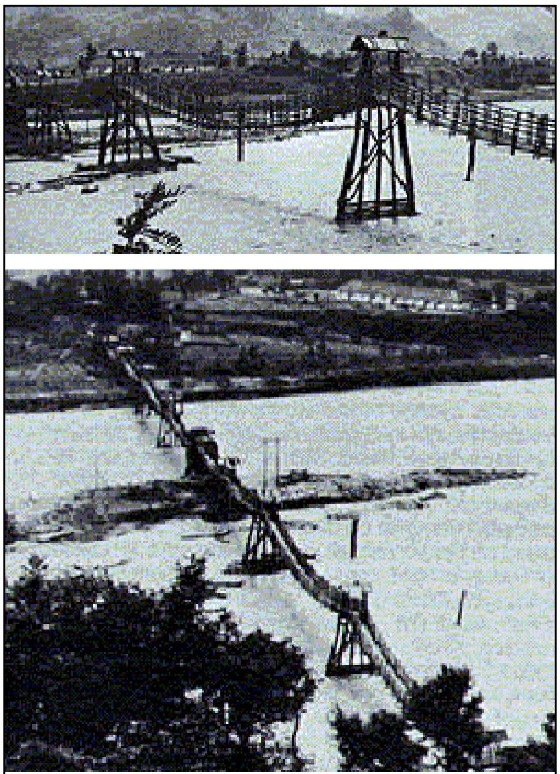

Fig. 3.1.
An-Lan Bridge, in Kuanshien (China)
Illustration taken from IL (1985)

In any case, it is evident that the development of steels and other alloys led to unpredicted outcomes in terms of resistance, weight and performances of materials, which enabled engineers and architects to create new designs and new structural concepts. These new materials not only served to increase the resistance of the components, but also to decrease their cross-section and, consequently, their weight.

However, the behaviour of elements under a load is different depending on the type of load. As illustrated in figure 3.2, when a lineal element is compressed allong its main axis, it has the tendency to augment its cross-section (due to

Poisson's ratio effect) and to buckle, which means it loses its straight shape (fig. 3.2.a). On the contrary, when the same element is tensioned in the same direction, it tends to become thinner and, more importantly, it "reaffirms" its straight axe (fig. 3.2.b). For this reason, the innovation in materials is essential for the future of pre-stressed structures, whose compressed elements must be more resistant to buckling, and whose tensioned members have to better resist the traction forces.

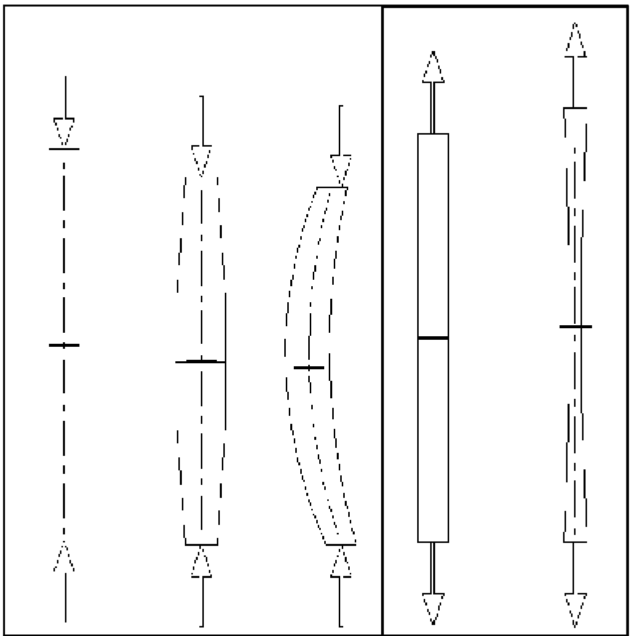

Fig. 3.2.a) and Fig. 3.2.b)
Deformation under compression and under tension.
Illustration drawn by the author.

3.3. Some precedents.

As has just been commented on, the new materials discovered during the 19th and 20th centuries, permitted the revolution of thinking in terms of architectural and engineering design. Before and after the discovery of tensegrity in 1948, some works were conceived to adopt the most recent resources and to take advantage of their most privileged properties, especially their tensile strength.

According to Tibert (1999), the first cable roofs were designed by V. G. Shookhov [2] in 1896. This Russian engineer built four pavilions with hanging roofs at an exhibition in Nizjny-Novgorod (Russia). After this first attempt, some other structures were proposed during the 1930s, but they were not very important examples.

[2] Philip Drew (1976) refers to him as "Shuchov".

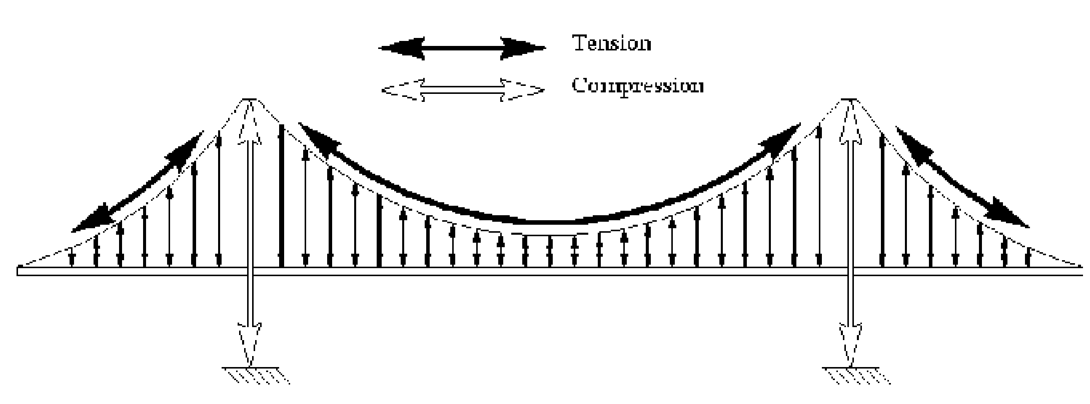

Fig. 3.3.a
“**Suspension bridge**”. Fundamental concepts.
Illustration drawn by the author.

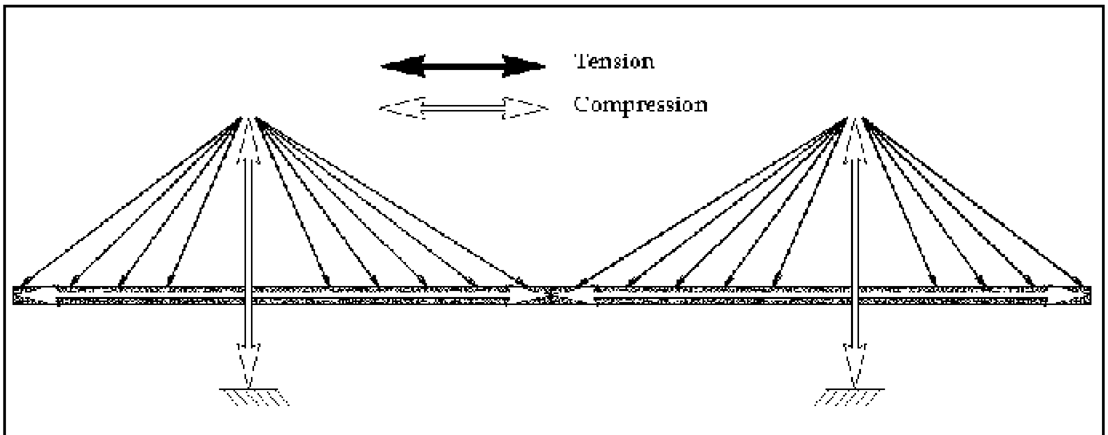

Fig. 3.3.b
“**Cable-stayed bridge**”. Fundamental concepts.
Illustration drawn by the author.

Apart from the suspension bridges, which were observed above and in fig. 3.3.a, some other types of bridges elevated the importance of tension to the same level that compression had had during the preceding centuries. This is the case with cable-stayed bridges, which make use of the stressed cables to support the deck and also put it under compression. Thus the deck is prestresed and put in equilibrium (cf. fig. 3.3.b). A very good example is the Barrios de Luna Bridge (fig. 3.4) in Asturias (Spain), by Javier Manterola, which shows this principle perfectly in both of its two towers and main span of 440 m.

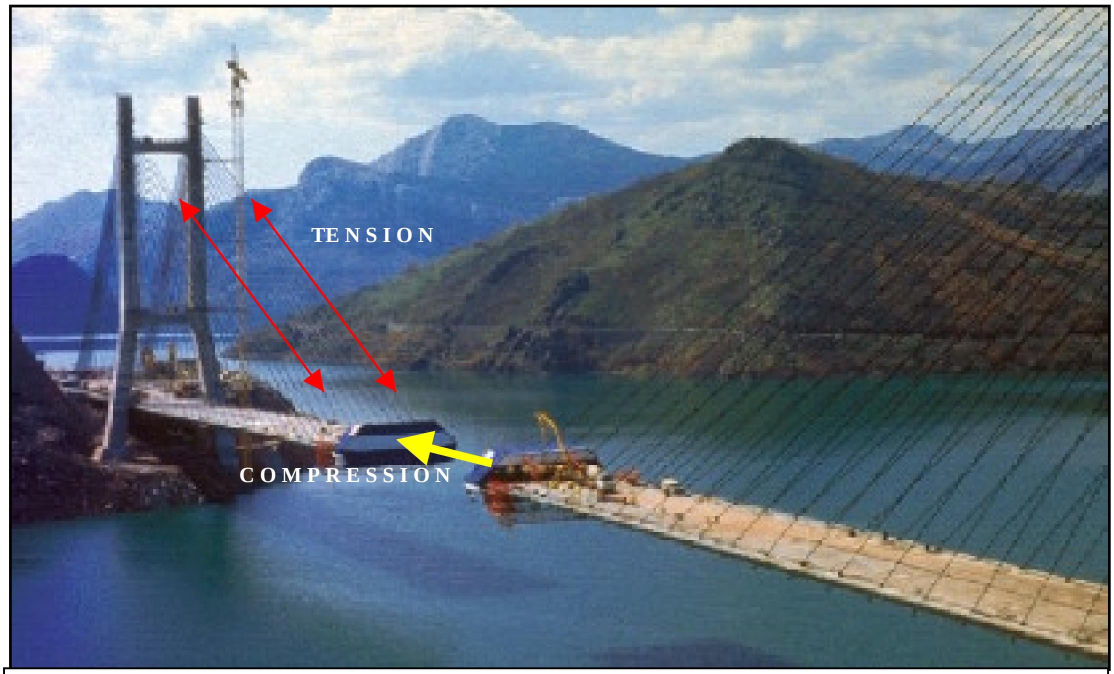

Fig. 3.4.
"**Barrios de Luna Bridge**" by J. Manterola. World record of cable-stayed bridges in 1983.
Illustration taken from Búrdalo (2004)

3.3.1. The Skylon.

In 1951, just three years after the official discovery of tensegrity, the Festival of Britain's South Bank Exhibition took place in London. In that occasion, a competition was organised to erect a "Vertical Feature", a staple of international exhibitions grounds. Philip Powell and Hidalgo Moya (helped and inspired by their former Felix Samuely) designed the Skylon (cf. fig. 3.5), which was selected as the best proposal and built near the Dome of Discovery.

Fig. 3.5.
"Skylon"
Illustration taken from King and Lockhart (2004)

Some authors (Cruickshank, 1995; Burstow, 1996) state that this needle-like structure was a monument without any functional purpose, but it became a symbol for the festival, a beacon of technological and social potentialities and, finally, a reference for future engineers and architects. The 300 foot high spire was a cigar-shaped aluminium-clad body suspended almost invisibly by only three cables, and seemed to float 40 feet above the ground.

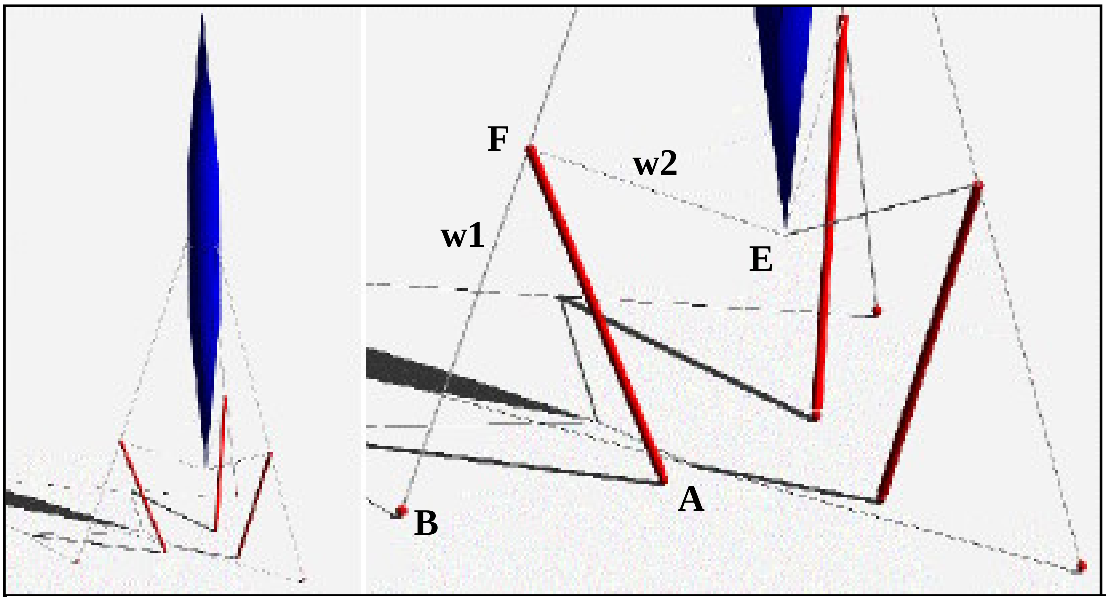

Fig. 3.6.
"**Skylon**". Representation of the different elements.
Illustration drawn by the author.

The structure, as it is shown in fig. 3.6., was composed of a cradle of pre-stressed steel wires and three splayed pylons. According to Moya, the father of the idea:

> "By an amazing stroke of genius [Felix Samuely] arranged a system of hydraulic jacks underneath the three smaller pylons. Once the whole structure was assembled, he pumped up these jacks and raised the pylons. This put tension or stresses into all the cables and by doing that the whole thing became a stressed structure. This reduced the number of wires needed to anchor the Skylon and halved the amount of oscillation in the structure. This lack of support made the structure look tremendously hazardous. You felt there weren't enough wires to hold it up, which made it tremendously exciting." (Cruickshank, 1995)

The cause of the feeling of not having enough cables to hold the zeppelin-like shape element is due to the stable equilibrium obtained by means of its particular configuration. As an illustration, a diagram inspired by Francis (1985) is presented in fig. 3.7, which explains the condition for stability of a post (pin-joint to the ground in *A*) supported by stressed cables. If one of the wires (*w1*) is attached to the ground in *B*, the equilibrium of the strut will depend on the position where the other string (*w2*) is held: If it is fixed in a point *C* below the level of *A*, it collapses. If it does it in *D*, at the same level, the post is in an instable equilibrium (any movement of *F* will lead it to fall down). In contrast, if it is held in a point *E* above the level of the ground, the system is in a stable equilibrium; in other words, when there is any disturbance of this situation, it tends to return to the upright position. In the diagram of Skylon in fig. 3.6., the cables are *w1* and *w2*, and the rest of the points are in association with the nomenclature of fig. 3.7.

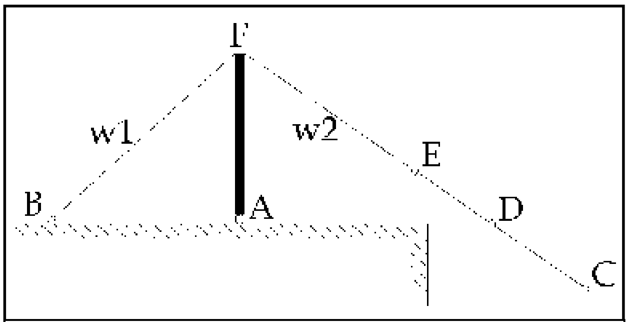

Fig. 3.7.
Equilibrium of a post supported by cables.
Illustration drawn by the autor

As a consequence, it has been demonstrated that the conditions for the equilibrium of a strut in a three-dimensional space are susceptible to the point of application of the ends of the wires that fix it. In paragraph 4.4.4 the equilibrium analysis will be further explained.

3.3.2. Suspended roofs and tensile structures

During the 1950s, the exploitation of cables in traction was not only improved, but also that of other elements such as membranes, materials and tissues.

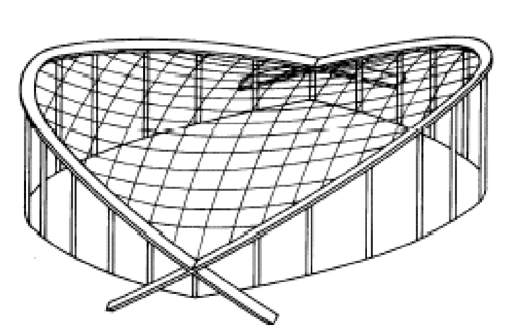

Fig. 3.8.
"**Raleigh Arena**" by Nowicki.
Illustration taken from Buchholdt (1985)

In 1950, the State Fair Arena, at Raleigh (North Carolina) was designed by Matthew Nowicki following his intuitive concepts of suspended roofs (fig. 3.8). That same year, a German student of architecture had a brief look at the drawings and plans during a exchange trip to the USA, and was completely fascinated by the innovative idea. As a result, he started a systematic investigation that was presented as his doctoral thesis in 1952. His name was Frei Otto and that was the first comprehensive documentation on suspended roofs (Drew, 1976; Tibert, 1999).

The Development Centre for Lightweight Construction was founded by him five years later in Berlin, and in 1964 was included in The Institute of Light Surface Structures at the University of Stuttgart, to further increase the research into tensile architecture (see Appendix I, Otto 1967-69, 1973). Hence, some important works were developed exploiting the tensile properties of materials, especially steel, but also polyurethane, polyester, PVC, glass fibre, cotton-polyester mix, acrylic panels, etc. Among these projects, there was an early four-point tent as a Music Pavilion of the Bundesgartenschau, Kassel (Germany) in 1955 (fig. 3.9), the first large cable net structure with fabric cladding, the German pavilion at the World's fair in Montreal 1967 (fig. 3.10) and the celebrated Olympic Stadium in Munich in 1972, whose structure was calculated by Jörg Schlaich.

These projects are important for the development of tensegrity structures since this kind of membrane can be adopted as the tensile component of tensegrities. For instance, Pugh (1976) built a dome made out of wooden struts and plastic skin, the latter being the component in tension that supported the compression members of the structure.

Fig. 3.9.
"**Music Pavilion**" by Frei Otto (1955)
Illustration taken from Atelier Warmbronn (2003)

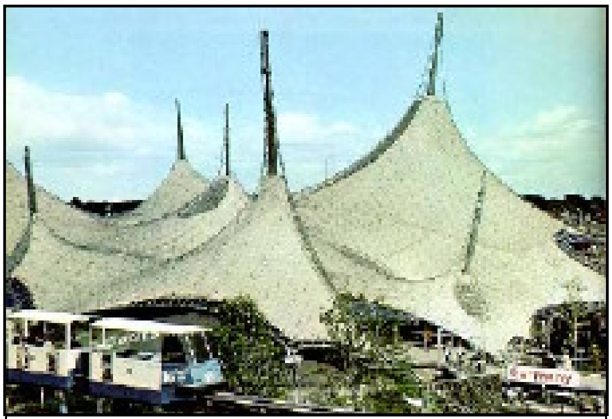

Fig. 3.10.
"**German Pavilion for Expo'67**" by F. Otto (1967)
Illustration taken from Stanton (1997)

3.3.3. Cable-Domes.

As W. O. Williams (2003) points out, the denomination of "tensegrity" has been extended to include any sort of pin-connected structure in which some of the frame members are wires in tension or bars only in compression. This is the case of the "Cable-Domes" or "Wire Wheel Domes", invented by David Geiger in 1986 [3] (see Bibliography: Geiger 1988, and Appendix C). Since then, several domes have been built following this technique, where a group of radial tensegrity beams is attached to an external ring in compression, and converges to an internal ring in order to join all of them.

Despite the fact that some architects and engineers consider these roof structures as tensegrities, Motro (2003) is quick to identify them as false tensegrities since they have a compressed member in the boundary. The reason behind this argument will be shown in the subsequent chapter (paragraphs 4.3 & 4.4.2). In fact,

[3] Even though Geiger did not refer directly to Buckminster Fuller, it should be recalled that Fuller (1964) patented a similar kind of structure, which he later called "Aspension". This can be seen in Appendix C.

Snelson does not regard them as real *floating compression* systems; when asked about the subject, the sculptor responds in a clear manner:

> "The (…) domes you cite can not be considered tensegrity, regardless what people wish to call them. They are, essentially, bicycle wheels. Did the world need a different name for that kind of solid rim, exoskeletal structure? I think not; same with a spider web." [4]

Admitting that they are different to tensegrities, it is evident that at least they are inspired by their principles: compressed struts that do not touch each other and are linked only by means of cables (cf. fig. 3.11)

The first cable-domes were designed by Geiger: for the Olympics in Seoul (1986), followed by the Redbird Arena in Illinois, the first oval cable-dome (1988), the Florida Suncoast Dome in St. Petersburg (1988), and the Tayouan Arena in Taiwan (1993). Indeed, the biggest dome in the world to date, which is a one of

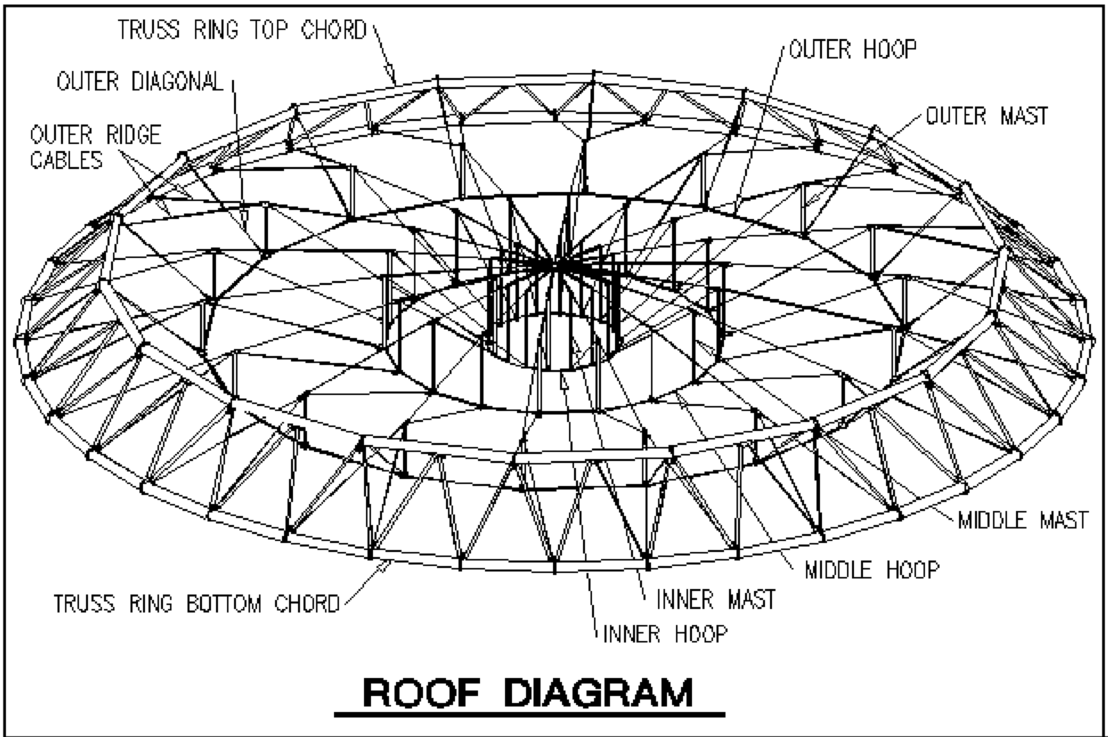

Fig. 3.11.
Roof diagram for a Cable-Dome
Illustration taken from Gossen et al. (1997)

[4] Kenneth Snelson: excerpt from an e-mail to the author, 3 Aug 2004. See Appendix D.

this type, is the Georgia Dome in Atlanta (1992) by Levy and Weidlinger Associates (see figs. 4.5 & 4.6 in next chapter).

It might be interesting to note that, because of the sparseness of the cable-dome network, these structures are not very determinate in classical linear terms and have several independent mechanisms, or in other words, inextensional modes of deformation (Pelegrino, cited in Gossen et al., 1997).

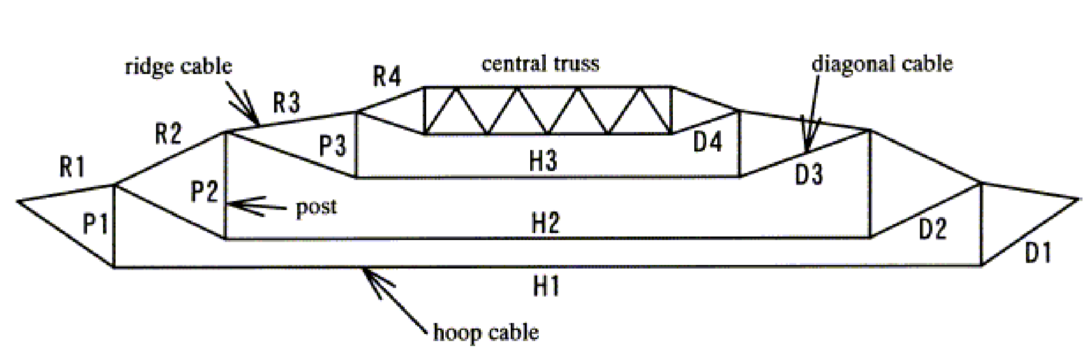

Fig. 3.12.
“**Cable-dome diagram**”. Symbols for structural members.
Illustration taken from Kawaguchi et al. (1997)

3.4. Tensegrity as a universal principle.

The origins of tensegrity are linked to sculpture; subsequently, they were related to architecture and mathematics; and at present, mainly civil and mechanical engineers are trying to research its properties and applications. Nevertheless, in the meantime some scientists, starting with Fuller and Snelson, conceive tensegrity as a basic principle in the Universe, from macrocosm to microcosm, as an answer to a general question about the nature of structure. Or even more, about the structure of nature (Burrows, 1989).

3.4.1. Tensegrity in Macrocosm and Microcosm.

In order to do the transposition of tensegrity to subjects other than material ones, it is necessary to establish some important concepts. Tensegrity can generally be considered as a structural principle, only if it does it corresponding to a particular field of forces, in a stable equilibrium, under a precise distribution of elements or components, and with the condition that the continuum of tensions is always surrounding the “islands” or components in compression. Compression and traction can be, for instance, associated with repulsion and attraction respectively, which is very convenient for gravitational and atomic examples (Motro, 2003)

Kurtz (1968) mentioned that Snelson notices all ways of connection through tensegrity: in Astronomy (a planet to the sun), in atomic physics (an electron to the nucleus) and in mechanics (a cable to a rod).

As was explained in chapter 2, Fuller’s writings are continuously referring to tensegrity as the essential pattern of the universe (cf. fig. 2.10 of chapter 2). In order to illustrate this fact, it has been stated by the author that in “Tensegrity”, a journal article written in 1961, he cited the word “universe” or anything else related to the universe in 19 occasions, “atom” was mentioned 12 times and terms related to the “nature” 13 times.

3.4.2 Tensegrity in Biology.

In addition to the last proposal, also described in paragraph 2.4, several suggestions have been put forward by different specialists from different fields.

The main one was contributed by **Donald E. Ingber**, professor of pathology at Harvard Medical School, in the early 80s. After some comments by Albert K. Harris about the elasticity of cells, it occurred to him that a view of the cell as a tensegrity structure could easily explain such behaviour (Ingber, 1998), and subsequently published with J.A. Madri and J.D. Jamieson a theory about the subject in 1981 (cf. 3.13)

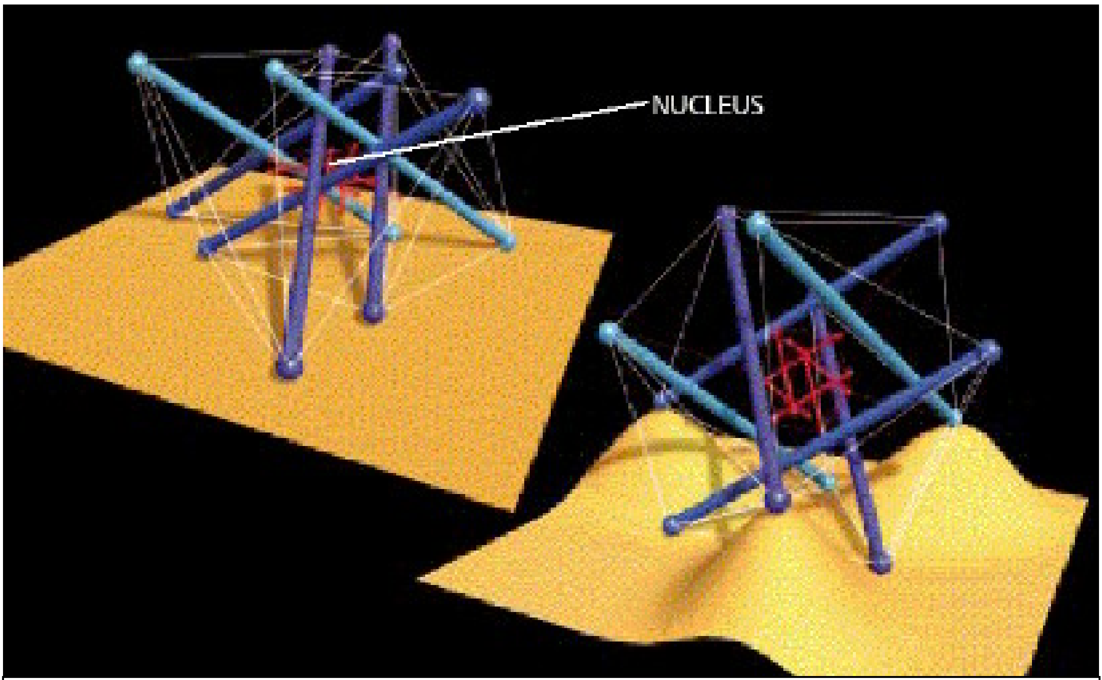

Fig. 3.13. "**Tensegrity model of a cell**".
Like a living cell, it flattens itself and its nucleus when it attaches to a rigid surface (left) and retracts into a spherical shape on a flexible substrate (right). Illustration taken from Ingber (1998)

"The tensegrity model", explains Ingber (ibid), "suggests that the structure of the cell's cytoskeleton can be changed by altering the balance of physical forces transmitted across the cell surface". In other publication, he added:

> "A discussion of how tensegrity may be used for information processing, mechanochemical transduction and morphogenetic regulation can be found elsewhere." (Ingber, 1993)

Despite the fact that it was only a preliminary hypothesis, based on several experimental works, some new discoveries have proved that the proposition is valid and mathematical formulations of the model predict many aspects of cell behaviour (Ingber, 2003a). For example, the biologist suggested that cells and nuclei do not behave like viscous water balloons, but are physically connected by tensile filaments, which has been demonstrated by Andrew Maniotis recently.

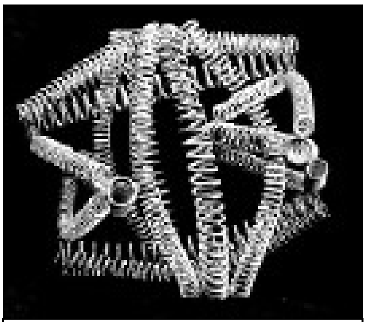

Fig. 3.14.
"Springs model"
Illustration from Ingber (2003)

According to Vesna (2000), Ingber discovered that, not only cells but also an incredibly large variety of natural systems are constructed following the tensegrity model: carbon atoms, water molecules, proteins, viruses, tissues, and other living creatures.

The only discordance with the established tensegrity principles is that, in contrast with other authors, Inberg (2003a) accepts flexible springs instead of rigid elements, as it is showed in fig 3.14. This configuration and use of materials confer different elasticities and, thus, behaviours under tension or compression.

Following this line of research, some other experts have been working on this hypothesis. Wendling, Oddou and Isabey (1999) proposed a quantitative analysis based on a theoretical model of a 29 element tensegrity structure[5], studying its nonlinear mechanical behaviour under static conditions and large deformations. The same year, some studies strongly suggested that tensegrity have

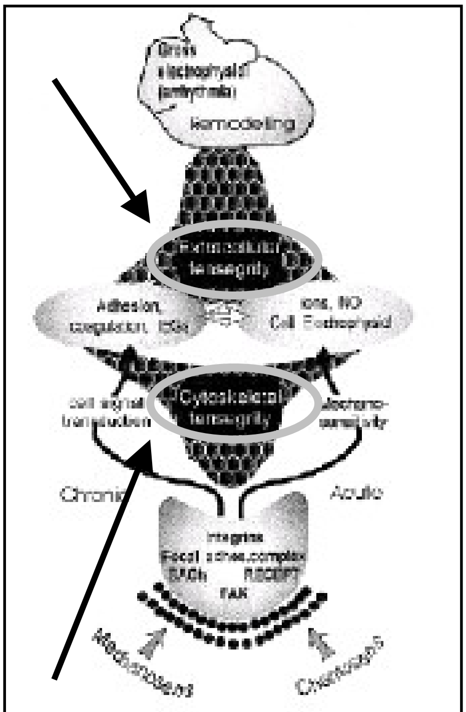

Fig. 3.15.
Diagram showing the role of tensegrity in heart functions.
Illustration taken from Lab (1998)

[5] More recently, it has been generated a tensegrity model composed of six rigid bars connected to a continuous network of 24 viscoelastic pre-stretched cables (Voigt bodies) in order to analyse the role of the cytoskeleton spatial rearrangement on the viscoelastic response of living adherent cells (Cañadas et al., 2002)

implications for all types of cell transplants requiring cell isolation (Thomas et al., 1999). Other authors (Volokh et al., 2000; Yamada et al., 2000) have been using the same theory applied to living cells with similar results and, as a result, it has been discovered for example that the function of tensegrity in the transmission of endocrines in the heart is essential because it facilitates integration of force and strain changes from area to area (Lab, 1998). See fig. 3.15.

3.4.3 Tensegrity in Inorganic Chemistry.

To date, it seemed that while organic chemistry (cells, viruses, pollen grains, water molecules, carbon atoms[6] or buckminsterfullerenes[7], vitamins[8], proteins[9], etc.) holds sway, widely rely on tensegrity, the inorganic things seemingly do not have the benefits of this principle. However, it is very interesting that, according to some new findings, even inorganic substances can be based on *floating compression*. Some authors (Tsu et al., 2003) have proposed a new tensegrity model for an amorphous silicone (a-Si:H) consisting of tensile and compressive agents that act to globally redistribute the effects of locally created defects. This leads to volume changes that appear to be experimentally corroborated by recent measurements.

> "Suppose for fun, we assign CRN[10] the compressive role, and the CLOs[11] the tensile role. So in a simplistic topological sense, the CRN is like a stiff rod, and the CLOs like flexible (but strong) cables. The composite structure is in a ''prestressed'' state where cables pull against rods in a multilateral relationship." (Tsu et al., 2003, pp.138)

As a result, this can be used to build better new heterogeneous structures and substances, but this must be the aim of further research.

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[6] See Bibliography: Ingber (1998)
[7] The *buckminsterfullerenes* or "bucky balls" are spherical groups of 60 carbon atoms (Carbon-60), named like that after it was suggested that its structure is similar to that of a geodesic sphere, invented by Buckminster Fuller (Lu, 1997)
[8] See Bibliography: Eckes et al. (1998)
[9] See Bibliography: Zanotti and Guerra (2002)
[10] CRN: continuous random network.
[11] CLOs: ''chain-like objects''.

3.4.4 Tensegrity in Anatomy.

It is very common to find the term "tensegrity" applied to biomechanics and, especially, to anatomy. In spite of having been used only as an example to illustrate the models, some sources (Heller, 2002; Wikipedia, 2004; Meyers, cited by Gordon, 2004) make use of the term to explain the relationship between muscles, tendons and bones in animals and humans. They claim that the skeleton is not just a frame of support to which the muscles, ligaments and tendons attach, but a set of compression components suspended within a continuous tension network.

The first reference to tensegrity in this subject was proposed by **Stephen M. Levin** in the early 1980s, when he wrote "Continuous Tension, Discontinuous Compression. A Model for Biomechanical Support of the Body". He focused his reflection in the system of the human spine, and indeed the remainder of the body, which deserves to be quoted in length:

> "We can examine the scapulothoracic articulation. The entire support system of the upper extremity is a tension system being supported by the musculature interweaving the spine, thorax and upper extremity into a tension support system. The scapula does not press on the thorax. The clavicle has been traditionally recognized as acting more as a compression strut, as it would in a tensegrity model (…) We therefore can see in readily discernible anatomical studies that the tensegrity system is utilized in two of the major support joints of the body, the scapulothoracic and the sacroiliac joints." (…) "External forces applied to the system are dissipated throughout it so that the "weak link" is protected. The forces generated at heelstrike as a 200 pound linebacker runs down the field, for example, could not be absorbed solely by the os calcis but have to be distributed—shock absorber-like—throughout the body." (Levin, 1982)

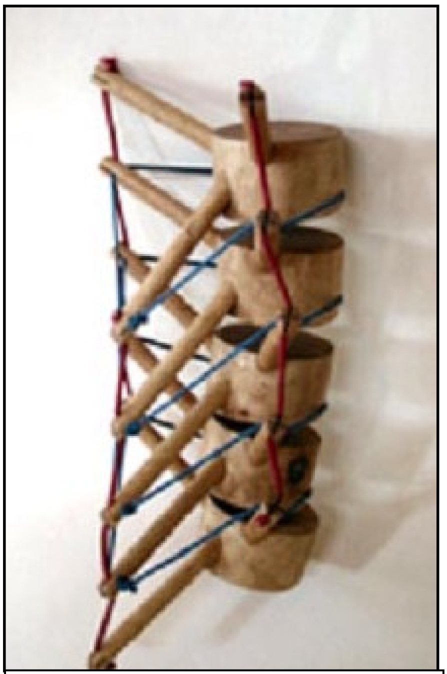


Fig. 3.16.
"**Tensegrity Thoracic Vertebrae**"
Illustration taken from Levin (2002)

The latter sentence refers to one of the main properties of tensegrity systems, the capacity to distribute the forces, which will be exposed in next chapter.

Nevertheless, Levin declared that the methane molecule, one of the simplest organic substances, has in itself the physical shape and properties of a *continuous tension-discontinuous compression* structure. He also observed that radiolaria, amoeboid protozoa that produce intricate mineral skeletons, employed this principle as well, something that was mentioned by Fuller 30 years before (Fuller, 1961).

Finally, it has been recently proposed that the central nervous system also functions as a tensegrity. According to Wilken (2001), the sensory neurons are always sensing information (continuously pulling) while the motor neurons are only occasionally involved in some motor action (discontinuously pushing).

In summary, it can be concluded that *floating compression* is, from the point of view of some specialists, something else rather than just a spatial structure made of struts and strings. Tensegrity has even been used to denominate the modernized version of some movements called “magical passes” (a series of meditative stretches, stances and movements) developed by Native American shamans, because it connotes the two driving forces of the magical passes (Castañeda, 1996). It has become a basic principle of Nature, and has been applied to so many fields of Science that it is perhaps loosing its main meaning.

In next chapter, tensegrity will be defined, described and characterized, in order to make clear difference between each subject and to find out what are its main advantages and disadvantages.

Chapter 4

Definitions and Basic Principles

Chapter 4. Definitions and Basic Principles

4.1. Introduction.

For so many years, some authors have been trying to find a "definitive definition" of tensegrity, which is unambiguous and accepted by the whole scientific community. It is essential to specify precisely what a tensegrity structure is because, depending on the different definitions, we will be able to consider some kinds of structures as real or false tensegrities.

As was mentioned in previous chapters, there are a lot of cases where the term "tensegrity" is being used incorrectly to denominate any type of structure based on compressed and tensioned components. Obviously, this is a mistake, as tensegrity is a very distinct principle. As an illustrative and peculiar example, two very curious patents will be mentioned: the "Female condom employing tensegrity principle" (Glenn and Tam, 2002) and the "Sports catch glove with stiffner" (Goldsmith, 1998) [1]. Of course, none of them is really a tensegrity application at all. In chapter 6, more examples of false tensegrity will be shown which relate to such applications.

4.2. Definitions.

In order to show the evolution of the analysis of these systems, different definitions will be explored in a chronological order.

The first descriptions, which were explained in the chapter 2, were given by the authors of the patents, trying to describe what they had discovered. Obviously,

[1] Both patents are referred to in Appendix C.

in those days it was very difficult to generalise and find a complete definition that could summarise such a complex entity as tensegrity.

In the article called *Tensegrity*, **Buckminster Fuller** (1961) explained very profusely the principles and main concepts that govern the tensional-integrity systems, but he did not give any precise definition. In his patent, he describes this kind of structures as "a plurality of discontinuous compression columns arranged in groups of three non-conjunctive columns connected by tension elements forming tension triangles" (Fuller, 1962, p.1). However, he gives a very short explanation, which has been passed to the annals of the history of tensegrity: "The compression elements become small islands in a sea of tension" (ibid). Some years later, he wrote in *Synergetics* an extended explanation:

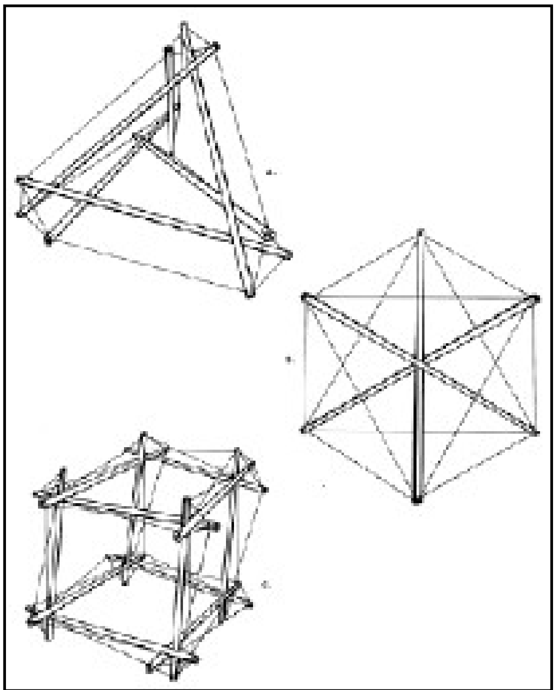


Fig. 4.1.
Some Fuller's tensegrities.
Illustration taken from Fuller (1975b)

"Tensegrity describes a structural-relationship principle in which structural shape is guaranteed by the finitely closed, comprehensively continuous, tensional behaviors of the system and not by the discontinuous and exclusively local compressional member behaviors" (1975b, 700.011)

The other "father" of tensegrity, **David G. Emmerich**, declared in his patent that his invention could be further described in a non-limitative manner with reference to several examples, shown by accompanying drawings. In this way, he avoided the difficult task of giving a strict description.

Perhaps **Kenneth Snelson** is clearer in his definition. In his patent, he explained:

"The present invention relates to structural framework and more particularly, to a novel and improved structure of elongate members which are separately placed either in tension or in compression to form a lattice, the compression members being separated from each other and the tension members being interconnected to form a continuous tension network." (1965, p.1)

Even although he prefers to call them "*Floating compression* structures", he describes them as follows (thus collaborating with the previous description):

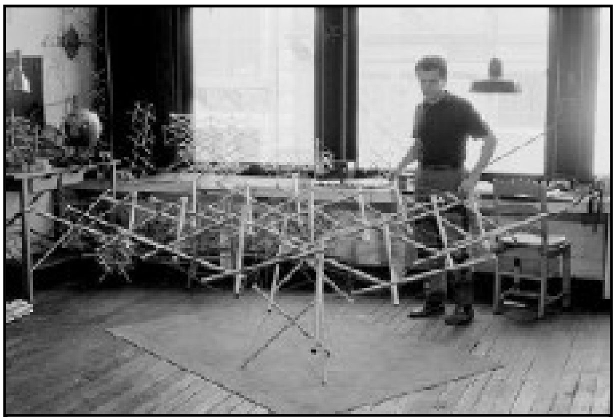


Fig. 4.2.
Snelson with a double planar structure (1961)
Illustration donated by the artist to the author.

"Tensegrity describes a closed structural system composed of a set of three or more elongate compression struts within a network of tension tendons, the combined parts mutually supportive in such a way that the struts do not touch one another, but press outwardly against nodal points in the tension network to form a firm, triangulated, prestressed, tension and compression unit." (Snelson, 2004)

Additionally, as mentioned in previous chapters, he made a very clear distinction:

"Tensegrity structures are endoskeletal prestressed structures -- and that restriction leaves out endless numbers of items".[2]

Some years later, **Anthony Pugh** gave the following characterisation of tensegrity, which has been accepted almost universally by the rest of the specialists, due to its well adapted constitution for an extended definition, possibly the first one of its kind:

"A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space" (1976, p.3).

[2] Kenneth Snelson: excerpt from an e-mail to the author, 3 Aug 2004. See Appendix D.

It was not until the 90s that **Schodeck** (1993) realized that a definition based on redundancies and degrees of movement may be a better description than the ambiguous notions formulated at that moment. Therefore, he labelled tensegrities as rigid structures made of discontinuous rods in compression and continuous cords in tension in which each component has one degree of member redundancy.

Bin-Bing Wang (1998) went beyond the previous definition, identifying other important characteristics: tensegrity structures are self-supporting and rigidified by self-stressing (something that had already been advanced by Emmerich and Kenneth). The wider definition given by Wang and Li (1998, 2003) is the following:

"Tensegrity systems are free-standing pin-jointed cable networks in which a connected system of cables are stressed against a disconnected system of struts and extensively, any free-standing pin-jointed cable networks composed of building units that satisfiy aforesaid definition." (pp. 93)

There are further and more complex definitions depending on the perspective of the authors. **Kanchanasaratool and Williamson** (2002) state that a tensegrity system is a stable connection of axially-loaded members, being a Class k tensegrity structure if at most "k" compressive members are connected to any node. E.g., a traditional tensegrity structure is a class 1 structure because only one compression member makes a node.

Ariel Hanaor described tensegrity structures as "internally prestressed, free-standing pin-jointed networks, in which the cables or tendons are tensioned against a system of bars or struts". While **Miura** and **Pellegrino** (cited in Tibert, 2002) gave a narrower interpretation: "A tensegrity structure is any structure realised from cables and struts, to which a state of prestress is imposed that imparts tension to all cables", adding later, "as well as imparting tension to all cables, the state of prestress serves the purpose of stabilising the structure, thus providing ?rst-order sti?ness to its in?nitesimal mechanisms."

Finally, **René Motro** (2003) tried to distinguish two different concepts. He makes the distinction between the "patent based" and the "extended" definition. The first one is established on the basis of patents (see preceding definitions and Appendix B), as all three describe the same structure:

"Patent based definition: Tensegrity systems are spatial reticulate systems in a state of self-stress. All their elements have a straight middle fibre and are of equivalent size. Tensioned elements have no rigidity in compression and constitute a continuous set. Compressed elements constitute a discontinuous set. Each node receives one and only one compressed element." (p.18)

The other description, the extended one, has some common points with Pugh's' definition, but has additional factors: the compressed elements are included **inside** the continuous set in tension, and the system has **self-equilibrium** stability. As a result, René Motro suggests the following:

"Extended definition: Tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components." (p.19)

4.3. General Characteristics

If this last definition is accepted as being sufficiently comprehensive and concise to define the term, it is possible to distinguish true and false tensegrity due to their respective characteristics. It would also be possible to state the following, as Motro suggests:

System: In relation to the theory of systems, it has components (two kinds, in compression and in tension), relational structure (between the different components), total structure (associating relational structure with characteristics of components) and form (projected on to a three-dimensioned referenced system).

Stable self-equilibrated state: Stable because the system can re-establish its equilibrium after a disturbance, and self-equilibrated because it doesn't need any other external condition, it is independent of external forces (even gravity) or anchorages due to its self-stress initial state. It is stable even in orbit.

Components: in contrast to the term "element", it can be a strut, a cable, a membrane, an air volume, an assembly of elementary components, etc.

Compressed or tensioned components: instead of compression and tensile components, because the key is that the whole component has to be compressed **or** tensioned depending on its class.

Continuous tension and discontinuous compression: because the compressed components must be disconnected, and the tensioned components are creating an "ocean" of continuous tension.

Inside: This is a crucial point since it will permit the differentiation of two sorts of structures: the conventional, where compression is the basis of the load support, and the tensegrities, where this role is played by the tension. In order to avoid controversial systems, such as the torus, with different "insides" and "outsides", Motro defines a system as one of tensegrity when all its compressed components are inside the system, and a compressed element is inside when the points between its ends do not belong to the boundary (or envelope). Thus, in a tensegrity system, the action lines lying on the boundary surface are tension lines.

See the models of next figs. 4.3 & 4.4 as examples:

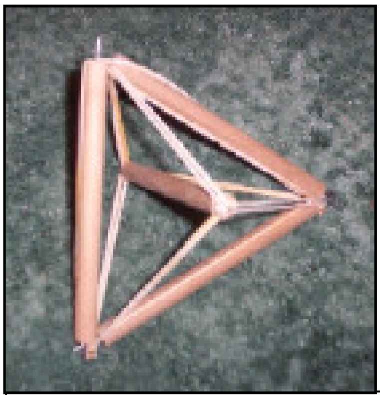


Fig. 4.3.
"**Octahedron**" False tensegrity.
The compressed square, assembly of three struts, belongs to the boundary.
Model built by the author.

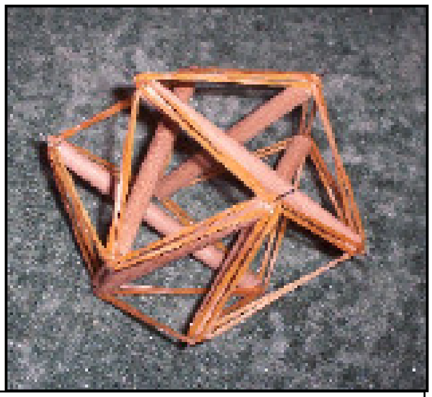


Fig. 4.4.
"**Expanded octahedron**" Pure tensegrity.
The boundary has no compressed component
Model built by the author.

This last characteristic could possibly seem superfluous for people who are not very familiar with these structures. Nevertheless, this is the point that allows us, for example, to consider the biggest dome in the world, the "Georgia Dome" in Atlanta (see figs. 4.5 & 4.6), as a pure or as a false tensegrity. Some purists don't consider that it belongs to this type of structure, since it has a compression ring surrounding the net of cables and struts, and, consequently, in the boundary of the system. Thus, in their opinion it is in the range of pre-stressed systems as a "cable dome" and not as a "tensegrity dome", as it was explained in the previous chapter.

Fig. 4.5
"**Georgia Dome**" spanning 233.5x186m (by Weidlinger Asscts.)
Illustration taken from Setzer (1992)

Fig. 4.6.
"**Georgia Dome**"
Detail of the compressed ring.
Illustration taken from Setzer (1992)

4.4. Basic Principles

Since the mid 20th Century, it has been accepted that tensegrity is a new and very particular structural principle. One of its unique aspects is the surprising and not always understood equilibrium of islanded struts floating in the air. How can they be in that position only attached by the wires?

4.4.1. Main Concepts.

Until the last century, the technique of construction and the philosophy of building have been very simple: everything was held in place by weight, so the continuities of stress were basically compressive. For instance, each component of a stone dome is pulled by tension "downward" through the structure, but the actual shape of the dome is responsible for maintaining its stability. In a concrete, wood or steel dome, the weight is much lower because we distinguish between "skin" and "bones", but the compressive continuity is still in charge of sustaining most of the load. After this consideration, the only thing to do is to reinforce the weak points.

Tensegrity structures are based on a completely different approach. Instead of the "weight and support" strategy, they are made as a "system of equilibrated omnidirectional stresses" (Kenner, 1976). Furthermore, they do not have to be supported as they are self-equilibrated and pre-stressed, so they are not depending on gravity factors for their own equilibrium; the tension created by the attraction of the Earth is replaced by the multidirectional tension of their members.

Moreover, Fuller (1975b) affirms that the example of Nature shows that tension must be included in every design since the beginning of its conception. "In fact, tension must be primary" (Edmonson, 1987).

4.4.2. Some analogies.

For 50 years, since the birth of the *floating compression*, people have been looking for mechanical and structural explanations, seeking for analogies in order to understand their principles in a clearer way.

The most common of them has been the comparison between tensegrity and **pneumatic structures**. In fact, several authors (Fuller, 1961, 1975b, 1982; Kenner, 1976; Pugh, 1976; Edmonson, 1987; Snelson and Von Baeyer, 1989; Motro, 2003; Burkhardt, 2004) admit that inflatable constructions are tensegrities because they are self-equilibrated systems composed by an exterior tensile component which embraces the atoms of gas behaving as discontinuous components in compression (cf. fig. 4.7.). Both, tensegrities and pneumatics, are compressible, expandable, self-balanced, elastic, lightweight and local-load-distributing structures.

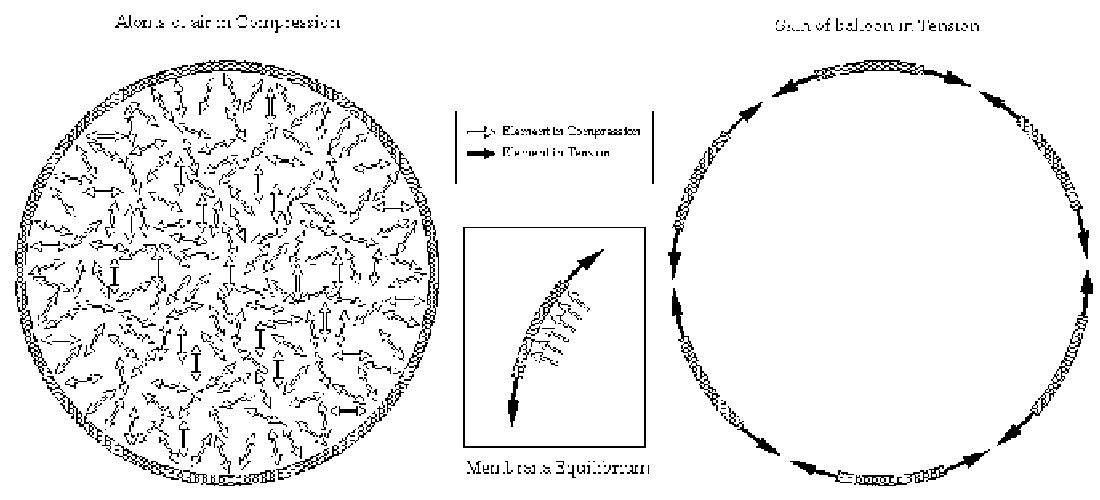


Fig. 4.7. “**Analogy of the balloon**” Illustration drawn by the author.

Nevertheless, when we deal with proper tensegrities, we consider the compressed components other than air or gas, so pneumatics are only an extension of the proper definition. In this research, the main members will be struts and cables, for compression and tension respectively.

As a consequence, the second analogy applied to explain the fundamental concepts of tensegrity is the comparison with the **wire wheel** (also mentioned in chapter 3). Fuller turned to this example very often, as he thought it inaugurated a new era of thinking in terms of comprehensive tensions and discontinuous compression.

In contrast to general opinion, the main load-transfer system of the wire wheel is not the forces of compression supported by the vertical spokes of the bottom; in fact, the axle load of wheel, applied on the hub, is hung up from the spokes at the top, which works in traction (cf. fig. 4.8.a). The effect is that the rim tries to belly out, so the horizontal spokes keep it from deforming (cf. fig. 4.8.b), while the whole rim stays in compression. As for pneumatics and tensegrity, gravity is also secondary in terms of stability in the wire wheel.

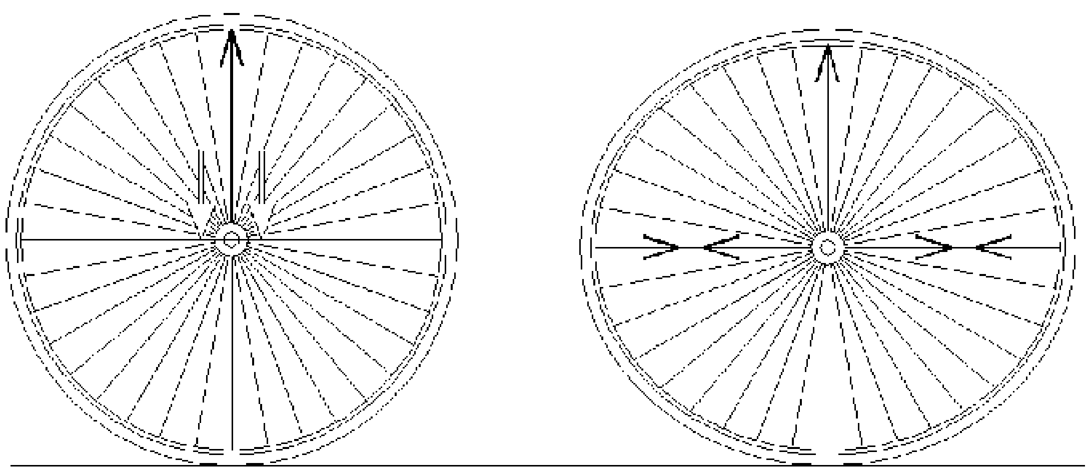


Fig. 4.8a. and Fig. 4.8.b. "**Analogy of the wire wheel**" Illustration drawn by the author.

According to Francis (1980), during the 1960s and 70s there was much development in pre-stressed steel construction and, as a result, "cycle wheel" roofs appeared on a huge scale (e.g., the roof of the Leningrad Sports Palace) and have been improved in recent times as shown in paragraphs 4.3 and 3.3.3. Nonetheless, and consistent with the previous quote by Snelson, they can't be judged as tensegrities.

4.4.3. The Creation of the Simplest Configurations.

Due to the complexity of such an interesting type of structure, and because it does not exhibit very intuitive principles, maybe it is better to explain the generation of the easiest tensegrity designs.

The most primitive case of stressed structures is not the wire wheel but, probably, the **kite** (Coplans, 1967; Fox, 1981). This antique toy is simply based on two crossed sticks with a tensioned string around it, joining the four extremes defined by them. This is basically a two-dimensional structure, which can't be considered tensegrity because the two rods in compression are touching each other in the middle of the kite.

It is not a coincidence that Snelson achieved his first tensegrity sculpture (see photo #3 of Appendix A) from kite-like modules out of plywood. Moreover, his patent (see Appendix B) employed X-shaped modules to generate several masts of *continuous tension-discontinuous compression* and to explain the generation of the simplest tensegrity structure: the "Simplex", "Elementary Equilibrium" or "Three-Struts T-Prism" (cf. fig. 4.9).

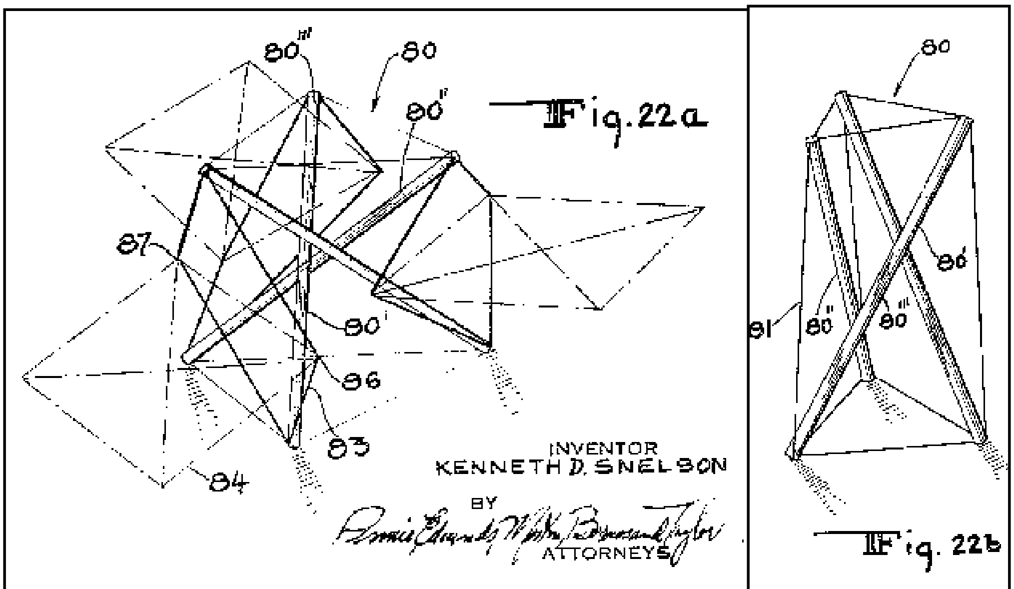


Fig. 4.9. "**Generation of the Simplex**" by Snelson. Illustration taken from Snelson (1965)

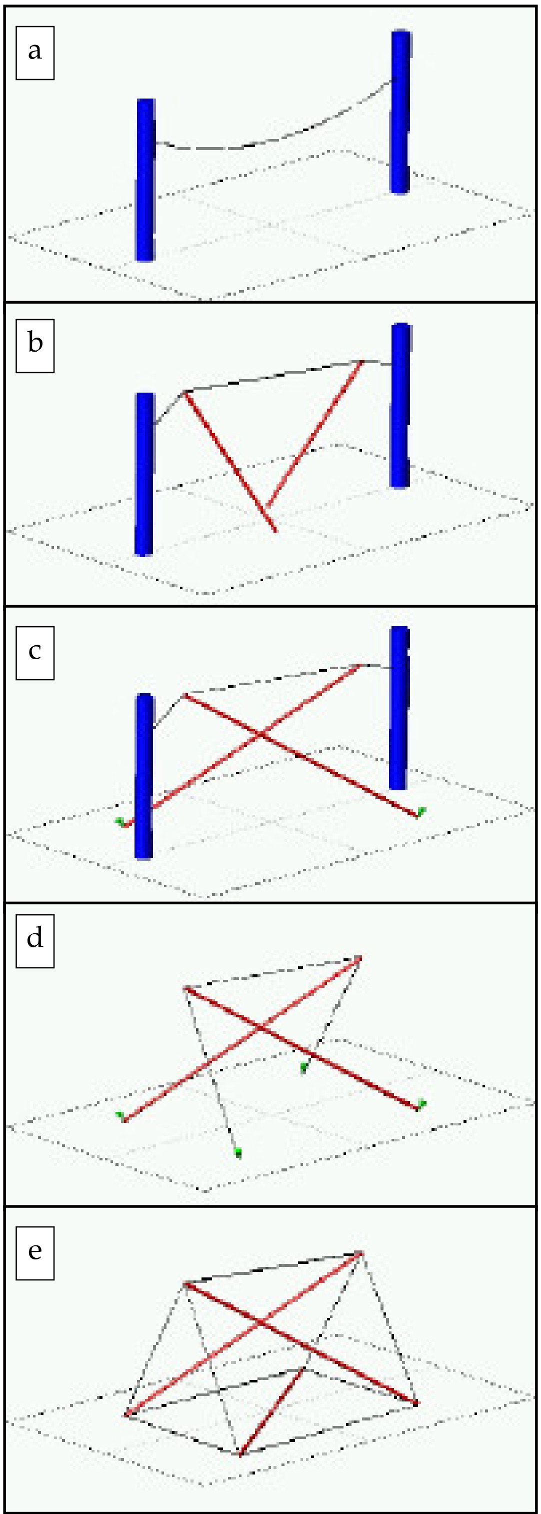


Fig. 4.10.
Kenner's derivation of the "Simplex"
Illustration drawn by the author.

Hugh Kenner (1976) obtained the "Simplex" from a different approach; although he does not make reference to Fuller's diagram that appeared in *Synergetics*, his explanation is inspired in the "Fig. 712.01 Tensegrity Behavior". He explained it by means of evolution of a system consisting of a single clothesline attached to two trees and supported in the mid way by two poles. Figure 4.10 illustrates his main idea, although designed by the author in a more developed graphic. When the two poles are very oblique, there is the risk of sliding, so they have to be attached to the ground (fig. 4.10.c). With the rods in this position, the support of the trees can be substituted by fixing the ends of the rope to the ground (fig. 4.10.d). In such a situation, perfectly stable, a tent without centre-pole has been originated. Finally, if we join the two ends of the rope by a third pole and we add 4 more strings as in fig. 4.10.e, we obtain the stable and self-sufficient "Symplex".

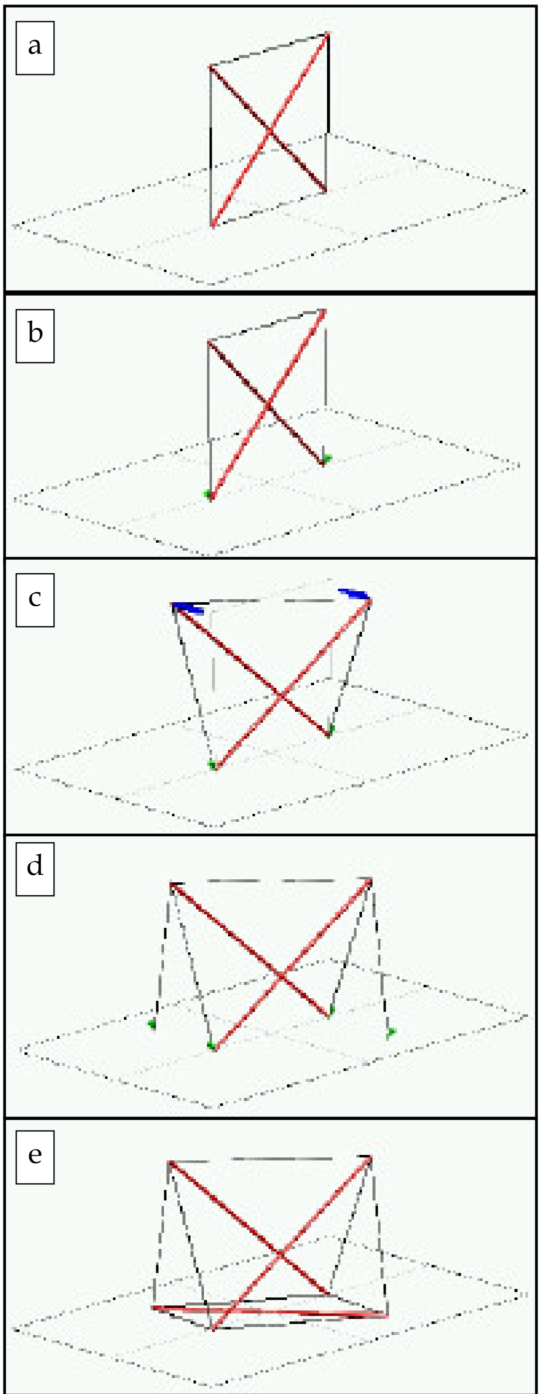


Fig. 4.11.
Author's derivation of the "Simplex"
Illustration drawn by the author.

In addition to this latter explanation and to Snelson's description, the author dares to add another method to create the "Elementary Equilibrium", graphically shown in fig. 4.11.

Beginning with a kite-like module (fig. 4.11.a), when we fix two of its corners to the ground, we can remove the string between them (fig. 4.11.b). As pointed out above, in order to consider this configuration as tensegrity, it is necessary to separate the two struts, which are in contact at their middle point. So, we push the other two corners as in fig. 4.11.c, and fix this situation by attaching two tendons to the ground (fig. 4.11.d). Finally, we add the third pole between these two points and tie its ends to the corners of the kite lying on the ground.

4.4.4. Equilibrium Analysis.

Once it has been described how a very simple example of tensegrity can be set up, and we know its basic design, it is less difficult to have an idea of the major principles that govern it.

To understand the self-equilibrating behaviour of *continuous tension-discontinuous compression* systems, it is necessary to develop a static analysis of the tension and compression forces acting on each node (Schodeck, 1993). Each vertex must be in equilibrium in order to provide the whole structure with stability. Sometimes a mechanical study can be very complex because of the geometry and number of elements of the structure, and it is usually necessary to use computer programs to accomplish this task.

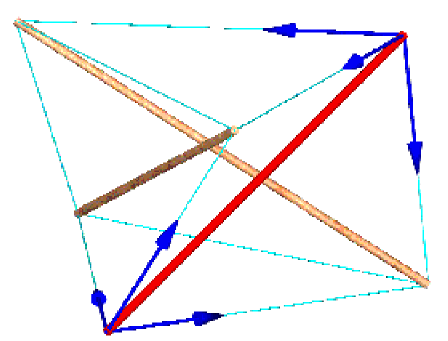


Fig. 4.12.
Set of forces acting on a strut.
Illustration drawn by the author

The figure 4.12 serves as an illustration of the static forces involved in this kind of analysis. Each strut is acted upon by the tension of the cords. As it is a three-dimensional system, in each end of the strut we should have at least three cables attached to the node (the conditions of stability of posts supported by only two cables was explained in paragraph 3.3.1 and shown in fig. 2 of Emmerich´s patent in Appendix B). This is also remarked by Snelson: “I know I need a minimum of three wires on any end of any stick” (Snelson and Von Baeyer, 1989). The resultant of each triad of forces at each node, added to the relatively small weight of each component, has to be in line with the axis of the strut, because otherwise the rod would be affected by a bending moment and would not be in equilibrium, i.e. there is a three-dimensional equilibrium of tensions and compressions at each node.

The same reasoning could be applied to the wires (fig. 4.13), which are attached to the ends of two struts [3] and influenced by, at least, the other two cables in each node. As a consequence, each string is in equilibrium if it is put under a particular tension, which is usually a pretensioning force.

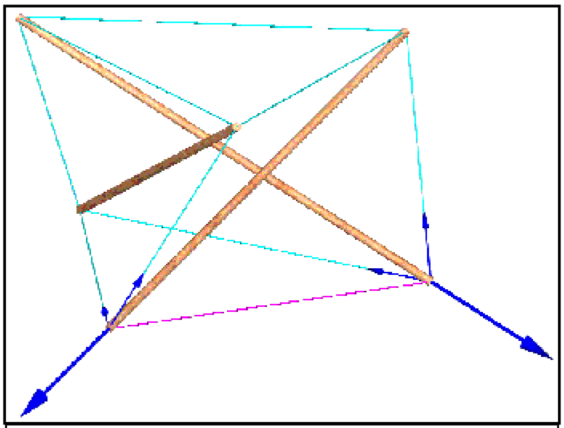


Fig. 4.13.
Set of forces acting on a cable.
Illustration drawn by the author

It should be noted that the equilibrium conditions of the *continuous tension-discontinuous compression* systems were already anticipated by Möbius and, after thirty years, rediscovered by Maxwell. According to Calladine (1978), Clerk Maxwell showed that b bars assembled into a frame, having j joints, would be simply stiff if $b = 3j - 6$. However, some tensegrity structures have fewer struts than are needed to satisfy Maxwell's rule, and are not "mechanisms" as it could be expected, but are actually rigid structures. He also predicted that their stiffness will "be of a low order" and permit at least one state of "self-stress" in the frame.

A particularity of tensegrity structures is that the forces acting on them are visible in a sense. For instance, Snelson affirms about his sculptures: “I am showing you, for the very first time, what structural space really looks like” (Schneider, 1977). In other words, in a tensegrity structure the two types of forces in essence, tension and compression, are completely separated and you can see them in their pure state. Where there is a strut, there is pure compression; and where there is

[3] Sometimes they are attached to a node responsible for joining a set of cables, but it is not very usual.

a cable, there is pure tension [4].

It is not the aim of the present work to explain in depth the extended laws that govern the finite and infinitesimal mechanisms of tensegrity. Because of the complexity of the subject, it is more suitable to refer the reader to the bibliography, especially to Motro (2003), chapter 3.

4.5. Features.

The precise and detailed configuration of the "floated compression" structures, make it possible to accept the assumption that they have very special characteristics. In the following pages, they will be described, with their main advantages and disadvantages.

4.5.1. Properties:

- They are very lightweight in comparison to other structures with similar resistance, or if preferred, they have a high resistance in comparison to other structures with similar weight. In contrast, Wang (2003) states that this characteristic is not inherent, as for example tensegrity grids are heavier than conventional structural grids.
- They have no redundant parts, although new tendons can be added to consolidate the structure. (Kenner, 1976).
- They don't depend on gravity due to their self-stability, so they don't need to be anchored or leaned on any surface. The systems are stable in any position. The force of gravity, basis of the conventional architecture, is nullified (Perlberg, 1977)

[4] Fuller and Edmonson argue that there is neither pure tension nor pure compression members, but members "at the high tide" of a compressional aspect. Tension and compression always coexist.

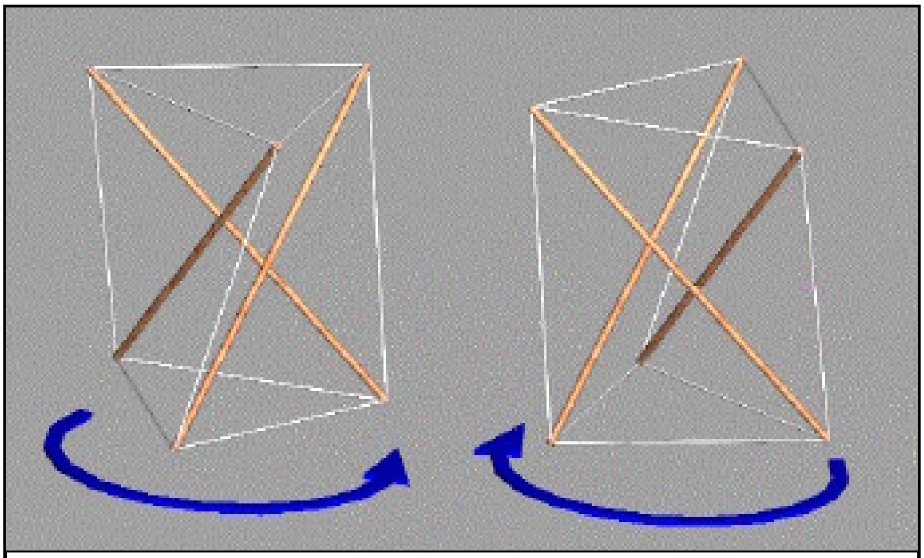


Fig. 4.14.
Right-handed and Left-handed Simplex ("Dextrorse" and "Sinistrorse")
Illustration drawn by the author.

- The majority of tensegrity systems are enantiomorphic. This means that they exist as right and left-handed mirror pairs, "dextrorse" and "sinistrorse" respectively (Kenner, 1976; Pugh, 1976; Snelson 2004). For an illustration, see fig. 4.14.
- Elemental tensegrity modules can be joined in order to create masts, grids or conglomerates made of the same or different figures.
- If the self-stressing is higher in a tensegrity system, its load-bearing capacity is higher too. Using the analogy of the balloon, if a balloon is more inflated, the tension forces in the skin are greater and it is harder to deform it (Pugh, 1976).
- The degree of tension of the pre-stressed components is proportional to the amount of space that they occupy (Muller, 1971).
- As the components in compression are discontinuous, they only work locally. The compression is located in specific and short lines of action, so they are not subject to high buckling loads.

- Due to this discontinuity in compression, they don't suffer torque at all. Tensegrity is the answer to the question:

  > "What's the minimal structure that can support a weight and oppose horizontal forces, that uses compression and tension, but experiences no torque?" (Fuller, cited in Flavin, 1996)

- They have the property of synergy where the behaviour of the whole systems is not predicted by the behaviour of any of their components taken separately. (Fuller, 75; Levin, 82)
- The resilience (flexibility) or stiffness of the structure depends on the materials employed, and by their method of assembly. They can be very flexible or very rigid and quite strong. (Vesna 2000)
- Due to the previous characteristic, they are very sensitive to vibrations under dynamic loads.
- They have the ability of respond as a whole, so local stresses are transmitted uniformly and absorbed throughout the structure.
- Elasticity multiplication is inherent to them: When separating two struts by a certain distance, the stretching of the tendons is much less than this amount. For example, in the expanded octahedron (fig. 4.15), if the struts are separated by 1%, the tendons stretch 0.00166% (600 times less!), so the whole system has the capacity to multiply the elasticity of the tendon by 600 times. (Kenner, 1976). For an

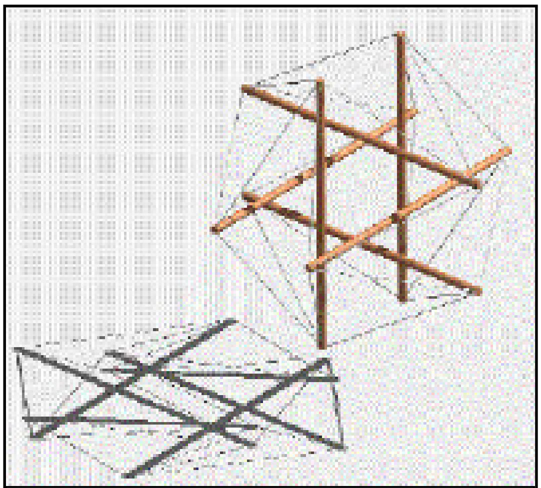


Fig. 4.15.
"Expanded octahedron" or "Icosahedron"
Illustration drawn by the author.

example, the deflection of the expanded octahedron modelled by cables and beams finite elements (Mijuca, 1997), can be seen in Appendix E.

- The response to the loads is non linear. They are more flexible under light loads, but their stiffness increases rapidly as the load is higher, like a suspension bridge (Kenner, 1976; Smaili, 2003; Wang 2003).
- Some tensegrities, under axial load, experience a rotation around this axe (Kenner, 1976; Snelson, 2004). The direction of this rotation depends on the handedness of the system (enantiomorphic characteristic explained above).

4.5.2. Advantages:

- The multidirectional tension network encloses fortuitous stresses where they take place, so there are no points of local weakness. (Kenner, 1976)
- Due to the ability to respond as a whole, it is possible to use materials in a very economical way, offering a maximum amount of strength for a given amount of building material (Ingber, 1998). In Vesna's and Fuller´s words (2000), tensegrity demonstrates ephemeralisation, or the capability of doing more with less. Perhaps, 'ethereal' is more adequate than 'ephemeral'.
- They don't suffer any kind of torque or torsion, and buckling is very rare due to the short length of their components in compression.
- Tensional forces naturally transmit themselves over the shortest distance between two points, so the members of a tensegrity structure are precisely positioned to best withstand stress.
- The fact that these structures vibrate readily means that they are transferring loads very rapidly, so the loads cannot become local. This is very useful in

terms of absorption of shocks and seismic vibrations (Smaili, 2003). Thus, they would be desirable in areas where earthquakes are a problem.

- The spatial definition of individual tensegrity modules, which are stable by themselves, permits an exceptional capacity to create systems by joining them together. This conception implies the option of the endless extension of the assembled piece (Muller, 1971). Further explanations will be provided in the next chapter.
- For large tensegrity constructions, the process would be relatively easy to carry out, since the structure is self-scaffolding (Whelan, 1981). An example is the illustration of fig. 4.16.

Fig. 4.16.
"**Easy-K Installation**" by Snelson in 1970. Arnhem, (Holland)
Illustration taken from Snelson (2004)

- Burkhardt (1994-2004) sustains that the construction of towers, bridges, domes, etc. employing tensegrity principles will make them highly resilient and, at the same time, very economical.
- The kinematic indeterminacy of tensegrities is sometimes an advantage. In foldable systems, only a small quantity of energy is needed to change their configuration because the shape changes with the equilibrium of the structure. Consequently, Skelton and Sultan have explored the use of tensegrity structures as sensors and actuators (Tibert, 2002).

4.5.3. Disadvantages:

- According to Hanaor (1997) tensegrity arrangements need to solve the problem of bar congestion. As some designs become larger (thus, the arc length of a strut decreases), the struts start running into each other.
- The same author stated, after experimental research, "relatively high deflections and low material efficiency, as compared with conventional, geometrically rigid structures" (Hanaor, 1987, pp. 45)
- The fabrication complexity is also a barrier for developing the *floating compression* structures. Spherical and domical structures are complex, which can lead to problems in production. (Burkhardt, 2004)
- The inadequate design tools have been a limitation until now. There was a lack of design and analysis techniques for these structures. Kenner (1976) proposed shell analysis as the best way, although this is a bit distant from structural reality. In spite of this evidence, Pugh (1976) estimated, incorrectly, that as the connections between struts and tendons are pinned joints, the design and calculation of these figures was relatively simple. For

the past ten years, Burkhardt has been working on a computer program that, seemingly, works well enough to design and calculate tensegrities.[5] And recently new software, “Tensegrité 2000”, has been developed by René Motro and his group at the Laboratoire de Génie Civil in Montpellier.

- In order to support critical loads, the pre-stress forces should be high enough, which could be difficult in larger-size constructions (Schodeck, 1993).

[5] See Appendix D: Personal correspondence with Robert W. Burkhardt.

Chapter 5

Typologies, classification and assemblies

Chapter 5. Typologies, classification and assemblies

When developing a new field of knowledge, it is essential to describe, denominate and categorize in order to develop a complete and extensible classification of the subject in question. Tensegrity systems are not an exception, but at present there are some discrepancies among the authors and specialists.

5.1. Nomenclature

It has been stated throughout previous chapters that the definitions for the highlighted examples are not categorised in a standard way. For instance, the simplest tensegrity system has already been denominated as “simplex”, “elementary equilibrium”, “3 struts T-prim”, “3 struts, 9 tendons”, “twist element”, “3 struts single layer”, “(3,9;2,1)” and so on. Other known systems are not excluded from these circumstances.

As a result, some authors have tried to create a definitive nomenclature, which is clear and systematic. This would permit the categorisation of *floating compression* systems and, at same time, would give enough information about them.

At present, the author has come across a couple, which are very logical and similar, based on the definition of the geometry by means of basic and systematic rules. Williamson and Whitehouse (2000) employ just numbers, colons and comas in brackets, while Motro (2003) uses numbers and letters in intuitive way.

The former considers a general class of (N, S; P_1, P_2, ... , P_M) tensegrity structures consisting of **N** compression members (i.e. struts) and **S** tensile members (i.e. cables). The structure has M stages with $\mathbf{P_M}$ struts per stage. As an illustration, the "simplex" (fig. 5.2.b & 2.2) would be (3,9;3).

The latter organizes them following an alphanumeric code, explaining each term with the initials followed by the number of items, being listed:

n = Nodes,

S = Struts or compressed components,

C = Cables or tensile components,

R = Regular system or **I** = Irregular system depending on the case,

SS = Spherical system (homeomorphic to a sphere) if this is the case

For instance, the last example, the "elementary equilibrium" (fig. 5.2.b & 2.2), would be expressed as "n6-S3-C9-R-SS".

The author finds several advantages of the latter in comparison to the former. Sometimes it is difficult to make a distinction between the different stages that compose a *continuous tension-discontinuous compression system*. Moreover, a variant of these systems, proposed by Kono and other experts, uses nodes where only cables are jointed, thus sometimes it is necessary to define the number of nodes explicitly. Finally, in some cases it is essential to know whether the system is regular and inscribed in a sphere (e.g. in order to truncate it to transform it into a dome) or is irregular and non spherical.

In conclusion, the author will adopt Motro's nomenclature to describe and denominate the cited tensegrities. In any case, the nomenclature is not very useful when speaking about the most common figures.

5.2. Classification

It is probable that the first classification of tensegrities was carried out by

Fuller and his collaborators, but so far the author has only come across a general division into two broad structural classes: prestressed and geodesic tensegrities. The former is self-stable since there is a pre-existing tensile stress or isometric tension; the latter finds equilibrium as a result of the triangulation of its structural members, orientated along geodesic lines or minimal spherical paths (Ingber, 2003a; Armstrong, 2004).

Anthony Pugh (1976) was the first person to show a thorough catalogue of tensegrity systems. It is true that he did it almost exclusively related to polyhedra, but it is still very helpful. First, he described the simplest figures superficially (both 2D and 3D), depending on the relative position of their tendons (passing through their centres or not), on the complexity of the compressed components (single elements or groups of struts), on the number of layers or stages, etc. Then, he described the three basic patterns that can be used to configure spherical or cylindrical tensegrity structure: Diamond pattern, Circuit pattern and Zigzag pattern. This classification was based on the relative position of the struts of the figures, as is explained in fig. 5.1. Finally, he related the way of joining systems together and the construction of larger figures. In that section some grids, masts and domes were described, but not in an in-depth manner.

To achieve a clearer classification it could be useful to have an account of some other configurations and geometries. Some of the following points are based on chapter 4 of Motro's book "Tensegrity, Structural Systems for the Future" (2003).

5.2.1. Spherical systems

These systems are homeomorphic to a sphere, e.g. all cables can be mapped on a sphere without intersections between them and all the struts are inside this cable net creating a spherical cell. They are some of the most common *floating compression* figures, fitting the following classification:

5.2.1.1. Rhombic configuration.

This corresponds to the Diamond Pattern established by Pugh. The name of these types of figures responds to the way that they are constructed. Each strut of a rhombus system represents the longest diagonal of a rhombus formed by four other cables, folded following the diagonal (fig. 5.1.a). Tensegrity prisms (T-Prisms) are included in this section.

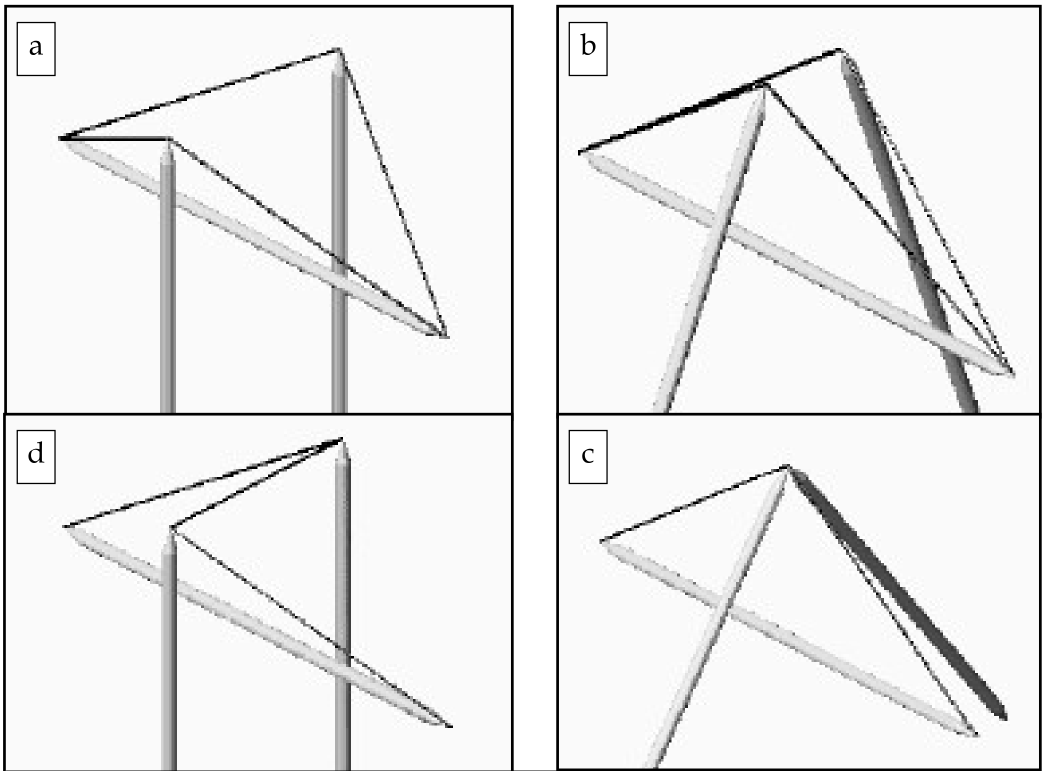


Fig. 5.1.
Classification of Spherical Systems. Illustration drawn by the author after Pugh's drawings.

T-Prisms or Prismatic tensegrities are generated from a straight prism where the cables are horizontal or vertical and the struts are diagonal between the vertices of the two different levels (fig. 5.2.a). If a relative rotation is intoduced between the upper and lower polygons, a tensegrity prism is obtained (fig. 5.2.b).

Kenner (1976) states that the rotation angle (a), or “twist angle”, depends on the number of struts (n=number of edges of the polygon) and is given by the formula demonstrated by Roger S. Tobie in 1967:

a = 90º - 180º/n

For instance, for, a triangular prim a=30º (cf. fig. 5.2), in a square configuration a=45º, in a pentagon a=54, in a hexagon a=60º, and so on. In any case and according to Pugh (1976), the higher the number of struts, the less stable and more flexible is the T-Prism.

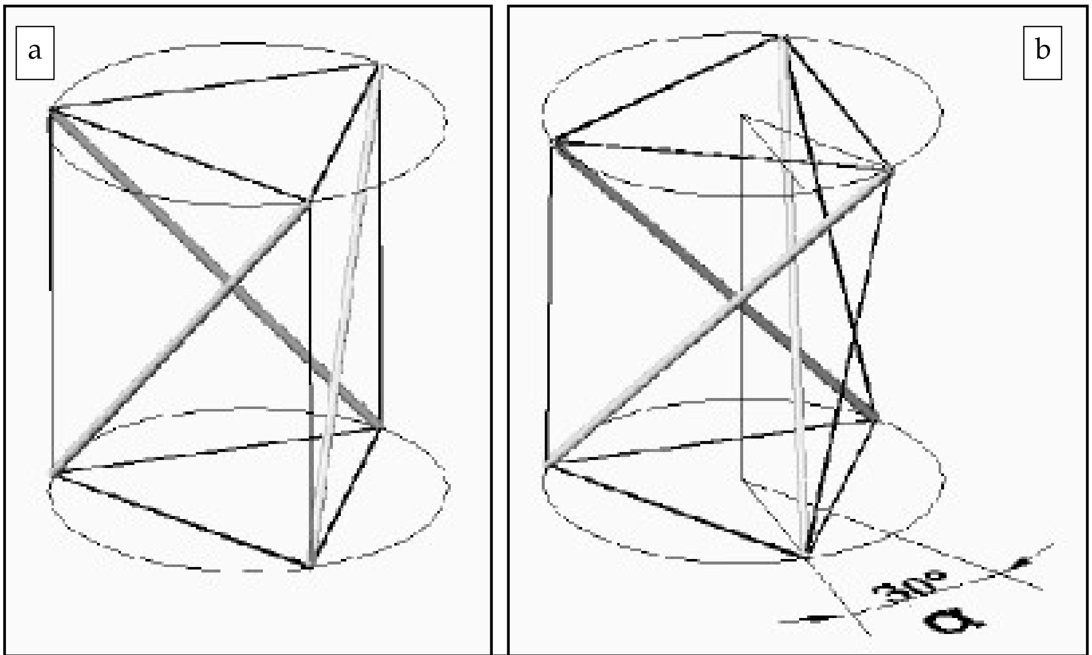


Fig. 5.2.
Generation of T-Prims. Illustration drawn by the author after Pugh’s drawings.

Each prismatic tensegrity system comprises of a single layer of struts, but other figures can be built by adding more stages and thus creating a kind of cylindrical rhombic system (cf. paragraph 5.2.3)

The most known exemplars of the rhombic configuration are the “simplex” and the “expanded octahedron” (also so-called “icosahedric tensegrity”).

The first one (n6-S3-C9-R-SS) has been shown in preceding graphics (figs. 5.2 & 2.2), and the latter (n12-S6-C24-R-SS) is a typical two layer tensegrity system, with a very strong symmetrical component, due to its three pairs of struts, parallel two by two (cf. figs. 5.4.a, 4.4, 4.15 and Appendix E).

5.2.1.2. "Circuit" configuration.

In this second class, the compressed components are conformed by circuits of struts, closing the rhombus generated by the struts and cables of the diamond pattern tensegrities (figs. 5.1.b & 5.1.c).

Several regular and semi-regular polyhedra can be built related to this class, e.g. cuboctahedron, icosidodecahedron, snub cube, snub icosahedron, etc. As can be seen in the fig. 5.3, the cuboctahedron is composed of four circuits of three struts (every circuit interweaving with each other) and the cables defining the edges of the polyhedron.

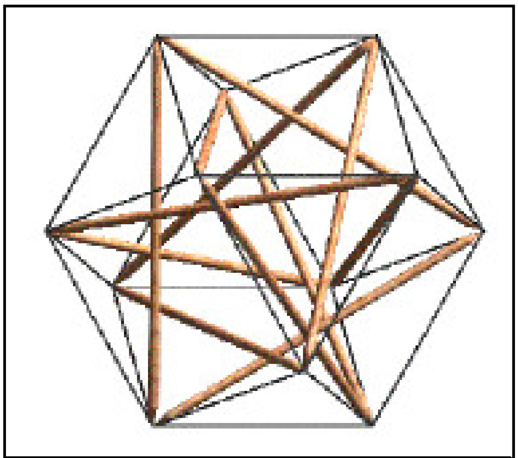


Fig. 5.3.
Cuboctahedron
Illustration drawn by the author

Moreover, circuit systems are also able to generate geodesic tensegrity spheres or domes if the breakdown frequency is a multiple of two. The procedure consists of dividing the polyhedra in question following the rules of geodesic spheres, defining a grid of triangles for each face, and then sketching the struts and tendons onto the grid (Armstrong, 2004). Anthony Pugh gave a complete list of figures built following this method; for instance, the biggest tensegrity polyhedron described in that catalogue, the eight-frequency truncated tetrahedron, was designed using 672 struts and 1344 tendons.

According to Pugh's experience, a circuit system is more rigid than a rhombic one with the same number of struts. This is understandable since the former evolves from the latter, but it becomes more compact and there is contact between its compressed elements.

5.2.1.3. "Zigzag" configuration or "Type Z".

When using a rhombic system as a basis, if some of the cables are changed in such a way that they form a 'Z' of three non aligned tendons (fig. 5.1.d), the "zigzag" configuration is obtained. It is important to remark that the substitution of the cables must be coherent in order to preserve the stability of the system.

For instance, if the configuration of an "expanded octahedron" (fig. 5.4.a) is changed and the cables are fixed following the zigzag pattern, the result is a "truncated tetrahedron" (fig. 5.4.b)

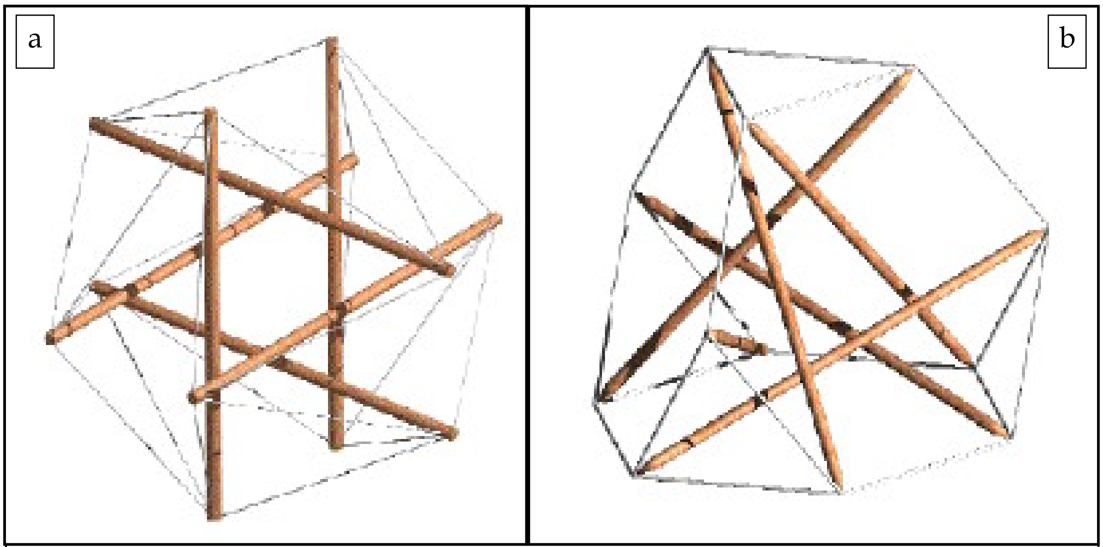


Fig. 5.4.
"**Expanded octahedron**" and "**Truncated Tetrahedron**"
Illustration drawn by the author.

As Motro (2003) remarked, it is not always possible to attain a balanced geometry and, therefore, sometimes the figures do not have a perfect definition of the polyhedron in question. Due to the orientation of the struts that converge in each face, it can be appreciated that a certain distortion of the regular polygons can arise. In any case, additional cables can be inserted into the original system to obtain the perfect geometry. If the aim is to create a geodesic figure, the process is similar to that of circuit systems, except that the breakdown frequency has to be a multiple of 3.

5.2.2. Star systems

Even though they are also spherical cells, they are considered as a derivation of the preceding class. For example, taking as a basis one of the rhombic system, if a vertical strut is inserted in the centre following the main axis of symmetry and linked to the rest of the cables by means of tendons, a star system is created. Another possibility could be proposed by inserting a small spherical node instead of the central strut.

5.2.3. Cylindrical systems

There is also a variation of the rhombic configuration, obtained by adding other layers of struts to the initial layer. Fig. 5.5.a shows the deployed bunch of bars and tendons of a four-strut rhombic cell. If a second line is added, as is represented in fig. 5.5.b, and subsequently closed all around itself again, a cylindrical mast is obtained. Depending on the number of layers, the resulting tower will be more or less tall.

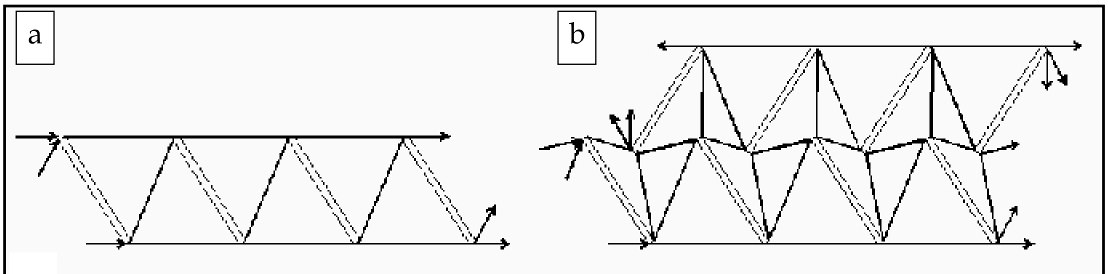


Fig. 5.5.
Deployed Single Layer System (n8S4C12) and **Double Layers System (n16S8C32)**
Illustration drawn by the author.

5.2.4. Irregular systems

In this section numerous figures are included that do not fit into previous classifications. For instance, a high percentage of Kenneth Snelson's sculptures could be regarded as irregular structures since they are not governed by any rule defined in this or other studies.

5.3. Assemblies

More complex systems may be achieved by joining the elementary cells described above. In the following sections some possibilities will be contemplated, although the list is not exhaustive.

5.3.1. Vertical Masts (horizontal beams)

One-dimensional systems can be generated by adding the different modules following an axis that rigidly dictates the geometry. Several straight towers have been built over the years, as will be explained in the next chapter, while contrarily not many *floating compression* beams have been regarded in such a way. Obviously, the reason is the lack of resistance of these structures to bending moment, although the cable-domes illustrated in previous chapters have improved this behaviour.

5.3.2. Grids

By assembling tensegrity cells in two dimensions, a planar structure is created with advanced characteristics in relation to one-dimensional beams. Obviously, this performance is strongly dependent on the way the different modules are joined.

This is the reason why **Ariel Hanaor**'s works are a reference and guide for specialists in tensegrity structures; he started in the 1980s by studying the geometric configuration of double-layer tensegrity grids (DLTGs) by means of the T-prisms defined above (which generated planar surfaces) and T-pyramids (for curved surfaces). Hanaor (1987) basically defined three types of connections:

Type I – Modules share only nodes

Type Ia - Type I applied to odd-sided polygons (right handed and left-handed modules), producing unique configurations.

Type Ib - Type I applied to even-sided polygons, producing symmetric configurations.

Type II – Modules also share portions of the base polygons, producing unique configurations too (hexagonal T-Prism excepting)

After these considerations, several geometric studies and load tests were carried out by him and other collaborators, concluding for example that triangular grids are more rigid than square grids, or that the efficiency of material utilisation was similar in the three grids.

However, more general conclusions were obtained. At that stage, it was stated that these grids had an overall good agreement in structural response and the major advantages of simple joints. They also recognised that those structures suffered large deflections and had low material efficiency compared with conventional rigid structures.

Further investigation was required; it has been accomplished since then and the main research has been carried out at the **Laboratoire de Génie Civil in Montpellier**, led by **René Motro**. Since 1998, several grids have been constructed attempting to avoid the lack of stiffness of the simple agglomeration of T-Prisms.

Vinicius Raducanu, who worked on the Tensarch Project at Montpellier, based his research on points of view such as analogy, geometry, topology, etc. The group used the same mechanical principle, the “V expander” (fig. 5.6), applied to different geometries: bi-, tri- and quadri-directional tensegrity grids.

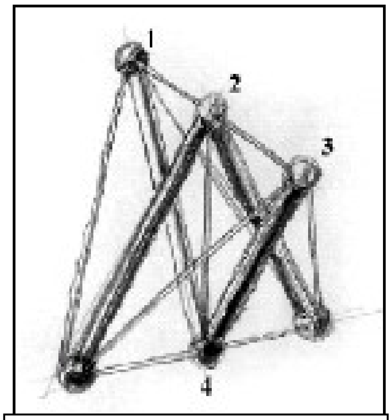


Fig. 5.6.
“**V expander**” Illustration taken from Motro and Bernard (2002)

A prototype of a bi-directional layout, certainly the simplest one (an extension of the module shown in fig.5.7), was built at the end of 2000, covering 82m^2 and weighting 900 kg. This steel structure was constructed according the Eurocode3 building standard for a 160daN/m^2 external downward load. It therefore proved the feasibility of this kind of grid that had a surprising rigidity. As a result, Raducanu and Motro (2001) patented the system, presented in Appendix C.

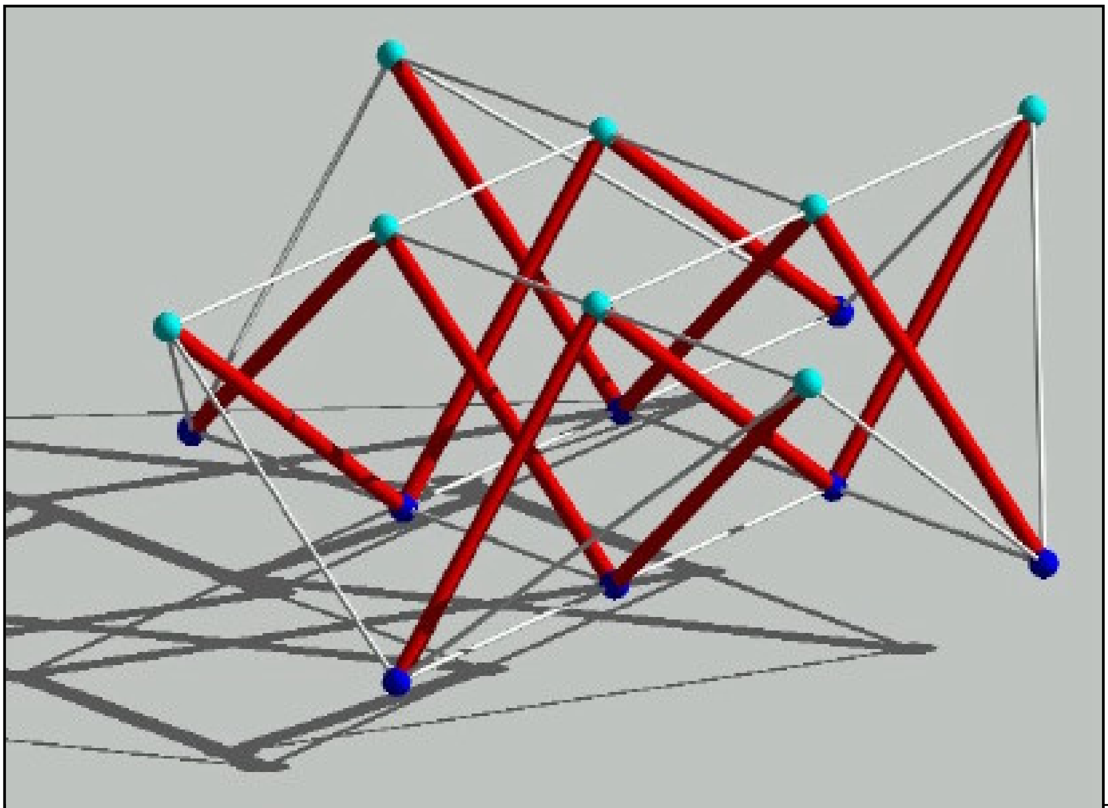


Fig. 5.7.
“**Bi-dimensional double-layer grid**” by Laboratoire de Mécanique et Génie Civil, Montpellier
Illustration drawn by the author

In every grid the extended definition given in chapter 4 is respected, because the compressed components are not the single struts but the frames and chains of bars composed in between the two layers.

As a conclusion, Motro and his collaborators stated that tensegrity grids are feasible, solid, adaptive, discrete pneumatic structures and rigid enough depending on their function. In fact, they proposed their application to walls (allowing the insertion of integrated architectural systems), roofs, coverings, etc.

5.3.3. Conglomerations

Finally, it is necessary to mention these systems although they have been barely studied. They are tensegrity solids without any predominant direction, so they have a three-dimensional shape. At the moment they have not been applied in any definite field.

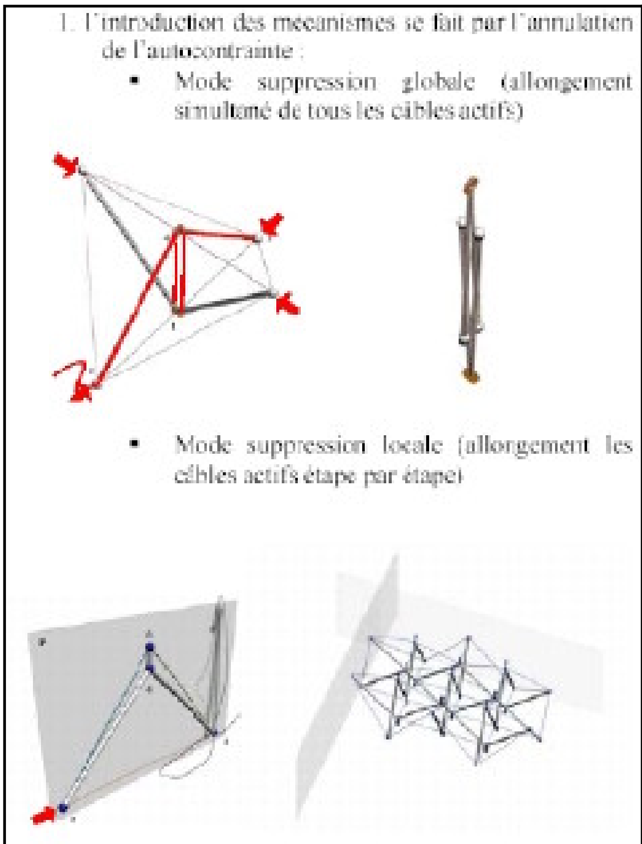
5.4. Deployable structures

Without any doubt, much of the future of *floating compression* relies on this significant characteristic; therefore, the field of application of these systems has been extended noticeably. In fact, folding tensegrity structures have been one of the main research topics for the past ten years.

It is not the aim of this work to deal with this subject in depth, as it would take many chapters to explain the advantages, possibilities and potentials of deployable tensegrities. The author considers that it is more suitable to refer to an extended bibliography (Appendix I) which mentions the main specialists that are dealing with the subject.

Pellegrino and Tibert's works (1991, 2003) have been very useful from the point of view of deployable masts and other structures disposed for the conquest of Space (cf. paragraph 6.2.6). Indeed, some of the results have been patented and are referred to in chapter 6, Appendix C and in the bibliography (Skelton, 1997; Knight et al., 2000; Stern, 2003).

Other experts have done recent research in foldable floating compression structures, e.g. A. Hanaor, R.E. Skelton, H. Furuya and H.Y.E. Pak. Once again, the research of René Motro and his laboratory is extremely important (especially A.E. Smaili (2003), V. Raducanu and M. Bouderbala), making an almost exhaustive revision of all the options that these systems offer and of all their potentials (fig. 5.8).



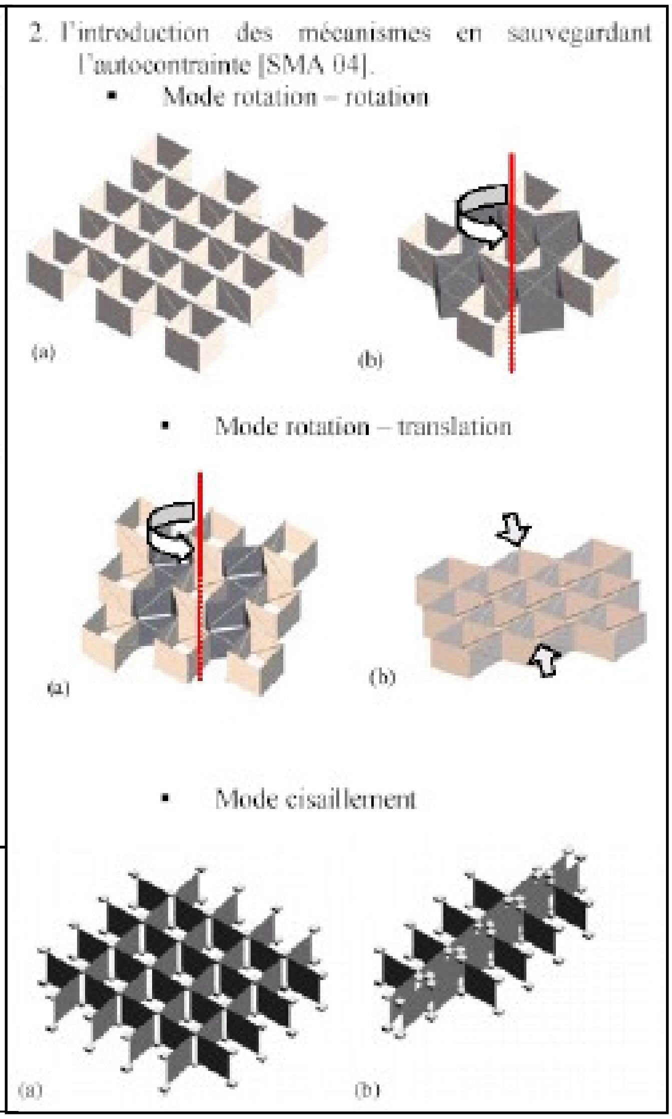


Fig. 5.8.
Folding Mechanisms, by Ali El Smaili.
Cancelling the prestress: Local suppression and global suppression
Maintaining the prestress: Rotation-rotation, rotation translation and shear.
Illustration taken from Smaili (2003)

Chapter 6

Applications and proposals

Chapter 6. Applications and proposals.

6.1. Introduction.

Once the basic fundaments and basic systems have been described, this chapter will deal with the task of showing the applications of this material with exemplars.

First, the most important examples of works already built will be presented, both the “real” and the “false” tensegrity structures, according to the definitions of chapter 4. In any case, this point is controversial since even in the group of the “real” tensegrities there are “pure” and “non pure” *floating compression* systems, depending on the contact, or not, of the struts in compression.

As soon as these examples are shown, the author will present some of his own proposals to apply the *continuous tension-discontinuous compression* principle to architecture, simple elements or more complex structures. It should be recalled that, due to the limitations of time, budget, software and infrastructures, these designs are not as developed and defined as professional works.

It might be interesting to note that some professionals, for instance **Daniel L. Schodek** (1993), affirm that even though a tensegrity sculpture is a fascinating spatial exploration, this does not mean that it has any special structural worth. The sculptor **Kenneth Snelson**, maybe the most important figure in the topic, is really convinced about the unfeasibility of applying these structures to any architectural or engineering construction. He refers to **Mario Salvadori**’s opinion about tensegrity Vs conventional beams, and then he extrapolates this argument to other structures (see last paragraph of Appendix A). As Snelson wrote to the author:

"It is my belief based on long experience and making endless numbers of tensegrity structures of all shapes and sizes that the principle in itself is impractical for building buildings. As you know many architects and engineers have worked toward that end and still do. Fifty years of it now. None have shown there is the slightest structural advantage in its use for such purposes." [1]

"[They] are also very flexible and I know of no instance where they've been put to use for any practical purpose." [2]

Certainly, it is true that some of the Fuller's announcements and propositions seemed like humbugs, like the possibility "to bridge the Grand Canyon with tensegrity" (ibid) or to cover a whole city with a geodesic dome. However, it is not the author's intention to despise or disdain any suggestion; Jules Verne said "*Anything one man can imagine, other men can make real*", and this is a great truth, especially in his case. The author does not consider himself authorised to make severe judgements. As an illustration, and according to the California Energy Commission (CEC, 2003), the Literary Digest predicts, in 1899, a "dim future for the automobile", claiming it will never "come into as common use as the bicycle".

Even if Snelson's opinions were true, it would not change the fact that numerous people are working in the subject, and more than a few publications, articles and papers are being circulated in different journals and conferences. "Tensegrity is now applicable to architecture as an established structural system, while it can be applied to other fields as well" concluded M. Kawaguchi, President of the IASS (International Association for Shell and Spatial Structures), in the preface of Motro's last book (2003). In the following paragraphs, the most significant examples will be recalled.

[1] Kenneth Snelson: excerpt from an e-mail to the author, 20 Jul 2004. (See Appendix D)
[2] Kenneth Snelson: excerpt from an e-mail to the author, 3 Aug 2004. (See Appendix D)

6.2. Actual examples.

6.2.1. Domes.

Perhaps, one of the most important books about domes is "Analysis, Design and Construction of Braced Domes" edited by **Z.S Makowski** (1984). It is a really significant fact that he did not mention any tensegrity dome, although he mentioned Fuller's patents as well as Pugh and Kenner's studies. This point serves to illustrate the degree of recognition of these structural constructions.

6.2.1.1. Different proposals for domes

Most of the works and studies in tensegrity have been done in relation to spherical or polyhedral configurations. Several authors have proposed different kinds of domes following the *continuous tension-discontinuous compression* fundaments, attributable to the facility to obtain a dome from a sphere or spherical polyhedron (see Appendix G, where the author shows possible truncations of a tensegrity truncated icosahedron). Figure 2.6. (chapter 2) has shown one of the first geodesic tensegrity domes, by **Buckminster Fuller** in 1953. According to Hanaor (1987), this concept can be applied to relatively small spans because if this is increased the curvature is also smaller and the components come into contact. Snelson has a definite opinion about this configuration, as in one of

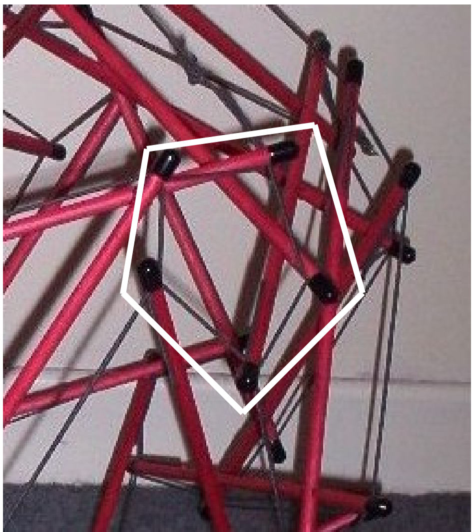


Fig. 6.1.
"**Apex of Truncated Icosahedron**"
Model made by the author

his letters to the author[3], he states that this truncated sphere is “as soft as a marshmallow”, and in other e-mail he cites it again saying that, due to the absence of triangulation, it could barely hold itself up. “His tensegrity domes (...) are as shaky and floppy as a Tensegritoy” [4], which refers to a construction puzzle that will be referred to in section 6.2.7.2.

In fact, with the absence of triangulation, any structure, but especially tensegrities, loses an important factor for stability. It is this detail that Snelson pointed out and that the author took into account for the design of some domes in section 6.3. Some of the domes obtained from truncated polyhedra, have the connections of the struts forming a polygon different of the triangle. In the example of fig. 6.1, each apex is formed by five struts creating a pentagon of tendons. This situation is not very convenient, but can be resolved by adding more wires between them and connecting other apexes of the dome.

A different kind of dome using *floating compression* was the one shown by **Kenneth Snelson** in his patent of 1965. It was not based on polyhedra, but on the x-shaped towers that he first discovered; each of the arches is formed by these towers

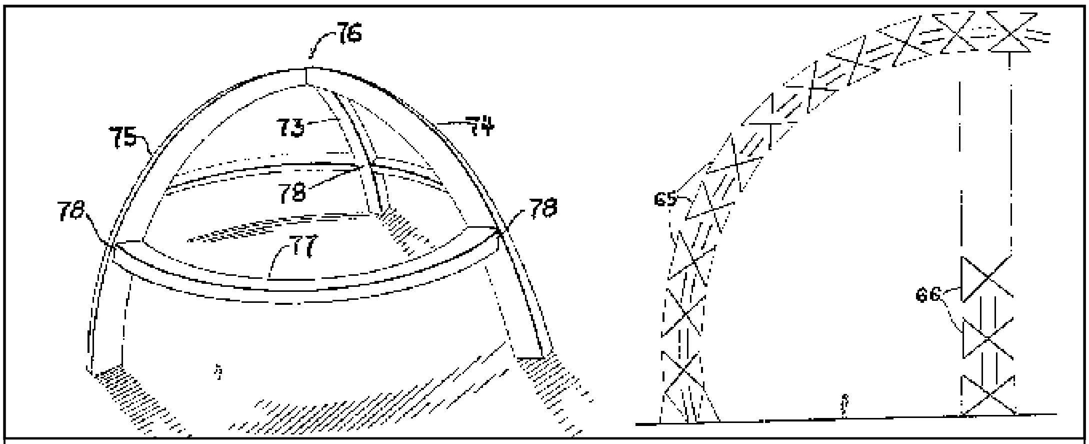


Fig. 6.2.
“**Dome projected by Snelson**” Illustration taken from Snelson (1965)

[3] Kenneth Snelson: excerpt from an e-mail to the author, 3 Aug 2004. (See Appendix D)
[4] Kenneth Snelson: excerpt from an e-mail to the author, 23 Aug 2004. (See Appendix D)

bending adequately, as is explained in fig. 6.2. Obviously, it was not very successful, as it was abandoned and never used for practical purposes.

J. Stanley Black (1972) proposed a new configuration based on tensegrity trusses fixed to a peripheral rim. The innovation cannot be considered a dome, since it is a grid with one or several layers, but it was the pioneer in the “wire wheel domes or cable domes, patented by Geiger ten years later. The subject will not be developed here as it was the main point of section 3.3.3.

Apart from his extensive list of models and configurations, **Anthony Pugh** (1976) also proposed some interesting models, one of them a relevant application. This was a geodesic tensegrity dome inspired by Fuller’s patent (1954) (cf. fig. 6.3) where the tendons had been substituted by a plastic skin that took the role of the continuous tension component (cf. fig. 6.4).

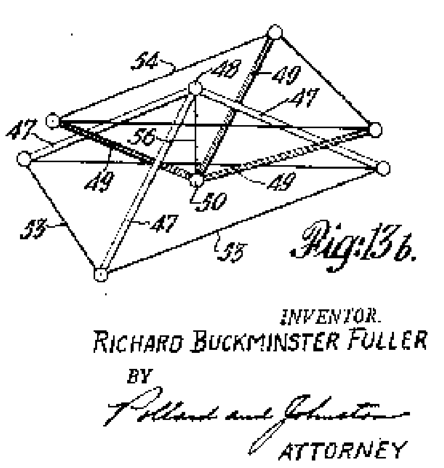


Fig. 6.3.
Detail of Fuller’s patent
Illustration taken from Fuller (1954)

In 1977, **Oren Vilnay** established a new concept, using regular planes nets (single layer) which can be employed to produce curved surfaces with small curvature and hence, large spans (Hanaor 1987; Motro 2003). However, the author considers that these systems are not as spherical as desirable, due to the extreme length of their struts, which can also induce the buckling of the bars.

Some years later, **Miodrag Nesterovic** (1987) published the project for a “Metallic Integrally Tensioned (Tensegrity) Cupola”, a double network of prestressed cables, mutually strutted by straining pieces. The structure was also very similar to the cable domes, except that it was not fixed to a rigid and prestressed concrete ring, but to two pin connections at different levels. As it was not self-stable, it is considered a “false tensegrity” like the rest of the domes.

At the same time, the first double layer tensegrity grids, referred to in the previous chapter, were propounded by **René Motro** (1987). When generating a single or double curvature from them, it is possible to obtain a space structure similar to a dome. Those first studies were further developed in the Laboratoire de Génie Civil de l’Université de Montpellier, resulting in more sophisticated bi-dimensional assemblies of cells or double layer *floating compression* cupolas. They can be perfectly judged as tensegrities, although their components in compression are in contact with each other. This was not the case for a proposal by **Ariel Hanaor**, who defined a dome made of tensegrity modules and built on a node-on-cable principle (Hanaor, 1987). In any case, the mechanical behaviour of these curved grids was not satisfactory enough.

It is important to mention **Robert W. Burkhardt**’s research on this subject. Apart from his other work cited in the Bibliography, he started to develop “A Technology for Designing Tensegrity Domes and Spheres” (1999-2004), which is constantly being revised. He considers double-layer domes, where an outer and an inner layer of cables are inter-connected by bars, as well as additional wires in order to obtain the crucial triangulation that contributes to the stability of the structures.

Finally, some other authors (Huegy, 1990; Wesley, 1996) have patented other types of tensegrity domes, which are illustrated in the Appendix C.

6.2.1.2. Calculation of the load response

In the latter study, the member force analysis had been carried out by Burkhardt taking into account the endogenous factors, due to the internal prestress of the structure itself, and the exogenous factors, due to external loads, gravity, foundations, etc. (cf. fig. 2.9 of chapter 2)

By means of a mathematical programme procedure, he first calculates the geometrical design of the structure. It can be obtained by minimizing a weighted sum of the second powers of the lengths of the members, where positive and negative weights are used for tendon and strut lengths respectively. Once the total geometry is defined, he computes the endogenous state by applying the Principle of Minimum Potential Energy. The analysis of the response to exogenous forces is achieved by adding an independent force vector to the forces present at a hub, so the new configuration is derived by solving a system of equations rather than by solving the problem as before.

In this study, the clearances in tensegrities are also considered, in other words, the distances separating the different elements of the structure. This is an important contemplation, since the interferences can change the behaviour under loads, as well as generate bending moments in the struts. Other authors (Le Saux at al. 1999; Motro, 2003; Smaili, 2003) have also thought about this point for the considerations in folding tensegrity systems.

6.2.1.3. Advantages and applications for domes

Burkhardt (1999-2004) summarises the main advantages of tensegrity domes, for instance: use of equal-length struts and simple joints, improved rigidity, extreme resilience, high lightness, etc.

The following are some of the possible applications that he points out, perhaps inspired by some of other Fuller’s ideas:

- ✓ Superstructures for embedded substructures in order to escape terrestrial confines where this is convenient (e.g. in congested or dangerous areas, urban areas, flood plains or irregular, delicate or rugged terrains).
- ✓ Economic large-scale protection for storage, archaeological, agricultural, construction, electrical or electromagnetic shielding or other delicate sites.
- ✓ Refugee or hiking shelters. Some similar proposals, following the tensile skin domes projected by Pugh (see fig 6.4), have been made by Shelter Systems (1996-2001) and Daniel Ng (2001-2004), although some of their constructions are not pure tensegrity.

Fig. 6.4.
“**Tensile skin dome**”
Illustration from Shelter Systems (1996-2001)

Fig. 6.5.
“**Snowdon Aviary**”
Illustration taken from Ford (2004)

- ✓ Frames over cities for environmental control, energy transformation and food production.
- ✓ Exclusion or containment of flying animals or other objects, similar to the Snowdon Aviary in London, by Tony Armstrong-Jones (Lord Snowdon), Cedric Price and Frank Newby (cf. fig. 6.5). The author proposes a comparable structure in the following section.

- ✓ Earthquake-resistant buildings, bridges, shelters, etc. As was mentioned by Pugh (1976) and Fuller (1975b), these structures are extremely resilient and testing would very likely show they could withstand large structural shocks like earthquakes. Thus, they would likely be desirable in areas where earthquakes are a problem. Nevertheless, Kenner (1976) pointed out the fact that both, frame and skin should have analogous flexibility, while Wang (2003) estimates very opportunely the necessity of dynamic analysis to explore the mechanical properties further.
- ✓ Following Frei Otto's conceptions, low-environmental-impact shells for musical performances, indoor/outdoor pavilions for expositions, fairs, trade shows, entrances to events, etc.
- ✓ Supports to hold sunscreen protection for vulnerable amphibians.
- ✓ Watersheds to keep rain water from percolating through contaminated soils into groundwater, perhaps temporarily during in-situ remediation.
- ✓ Micro-meteorite protection, sun-shielding for Martian colonies or spherical superstructures for space stations. In addition, some other possibilities related to lunar stations were suggested by Literati (2001), which will be dealt with in detail below.
- ✓ Some other interventions in a smaller scale, as frames for hanging plants or other objects to dry, pergola, trellis, or topiary framework.

A more unadventurous catalogue of applications can be found in Ariel Hanaor's article "Tensegrity: Theory and Application" written in 1997. The author suggests another possibility:

- ✓ Portable and foldable structures: Due to the particular characteristics of tensegrity, domes using this principle could be very useful in:

- Devastated areas (disaster relief)
- Nomadic people
- Field hospitals

In conclusion, *continuous tension-discontinuous compression* principles seem to be appropriate for application to domed structures. However, further research must be done in order to have a better understanding of their load resistance and to improve the techniques of folding, plication and transport.

Fig. 6.6.
"8v Double-Layer Tensegrity Dome"
Model built and published by Burkhardt (1999-2004)

6.2.2. Towers.

In Motro's last book (2003), the past president of the IASS, Stefan J. Medwadowski, stated:

> "Apart form the tower, until very recently the one notable field of application was the tensegrity dome, a number of which are in existence." (Preface I)

Once the potential of the domes have been related, the tower will be the subject of the following paragraphs.

Fig. 6.8.
"**Needle Tower II**" 30m height
Illustration taken from Snelson (2004)

6.2.2.1. Different proposals for towers

Without any doubt, the main contributor to the development of tensegrity towers has been the artist **Kenneth Snelson**. He had already designed a tensegrity mast the year after the tensegrity principles were discovered. This mast was shown by Fuller in his book "The Dymaxion World of Buckminster Fuller". His first proposals were described in 1960 in his patent of *Continuous tension-discontinuous compression structures* (Snelson, 1965). In those papers four different columns were designed, three of them based on X-shaped modules (cf. fig. 4.11 of chapter 4) and other one based on the "simplex" or three legged structure (cf. fig. 4.9 of chapter 4). The different arrangements are shown in fig. 6.7.

In his patent, Snelson wasn't as sure as he is at present about the unfeasibility of applying his discoveries to any field in particular. In fact, he suggested a possible function for the X-shaped tower (cf. fig. 6.7) with some function, as it is quoted:

> "The passageway formed by the crossed compression members which follows the axis N—N might, under certain circumstances (where large scale towers are constructed) serve as a central shaft for the passage of an elevator suspended by cables from the horizontal beam 57." (pp. 6, lines 58-63)

Following these drawings, he has built several masts over the past 40 years: 4-way tower (1963), Tetra Tower (1963-2001), Needle Tower (1968), E.C. Column (1969-81), Needle Tower II (1969) and Penta Tower (2001-03). They are configured as assemblies of the T-prisms that were explained in chapter 5.

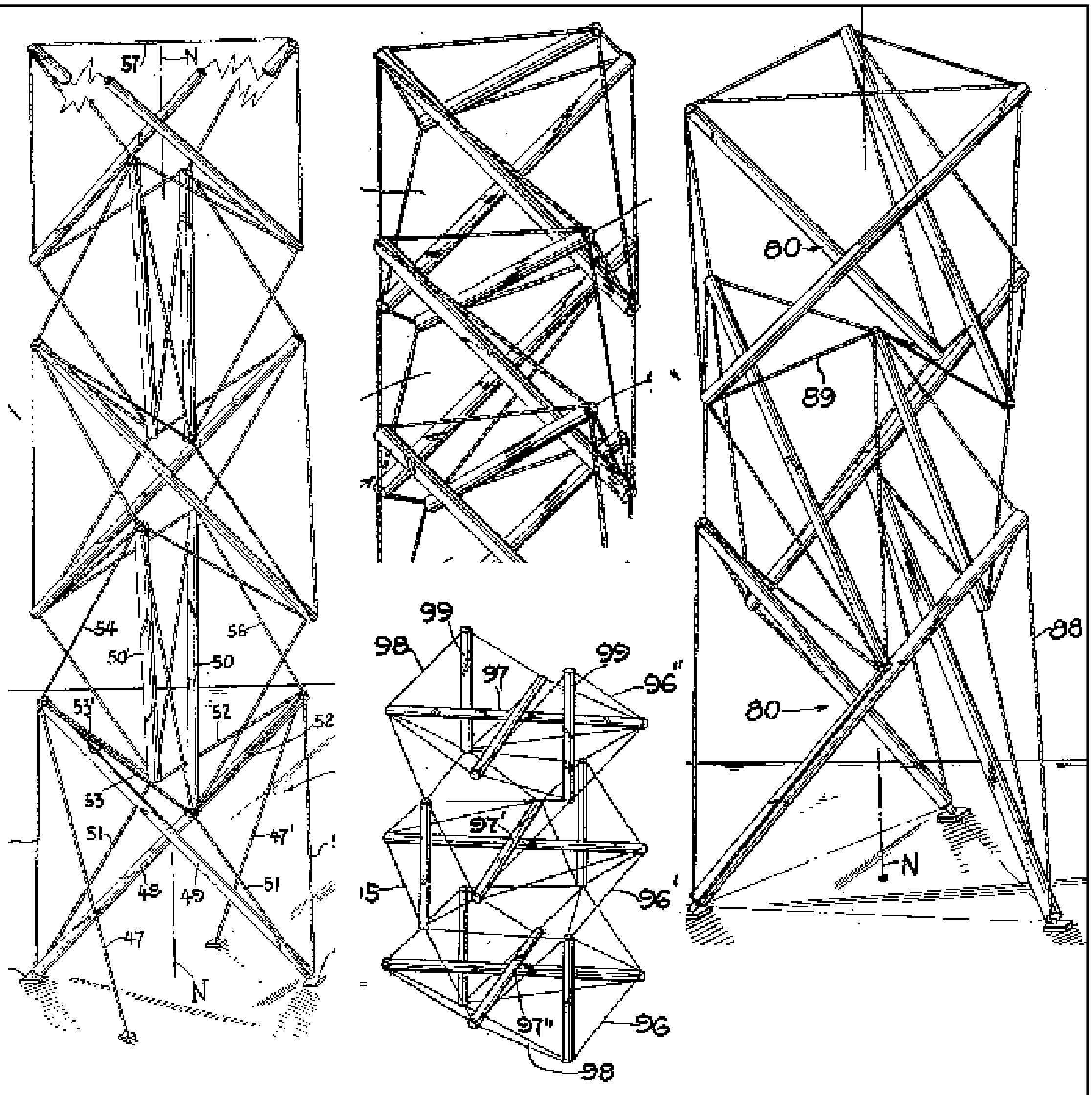


Fig. 6.7.
Continuous tension-discontinuous compression Columns, by Sneslon
Illustration taken from Snelson (1965)

It should be pointed out that Snelson proposed another possibility: he intended to build a sculpture as tall as the Eiffel Tower some day, but the obstacle was money (Whelan, 1981). Technically it would be moderately easy to construct, and one of the reasons is that these sculptures are self-scaffolding (cf. fig. 4.16).

Apart from some other masts erected by Fuller and Emmerich (cf. fig. 2.3) in the 1950s and some obelisks built by Burkhardt (2000-2004), the author has not found any more examples of “pure” tensegrity towers. In any case, the most relevant example of tensegrity towers, despite it being a "false" tensegrity is the Tower of Rostock.

6.2.2.2. Tower of Rostock.

Jörg Schlaich, one of the greatest engineers at present, stated that tensegrity has "no real practical use, only fancy sculptures; food for thought" [5]. However, his consulting firm *Schlaich Bergermann und Partner*, led by his son Mike Schlaich, has raised the highest tensegrity tower of the world (62.3 m)

The Tower of Rostock (see fig 6.9) was conceived as a symbol, landmark and visual reference of the Rostock fair and the International Garden Exposition (IGA 2003). The original idea corresponded with the architects *von Gerkan, Marg und Partner,* but it was really designed, defined and analysed by Mike Schlaich and his group in Stuttgart, as was admitted by him in an e-mail to the author (see Appendix D, personal correspondence). Since this construction did not have to support any external load, apart from self-weight and wind, it was decided to use the *floating compression* principle.

According to M. Schlaich (2003), the tower consists of six "simplex" or twist modules (8.3 m height each), made of three steel tubes (Ø=273 mm, t=12 to 40 mm) and six high-strength steel cables, three of them horizontal (Ø=30 and 50 mm) and three other thicker diagonal wires (Ø=50 and 75 mm) (cf. fig. 6.9). Each of these twist modules are disposed in a similar way to that of the "Needle Tower" (alternating right-handed and left-handed "simplex"), but the difference is that they are rotated 30 degrees, so the bars of one level enter in contact with the bars of adjacent levels.

[5] Personal correspondence, excerpt from letter received the 4th July 2004.

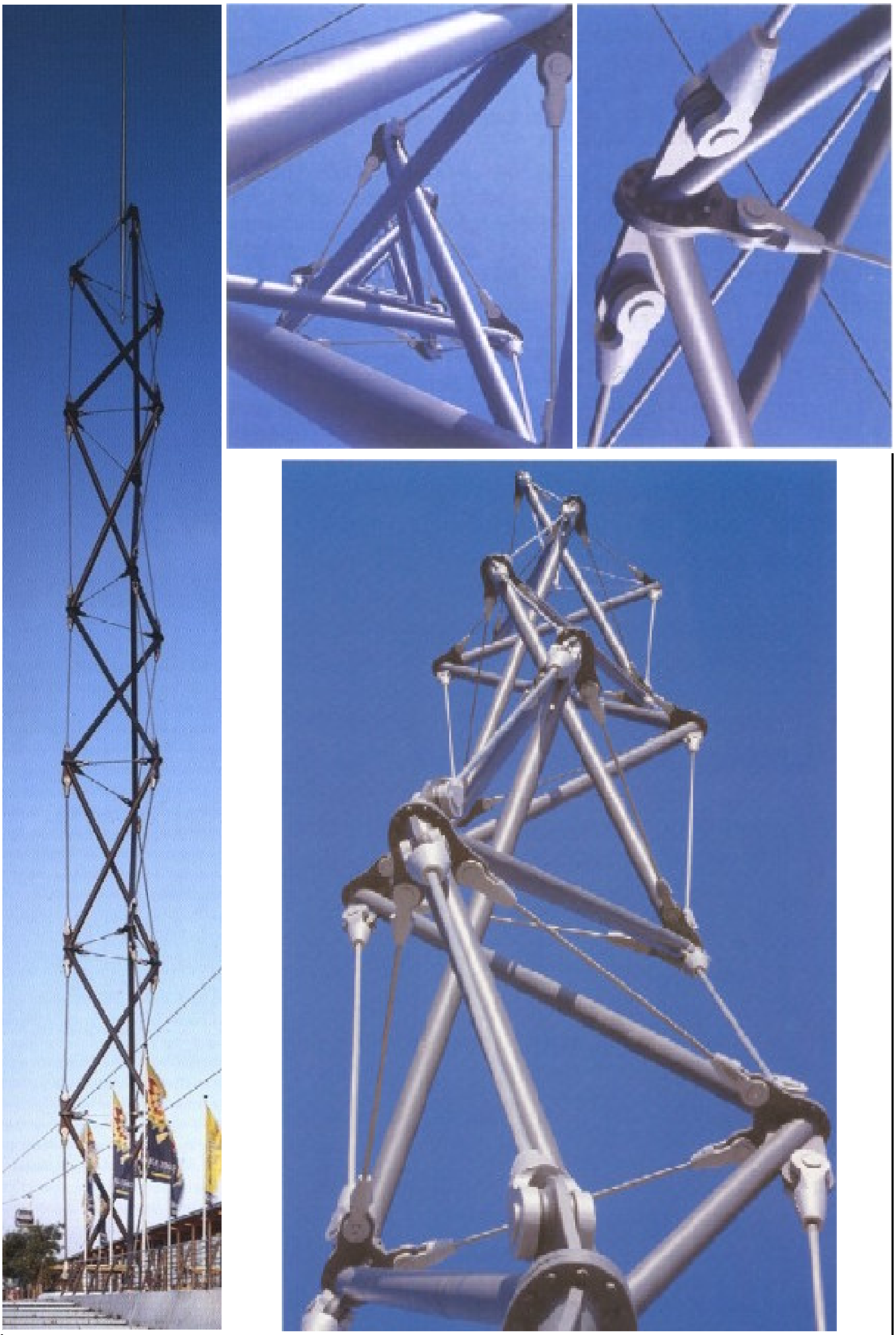


Fig. 6.9.
"**Tensegrity Tower of Rostock**"
Illustrations taken from M. Schlaich (2003) and Ruiz de Villa (personal correspondence)

From a very strict point of view, this factor would be enough to consider the structure as “false” tensegrity. Nevertheless, as was discussed in chapter 5, Motro would estimate that the Tower of Rostock comprises of a continuous net of wires and three compressed components, each of them made of a chain of six struts. Since the three components in compression do not touch each other, the system would be identified as a “true” tensegrity. It would be a tensegrity ‘class 2’, because at most two compressive members are connected to any node.

The structure was calculated by **Arturo Ruiz de Villa** [6], employing “Sofistik”, a computer program that served to accomplish the geometric non-linear analysis. This aspect was important because of the highly pretensioned state of the structure, thus it was necessary to use third order the theory for large deformations. Some other details were analysed using a 3D finite element model, as at the joints, anchorage and upper needle (a stainless steel needle placed on top of the tower).

This type of structure is only under the action of the wind and its self-prestress. In fact, the wind determinates the degree of pre-tensioning, because the tower is so light that its own weight can be neglected. Thus, the dynamic analysis started studying the vibrations of the structure and, from them, an aerodynamic study was developed in order to discern the influence of the wind. Finally, the pre-tensioning was decided to be 1100 kN for the diagonal cables (30% of the tensile strength of the cables). If this value is smaller, the bars have to support a bigger tension as they are rigidly connected, and there is more deformation. In contrast, if high pre-tensioning arises, there is less deflection and less movement in the tower, while the total security against break-up is the same, as proved in Schlaich’s article.

[6] Personal correspondence, e-mail to the author, 25 August 2004 (See Appendix D)

With 1100 kN on these cables, the maximum displacement on the top of the tower is 850 mm (1200 mm on the top of the needle).

The tower is fixed to a pile cap in concrete (Ø=8m, h=2m) that provides the weight necessary to prevent the tower from ‘blowing in the air’, due to its lightness. At the same time, it is anchored to the ground by means of 6 drilled piles of Ø=500 mm.

The initial budget, and final price, for its construction was around 500.000 € (£ 330.000), which in Schlaich’s opinion is quite an expensive amount due to the absence of application of the tower.

The responsible engineer of the Tower of Rostock called attention to some conclusions:

1. It is possible to construct large-scale tensegrity structures of this kind.
2. Computer software is available, which describes the structural design and analyses these structures.
3. It is not a problem for contractors to fabricate and erect *floating compression* structures with the required precision.
4. The expensive cost of additional design and production labours can be compensated by savings in material and weight.
5. The potential of tensegrity for roof structures is considerable. In this field many practical, light and graceful structures can still be produced. (Schlaich, 2004)

6.2.2.3. Some other applications for tensegrity towers

After considering the conclusions derived from the construction of the tower in Rostock, the author dares to add to the list some other fields where tensegrity towers or columns could be useful:

Lightning conductors: As it is not required to have these elements in a completely static situation, and they tolerate certain small movements, they could serve perfectly for this application.

Communications: In situations where the margin of displacements is not very strict, tensegrity towers can be employed to support antennas, receptors, radio-transmitters, mobile telephone transmitters, etc.

Wind parks: Even if it seems unfeasible, there should be some study to analyse the effects of turbines installed on the top of a single or a group of tensegrity towers. The lightness of these structures could minimize the visual impact of these energetic installations.

Aesthetic elements: In general, a study should be carried out in relation to any vertical structure that can damage the visual landscape of an area.

For instance, as was mentioned in chapter 4, Skelton and Sultan have been exploring the use of tensegrity structures as sensors and actuators due their kinematic indeterminacy (Tibert, 2002).

6.2.3. Roof structures.

First of all, it is necessary to say that there are not any roof structures based on the principles of *continuous tension-discontinuous compression*, or at least the author has not found any significant examples.

The author has come across only two references related to tensegrity roof structures. The first one was the “tensegrity structures to atrium roofs” for the Reuters HQ in London, by the architects *Sidell Gibson Partnership* and *Buro Happold* Engineers, but it was never built. The second one was the new Stadium in

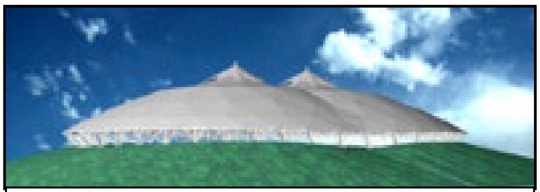


Fig. 6.10.
"**La Plata Stadium**"
Illustration from Weidlinger Associates (2002)

La Plata (Argentina), based on a prize-winning concept developed by architect Roberto Ferreira. The design adapts the patented *Tenstar* tensegrity roof concept to the twin peak contour and the plan configuration, and consequently, it is more similar to a cable-dome structure than to a conventional roof structure. It is worthwhile to remark that the structural engineers are *Weidlinger Associates*, who also worked on the analysis of some Snelson's sculptures and of the "Georgia Dome" in Atlanta.

The first studies for the design of tensegrity grids were carried out by Snelson (cf. fig. 4.2), but he did not find applications other than his own sculptures. As one can anticipate, some other experts are working at present in this field. For instance, **Ariel Hanaor** (1987) started researching the double layer planar configurations in the 1980s, proposing different systems for assembling tensegrity prisms (detailed in chapter 5). The result was an interesting debate about the load bearing capacity of these grids.

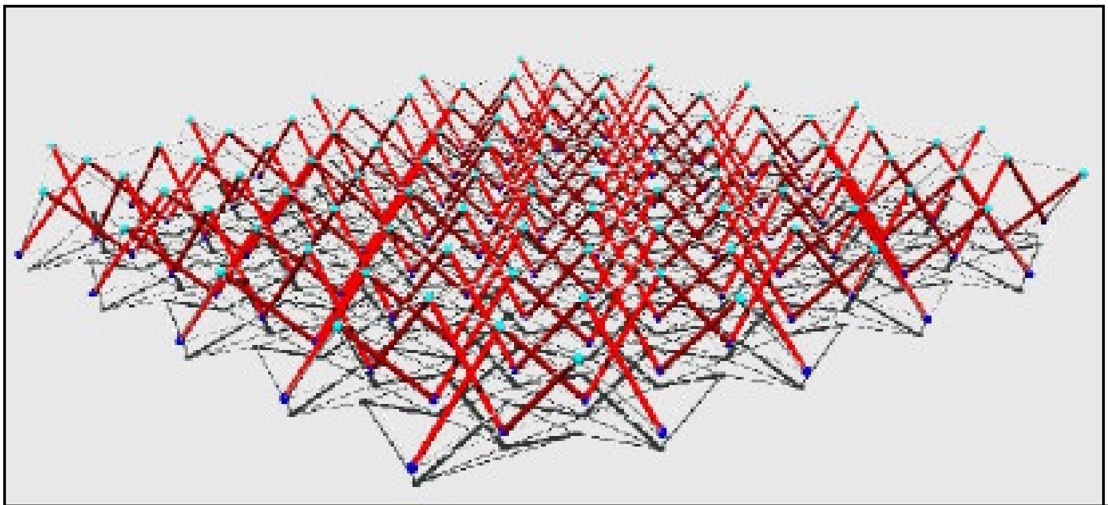


Fig. 6.11.
"**Double-layer grid**" by the Laboratoire de Mécanique et Génie Civil in Montpellier
Illustration drawn by the author

Maybe the most outstanding research is by **René Motro** and the **Laboratoire de Génie Civil in Montpellier**. For the past few years, their main projects have been focused in the development of double-layer tensegrity grids (cf. figs. 6.11 & 5.8) and foldable tensegrity systems. As already explained in chapter 5, this kind of grid has its most feasible possibilities in the field of walls, roofs and covering structures.

Finally, Tibert (2002) reports that Skelton, Helton, Adhikari, Pinaud and Chan analysed planar tensegrity structures and concluded that they can be perfectly efficient in bending.

Fig. 6.12.
Tensegrity Arches
Illustration taken from Burkhardt (1999-2004) and Snelson (2004)

6.2.4. Arches

As for roofs, until now no applications of arches have been brought into being. Nevertheless, it is true to say that some of these elements using *continuous tension-discontinuous compression* principles have been constructed and erected. Some examples are given in fig.6.12, showing arches respectively based on “simplex” by Maxim Schrogin (a), X-modules by Robert Burkhardt (b) and “simplex” again by Snelson (c).

It might be interesting to note that, presently, there is a research project carried out in the Tor Vergatà University (Rome), in collaboration with Italian and French institutions, to build a tensegrity arch in order to estimate the effective actions of the wind. It is projected to span a distance a 50 m by assembling expanded octahedrons (Motro, 2003).

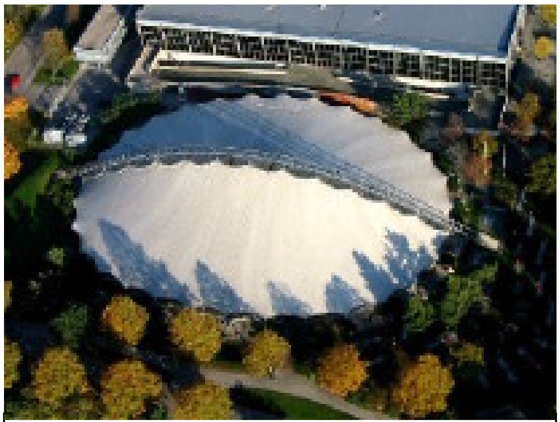


Fig. 6.13.
Ice Rink Roof in Munich, by Schlaich
Illustration taken from Janberg (1998-2004)

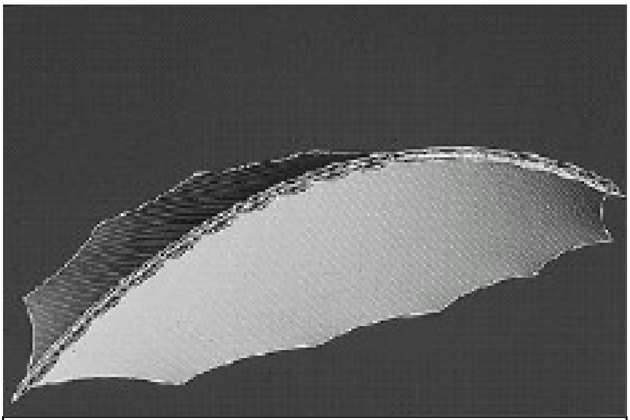


Fig. 6.14.
Tensegrity Arch supporting membrane.
Illustration taken from Adriaenssens and Barnes (2001)

Finally, the research achieved by Adriaenssens and Barnes (2001), is quite remarkable. They have been investigating the use of tensegrity arches and spline beams to support large-span membranes. In some way, it is correlated with Frei Otto’s projects in the Kuwait Sports Centre or the Schlaich’s Ice Rink Roof in Munich (fig. 3.13). However, in this case the properties of the *floating compression* arch are very suitable to accommodate the asymmetric loads and avoid the stress concentrations in the tensile structure, due to the torsional freedom of the arch that equilibrate the stresses (fig. 6.14)

6.2.5. Tent-like structures

This section is dedicated to tent-like structures and shadow roofs, which show typical examples of false tensegrity. In this case, there are compressed components in the boundary and the strut-strut contact or similar contemplations, but there is also an absence of self-stability and pre-stress in the structure.

Fig. 6.15.
"**Shade Structure**"
Illustration taken from Daniel Ng (2001-2004)

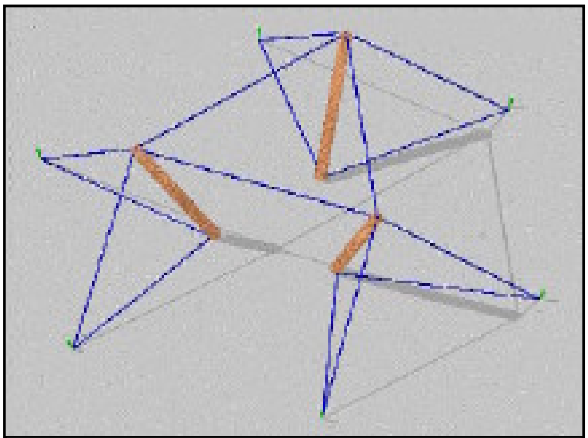


Fig. 6.16.
"**Shade Structure**" Basic structure
Illustration drawn by the author

Figure 6.15 shows an example of a so-called Tensegrity Shade Structures, created and presented by Daniel Ng (2001-2004). The same system has also been represented in fig. 6.16 in order to show a clearer perspective without the tensile membrane that covers the inner space. It can be noted that the system has no self-equilibrium stability since it needs to be anchored to the ground in three points and the struts are not stable if they are not *resting* on the ground. Moreover, the absence of prestress is definitive to deny the denomination of tensegrity to this shadow roof.

Another case produced in Edinburgh (fig.6.17) is very different to the previous one in terms of stability; if the other tent is not stable, this marquee is perfectly tensed and conformed without the action of the cables, which play a role in giving more rigidity to the system. Besides, each module is attached to the ground by means of a fixed basement, not necessary in true tensegrities.

Fig. 6.17.
Tent-like Marquee, shopping centre in Edinburgh. Picture taken by the author (2004)

Nevertheless, the author would like to emphasize that *floating compression* could be applied to tent-like structures, so useful and interesting in expositions, exhibitions, etc., as will be proposed in following paragraphs.

6.2.6. Outer Space structures

Since the beginning of the "tensegrity era", one of the most recurring applications found for the *floating-compression* has been its use in moon-colonies. In 1961, Buckminster Fuller revealed his new inventions: potential prototypes of satellite and moon-structures conceived as tensional integrity, foldable, extremely light, omni-triangulated, prestressed, etc. (cf. fig. 6.18). Basically, "spherical nets in which local islands of compression act only as local sprit-stiffeners" (Fuller, 1961). It is not very surprising to arrive at these conclusions, since one of the particular characteristics of tensegrity structures is that they don't depend on gravity, so they are stable in any position.

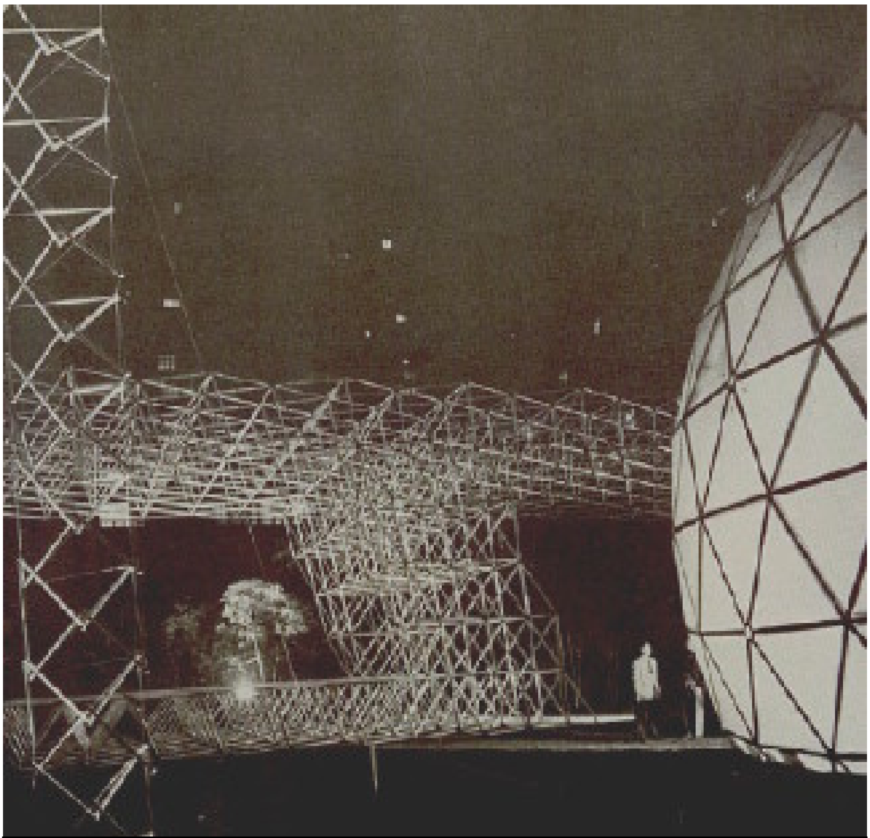


Fig. 6.18.
"**Lunar applications**" Fuller exhibition, Modern Museum, N.Y.
Three of his basic structures: Tensegrity mast, Geodesic dome, Octet truss.
Illustration taken from Fuller (1961)

Since then, many proposals along the same lines have been given by different people, but not without avoiding the task of evaluating the consequences of their propositions in-depth.

Maybe the exception is the research of Tibert and Pellegrino. The former has been studying deployable tensegrity structures for Space applications, mainly foldable reflector antennas[7] and masts (2002) and the latter has dealt with large retractable appendages in spacecraft (1995).

Recently, a very defined project has been carried out from another approach (Literati, 2001). In this case, tensile integrity structures were not the starting point, but a resource to achieve another objective: the establishment of a self-sustainable society in the moon. *Floating compression* options are included in a long list of suggestions, e.g. the utilisation of lunar regolith to produce concrete, the technology needed to obtain a source of energy, etc. This project sought the improvement of new structural concepts that experience completely different external loads (1/6 of Earth's gravity, meteorite impacts, moonquakes, etc.), different risks (like pressure containment, radiation, etc) and different environmental conditions (atmosphere, light, wind, dehydration, etc).

It could be claimed that in this case we are not dealing with conventional architecture. There is no doubt about it. However, in any case, it is still architecture, it is lunar architecture and some day it will be necessary to face circumstances of this kind.

6.2.7. Different applications besides Architecture

As a curiosity and illustration of interesting initiatives, this section is dedicated to show some other functions that have been found with *continuous tension-discontinuous compression*.

[7] See also "Deployable Antenna" patented by Knight et al. (2002) and "Deployable Reflector Antenna" by Ian Stern (2003). (Appendix C).

6.2.7.1. Furniture

Chairs, tables, lamps, ornaments are some examples of attractive applications (fig. 6.19). For more models, see the patents of Wiesner (1973), Miller (1977) and Barber (2003a, 2003b, 2003c & 2004) in Appendix C.

Fig. 6.19.
Tensegrity Furniture Illustrations taken from Koennig (2004) and Werta (2003)

6.2.7.2. Puzzles, toys and leisure.

In Appendix C it is possible to see the characteristics of these patents by Kittner and Quimby (1988) and Mogilner (1972). There are other exemplars like the

"Skwish Classic", but it might be interesting to remark that the "Tensegritoy" has been developed from the first patent. This is the instrument that the author has been using for the configuration of the simplest models as it is very useful for spherical tensegrity polyhedra.

6.2.7.3. Sculptures

In addition to Kenneth Snelson's sculptures, even Buckminster Fuller dedicated some of his efforts to this field of art. As a result of such a fascinating facet, he created the 60-strut stainless steel and wire sphere, installed hanging from the roof of the Engineering Centers Building atrium, University of Wisconsin-Madison (fig. 6.20).

Fig. 6.20.
"**Sixty Strut Tensegrity Sphere**" by Fuller
Illustration taken from BRUW System (2002)

6.2.7.4. Submarines.

UCSD Flow Control Lab (2004) is currently studying how to optimize the compliance properties of a compliant tensegrity fabric in order to reduce the skin-friction drag induced by a turbulent flow. Such a surface could move in response to the pressure and skin-friction fluctuations of an overlying wall-bounded turbulent flow, and could be applied to the external surface of the submarines.

6.3. Personal proposals

In the following sections some potential applications will be explained, while the respective drawings, plans and images will be presented in Appendix H. It should be noted that the designs are ideas that might be developed further, rather than detailed drawings proposed for a real project. Therefore, they do not achieve the requirements of professional projects since they are not necessary at this stage.

6.3.1. Tensegrity dome from the Truncated Icosahedron

The original idea was to take advantage of one of the configurations shown in Appendix G (tensegrity models, figs. G.14, G.15 & G.16), where a Tensegrity Truncated Icosahedron is truncated again to conform to a dome (3/4 of a sphere).

As is mentioned by Snelson, this system is not triangulated, so it is not as stable as desirable. Therefore, some additional cables, shown in the plans (cf. Sheet 1), have been incorporated in order to give more rigidity and minimize the typical deflections of *floating compression* structures.

In the design, a small dome is proposed to contain an atypical architectural space, dedicated to versatile uses such as an exposition centre, art pavilion, offices, etc. Three floors are considered, taking advantage of the vertices of the polyhedra. In fact, these floors have also the purpose of making the structure firmer by connecting the apex located in the same horizontal plane.

In the drawings (Sheet 1 of Appendix H), nothing is defined in more detail because the main purpose is to show feasible applications rather than developments in depth. The dimensions are also relative, but the diameter could be approximately 20 meters.

In the 'render' images (cf. Appendix H. 1 & H.2), the skin of the dome has been set up as transparent, but the reason for that is just to make the inner distribution of the space clearer.

6.3.2. Lightning rod from the Helix Tower

Taking the "simplex" as a basis, a new configuration for a tower is proposed in Sheets 2 & 3, which is called the Helix Tower. It was created by adding one of these "simplex" modules over another module and rotating it 30º until the end of one strut enters in contact with the end of other one at the lower level. If this step is repeated, a helicoidal tower is obtained. Following this process, but adding smaller modules each time, the result is a pyramidal Helix Tower that will be employed for the lightning rod (fig. H.3 & H.4).

On the top of the mast, there is a needle whose function is to receive the lightning in case of a discharge in the surroundings (cf. fig. H.5). The conduction of the lightning is through a cable, covered with insulating material, inserted into the struts until it arrives at ground level. If the conductor was installed vertically along the axis of the tower, it could be dangerously exposed and would disturb the elegant figure of the tower.

A study for the Lightning rod is shown in Appendix G (figs. G.10-G.13).

6.3.3. Roofing for Stadiums by assembly of modules

This is maybe the most ambitious proposal. When working with the models, the author was trying to define the shape of a system that would be able to support a certain asymmetric hypothesis of external loads. He accidentally discovered a tensegrity figure made with six struts and 20 cables (cf. fig. G.5). The model was peculiar because of its capacity to be folded and unfolded (cf. figs. G.6 & G.7). In sheets 4, 5 and 6 it is possible to see the different steps of folding, and also the lengths and the relative member prestress force magnitudes. The latter are relative values to be scaled up or down (everything multiplied by a single positive constant) depending on how much the structure is to be prestressed.

Taking this consideration into account, a new system was conceived, based on these modules as part of the roofing of stadiums in general. Due to their adaptability, they would be optimum for covering the stands of stadiums with different shapes: circular, elliptical, square, etc. Some examples are provided (Sheets 7 & 8, figs. H6, H7 & H8). The fact that they are foldable could facilitate their pre-construction and assembly, in order to transport them to the site, where they could be unfolded and prestressed. Once they are located in their place, additional cables and cladding would be necessary to give more rigidity and protection.

Even though every module is self-stable and could rise on its own over the stands, the possibility of adding a cable attached to a marquee or balcony has been considered, in order to balance the weight of the cantilevered roof (see graphics). In the mentioned examples, only the option of the marquee has been contemplated.

6.3.4. Pyramidal roof from assembly of Truncated Tetrahedra

After some experiments with models in space (cf. figs. G.7, G.8 & G.9), the author achieved a conglomeration of tensegrities by assembling several tensegrity tetrahedra based on the faces defined by their truncated vertices (cf. Sheet 9). When joining the Truncated Tetrahedra (cf. fig. G.1) in this way, a pyramidal configuration is achieved, which could easily cover triangular areas.

In order to show a comprehensible example of this application, some images (cf. fig. H.9 & H.10) have been included. The transparency of the cladding is intended to give a clearer and more aesthetic perspective of the assembly.

6.3.3. Footbridge from assembly of “Simplex” modules

This last example is conceived as a small footbridge in an urban context, for instance, linking two buildings or spanning narrow rail lanes or roads. It is the result of assembling several “simplex” along their main axis (cf. Sheet 10). Even though the new structure is self-stable, additional cables would be necessary to give more rigidity and to permit larger spans.

The main structure of the footbridge could be easily installed by means of a crane, because of its lightness. Moreover, it could be supported in just four points (cf. H.11), although it could also be considered for other possibilities. Figure H.14 shows an additional cable-stayed structure to support this footbridge for longer spans.

Other figures of Appendix H (H.12 & H.13) show the final configuration of the structure and other installations (deck, railing, lights...). Transparent elements have been chose in order to achieve understandable perspectives.

6.3.5. Other suggestions to develop

In this chapter, some possibilities have been suggested, but obviously they might be investigated in more detail: moon stations, communication towers, wind parks, etc. The author also suggests studying the feasibility of marquees for entrances, marquees to cover parking places, structures for seismic areas, etc.

It might be interesting to project a tensegrity structure conceived as an exclusion or containment of flying animals or other species. The idea came after seeing the Snowdon Aviary in London, by Tony Armstrong-Jones (Lord Snowdon), Cedric Price and Frank Newby. The author would like to point out the possibility of generating a similar structure using large bars as isolated components in compression with the tensile surface working as the prestressed component. For instance, it could be considered the shape of a Truncated Octahedron (cf. fig. G.2). The latter might be conceived as a transparent membrane skin or, perhaps more suitably in terms of conservation, as a cable net with dense grid. The main advantage would be that, due to the lightweight and self-stability of the structure, it would not need to be anchored at all and, thus, could be transported easily without the inconvenience of changing the animals from their habitat.

Some other applications could depend on the evolution of the investigations on foldable tensegrity structures. As a result, they could be used for disaster relief in areas devastated by earthquakes, hurricanes, floods and so on, by installing deployable systems in the form of temporal dwellings, bridges, field hospitals, etc. However, like any other proposal mentioned in this work, a further research must be carried out to develop these potential applications.

Chapter 7

Questionnaires and Interviews

Chapter 7. Questionnaires and Interviews

During the preparation and planning of the present work, it was decided to carry out both qualitative and quantitative research techniques in order to understand some important points related to the topic in question. The characteristics and results of the studies will be listed in the following paragraphs, although the preliminary interviews with some professors will not be included as they served only as a help to focus the dissertation.

7.1. Questionnaires

Three kinds of questionnaires have been organised and prepared, however, only two of which have been utilised.

7.1.1. Questionnaires to professionals:

The first aim of this study was to discover if the knowledge of tensegrity structures, and their basic principles, are widespread among architects and engineers. The second aim was to gather more information about tensegrity from those professionals that had any knowledge of it.

Therefore, a general and basic questionnaire, which is attached in Appendix F, was prepared and sent by email to professionals of both subjects, architecture and engineering, to various places in Europe. As the author anticipated a low rate of response, it was decided to send them to the departments of structures in the three universities where he carried out his studies: Universidad de Cantabria (Spain), Université de Liège (Belgium) and Queen’s University Belfast (Northern

Ireland). In addition, due to other circumstances, it was also sent to the Universidad Politécnica de Madrid, Universidad Politécnica de Cataluña, Universidad Politécnica de Valencia (Spain) and University of Bath (UK).

In effect, the rate of response was very low; the questionnaire was sent to 139 e-mail addresses and only 21 answered (15% aprox.). Even though it was remarked in the cover letter of the questionnaire that no knowledge of tensegrity was needed in order to answer it, the author considers that this low number of replies could be due to the unawareness of the subject.

The results are clear enough: only 10 of 21 had heard about tensegrity before. Some of them did not have a clear concept but a vague idea, or even recognized that they did not know that much about it. Taking into account that they are specialists in structural subjects, it is easy to deduce that it is not a commonly known type of structure and not very well known among architects and engineers.

It should be emphasized that some of these questionnaires, (included in the 10 positive answers) were addressed to experts that have been dealing with tensegrity structures. In this case, the result was to obtain more information about tensegrity rather than studying the number of professionals aware of *floating compression* principles. Some of these experts were Chris J K Williams (University of Bath), Celso Iglesias and Avelino Samartín (Universidad Politécnica de Madrid)

7.1.2. Questionnaires to specialists:

A similar survey was carried out, but this time with some changes since they were addressed to experts that have been working with tensegrity structures. In this instance, the questions were very similar but, obviously, the answers expected from them were to be more concise. Some of these questionnaires were sent to

Schlaich Bergermann und Partner, because of their participation in the Tower of Rostock; to *Arenas y Asociados*, for the same reason; and finally to *Buro Happold* and *Sidell Gibson Partnership*, for a common project in Blackwall Yard (London) which had a tensegrity roof. The information obtained from their replies is included in the text.

The author is proud to report that this questionnaire has been filled and returned by two of the most important engineers of the world at present: Javier Manterola Armisén and Jörg Schlaich. Their collaboration has been very useful and doctrinal, and at the same time a privilege and an honour.

7.1.3. Questionnaires to the general public

It is obvious that this type of structure is tantalizing, since it is not very instinctive in the way it works and how the struts can be "floating" in the middle of a group of cables. Therefore, the author had the idea of confirming the impression of excitement that people have when seeing a tensegrity structure. An informal survey was carried out in order to discover the most predominant opinions, but it was abandoned not much later because the unique opinion was generalized. Every single person that saw any of the models thought that it was "really amazing", "gorgeous", "stunning", using these or similar expressions. Therefore, it was not worthwhile to gather all these opinions when the point of view was basically the same.

7.2. Interviews

Once the major work of research was completed and after gathering a large amount of information from diverse sources, the author looked for a new phase in the process of completing the data already obtained.

The interviews were established by means of several and continuous e-mails with the experts in question, due to their geographic inaccessibility. The most important results are reflected along the main discourse and collected in the Appendix D of Personal Correspondence, where only the answers of the specialists are shown because the questions can be easily inferred from them.

There is principally contact with four different people: **Kenneth Snelson**, the sculptor who discovered the tensegrity fundaments in 1948 and who kindly shared his knowledge with the author; **Mike Schlaich**, Civil Engineer responsible of the design of the Rostock Tower; **Arturo Ruiz de Villa**, Civil Engineer responsible of the calculation of the same tower; and finally, **Robert W. Burkhardt**, the author of the publication “A practical guide to tensegrity design”, who has been collaborating in the calculations of some of the models proposed by the author.

It might be interesting to note that another interview was sent to **René Motro** to Montpellier (France), but unfortunately he failed to reply, which seems to be something usual for this outstanding researcher.

In any case, all of these personal correspondences have been really fruitful and profitable, and it is not an exaggeration to recognize that the author did not expect such an important source of knowledge.

Chapter 8

Discussion and conclusions

Chapter 8. Discussion and conclusions

This concludes the main body of research and design work developed during the last months. Personally it is considered that the objectives programmed at the beginning have been achieved.

8.1. Discussion and conclusions

Throughout the research work, the author has come across a large number of references about tensegrity, and other structures, in Nature. It seems like the *floating compression* is present in every single atom of our Universe, which recalls some of the quotations of the first pages. Moreover, natural principles are not only a constitutive of biotensegrity, or vice versa, but also of some other examples in the history of Architecture.

Antoni Gaudí, Santiago Calatrava and Frei Otto are only some of these cases. Take, for instance, the studies developed by the latter: he used the structural fundaments of soap films, spider webs, vertebral spines, oil drops, etc. to achieve an improvement in his designs. He invoked biological functionalism to support the concept that lightweight is a real measure of structural effectiveness (Drew, 1976).

The author realized that, to date, some scientific methods followed the sequence: researching ? developing systems/theories ? finding them in Nature. Tensegrity is not an exception. The experience of the architects mentioned above shows that maybe it is more logical to follow this other sequence: researching in Nature ? finding systems/theories ? developing them in other fields.

In his manifesto of futurist architecture, written in 1914, Antonio Sant'Elia (cited in Drew, 1976) predicted a new architecture with new qualities: revolutionary, elastic, light, expandable, active, mobile and dynamic. Thus, he identified the most important features of tensegrity structures. Needless to say few things can be achieved without more investigation, but tensegrity could be one of the structural systems of the future.

From the author's point of view, an important step was reached by finding several examples of tensegrity prototypes that could be applied to Architecture and Engineering. His own proposals could serve as an illustration to the feasibility of tensegrity as a lightweight structure to cover large spans, bridge shorter distances or support light infrastructures. Of course, a much more detailed structural investigation would be necessary, but at least the presupposed idea of tensegrity as an inapplicable system has been disproved.

8.2. Further research

In chapter 6, some possibilities have been briefly pointed out, but obviously they could be investigated in more detail: moon stations, communication towers, wind parks, marquees for entrances, marquees to cover parking places, structures for seismic areas, etc.

Some other applications could depend on the evolution of the investigations on foldable tensegrity structures. As a result, they could be used for disaster relief in areas devastated by earthquakes, hurricanes, floods and so on, by installing deployable systems in the form of temporal dwellings, bridges, field hospitals, etc. However, as for other proposals mentioned in this work, further research must be carried out to develop these potential applications.

Appendices

Appendix A. Motro's correspondence from Snelson

From Kenneth Snelson to R. Motro, published in November 1990, *International Journal of Space Structures,* in Motro (2003) and in http://www.grunch.net/snelson/rmoto.html

R. Motro International Journal of Space Structures
Space Structures Research Centre
Department of Civil Engineering
University of Surrey, Guildford
Surrey GU2 5XH

Dear Mr. Motro:

I regret it has taken me so long to respond to your letter about the special issue of Space Structure dedicated to tensegrity.

As you probably know, I am not an engineer but an artist so I don't really feel qualified to write for an engineering journal. Nonetheless I know something about this particular form of structure from making so many sculptures over the years which use the principle which I prefer to call floating compression.

I have long been troubled that most people who have heard of "tensegrity" have been led to believe that the structure was a Bucky Fuller invention, which it was not. Of course, we are now in the year 1990 and not 1948 so all of this fades into the dim footnotes of history. There is a line somewhere in a theater piece which goes, "But that was long ago in another land -- and besides, the wench is dead."

Whenever an inventor defends his authorship the issue invariably turns out to be important only to the author himself, to others it is trivia. Maybe you're acquainted with the tale of Buckminster Fuller and me, but I'd like, somehow, to set the record straight, especially because Mr. Fuller, during his long and impressive career, was strong on publicity and, for his own purposes, successfully led the public to believe tensegrity was his discovery. He spoke and wrote about it in such a way as to confuse the issue even though he never, in so many words, claimed to have been its inventor. He talked about it publicly as "my tensegrity" as he also spoke of "my octet truss". But since he rarely accredited anyone else for anything, none of this is all that surprising. What Bucky did, however, was to coin the word tensegrity as he did octet truss and geodesic dome, dymaxion, etc., a powerful strategy for appropriating an idea. If it's his name, isn't it his idea?

As many new ideas do, the "tensegrity" discovery resulted in a way from play; in this case, play aimed at making mobile sculptures. A second-year art student at the University of Oregon in 1948, I took a summer off to attend a session in North Carolina at Black Mountain College because I had been excited by what I had read about the Bauhaus. The attraction at Black Mountain was the Bauhaus master himself, the painter Josef Albers who had taught at the German school and immigrated to the U.S. in 1933 to join the faculty of that tiny liberal arts college (fifty students that summer) in the Blue Mountains of North Carolina, fifteen miles from Asheville.

Buckminster Fuller, unknown to most of us in those early days, turned up two weeks into the session, a substitute for a professor of architecture who cancelled a week before the summer began. Josef Albers asked me to assist the new faculty member in assembling his assortment of geometric models for his evening lecture to the college. There was no such thing as a tensegrity or discontinuous compression structure in his collection, only an early, great circle, version of his geodesic dome. Albers picked me to help because I had shown special ability in his three-dimensional design class.

During his lecture that evening Professor Fuller mesmerized us all with his ranging futurist ideas. As the summer quickly went by with most of the small school monitoring Fuller's classes I began to think I should try something three-dimensional rather than painting. Albers counselled me that I demonstrated talent for sculpture. But, more importantly, I had already become the first in a trail of students from colleges and universities who, over the years, were to become electrified "Fullerites". He had that cult-master's kind of charisma. I blush for it now, but it was true. We were young and looking for great issues and he claimed to encompass them all.

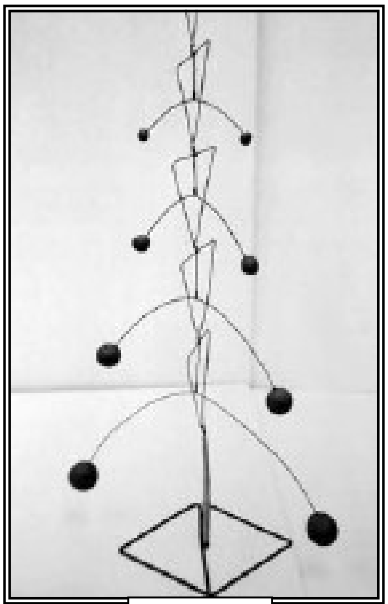


Photo #1

At the end of the summer session, I returned home to Pendleton, Oregon. In my Fullerian trance the descent into the real world was greatly confusing. I spent the autumn at home, making my parents miserable by moping and spending hours in the basement, building things; small mobile sculptures mostly, using thread, wire, clay, metal from tin cans, cardboard, etc. I had learned much about geometry from Fuller as well as art and design from the Bauhaus. While Albers' teachings were imparted as useable ideas in public-domain, Bucky's lessons were laden somehow with the sense that the ideas were proprietary -- "his" geometry. I believed, literally, because he claimed so, that before Buckminster Fuller came along, no human had ever noticed, for example, that to inscribe the diagonals of the square faces of a cube was to define two interlocking tetrahedra within. Students joked that, after all, hadn't Bucky invented the triangle? None of us knew, for example, of Alexander Graham Bell's early space frames, nor anything at all about crystallography.

In the autumn of 1948, as I said, I made numbers of small studies. Were they structures or sculptures? They incorporated the attitudes of both Fuller and Albers. The three small works which are of interest here were concerned both with balance of successive modular elements hinged one-to-another and stacked vertically as seen in photo #1; and, later, suspended one-to-the-next by means of thread-slings as shown in photograph #2. They were, of course, but amplifications of the familiar balancing toys seen often in novelty shops. My small discoveries in these two pieces were logical enough, though one could imagine that they might just as well lead to something other than to the first tensegrity structure; perhaps to variations on Calder mobiles.

It was the effort to make the pieces move which resulted in their spinal-column, modular, property. If I pushed on them lightly or blew on them, they swayed gently in a snake-like fashion. In photo #2 one can see module-to-module sling tension members replacing the wire hinges connecting the modules shown in photo #1. I thought of these threads as adding a note of mystery, causing the connections to be more or less invisible, at least as invisible as marionette strings; an Indian rope trick.

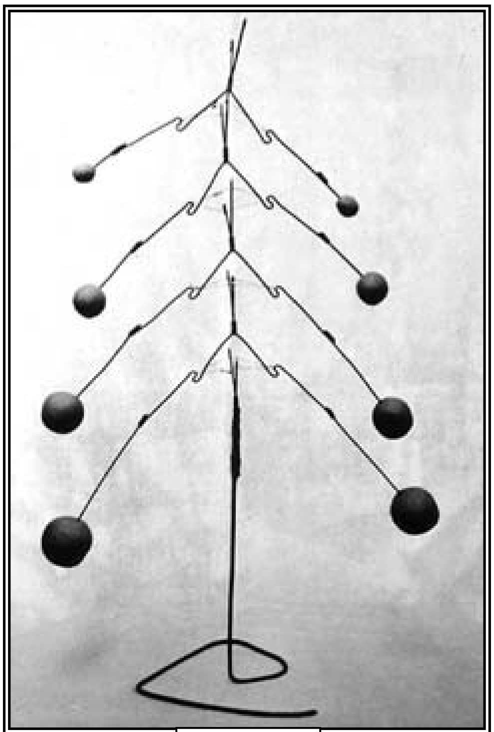


Photo #2

One step leading to the next, I saw that I could make the structure even more mysterious by tying off the movement altogether, replacing the clay weights with additional tension lines to stabilize the modules one to another, which I did, making "X", kite-like modules out of plywood. Thus, while forfeiting mobility, I managed to gain something even more exotic, solid elements fixed in space, one-to-another, held together only by tension members. I was quite amazed at what I had done. Photo #3

Still confused about my purposes and direction in school, I enrolled for engineering that winter ('48-'49) at Oregon State College. The classes depressed me even further. I hated it and did very poorly. I corresponded with Bucky and I told about my dilemma and also sent photos of the sequence of small sculptures. He must have understood from the letter how confused and depressed I was at school for he suggested I return for another Black Mountain Summer Session.

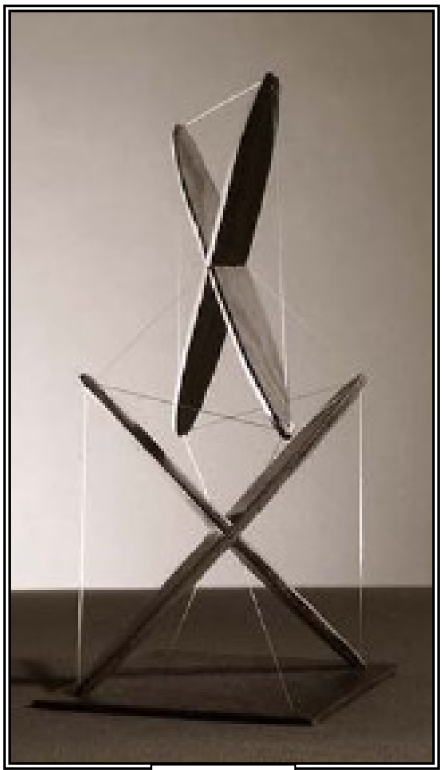


Photo #3

When we got together again in June I brought with me the plywood X-Piece (Fig. #3). When I showed him the sculpture, it was clear from his reaction that he hadn't understood it from the photos I had sent. He was quite struck with it, holding it in his hands, turning it over, studying it for a very long moment. He then asked if I might allow him to keep it. It hadn't been my intention to part with it, but I gave it to him, partly because I felt relieved that he wasn't angry that I had employed geometry (Buckminster Fuller's geometry) in making art. That original small sculpture disappeared from his apartment, so he told me at the end of the summer.

Next day he said he had given a lot of thought to my "X-column" structure and had determined that the configuration was wrong. Rather than the X-module for compression members, they should be shaped like the central angles of a tetrahedron, that is like spokes radiating from the gravitational center, to the vertices of a tetrahedron. Of course the irony was that I had already used that tetrahedral form in my moving sculpture #2, and rejected it in favor of the kite-like X modules because they permitted growth along all three axes, a true space-filling system, rather than only along a single linear axis. Those were not yet the years when students easily contradicted their elders, let alone their professors.

Next day I went into town and purchased metal telescoping curtain rods in order to build the "correct" structure for Bucky. I felt a little wistful but not at all suspicious of his motive as he had his picture taken, triumphantly holding the new structure I had built.

The rest of the story is one of numerous photographs and statements in print, grand claims in magazine articles and public presentations. In Time magazine he declared that, with "his" tensegrity, he could now span the Grand Canyon. He also described it as a structure which grows stronger the taller you build it -- whatever that may have meant.

The absorption process began early, even though Bucky penned the following in a letter to me dated December 22, 1949:

> *"In all my public lectures I tell of your original demonstration of discontinuous - pressure - (com-pressure) and continuous tension structural advantage; - in which right makes light in a prototype structure, the ready reproduction of which, properly incorporated in fundamental structures, may advance the spontaneous good will and understanding of mankind by many centuries. The event was one of those 'It happened' events, but demonstrates how the important events happen where the atmosphere is most favorable. If you had demonstrated this structure to an art audience it would not have rung the bell that it rang in me, who had been seeking this structure in Energetic Geometry. That you were excited by the latter, E.G., into spontaneous articulation of the solution, also demonstrates the importance of good faith of colleagues of this frontier. The name of* Ken Snelson *[his underline] will come to be known as a true pioneer of the realized good life and good will."*

Bucky's warm and uplifting letter arrived about six months after I first showed him my small sculpture. In that it was dated three days before Christmas, I suppose he was in a festive, generous, mood. A year later, January 1951 he published a picture of the structure in Architectural Forum magazine and, surprisingly, I was not mentioned. When I posed the question some years later why he accredited me, as he said, in his public lectures and never in print, he replied, **"Ken, old man, you can afford to remain anonymous for a while."**

Finally, in 1959 I learned that Fuller was to have a show at the Museum of Modern Art in New York and included in it was to be a thirty-feet high tensegrity "mast". Calling it a mast seemed especially obtuse, but he regarded himself as a man of the sea. With some persistence and with the lucky aid of Bucky's assistant I was able to get word to Arthur Drexler, curator at the Museum, about my part in tensegrity. This forced Bucky's hand. At last, my credit for tensegrity found its way into the public record.

One of the ironies of this not-too-unusual tale in the history of teacher-student relationships, is that by Bucky's transposing my original "X" module into the central-angles-of-the-tetrahedron shape to rationalize calling it his own, he managed successfully to put under wraps my original form, the highly adaptable X form. He could not have lived with himself with the blatant theft of my original system, of course, and besides, he had denounced it as the "wrong" form. As a result, none of the many students in schools where he lectured ever got to see it. In those years, any number of students labored to constructed their own "masts", but all were built using the tetrahedral form. That moment of recognition at the Museum of Modern Art in November 1959, transitory as it was, was quite fortifying and enabled me to once again pick up my absorbing interest in this kind of structure with the feeling that now I was free and on my own. Especially I picked up where I had left off with the neglected X-module which was left unnoticed for an entire decade. I no longer felt anonymous.

As I said earlier, this is but a footnote to a storm in a teapot. I have continued to make sculptures which now stand in public sites in many places. Sorry there are none in England or France. The ghost of Bucky Fuller continues to muddy the water in regard to "tensegrity". I tell myself often that, since I know where the ideas came from, that ought to be enough.

As I see it, this type of structure, at least in its purest form is not likely to prove highly efficient or utilitarian. As the engineer Mario Salvadori put it to me many years ago, "The moment you tell me that the compression members reside interior of the tension system, I can tell you I can build a better beam than you can." He was speaking metaphorically about this type of structure in general, of course. Over the years I've seen numbers of fanciful plans proposed by architects which have yet to convince me there is any advantage to using tensegrity over other methods of design. Usually the philosophy is akin to turning an antique coffee-grinder into the base for a lamp: it's there, so why not find a way to put it to some use. No, I see the richness of the floating compression principle to lie in the way I've used it from the beginning, for no other purpose than to unveil the exquisite beauty of structure itself. Consciously or unconsciously we respond to the many aspects of order in nature. For me, these studies in forces are a rich source for an art which celebrates the aesthetic of structure, of physical forces at work; force-diagrams in three-dimensional space, as I describe them.

Whether or not you are able to use this narrative about the beginnings of tensegrity, I wish you the very best with your special issue on the subject.

Sincerely,

Kenneth Snelson
140 Sullivan Street
New York, New York 10012

Appendix B. Original Tensegrity Patents.

An illustration of the following patents will be presented in this Appendix:

FULLER, R.B. (1962) *Tensile-Integrity Structures*, U.S. Patent No. 3,063,521, November 13, 1962.

EMMERICH, D.G. (1964), *Construction de réseaux autotendants*, French Patent No. 1,377,290, September 28, 1964

EMMERICH, D.G. (1964), *Structures linéaires autotendants*, French Patent No. 1,377,291, September 28, 1964

SNELSON, K. (1965) *Continuous tension, discontinuous compression structures*, U.S. Patent No. 3,169,611, February 16, 1965.

United States Patent Office

3,063,521
Patented Nov. 13, 1962

1

3,063,521
TENSILE-INTEGRITY STRUCTURES
Richard Buckminster Fuller, 164—91 Metropolitan Ave., Forest Hills 75, N.Y.
Filed Aug. 31, 1959, Ser. No. 837,073
7 Claims. (Cl. 189—34)

The invention relates to a system of construction which utilizes the tensile properties of structural materials to the fullest advantage. It has special application to structures of vast proportions such as free-span domes capable of roofing a stadium or housing an entire village or city, and to mammoth air-flotable spheres as well as collapsible light weight structures adapted to be transported by rocket. In general, my invention is useful wherever it is advantageous to make the largest and strongest structure per pound of structural material employed. It is applicable also to geodesic structures such as described and claimed in my prior Patent No. 2,682,235.

2

connecting tension elements, called a three-strut octahedral tensile integrity unit, or "tensegrity."

FIG. 2 shows an assemblage of the three-strut tensegrities of FIG. 1. This view is analytical, for in the actual structure struts of adjacent tensegrities are integrally joined in "apparent" compressional continuity. This actual structure is shown in

FIG. 3, which otherwise corresponds to FIG. 2, and shows the discontinuous compression structural complex.

FIG. 4 is a side elevational view of the strut and tension sling component of the discontinuous compression structural complex of FIG. 3, called a "boom."

FIG. 5 is a plan view of the boom of FIG. 4.

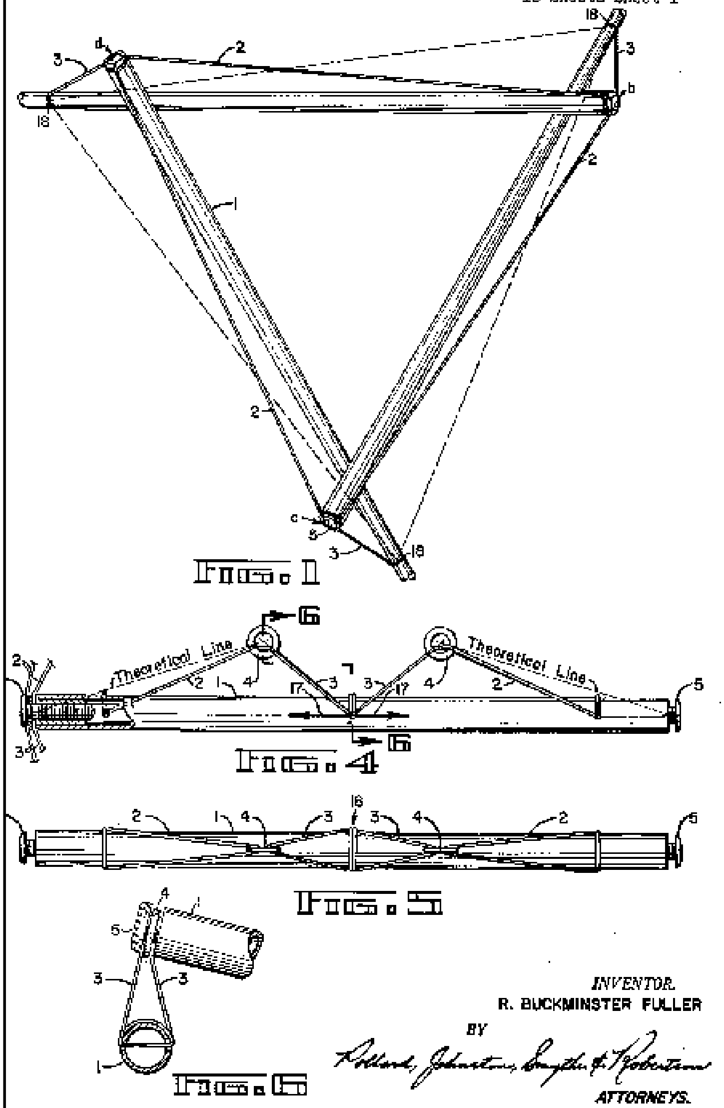
FIG. 6 is a sectional view taken on line 6—6 of FIG. 4.

FIG. 7 is a boom dimension schedule for a 270-boom tensegrity sphere.

FIG. 8 is a color code for assembling the booms of FIG. 7 according to one embodiment of my invention.

FIG. 9 is a further color code for assembling the booms.

Nov. 13, 1962 R. B. FULLER 3,063,521
TENSILE-INTEGRITY STRUCTURES
Filed Aug. 31, 1959 13 Sheets-Sheet 1



Extract of Fuller's patent

RÉPUBLIQUE FRANÇAISE

MINISTÈRE DE L'INDUSTRIE

SERVICE
de la PROPRIÉTÉ INDUSTRIELLE

BREVET D'INVENTION

P.V. n° 931.099 N° 1.377.290

Classification internationale : E 04 b

Construction de réseaux autotendants.

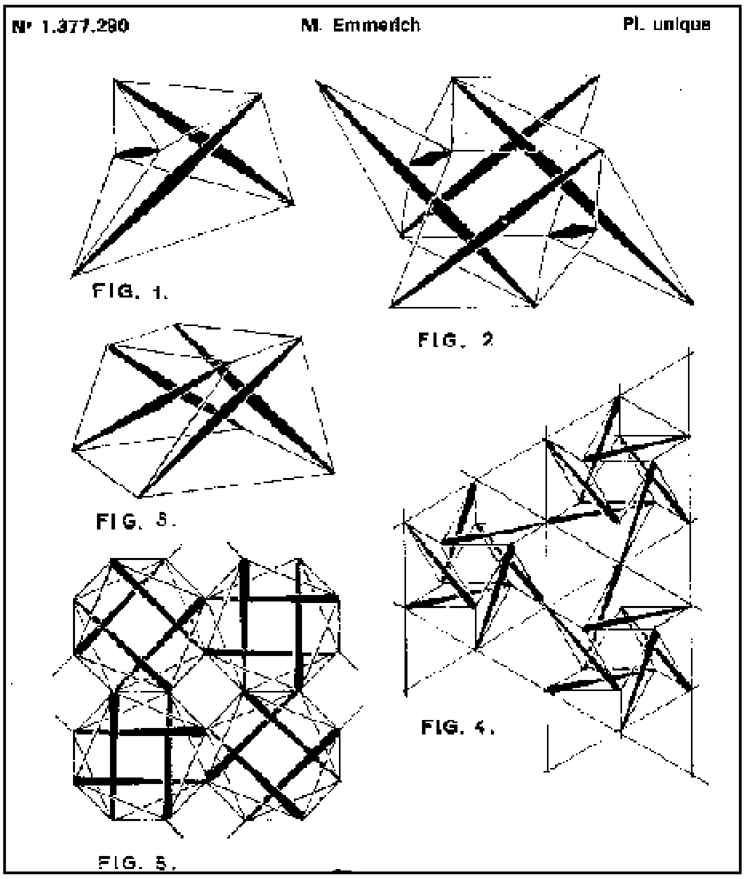
M. DAVID GEORGES EMMERICH résidant en France (Seine).

Demandé le 10 avril 1963, à 15h 50m, à Paris.
Délivré par arrêté du 28 septembre 1964.
(*Bulletin officiel de la Propriété industrielle*, n° 45 de 1964.)
(*Brevet d'invention dont la délivrance a été ajournée en exécution de l'article 11, § 7, de la loi du 5 juillet 1844 modifiée par la loi du 7 avril 1902.*)

La présente invention a pour objet un nouveau moyen de construction utilisable en particulier dans l'industrie du bâtiment, des travaux publics et des télécommunications, et qui se prête à une fabrication en grande série; il se réalise par la combinaison de deux ou d'un nombre très réduit de types d'éléments et qui permet de composer des réseaux de structures d'une variété pratiquement infinie.

En principe, une structure se compose d'un ou plusieurs solides polyédriques, chacun constitué d'un groupe de barres et de tirants. Le rôle de ces polyèdres pourrait être comparé à celui des hourdis d'un plancher ou d'une voûte; en en organisant un nombre quelconque en plan ou en volume, on obtient un réseau autotendant. Selon l'invention les polyèdres sont des équilibrums sions tendu par un certain nombre de baguettes; le plus simple de ces filets n'a que cinq mailles, six noeuds et trois barres pour le tendre.

En principe, dans les cas élémentaires, la face supérieure ou inférieure de l'équilibrum est un polygone quelconque; par exemple triangle, carré, pentagone, hexagone..., le nombre des barres est respectivement trois, quatre, cinq, six..., et le nombre des sommets respectivement six, huit, dix, douze... Mais on peut créer aussi un équilibrum par l'interpénétration de deux ou plusieurs équilibrums élémentaires identiques ou différents. Dans ce cas, les faces supérieure et inférieure du graphe resteront respectivement des triangles, carrés, pentagones, hexagones..., mais le nombre des barres et des sommets se multiplie autant de fois que le nombre de corps



Extract of Emmerich's patent

RÉPUBLIQUE FRANÇAISE

MINISTÈRE DE L'INDUSTRIE

SERVICE
de la PROPRIÉTÉ INDUSTRIELLE

BREVET D'INVENTION

P.V. n° 931.100 N° 1.377.291

Classification internationale : E 04 b

Structures linéaires autotendantes.

M. DAVID GEORGES EMMERICH résidant en France (Seine).

Demandé le 10 avril 1963, à 15h 51m, à Paris.
Délivré par arrêté du 28 septembre 1964.
(*Bulletin officiel de la Propriété industrielle*, n° 45 de 1964.)

(*Brevet d'invention dont la délivrance a été ajournée en exécution de l'article 11, § 7, de la loi du 5 juillet 1844 modifiée par la loi du 7 avril 1902.*)

La présente invention a pour objet un nouveau moyen de construction utilisable en particulier dans l'industrie du bâtiment, des travaux publics et des télécommunications, et qui se prête à une fabrication en grande série; il se réalise par la combinaison de deux ou d'un nombre très réduit de types d'éléments et qui permet de composer des structures oblongues d'une variété pratiquement infinie.

En principe, dans les cas élémentaires, la face supérieure ou inférieure de l'équilibrum est un polygone quelconque: par exemple triangle, carré, pentagone, hexagone..., le nombre des barres est respectivement trois, quatre, cinq, six..., et le nombre des sommets respectivement six, huit, dix, douze... Mais on peut créer aussi un équilibrum par l'interpénétration de deux ou plusieurs équili-

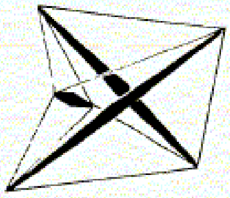


FIG. 1.

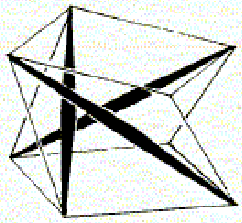


FIG. 2.

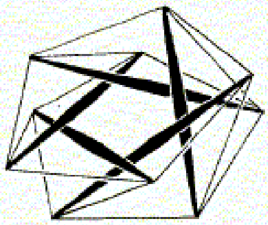


FIG. 3.

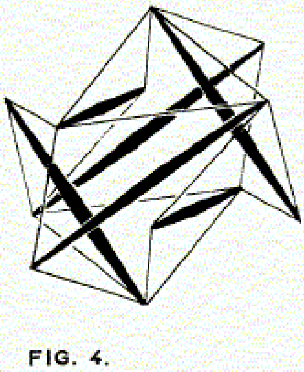


FIG. 4.

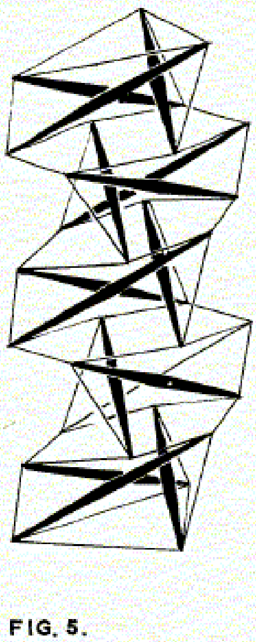


FIG. 5.

Extract of Emmerich's patent

United States Patent Office

3,169,611
Patented Feb. 16, 1965

1

3,169,611
CONTINUOUS TENSION, DISCONTINUOUS COMPRESSION STRUCTURES

Kenneth D. Snelson, New York, N.Y.
(P.O. Box 404, Sagaponack, Long Island, N.Y.)

Filed Mar. 14, 1960, Ser. No. 14,491
6 Claims. (Cl. 189—34)

The present invention relates to structural framework and more particularly, to a novel and improved structure of elongate members which are separately placed either in tension or in compression to form a lattice, the compression members being separated from each other and the tension members being interconnected to form a continuous tension network.

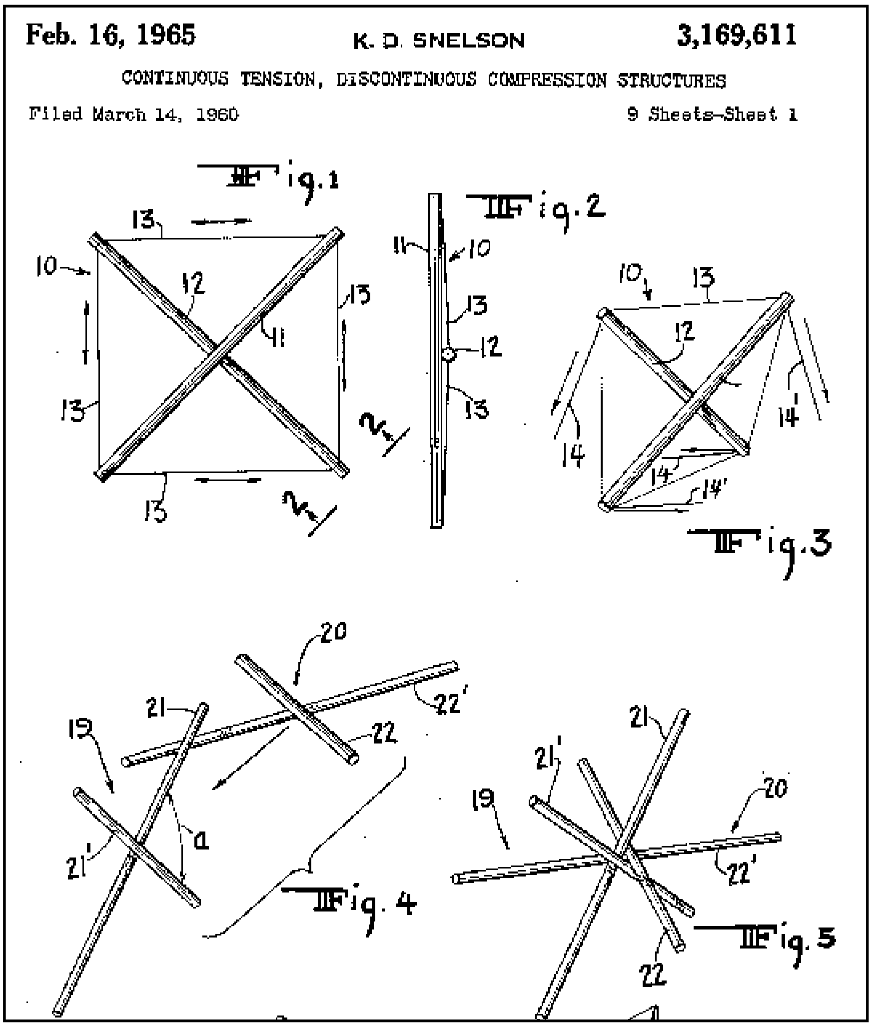
The present invention forms a part of a recently developed class of structures possessing, what may be termed discontinuous compression, continuous tension characteristics. This type of structure is an outgrowth of much earlier forms such as, for example, the wire or tension spoked wheel in which use of tension members has been made to support external compressive loads. Significant weight/strength ratios have been achieved in structures of this type by eliminating heavier compression members and supplanting them with lighter tension members wherever possible. It has been found that materials may be selected which, for a given weight, have tensile strengths several times greater than their ability to withstand compression loads. In fact, most advances in strengths of materials have seen an increase in tensile strengths while compression strength has remained relatively static.

2

being determined by the number of planes defined generally by the ends of the elongated compression members throughout the structure.

It is a basic objective in utilizing the foregoing principles to produce an ultimate structure (such as a dome, sphere, etc.) which can absorb large loads relative to the amount of a given material used. Practically, this requires the greatest use of tension members and the least possible use of members in compression, since the former may be made considerably lighter to withstand tensional forces than the latter to withstand compressional forces. In the evolution or development of new modules there has thus been a constant attempt to develop simpler forms, i.e., units or modules which contain fewer and fewer compression members. To date, the simplest known structure resembles a 3-legged collapsible chair, wherein three elongate compression members are held by a continuous tension network to be self-supporting. The three compression members cross in a spiral intermediate their ends to make this structure resemble the familiar tripod spiral of a sling seated 3-legged collapsible chair.

It is a basic purpose of the present invention to disclose the simplest modular form thought to be possible for a structure of this type. Because of its basic simplicity, the module of the invention lends itself naturally to many applications for use as a basic building block in constructing more complicated structures. Consequently, this structure utilizes tension more efficiently than before possible with the more complicated module forms, to thus bring about a corresponding decreased weight/load ratio.



Extract of Snelson's patent

Appendix C. Other Tensegrity Patents

An illustration of the following patents will be presented in this Appendix:

AUSTIN, G.D. and TAM, L. (2002) *Female condom employing tensegrity principle*, U.S. Patent No. 2002/0038658 A1, April 4, 2002

BARBER, G.T. (2003a) *Lamp composed of non-contacting compression members and tension members*, U.S. Patent No. D473,676, April 22, 2003.

BARBER, G.T. (2003b) *Table composed on non-contacting compression members and tension members*, U.S. Patent No. D471,741, March 18, 2003.

BARBER, G.T. (2003c) *Chair composed on non-contacting compression members and tension members*, U.S. Patent No. D481,880, November 11, 2003.

BARBER, G.T. (2004) *Four-strut support composed of non-contacting compression members and tension members*, U.S. Patent No. D487,155, February 24, 2004.

GEIGER, D.H. (1988) *Roof structure*, U.S. Patent No. 4,736,553, April 12, 1988.

GLENN, A. and TAM, L. (2002), *Female condom employing tensegrity principle,* U.S. Patent No. US2002038658, April 4, 2002.

GOLDSMITH, E.M. (1998) *Sports catch glove with stiffner*, U.S. Patent No. 5,717,994, February 17, 1998

HUEGY, C.W. (1990) *Spiral helix tensegrity dome*, U.S. Patent No. 4,901,483, February 20, 1990

KITRICK; C.J. (1980), *Tensegrity module structure and method of interconnecting the modules*, U.S. Patent No. 4,207,715, June 17, 1980

KITTNER, C. and QUIMBY, S.R (1988), *Compression-tension strut-cord units for tensile-integrity structures*, U.S. Patent No. 4,731,962, March 22, 1988

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SKELTON, R.E. (1997), *Deployable tendon-controlled structure*, U.S. Patent No. 5,642,590, July 1, 1997

STERN, I. (2003) *Deployable reflector antenna with tensegrity support architecture and associated methods*, U.S. Patent No. 6,542,132, April 1, 2003.

TERRY, W.L. (1996) *Tension braced dome structure*, U.S. Patent No. 5,502,928, April 2, 1996.

WIESNER, S.J. (1975) *Stressed structure for supporting weight*, U.S. Patent No. 3,901,551, August 26, 1975.

(19) **United States**
(12) **Patent Application Publication**
Austin et al.
(10) **Pub. No.: US 2002/0038658 A1**
(43) **Pub. Date: Apr. 4, 2002**

(54) **FEMALE CONDOM EMPLOYING TENSEGRITY PRINCIPLE**

(76) Inventors: **Glenn D. Austin**, Seattle, WA (US); **Lisa Tam**, Seattle, WA (US)

Correspondence Address:
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SUITE 1100
WASHINGTON, DC 20001 (US)

(21) Appl. No.: **09/921,016**

(22) Filed: **Aug. 3, 2001**

Related U.S. Application Data

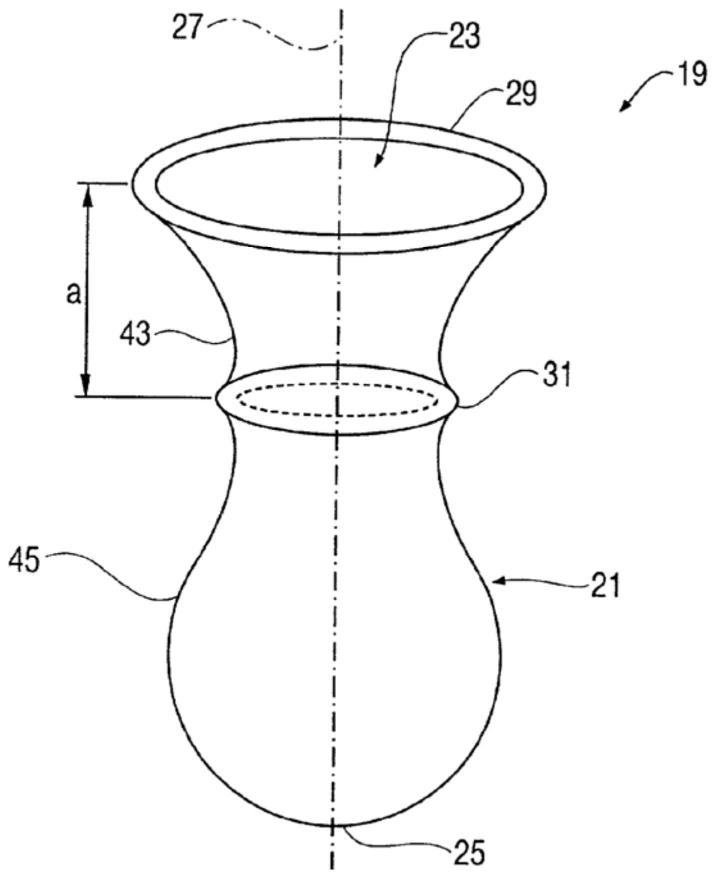
(63) Non-provisional of provisional application No. 60/223,036, filed on Aug. 4, 2000.

Publication Classification

(51) **Int. Cl.**[7] **A61F 6/06**
(52) **U.S. Cl.** **128/830**

(57) **ABSTRACT**

Employing the known "tensegrity" principle, a female condom is configured such that when the condom is inserted into a woman's vagina, the woman's introitus acts on a proximal section of an elongated pouch extending between internal and external biasing members (e.g., rings) of the condom. Inward compressive forces exerted by the introitus on the inner ring of the condom cause the inner ring to be pushed distally within the vaginal canal, and the proximal pouch section to become a tension member pulling against the external ring. This causes a "tenting" of the proximal pouch section against the introitus. The resulting interaction of compression and tensile forces (a tensegrity effect) serves to provide the condom with a high degree of internal and external stability, including resistance to twisting and slippage.



(12) **United States Design Patent** (10) **Patent No.: US D487,155 S**
Barber (45) **Date of Patent: ** Feb. 24, 2004**

(54) **FOUR-STRUT SUPPORT COMPOSED OF NON-CONTACTING COMPRESSION MEMBERS AND TENSION MEMBERS**

(75) Inventor: **Geoffrey T. Barber**, Reno, NV (US)

(73) Assignee: **TAT, LLC**, Reno, NV (US)

(**) Term: **14 Years**

(21) Appl. No.: **29/158,690**

(22) Filed: **Apr. 5, 2002**

(51) **LOC (7) Cl.** **25-02**
(52) **U.S. Cl.** **D25/61**
(58) **Field of Search** 52/81.2, 80.1, 52/81.1; D25/61, 66; 248/346.01

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Primary Examiner—Doris Clark
(74) *Attorney, Agent, or Firm*—Fenwick & West LLP

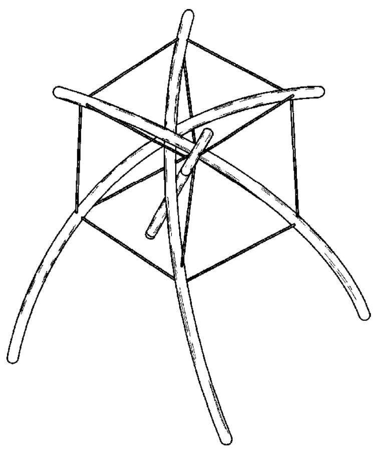
(57) **CLAIM**

The ornamental design for the four-strut support composed of non-contacting compression members and tension members, substantially as shown and described.

DESCRIPTION

FIG. **1** is a perspective view of a four-strut support composed of non-contacting compression members and tension members according to the present invention;
FIG. **2** is a front view thereof;
FIG. **3** is a rear view thereof;
FIG. **4** is a left side view thereof;
FIG. **5** is a right side view thereof;
FIG. **6** is a top view thereof; and,
FIG. **7** is a bottom view thereof.

1 Claim, 4 Drawing Sheets



(12) **United States Design Patent** (10) **Patent No.:** **US D470,667 S**
Barber (45) **Date of Patent:** ** **Feb. 25, 2003**

(54) **LOUNGE CHAIR COMPOSED OF NON-CONTACTING COMPRESSION MEMBERS AND TENSION MEMBERS**

(76) Inventor: **Geoffrey T. Barber**, 2665 Outlook Dr., Reno, NV (US) 89509

(**) Term: **14 Years**

(21) Appl. No.: **29/158,713**

(22) Filed: **Apr. 5, 2002**

(51) **LOC (7) Cl.** **06-01**
(52) **U.S. Cl.** **D6/361**
(58) **Field of Search** D6/334, 335, 361, D6/368, 370, 500, 501, 502; 297/445.1, 452.63

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3,663,346	A	*	5/1972	Schoen	
3,866,366	A	*	2/1975	Fuller	
3,925,941	A	*	12/1975	Pearce	
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3,937,426	A	*	2/1976	Pearce	
3,974,600	A	*	8/1976	Pearce	
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* cited by examiner

Primary Examiner—Gary D. Watson
(74) *Attorney, Agent, or Firm*—Fenwick & West LLP

(57) **CLAIM**

The ornamental design for the lounge chair composed of non-contacting compression members and tension members, substantially as shown and described.

DESCRIPTION

FIG. **1** is a perspective view of a lounge chair composed of non-contacting compression members and tension members according to the present invention;
FIG. **2** is a front view thereof;
FIG. **3** is a rear view thereof;
FIG. **4** is a left side view thereof;
FIG. **5** is a right side view thereof;
FIG. **6** is a top view thereof; and,
FIG. **7** is a bottom view thereof.

1 Claim, 7 Drawing Sheets

(12) **United States Design Patent** (10) **Patent No.:** **US D473,676 S**
Barber (45) **Date of Patent:** ** **Apr. 22, 2003**

(54) **LAMP COMPOSED OF NON-CONTACTING COMPRESSION MEMBERS AND TENSION MEMBERS**

(76) Inventor: **Geoffrey T. Barber**, 2665 Outlook Dr., Reno, NV (US) 89509

(**) Term: **14 Years**

(21) Appl. No.: **29/158,712**

(22) Filed: **Apr. 5, 2002**

(51) **LOC (7) Cl.** **26-03**
(52) **U.S. Cl.** **D26/93**
(58) **Field of Search** D26/51, 58, 93–112; 362/410–414, 33, 97, 127, 131, 133, 145, 153, 153.1, 431, 806; D6/399

(56) **References Cited**

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D199,126	S	*	9/1964	Barrett	D26/58 X
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3,663,346	A		5/1972	Schoen	
3,866,366	A		2/1975	Fuller	
3,925,941	A		12/1975	Pearce	
3,931,697	A		1/1976	Pearce	
3,937,426	A		2/1976	Pearce	
3,974,600	A		8/1976	Pearce	
4,133,152	A		1/1979	Penrose	
4,207,715	A		6/1980	Kitrick	
4,614,502	A		9/1986	Nelson	
4,711,062	A		12/1987	Gwilliam et al.	
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5,265,395	A		11/1993	Lalvani	
5,331,779	A		7/1994	Hing	

* cited by examiner

Primary Examiner—Alan P. Douglas
Assistant Examiner—Linda Brooks
(74) *Attorney, Agent, or Firm*—Fenwick & West LLP

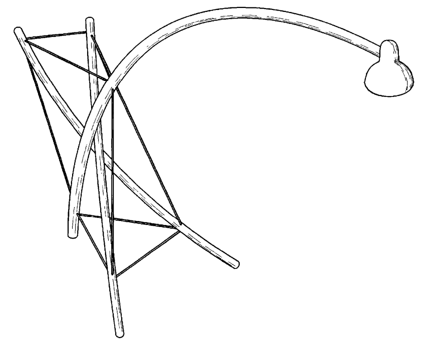
(57) **CLAIM**

The ornamental design for a lamp composed of non-contacting compression members and tension members, substantially as shown and described.

DESCRIPTION

FIG. **1** is a perspective view of a lamp composed of non-contacting compression members and tension members according to the present invention;
FIG. **2** is a front view thereof;
FIG. **3** is a rear view thereof;
FIG. **4** is a left side view thereof;
FIG. **5** is a right side view thereof;
FIG. **6** is a top view thereof; and,
FIG. **7** is a bottom view thereof.

1 Claim, 7 Drawing Sheets



(12) **United States Design Patent** (10) **Patent No.:** **US D471,741 S**
Barber (45) **Date of Patent:** ** **Mar. 18, 2003**

(54) **TABLE COMPOSED ON NON-CONTACTING COMPRESSION MEMBERS AND TENSION MEMBERS**

(76) Inventor: **Geoffrey T. Barber**, 2665 Outlook Dr., Reno, NV (US) 89509

(**) Term: **14 Years**

(21) Appl. No.: **29/158,707**

(22) Filed: **Apr. 5, 2002**

(51) **LOC (7) Cl.** **06-03**
(52) **U.S. Cl.** **D6/487**; D6/480
(58) **Field of Search** D6/480–489, 495–499, D6/511; 108/150, 153.1, 155, 156, 157.1, 161; 248/188, 188.1, 188.8

(56) **References Cited**

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3,354,591	A		11/1967	Fuller	
3,600,825	A		8/1971	Pearce	
3,663,346	A		5/1972	Schoen	
3,866,366	A		2/1975	Fuller	
3,925,941	A		12/1975	Pearce	
3,931,697	A		1/1976	Pearce	
3,937,426	A		2/1976	Pearce	
3,974,600	A		8/1976	Pearce	
4,133,152	A		1/1979	Penrose	
4,207,715	A		6/1980	Kitrick	
4,614,502	A		9/1986	Nelson	
4,711,062	A		12/1987	Gwilliam et al.	
5,007,220	A		4/1991	Lalvani	
5,036,635	A		8/1991	Lalvani	
5,155,951	A		10/1992	Lalvani	
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D386,328	S	*	11/1997	Good	D6/480
D396,974	S	*	8/1998	D'Urbino et al.	D6/480

* cited by examiner

Primary Examiner—Janice E. Seeger
(74) *Attorney, Agent, or Firm*—Fenwick & West, LLP

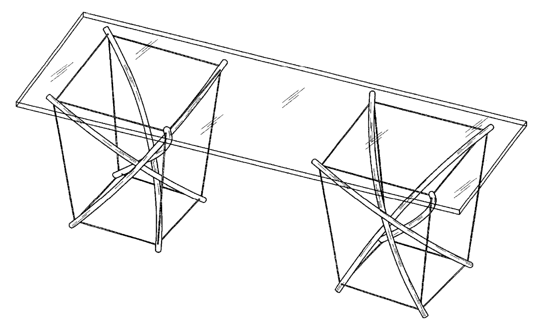
(57) **CLAIM**

The ornamental design for the table composed of non-contacting compression members and tension members, substantially as shown and described.

DESCRIPTION

FIG. **1** is a perspective view of a table composed of non-contacting compression members and tension members according to the present invention;
FIG. **2** is a front view thereof;
FIG. **3** is a rear view thereof;
FIG. **4** is a left side view thereof;
FIG. **5** is a right side view thereof;
FIG. **6** is a top view thereof; and,
FIG. **7** is a bottom view thereof.

1 Claim, 6 Drawing Sheets



(12) **United States Design Patent** (10) **Patent No.:** **US D481,880 S**
Barber (45) **Date of Patent:** ** **Nov. 11, 2003**

(54) **CHAIR COMPOSED OF NON-CONTACTING COMPRESSION MEMBERS AND TENSION MEMBERS**

(75) Inventor: **Geoffrey T. Barber**, Reno, NV (US)

(73) Assignee: **TAT, LLC**, Reno, NV (US)

(**) Term: **14 Years**

(21) Appl. No.: **29/158,676**

(22) Filed: **Apr. 5, 2002**

(51) **LOC (7) Cl.** **06-01**
(52) **U.S. Cl.** **D6/370**
(58) **Field of Search** D6/334, 335, 368, D6/370, 374, 375, 500, 501, 502; 297/452.63

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D470,318	S	*	2/2003	Barber	D6/370

* cited by examiner

Primary Examiner—Gary D. Watson
(74) *Attorney, Agent, or Firm*—Fenwick & West LLP

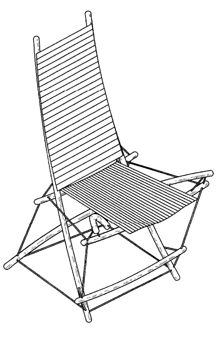
(57) **CLAIM**

The ornamental design for the chair composed on non-contacting compression members and tension members, substantially shown and described.

DESCRIPTION

FIG. **1** is a perspective view of a chair composed of non-contacting compression members and tension members according to the present invention;
FIG. **2** is a front view thereof;
FIG. **3** is a rear view thereof;
FIG. **4** is a left side view thereof;
FIG. **5** is a right side view thereof;
FIG. **6** is a top view thereof; and,
FIG. **7** is a bottom view thereof.

1 Claim, 4 Drawing Sheets



United States Patent [19] [11] **Patent Number: 4,736,553**
Geiger [45] **Date of Patent: Apr. 12, 1988**

[54] **ROOF STRUCTURE**

[76] Inventor: **David H. Geiger,** Kirby La., Rye, N.Y. 10580

[21] Appl. No.: **939,170**

[22] Filed: **Dec. 8, 1986**

Related U.S. Application Data

[63] Continuation of Ser. No. 608,424, May 9, 1984, abandoned.

[51] **Int. Cl.**[4] **E04B 1/342;** E04C 3/02
[52] **U.S. Cl.** **52/81;** 52/694; 135/103; 135/DIG. 8
[58] **Field of Search** 14/8, 20, 21, 22, 18; 135/DIG. 8, 101, 102, 103, 97, 104; 52/63, 83, 227, 646, 645, 641, 86, 694, 81, 82

[56] **References Cited**

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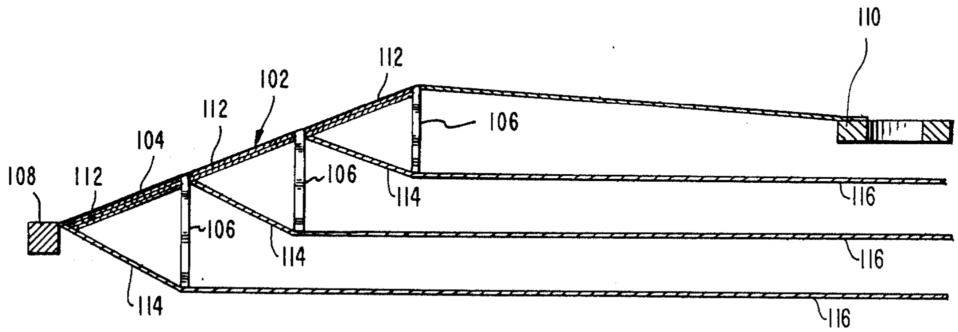
Glass Tension Structures and Space Frames by Architectural Institute of Japan 1972, pp. 537–541.

Primary Examiner—John E. Murtagh
Attorney, Agent, or Firm—Mortenson & Uebler

[57] **ABSTRACT**

A cable truss dome which is not triangulated is constructed from a plurality of cables under tension and compression members arranged in triangles having non-common sides. The cable truss dome is adapted for spanning large areas where the cables form a low shallow arch which supports a flexible membrane as a covering. The non-common vertex of the formed triangles are connected to similarly placed vertical sides of other triangles through continuous nested tension rings.

15 Claims, 7 Drawing Sheets



United States Patent [19]
Goldsmith

[11] **Patent Number: 5,717,994**
[45] **Date of Patent: *Feb. 17, 1998**

[54] **SPORTS CATCH GLOVE WITH STIFFNER**

[75] Inventor: **Edward Michael Goldsmith**, Bloomfield, Mich.

[73] Assignee: **Mike Vaughn Custom Sports, Inc.**, Lake Orion, Mich.

[*] Notice: The term of this patent shall not extend beyond the expiration date of Pat. No. 5,551,083.

[21] Appl. No.: **703,199**

[22] Filed: **Aug. 26, 1996**

Related U.S. Application Data

[63] Continuation of Ser. No. 496,024, Jun. 28, 1995, Pat. No. 5,551,083.

[51] **Int. Cl.**^{6} **A41D 13/10**
[52] **U.S. Cl.** **2/19**; 2/161.1
[58] **Field of Search** 2/19, 159, 161.1, 2/161.2, 163, 16, 18, 158, 160, 161.6, 164

[56] **References Cited**

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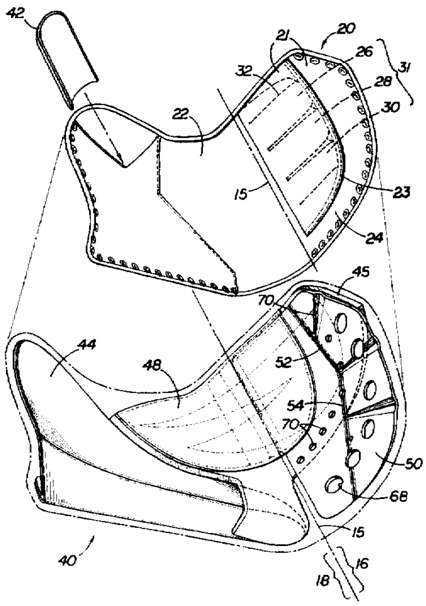
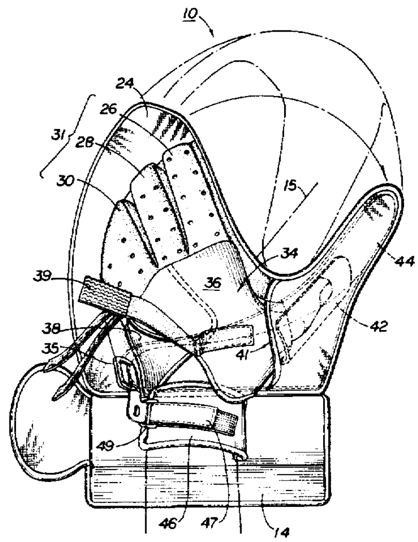
Primary Examiner—C. D. Crowder
Assistant Examiner—Larry D. Worrell, Jr.
Attorney, Agent, or Firm—James L. Ewing, IV; Kilpatrick Stockton LLP

[57] **ABSTRACT**

A sports catch glove according to the present invention offers superior control and effectiveness over conventional catch gloves. The glove incorporates a dished tensegrity stiffener in its distal finger portion that weighs less but is more than ten times stiffer than stiffeners employed in conventional gloves. To allow the wearer to gain maximum benefit from this added stiffness in the distal finger portion, the glove also incorporates a close-fitting inner glove, at least a portion of which is made of an elastomeric material. The inner glove keeps the wearer's hand more closely coupled to the glove than in conventional gloves, thus allowing the wearer to maintain control over the glove under the severe forces imposed when catching fast-moving, hard objects.

15 Claims, 6 Drawing Sheets





United States Patent [19]
Huegy

[11] **Patent Number:** **4,901,483**
[45] **Date of Patent:** **Feb. 20, 1990**

[54] **SPIRAL HELIX TENSEGRITY DOME**

[76] Inventor: **Charles W. Huegy**, 2 Mann St., Irvine, Calif. 92715

[21] Appl. No.: **248,340**

[22] Filed: **Sep. 20, 1988**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 891,401, May 2, 1986, abandoned, which is a continuation-in-part of Ser. No. 603,341, Apr. 16, 1984, abandoned.

[51] **Int. Cl.**[4] **E04B 1/32**
[52] **U.S. Cl.** **52/81**; 52/DIG. 10
[58] **Field of Search** .... 52/81, DIG. 10

[56] **References Cited**

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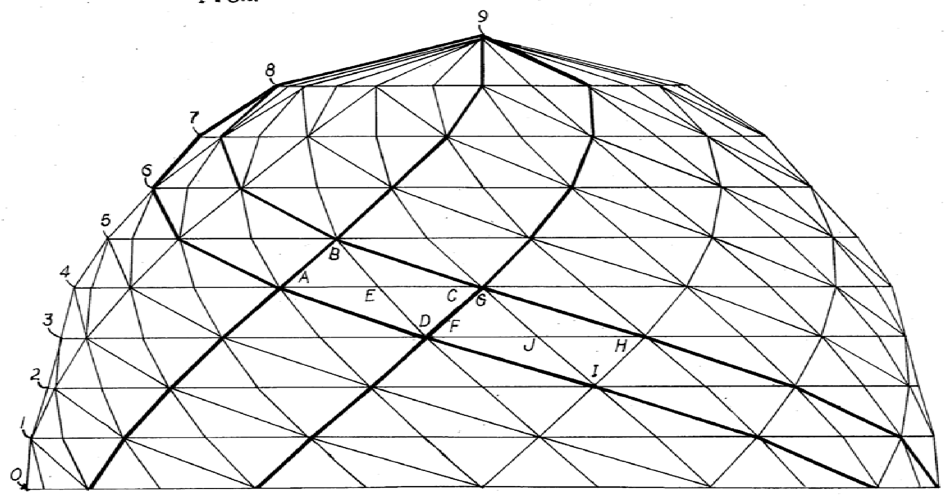
Primary Examiner—John E. Murtagh

[57] **ABSTRACT**

A building of geodesic dome type based on a variant of the helix formula and exhibiting the engineering characteristic known as tensegrity. All juncture points are precisely located from the jig for construction. A method of top closure enabling easy construction is included.

5 Claims, 17 Drawing Sheets

FIG.1.



U.S. Patent　Feb. 20, 1990　Sheet 1 of 17　4,901,483

United States Patent [19] [11] **4,207,715**
Kitrick [45] **Jun. 17, 1980**

[54] **TENSEGRITY MODULE STRUCTURE AND METHOD OF INTERCONNECTING THE MODULES**

[76] Inventor: **Christopher J. Kitrick,** 3500 Market St., Philadelphia, Pa. 19104

[21] Appl. No.: **942,301**

[22] Filed: **Sep. 14, 1978**

[51] **Int. Cl.**[2] **E04B 1/32**
[52] **U.S. Cl.** **52/81;** 52/747; 52/DIG. 10
[58] **Field of Search** .... 52/81, DIG. 10, 747

[56] **References Cited**

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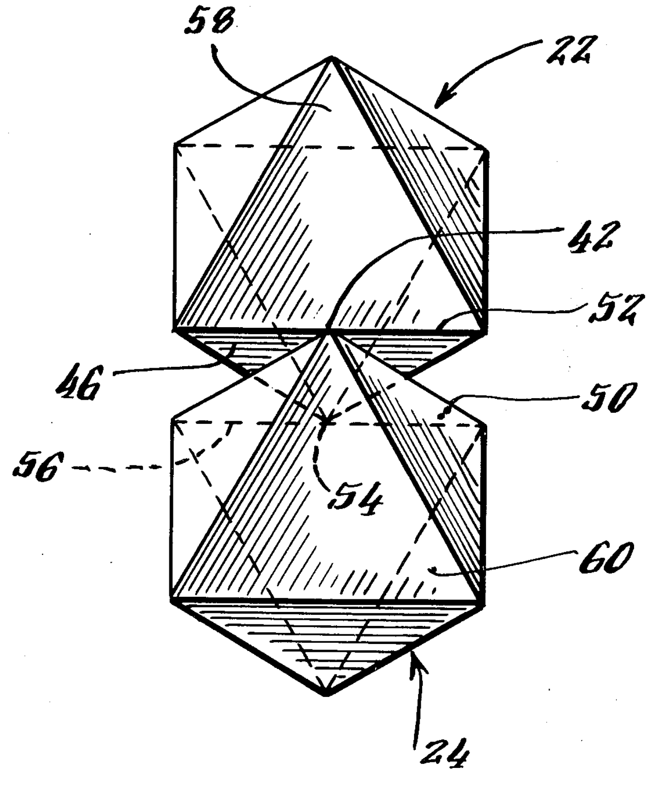
Primary Examiner—Price C. Faw, Jr.
Assistant Examiner—Carl D. Friedman
Attorney, Agent, or Firm—Parmelee, Johnson, Bollinger & Bramblett

[57] **ABSTRACT**

A tensegrity structure is formed from a plurality of interconnected tensegrity modules. Each module includes several column-like compression members and tension elements run between ends of the compression members to define a polyhedron. The tension elements form the edges of the polyhedron and intersect at the vertices of the polyhedron. The interconnected modules are joined to each other with triangular faces abutting but with the edges and faces of the abutting triangular surfaces of the respective modules rotated 180° away from superposition and with the vertices joined to tension element edges, being joined at a point located one-half or one-third of the way along the length of such edge.

7 Claims, 17 Drawing Figures



United States Patent [19]
Kittner et al.

[11] **Patent Number: 4,731,962**
[45] **Date of Patent: Mar. 22, 1988**

[54] **COMPRESSION-TENSION STRUT-CORD UNITS FOR TENSILE-INTEGRITY STRUCTURES**

[75] Inventors: **Cary Kittner; Stuart R. Quimby,** both of Barrytown, N.Y.

[73] Assignee: **Tensegrity Systems Corporation,** Barrytown, N.Y.

[21] Appl. No.: **945,808**

[22] Filed: **Dec. 24, 1986**

[51] **Int. Cl.**[4] **A63H 33/00;** E04B 1/32; E04H 12/18

[52] **U.S. Cl.** **52/81;** 52/645; 52/646; 52/720; 52/DIG. 10; 135/106; 446/107; 446/119

[58] **Field of Search** .... 52/81, 645, 646, 720, 52/DIG. 10; 135/106; 403/206; 124/23 R; 446/107, 119, 478

[56] **References Cited**

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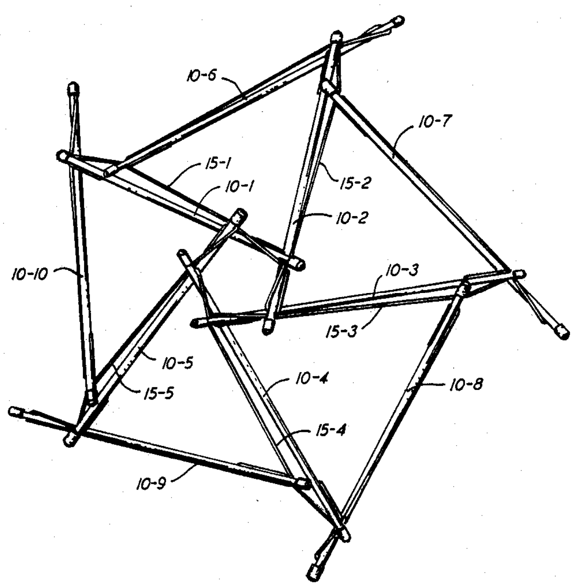
Primary Examiner—Alfred C. Perham
Attorney, Agent, or Firm—Charles J. Brown

[57] **ABSTRACT**

A compression-tension unit for use in a tensile-integrity structure wherein end portions of an elastic cord are passed through slots in the opposite ends of a strut with a stretched intermediate cord portion therebetween, and opposite tips of the cord are held in lateral holes in the strut end portions adjacent the slots, there being a choice of such lateral holes spaced longitudinally apart at each strut end portion so that the degree of stretch in the intermediate cord portion can be varied.

12 Claims, 6 Drawing Figures



(12) **United States Patent**
Knight et al.

(10) **Patent No.: US 6,441,801 B1**
(45) **Date of Patent: Aug. 27, 2002**

(54) **DEPLOYABLE ANTENNA USING SCREW MOTION-BASED CONTROL OF TENSEGRITY SUPPORT ARCHITECTURE**

(75) Inventors: **Byron F. Knight**, Vienna, VA (US); **Joseph Duffy**; **Carl David Crane, III**, both of Gainesville, FL (US); **Joseph Rooney**, Olney (GB)

(73) Assignee: **Harris Corporation**, Melbourne, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/539,630**

(22) Filed: **Mar. 30, 2000**

(51) **Int. Cl.**[7] **H01Q 15/20**; H01Q 15/14; H01Q 19/12

(52) **U.S. Cl.** **343/915**; 343/912; 343/840

(58) **Field of Search** 343/912, 915, 343/916, 753, 755, 897, 877, 881, 882, 832, 834, 840

(56) **References Cited**

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"Two–Dimensional Deployable Hexapond Truss" by Onoda, Fu and Minesugi, Journal of Spacecraft and Rockets, vol. 33, No. 3, May–Jun. 1996, pp. 416–421.

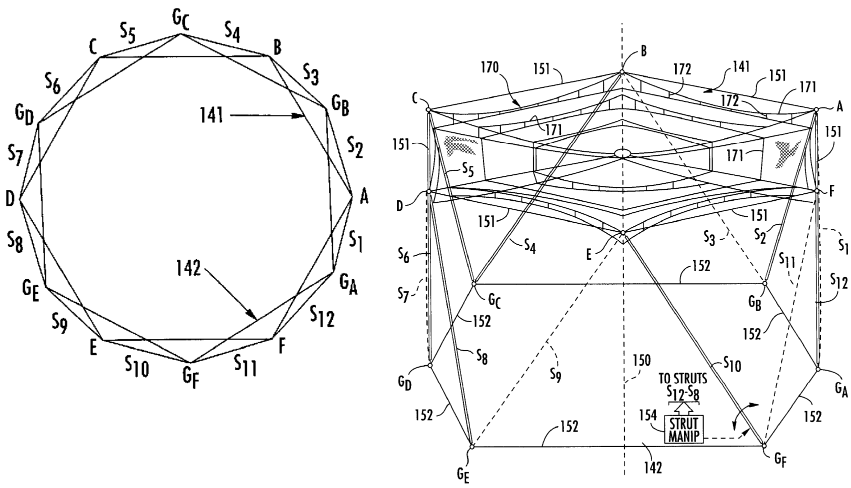
(List continued on next page.)

Primary Examiner—Don Wong
Assistant Examiner—Chuc Tran D
(74) *Attorney, Agent, or Firm*—Allen, Dyer, Doppelt, Milbrath & Gilchrist, P.A.

(57) **ABSTRACT**

A screw motion-driven tensegrity antenna support architecture is configured to stably deploy and adjustably control an energy-focusing surface, such as an RF wave-reflecting conductive mesh. A parallel platform structure is configured of an upper hexagonal platform and a lower hexagonal base, the perimeter geometry of each of which is defined by plural interconnected tensioned ties. Vertices of the hexagonal tie base and the hexagonal upper tie platform are interconnected by pairs of legs, each including a compression strut and a tension tie. The stability of the structure requires that the sum of the tie tension forces matches the sum of the compression forces in the struts. To control deployment from a stowed condition and the geometric parameters of the deployed RF reflecting surface, a screw motion-based drive system is coupled to the struts to define relative mutual rotation and pitch between the upper platform and lower base.

18 Claims, 6 Drawing Sheets



(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2003/0009974 A1**
Liapi (43) **Pub. Date: Jan. 16, 2003**

(54) **TENSEGRITY UNIT, STRUCTURE AND METHOD FOR CONSTRUCTION**

(76) Inventor: **Katherine A. Liapi**, Austin, TX (US)

Correspondence Address:
ERIC B. MEYERTONS
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AUSTIN, TX 78767-0398 (US)

(21) Appl. No.: **10/157,776**

(22) Filed: **May 29, 2002**

Related U.S. Application Data

(60) Provisional application No. 60/294,427, filed on May 29, 2001.

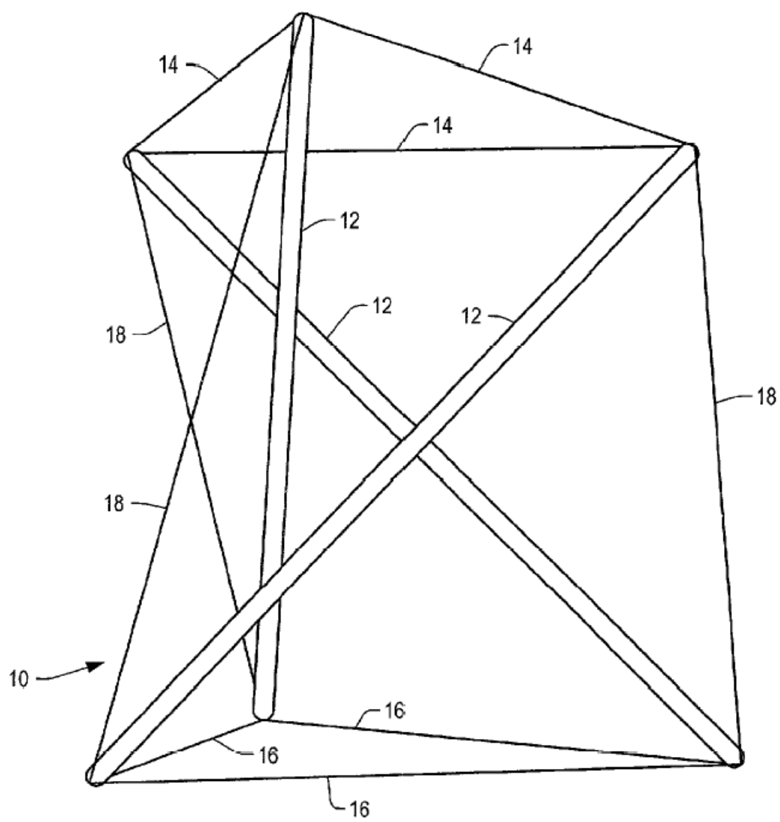
Publication Classification

(51) **Int. Cl.**[7] **E04B 1/18**

(52) **U.S. Cl.** **52/633**; 52/648.1; 52/652.1

(57) **ABSTRACT**

Tensegrity units may be used to form a tensegrity structure. Each tensegrity unit may include n face tension members, n continuous tension members, and n compression members. A bracket for the tensegrity unit may allow for adjustment of position of portions of the tension members when the tensegrity unit is not in a deployed state. The tension members may be coupled to the tensegrity unit so that there are no loose tension member ends. The unit may be deployed from a collapsed state by positioning the compression members and tension members in a proper orientation and adjusting the length of at least one compression member. Adjusting the length of at least the one compression member may allow tension to be applied to each tension member. A tensegrity structure may be formed from tensegrity units by joining a number of tensegrity units together.



United States Patent [19] [11] **4,148,520**
Miller [45] **Apr. 10, 1979**

[54] **PIECE OF FURNITURE**

[76] Inventor: **Ross M. Miller,** 514 E. First St., Moscow, Id. 83843

[21] Appl. No.: **765,823**

[22] Filed: **Feb. 4, 1977**

[51] **Int. Cl.**[2] **A47B 4/00**
[52] **U.S. Cl.** **297/16;** 52/648; 297/441
[58] **Field of Search** .... 297/16, 25, 45, 440, 297/441, 445, 449, 457; 52/648; 211/119.5, 119.01; 24/136 R

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3,206,037	9/1965	Woolsey	211/119.5
3,866,366	2/1975	Fuller	52/648
3,901,551	8/1975	Wiesner	297/16 X

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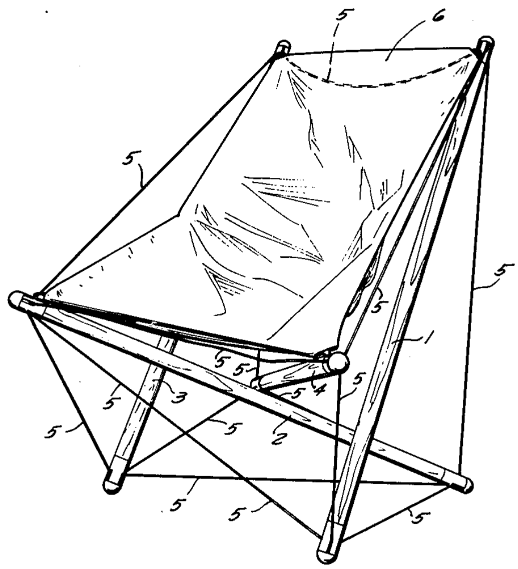
11379 of	1913	United Kingdom	297/16

Primary Examiner—Roy D. Frazier
Assistant Examiner—Peter A. Aschenbrenner
Attorney, Agent, or Firm—Michael J. Striker

[57] **ABSTRACT**

A chair has four poles the ends of which are connected by cables or other tension-transmitting elements so that the poles are held in generally upright, spaced and mutually inclined positions. A textile or other flexible support is connected to the upper ends of the poles and when a weight rests on this support the cable becomes taut and the poles fixed in their positions.

7 Claims, 2 Drawing Figures



United States Patent [15] **3,695,617**
Mogilner et al. [45] **Oct. 3, 1972**

[54] **TENSEGRITY STRUCTURE PUZZLE**

[72] Inventors: **Geoffrey A. Mogilner,** 2070 California St., W., San Diego, Calif. 92110; **Rodney D. Johnson,** San Diego, Calif.

[73] Assignee: **said Mogilner, by said Johnson**

[22] Filed: **June 11, 1971**

[21] Appl. No.: **152,055**

[52] **U.S. Cl.** **273/156,** 46/29, 52/81, 273/159

[51] **Int. Cl.** **A63f 9/08**

[58] **Field of Search** 273/156, 159; 52/81, 646

[56] **References Cited**

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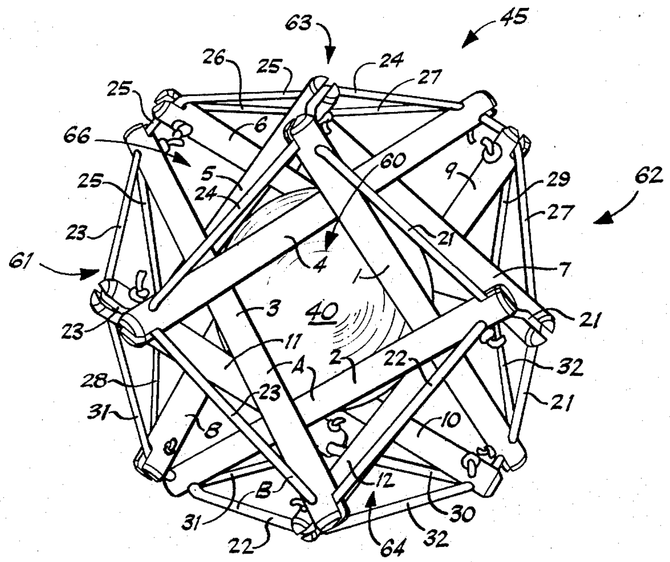
Primary Examiner—Anton O. Oechsle
Attorney—Bernard Kriegel

[57] **ABSTRACT**

A puzzle comprising a cage-like tensegrity structure including a plurality of rigid columns having flexible tension members connected between the opposite ends thereof and having a slot at each end thereof. Each of the columns is slidably supported at opposite ends thereof by the tension members of adjacent columns, which tension members extend through the slots in the columns. A solid or hollow object is positioned within the cage-like structure, the object having an outer dimension which is sufficiently large so as to prevent removal thereof from the structure except when the structure is manipulated to one of a limited number of geometric shapes. According to a preferred embodiment of the present invention, the structure comprises twelve columns and forms a polyhedron having six quadrilateral sides and eight hexagonal sides. The object may be removed from the cage-like structure by contracting four of the six quadrilateral sides and then expanding one of the two remaining quadrilateral sides.

13 Claims, 4 Drawing Figures



United States Patent [19]

Nelson

[11] Patent Number: 4,614,502

[45] Date of Patent: Sep. 30, 1986

[54] **TELESCOPING STRUT MEMBERS AND TENDONS FOR CONSTRUCTING TENSILE INTEGRITY STRUCTURES**

[76] Inventor: **William A. Nelson**, 52 High St., Middlebury, Vt. 05753

[21] Appl. No.: **710,629**

[22] Filed: **Mar. 11, 1985**

[51] **Int. Cl.**[4] **A63H 33/00**

[52] **U.S. Cl.** **446/119**; 52/645; 52/648; 52/DIG. 10; 135/106

[58] **Field of Search** .... 52/81, 648, 645, DIG. 10; 135/106; 446/119

[56] **References Cited**

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4,236,543	12/1980	Moss	135/106
4,404,240	9/1983	Varela	52/DIG. 10
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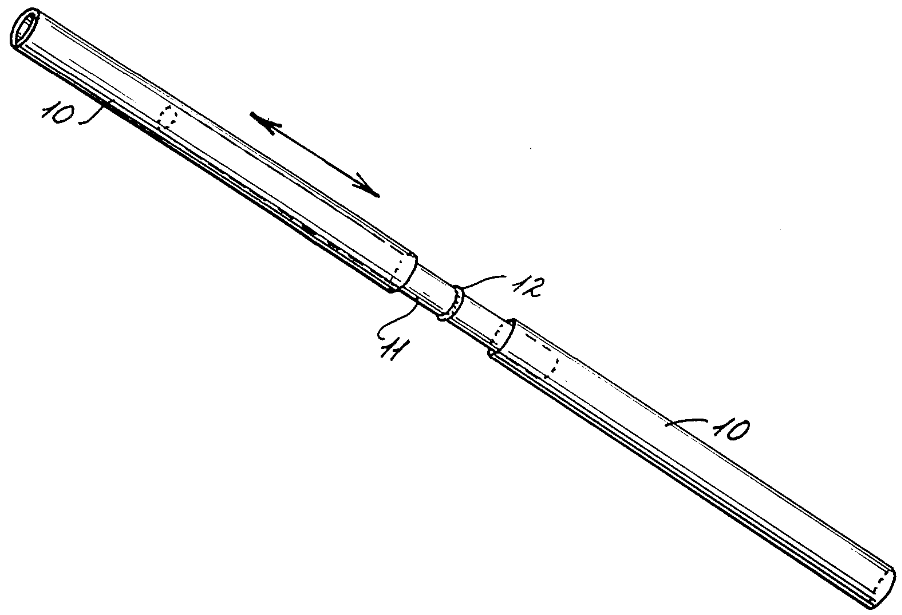
2396129	3/1979	France	52/DIG. 10

Primary Examiner—J. Karl Bell

[57] **ABSTRACT**

A construction kit consisting of telescoping strut members and pre-measured elastic or inelastic tendons, for the purpose of constructing tensile-integrity structures. The invention is made of reusable elements. By introducing struts which can be adjusted to various lengths the invention circumvents the necessity of measuring, cutting and tying different lengths of tendons for different structures and considerably simplifies the construction process.

3 Claims, 7 Drawing Figures



(12) DEMANDE INTERNATIONALE PUBLIÉE EN VERTU DU TRAITÉ DE COOPÉRATION EN MATIÈRE DE BREVETS (PCT)

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(22) Date de dépôt international : 3 avril 2002 (03.04.2002)

(25) Langue de dépôt : français

(26) Langue de publication : français

(30) Données relatives à la priorité :
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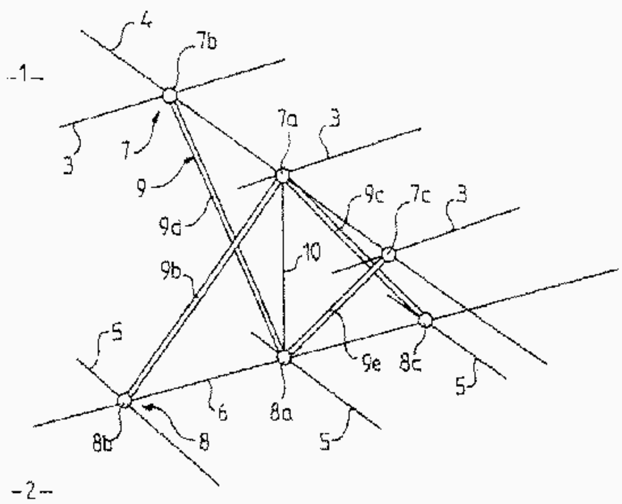
(72) Inventeurs; et
(75) Inventeurs/Déposants *(pour US seulement)* : **RADUCANU, Vinicius** [FR/FR]; 7, rue du Prof. Emile Tédenat, F-34070 Montpellier (FR). **MOTRO, René** [FR/FR]; 6, rue des Pilettes, F-34680 Saint Georges D'Orques (FR).

(74) Mandataires : **PEAUCELLE, Chantal** etc.; Cabinet Armengaud Aine, 3, Avenue Bugeaud, F-75116 Paris (FR).

(81) États désignés *(national)* : AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX,

(54) Title: STABLE SELF-BALANCING SYSTEM FOR BUILDING COMPONENT

(54) Titre : SYSTEME A AUTOEQUILIBRE STABLE POUR ELEMENT DE CONSTRUCTION



(57) Abstract: The invention concerns a criss-cross system, comprising surface layers (1, 2), delimiting its opposite surfaces, each layer including a set of criss-crossed cables (3-4, 5-6) forming an organised network of nodes (7, 8) whereon are articulated the ends of rigid rods (9), providing the link between the layers, said rods, associated with pull wires (10), forming in the space between the layers a plurality of spacers. Each of the spacers comprises two bundles consisting each of at least two rods converging towards and assembled by one common end to a node of a layer, their opposite ends being linked to neighbouring nodes of the other layer. Furthermore, each pull wire is arranged between two nodes belonging to the two bundles, said pull wire being tensioned to exert on the rods a compressive force and likewise tension the criss-crossed cables at the nodes of the layers, globally providing the assembly with stable self-balance.

[Suite sur la page suivante]

United States Patent [19]
Skelton

[11] **Patent Number: 5,642,590**
[45] **Date of Patent: Jul. 1, 1997**

[54] **DEPLOYABLE TENDON-CONTROLLED STRUCTURE**

[75] Inventor: **Robert E. Skelton**, West Lafayette, Ind.

[73] Assignee: **Dynamic Systems Research, Inc.**, LaJolla, Calif.

[21] Appl. No.: **551,010**

[22] Filed: **Oct. 31, 1995**

[51] **Int. Cl.**[6] **E04B 7/08**
[52] **U.S. Cl.** **52/81.1**; 52/641
[58] **Field of Search** 52/81.1, 81.3, 52/DIG. 10, 81.2, 80.1, 81.4, 291, 641, 646, 649.5, 109, 110, 111, 114; 135/124, 126, 128, 131

[56] **References Cited**

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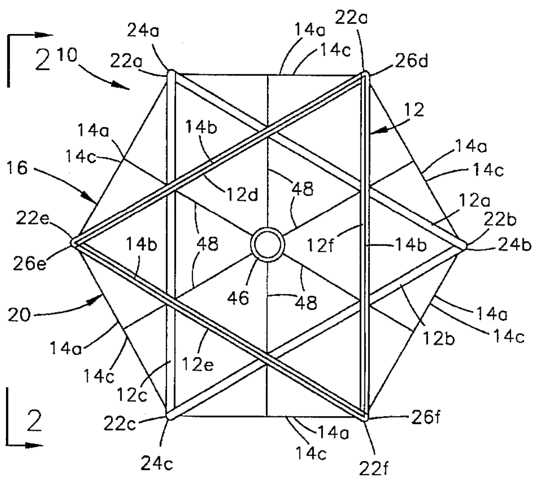
Primary Examiner—Creighton Smith
Attorney, Agent, or Firm—Gary M. Hartman; Domenica N. S. Hartman

[57] **ABSTRACT**

A lightweight, deployable structure capable of large displacements and sustaining high loads, and whose shape can be precisely monitored and controlled to acquire a wide variety of shapes and varying levels of stiffness, and precisely returned to a desired shape after being subjected to a disturbance force. As such, the structure is highly suitable for use in applications in which information concerning the shape and/or stiffness of the structure can be employed to precisely attain a desired shape, precisely return the structure to a desired shape after being subjected to a disturbance force, or to increase or decrease the structural stiffness in response to changing environmental conditions. The deployable structure is generally composed of one or more structural units, each of which can be articulated between two extreme configurations, one of which is a deployed configuration in which the deployable structure is fully extended. The shape and stiffness of each structural unit is established by rigid compression members that are interconnected by elastic tension members to form two interconnected tiers. The compression and elastic members are interconnected such that the compression members are subjected to essentially axial loads. The shape and stiffness of the structural unit is controlled by loosening and tightening one or more of the tension members and/or shortening and lengthening one or more of the compression members.

20 Claims, 3 Drawing Sheets



U.S. Patent **Jul. 1, 1997** **Sheet 1 of 3** **5,642,590**

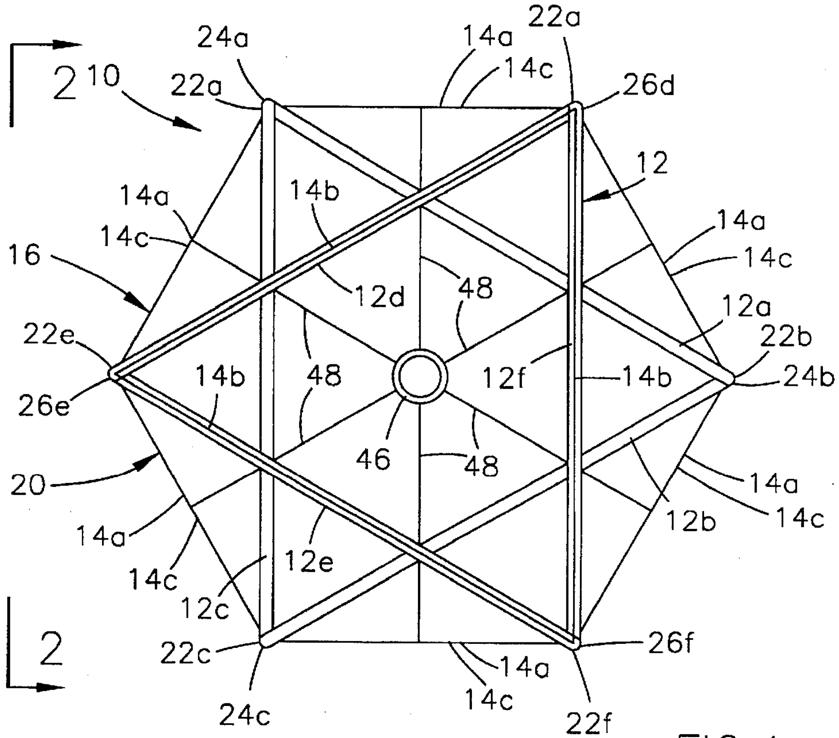


FIG. 1

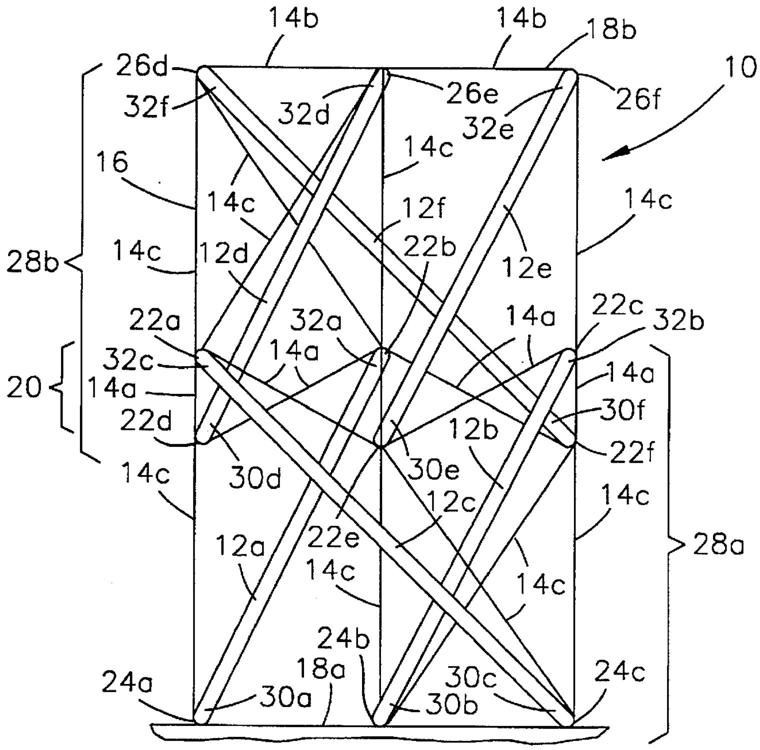


FIG. 2

(12) **United States Patent**
Stern

(10) **Patent No.:** **US 6,542,132 B2**
(45) **Date of Patent:** **Apr. 1, 2003**

(54) **DEPLOYABLE REFLECTOR ANTENNA WITH TENSEGRITY SUPPORT ARCHITECTURE AND ASSOCIATED METHODS**

(75) Inventor: **Ian Stern**, Melbourne, FL (US)

(73) Assignee: **Harris Corporation**, Melbourne, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 13 days.

(21) Appl. No.: **09/879,539**

(22) Filed: **Jun. 12, 2001**

(65) **Prior Publication Data**

US 2002/0190918 A1 Dec. 19, 2002

(51) **Int. Cl.**[7] **H01Q 15/20**
(52) **U.S. Cl.** **343/915**; 343/880
(58) **Field of Search** 343/912, 915, 343/916, 840, 880; H01Q 15/14, 15/16, 15/20

(56) **References Cited**

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UF News for 21st Century Campers and Soldiers, "A Tent that sets itself up" by Aaron Hoover dated Dec. 13, 1999.
Article on "Furlable Reflector Concept for Small Satellites" by A.G. Tilbert and S. Pellegrino published by the American Institute for Aeronautics and Astronautics.

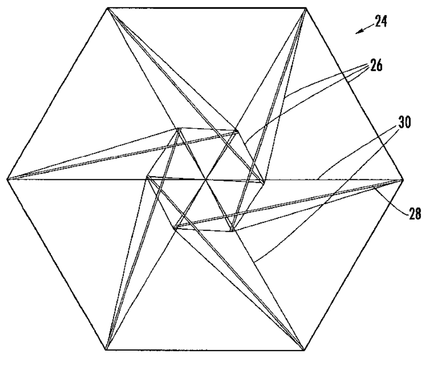
* cited by examiner

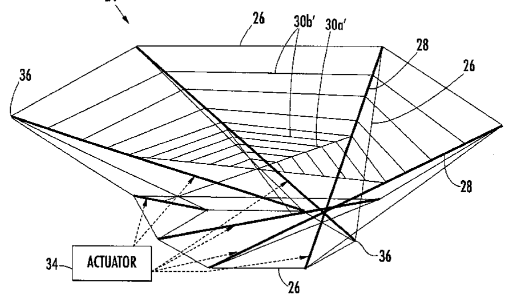
Primary Examiner—Michael C. Wimer
(74) *Attorney, Agent, or Firm*—Allen, Dyer, Doppelt, Milbrath & Gilchrist, P.A.

(57) **ABSTRACT**

The deployable antenna with the tensegrity support structure and mounting frame has improved specific mass, compact stowage volume and high deployment reliability. The reflector is mounted to the tensegrity support structure via the mounting frame which ensures proper deployment of the reflector in the desired antenna operating shape.

30 Claims, 7 Drawing Sheets





United States Patent [19]

Terry

[11] **Patent Number: 5,502,928**

[45] **Date of Patent: Apr. 2, 1996**

[54] **TENSION BRACED DOME STRUCTURE**

[75] Inventor: **Wesley R. Terry**, North Tonawanda, N.Y.

[73] Assignee: **Birdair, Inc.**, Amherst, N.Y.

[21] Appl. No.: **281,224**

[22] Filed: **Jul. 27, 1994**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 132,566, Oct. 6, 1993, abandoned.

[51] **Int. Cl.**[6] **E04B 1/32**

[52] **U.S. Cl.** **52/80.1**; 52/63; 52/83

[58] **Field of Search** 52/80.1, 80.2, 52/81.1, 63, 83, 22

[56] **References Cited**

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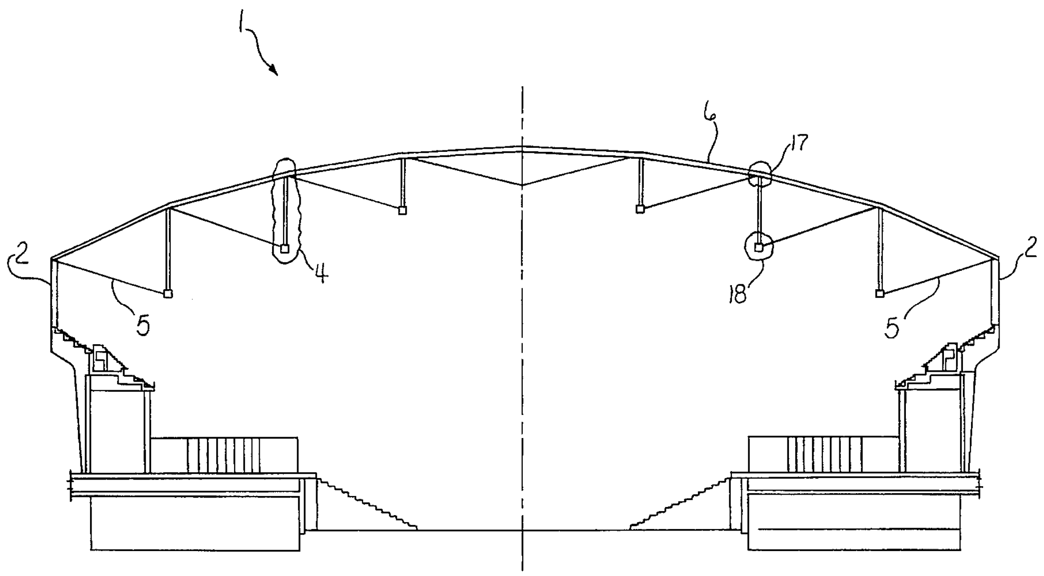
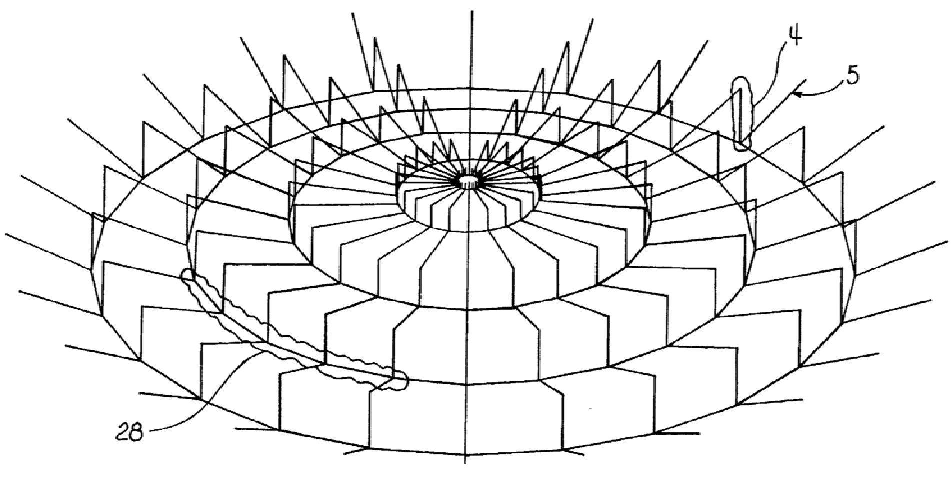
Primary Examiner—Carl D. Friedman
Assistant Examiner—Beth Aubrey
Attorney, Agent, or Firm—Kellie M. Muffoletto; Saperston & Day

[57] **ABSTRACT**

The present invention is a tension braced dome structure comprised of a top ridge having at least one upper ridge radial member and at least one circumferential member which is concentric with an edge member; wherein the upper ridge radial member and the circumferential member are capable of carrying compressive and tensile loading; and further comprising a tensegrity grid having at least one diagonal member, and at least one lower compression member, and at least one lower cicumferential member; wherein said diagonal member extends between the upper ridge radial member and the compression member; and still further having a means for resolving internal stresses as an integral part of the top ridge; and a means for adjusting tension in the diagonal member.

13 Claims, 7 Drawing Sheets





United States Patent [19]
Wiesner

[11] **3,901,551**
[45] **Aug. 26, 1975**

[54] **STRESSED STRUCTURE FOR SUPPORTING WEIGHT**

[76] Inventor: **Stephen J. Wiesner**, 2331 Oberlin, Palo Alto, Calif. 94306

[22] Filed: **Oct. 9, 1973**

[21] Appl. No.: **404,176**

[52] **U.S. Cl.** **297/447**; 52/648; 297/16; 297/45; 297/441

[51] **Int. Cl.**[2] **A47C 4/00**

[58] **Field of Search** 297/16, 25, 45, 440, 441, 297/445, 449, 457; 52/648

[56] **References Cited**

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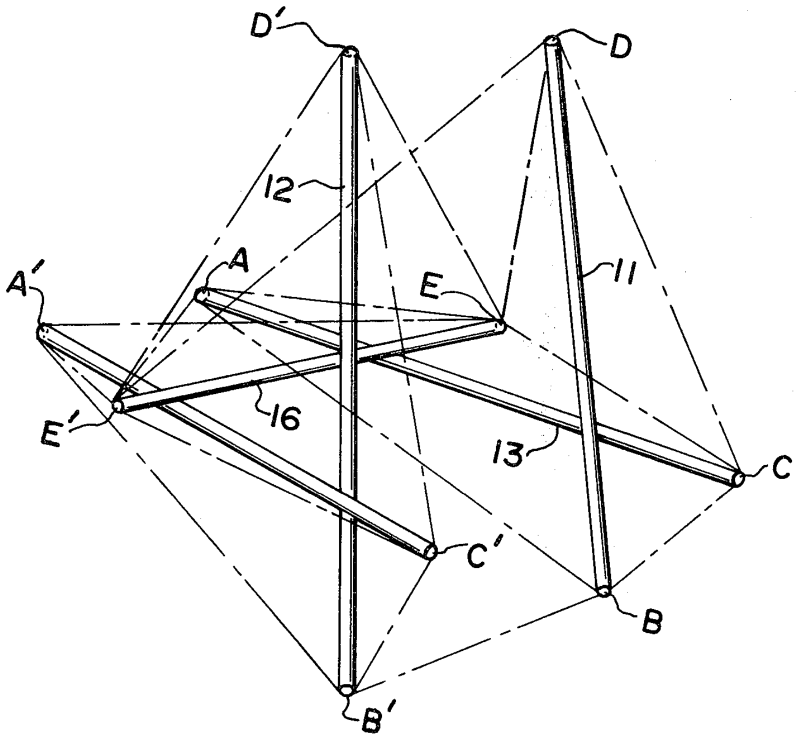
"Geodesics," by Edward Popko, 1972, Fig. No. 50.

Primary Examiner—Robert L. Wolfe
Assistant Examiner—Kenneth J. Dorner
Attorney, Agent, or Firm—Flehr, Hohbach, Test, Albritton & Herbert

[57] **ABSTRACT**

A stressed structure assembly providing support for a predetermined maximum weight, such as a chair having a framework supporting a seat. Framework members are assembled so that each member is in pure compression or tension. Framework member configuration is of comparatively light cross section due to the absence of necessity for supporting bending stress. The framework includes means for supporting the assembly on a surface which is conformable to irregularities in the surface.

3 Claims, 3 Drawing Figures



Appendix E. Deflection of the expanded octahedron

In order to show the Elasticity Multiplication of tensegrity systems, the deflection of the expanded octahedron modelled by cables and beams finite elements (Mijuca, 1997), can be seen in next figures:

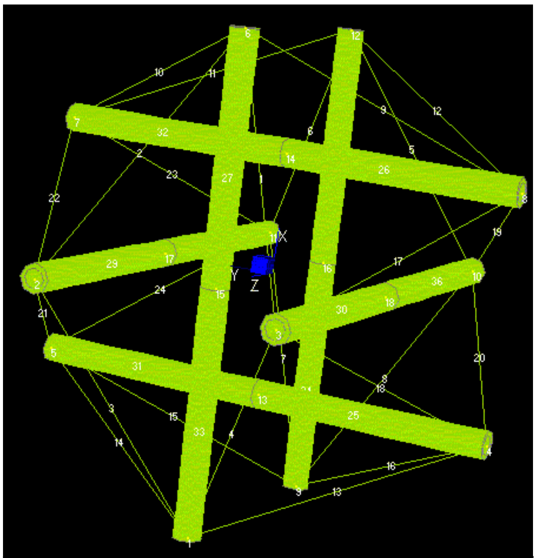


Fig. 1.
"Tensegrity, no deformation"
Illustration taken from (Mijuca, 1997)

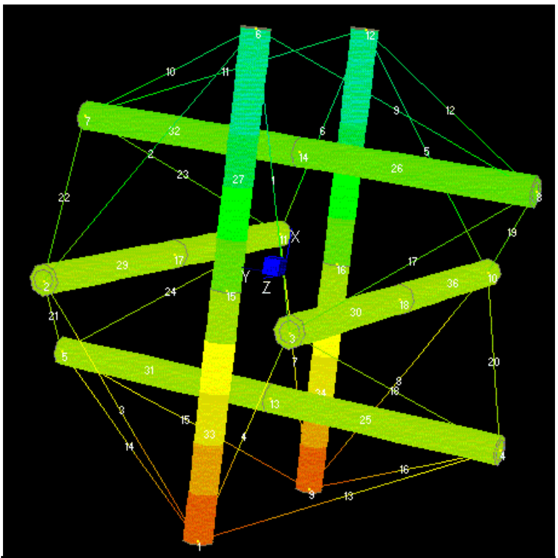


Fig. 2.
"Tensegrity, mid-deformation"
Illustration taken from (Mijuca, 1997)

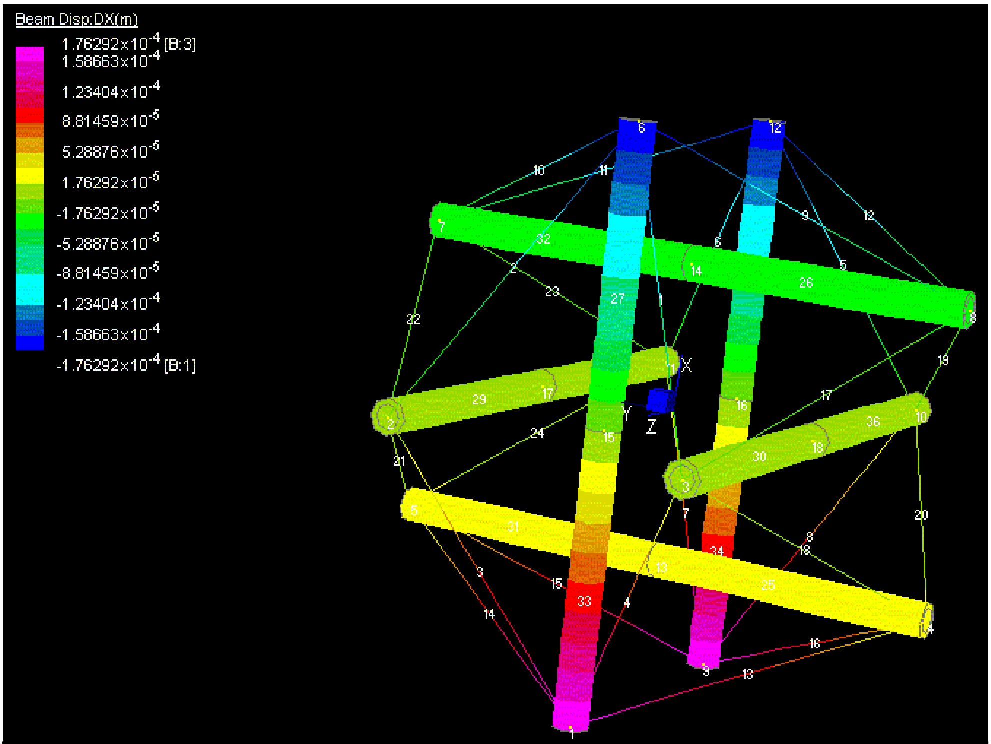


Fig. 3.
"Tensegrity, no deformation" Illustration taken from (Mijuca, 1997)

Appendix D. Personal correspondence

D.1. Correspondence with Kenneth Snelson.

Kenneth Snelson is a very recognized sculptor, Art studies in University of Oregon, Eugene, Oregon; Black Mountain College, Black Mountain, N.C.; Fernand Leger, Paris. He discovered *floating compression* in 1948, which Fuller popularised as *tensegrity*. However, his sculptures have done more to spread the concept of *tensegrity* than anybody else. For further references, see chapter 2.

D.2. Correspondence with Mike Schlaich.

Mike Schlaich is a Civil Engineer at the University of Stuttgart (Germany), and at the Suisse Federal Institute of Technology (ETH) in Zürich, Switzerland (Dipl.-Ing. ETH). Since the year 2000, he has been lecturing at the University of Stuttgart, class "Bauen mit Seilen" (building with cables). He is also a partner and managing director of the company “Schlaich Bergermann und Partner”. He was the director of the design of the Rostock Tower, in Rostock (Germany).

D.3. Correspondence with Arturo Ruiz de Villa Valdés.

Arturo Ruiz de Villa is a Civil Engineer, degree in the E.T.S. de Ingenieros de Caminos Canales y Puertos de Santander, Universidad de Cantabria (Spain). At present, he is working in “Arenas Y Asociados” (Santander). He was the person responsible for the calculation of the Rostock Tower while he was working in Schlaich’s consulting “Schlaich Bergermann und Partner”.

D.4. Correspondence with Robert W. Burkhardt.

Robert W. Burkhardt is the author of the publication “A practical guide to tensegrity design”, and in his web page he shows very interesting points about tensegrity applications (see Bibliography).

D.1. Correspondence with Kenneth Snelson.

Asunto:	Re: To K.Snelson - Questionnaire
Para:	"VALENTIN GOMEZ JAUREGUI"<valentin.gomez@alumnos.unican.es>
De:	kenneth snelson <k_snelson@mindspring.com>
Fecha:	Sun, 18 Jul 2004 13:09:37 -0400

Dear Mr. Jáuregui,

I appreciate that you are interested in my work. It would seem from your request that in your imagination I am sitting by a window somewhere trying to think of what I might do to kill time.
I'm happy to say this is not the case. I am overwhelmed with projects that take all of my time. I do not have empty hours to fill out forms or questionnaires. That is one of the benefits of publishing so many of my ideas and articles at my website. There is much to read and much to learn and, as a student, you should look there for your research to the extent that my work is part your thesis.

Best wishes for success in your dissertation,

Kenneth Snelson

Asunto:	Re: From Jauregui, Tensegrity dissertation
Para:	"VALENTIN GOMEZ JAUREGUI"<valentin.gomez@alumnos.unican.es>
De:	kenneth snelson <k_snelson@mindspring.com>
Fecha:	Tue, 20 Jul 2004 08:18:03 -0400

Dear Mr. Jauregui,

If my response to your inquiry was harsh it's because I receive many emails from people with rather pointless ideas which I spend time trying answering. I've grown weary of it especially since I never hear a word from them again. The web is wonderful but it's also a place where anonymity makes the contact seem a waste of time.
Yes, I will be send you pictures for your paper. In brief though, it is my belief based on long experience and making endless numbers of tensegrity structures of all shapes and sizes that the principle in itself is impractical for building buildings. As you know many architects and engineers have worked toward that end and still do. Fifty years of it now. None have shown there is the slightest structural advantage in its use for such purposes.

Fuller gained much of his fame as a salesman selling tensegrity snakeoil; claiming he could "bridge the Grand Canyon with tensegrity". Emmerich labeled me a "defeatist" because I said that tensegrity is not a sound building strategy.

However, just look at the range of my work compared with that of either of those two guys. They produced nothing useful nor enduring with tensegrity. See my 90' tower at the Kroeller Mueller in Holland or "Easy Landing" in Baltimore Md.

Enough said except that there are many theses from architectural students around the world that have been infected with the tensegrity fever. It's perhaps analogous to people's trying to achieve perpetual motion in the nineteenth century.

I am also struck by your having picked up somewhere on Bucky's endless claims of having invented everything in the universe. Where did you get the idea he had produced an atom model? If he did it's news to me. Some of his disciples often show my work with a sly implication that it is Fuller's. Maybe that's what you referred to in your question about atom models.

Tell me which pictures you need and I'll try to find time to locate files large enough for print.

Kenneth Snelson

Asunto:	Re: From Jauregui, some other points
Para:	"VALENTIN GOMEZ JAUREGUI"<valentin.gomez@alumnos.unican.es>
De:	Kenneth Snelson <k_snelson@mindspring.com>
Fecha:	Tue, 3 Aug 2004 15:16:00 -0400

1 TEXT/PLAIN 6852 bytes Adjunto mostrado debajo
2 IMAGE/JPEG 78626 bytes, "Cantilever30'1967.jpg"
3 IMAGE/JPEG 86218 bytes, "1961SpringSt.KenPlanar.jpg"

Dear Mr. Jáuregui,

It really comes down to this: until you actually build a few of these structures you won't understand the issues involved.

1)Bucky's "tensegrity dome" or sphere is by its nature as soft as a marshmallow; no way to avoid that as long as one stays with discontinuity. Most important: it's not a triangulated structure

2) the other domes you cite can not be considered tensegrity, regardless what people wish to call them. They are, essentially, bicycle wheels. Did the world need a different name for that kind of solid rim, exsoskeletal structure? I think not; same with a spider web. I've made this point in my writings which you probably have come across in your research. Yes, Fuller declared that everything in the universe was tensegrity. Tensegrity structures are endoskeletal prestressed structures -- and that restriction leaves out endless numbers of items. As I've also said elsewhere, if everything is tensegrity then tensegrity is nothing of any particular sort; so what's the point in using that word?

As for my friend Rene Motro's double-layer planes, I was fascinated with these when I first made them in 1961. Attached is a photo of the artist as a young man back then with one of my experiments. These planes are also very flexible and I know of no instance where they've been put to use for any practical purpose. Two of my planar pieces are in sculpture collections.

Here attached also is a photo of the "30' Cantilever" which I guess is the piece you are referring to. It's the only cantilever I've done whose name is Cantilever.

If I've repeated here what I said in my last message I wouldn't be surprised.

Best wishes,

Kenneth Snelson

Asunto:	Re: From Jauregui, from other address
Para:	"VALENTIN GOMEZ JAUREGUI"<valentin.gomez@alumnos.unican.es>
De:	Kenneth Snelson <k_snelson@mindspring.com>
Fecha:	Mon, 23 Aug 2004 15:03:24 -0400

1 TEXT/PLAIN 5787 bytes, "", "" Adjunto mostrado debajo
2 APPLICATION/MSWORD 35840 bytes, "", "MariaGough.doc"

Dear Mr. Jaurequi,

Once again, I don't know why, but here goes.

As you note, the sculpture by Ioganson that Rene Motro focuses on is not a prestressed structure. The other Ioganson piece, the one in the far background of the famous Constructivist Exhibition photo, was "replicated" from the photo by a Mr. Koleichu for the Guggenheim Museum exhibition a few years ago and was said to be the "first tensegrity". It was also the subject of an article in "October" magazine by Maria Gough, now at Stanford. My thoughts about it are included in the attached letter to Ms Gough about Ioganson whom she discussed in the article which will be included in her upcoming book. In any case, no, I was not influenced by Mr. Ioganson.

You use the expression, "a battle of egos" about Fuller and me. Is it not, rather, a matter for accuracy in reporting?

Also, for Bucky to have kept repeating the silly tale that (still in print on the web) "I told Ken, when I first saw his wood sculpture that what he had discovered was tensegrity." How perfectly goofy. It would have dated his using the word "tensegrity at least six years before he coined it.

His statements about tensegrity's magical property, very short compression members, that presumably make it a supernaturally efficient structure is, again, nonsense. Short compression struts mean long tension lines which mean extreme elasticity. The struts can't be all that lightweight because they must support enormous compression loads. They need heavy and robust end-fixtures in order to absorb the powerful tension forces that pull outwardly with great cumulative force. The short-compression-members assertion is somehow analogous to Bucky's glib answer when someone during a lecture challenged him about an echo-chamber effect inside one of his domes: "No problem at all: just place a sponge at the focal center to absorb the sound." At least his charlatanism was charming.

You say, "On the other hand, Fuller and Emmerich took the scientific approach, studying the different possible topologies...using mathematics." I strongly challenge your assertion that their method was somehow "science" as opposed to my blind approach. Science goes from theory to proof by testing. Fuller made grandiose claims with no testing whatsoever. No one has developed a computer program or algebraic formula that can design tensegrity with any degree of accuracy. There are simply too many variables including the ultimate "tuning" of the piece which can only be done in the field, empirically. If I had been a brilliant mathematician instead of a skillful and inventive model builder, my widely varied collection of works simply would not exist. Look at the facts: how many genuine tensegrity works did Fuller produce in his lifetime? Also compare the "structures" analytic study at my website against anything either Pugh, Fuller, Emmerich or Kenner have to tell you about how these structures work.

Why is it that you and others characterize artists as naifs whose work is frivolous whereas men who call what they do "science" are trusted to have profound understanding of heavyweight matters? Fuller built his tensegrity dome based on measurements of his small models. My bet is that Emmerich worked also with models and then built his larger pieces based on them as reference, measuring what actually turned out. What makes there work science? Other than the comparative output the main difference is that they were pursuing the goal of utility and neither succeeded in that.

You say about Fuller's domes: "However, the final application of Tensegrity was not as successful as he thought it would be; he was never able to produce a Tensegrity dome which could cover the whole city, as he intended." My God, man, even his cigar-strut "Geodesic Tensegrity Dome" you show sitting in that workspace could barely hold itself up. Despite all his celebrating of triangulation, his tensegrity domes are not triangulated and therefore are as shaky and floppy as a Tensegritoy. Show me any tensegrity structure whose tension network is not fully triangulated and I'll show you a flaccid structure as is the case for most of Connelly's and Black's inventory.

Again: "On the other hand, Kenner developed the useful "Geodesic Math and How to Use It" which shows how to calculate "to any degree of accuracy" the pertinent details of geodesic and tensegrity structure's geometry. Pertinent details? What does that mean? and for what variety of tensegrity structures?

You ask about the fabrication costs for my sculptures: Roughly, depending on the size of the work, the cost of fabricating an outdoor piece is roughly twenty-five percent of the gallery's selling price. Galleries take, after costs are subtracted, fifty-percent of the selling price. A piece like "Mozart I" would today sell for from four to five hundred thousand dollars.

I think this covers most of what I see as problems in Chapter 2. I trust that you'll be able to include the facts of this message and still find a way to get where you're going in your thesis. Omitting the truth about tensegrity won't improve the quality of your scholarship.

Best wishes,

Kenneth Snelson

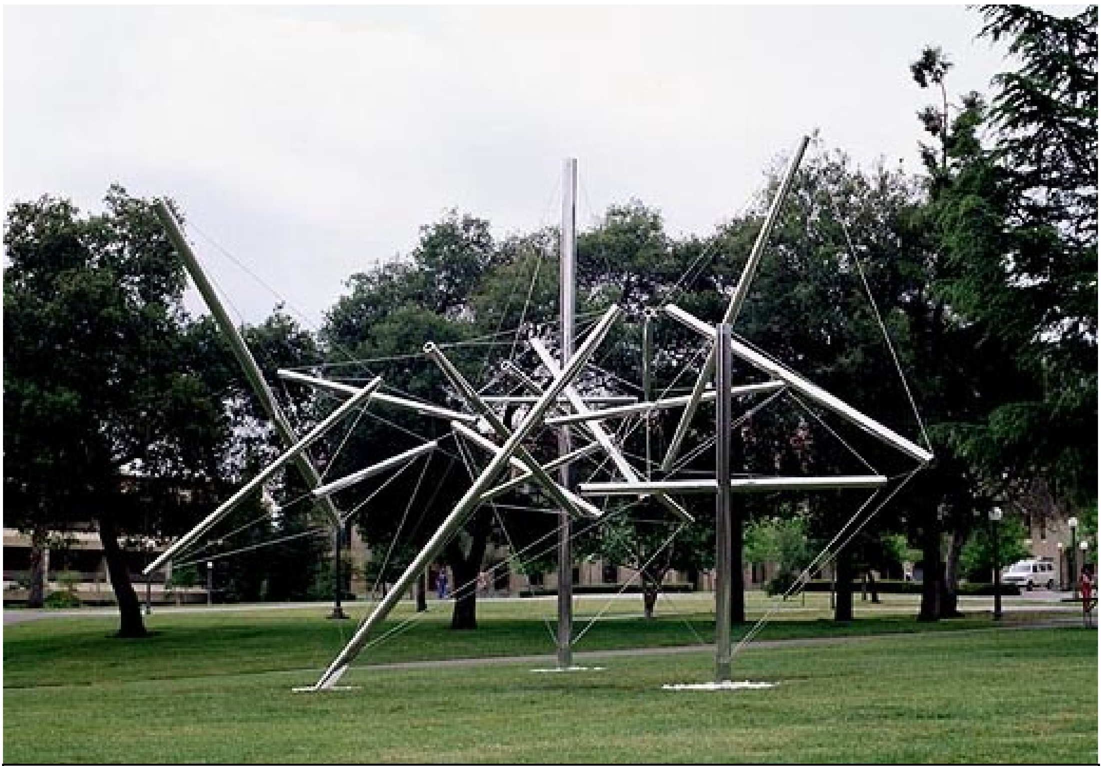


Fig. D.3.
“**Mozart 1**” by Kenneth Snelson (1982) Stainless steel (7x9x9m) Stanford University, CA
Illustration taken from Snelson (2004)

Letter from Kenneth Snelson to Maria Gough. June 17, 2003

Dear Maria Gough, June 17, 2003

What a surprise to learn that you were in the audience at my talk at Michigan. I do wish you had introduced yourself because I have your 1998 October 84 piece. I’m bad with names so when I got Ms Schwartz's email about pictures I regret I didn't make the connection that you are the author of that excellent paper.

I found the "In the Laboratory, etc." article fascinating and informative when a fellow from Latvia named Juris Sils faxed it to me in connection with an exhibition of Karl Ioganson’s work he was trying to make happen. Don’t know the end result of his plan.

I take it that your request for the particular pictures you wish to use in your upcoming book are in regard to the Karl Ioganson theme of your original paper? I appreciate your involvement with the Constructivists and their art and history and I want not to detract from your fine scholarship but I do wish you had talked with me beforehand since you try to deal with the subject of tensegrity and I don’t think you had the best of sources. Bucky Fuller’s claims about these structures are off the wall.

Karl Ioganson, according to your paper apparently struggled with those three octahedral variations, your illustration #10 “spatial constructions, which tell us something about his focus on crosses. He then, by some unrecorded steps, came across what one now calls a three-way, or three-strut, tensegrity module. By the way, the entire three-way structure is the module if used as such. The individual sticks are not modules but simply compression struts. A module is a whole object or closure that, when attached or interconnected with similar objects can create a more complex form. If Ioganson had made another three-strut tensegrity, or several of them, and connected them together in one of several ways, that expanded object would be a modular structure, say like my “Needle Tower”. But in themselves, neither the individual struts nor the individual tendons are modules, only parts. Attached are two pictures from early studies, primitive works composed of two-way, or x-modules. The materials are wooden dowel sticks painted silver and string.

When I saw the 1992 catalog of the Guggenheim show with Mr. Koleichuk’s reconstructions of Ioganson’s small sculptures, I thought, “Well, it’s curious since even I wouldn’t have been able to make out from that famous jumbled 1921 exhibition photo that Ioganson’s piece (marked number IX) was indeed a three-strut tensegrity structure.” I then considered, since even I wouldn’t have been able to verify it as such, that Koleichuk would have no way of guessing at the object, sticks positioned and strings properly attached, except that he had studied my work, or Bucky Fuller’s or David Emmerich’s. No one on Earth would have been able to discern the nature of IX without prior acquaintance with the tensegrity primary. The hint that he had studied me was your quote from Koleichuk which is an appropriated paraphrase, “It is as if they are floating in a net of... Wires” Coming across one’s own words mouthed by a stranger is eerie indeed. My standard descriptive name, “floating compression” goes back to, at least, 1962.

So, is number IX indeed what Koleichuk says it is? Once you see his model it looks like the piece there in the background. If indeed it is, is it not uncanny that Ioganson nor anyone else left a comment about this surprising object; that he himself placed no emphasis on it; that he apparently quite abandoned his amazing discovery with no follow-up? Did none of the other artists or visitors think it represented a remarkable phenomenon? Wouldn’t one expect him to take a next step, any next step that would let us know he had a grasp of what was going on with the structure? Apparently not. As far as we can tell, the startling discovery just sat there among his other works and those of his colleagues, absent of discussion.

Your paper argues that he didn’t have sufficiently high-tech materials in order to move forward. This is less than convincing since he would have had sticks and strings, the materials he already was using, that I was using at the beginning. Would he not have asked, “What if I use four sticks instead of three, will that work?” It doesn’t hold water that Karl Ioganson was thwarted by inadequate materials. Perhaps some political pressure ended his quest or perhaps his inventiveness or inquisitiveness simply had its limits.

At the end of your paper, you compare the Stenberg brothers’ and Ioganson’s aspirations with their actual achievements and you award Mr. Ioganson the prize: “(Karl Ioganson) invents a new principle -- a prototensegrity principle -- that would come to have, in the course of the twentieth century, enormous functional significance.” The unfortunate fact is that tensegrity is not and never was functional except for the function in my sculptures of permitting viewers to admire the nature of pure structure. As I no doubt said at Michigan, tensegrity works the way it does because it is an equilibrium of contesting forces within a closed system. But the forces within the system need to be so huge that the structure becomes inefficient for supporting any external loads.

Over the past fifty years, if a clever architect, a real estate agent or a greedy entrepreneur had figured out a way to make tensegrity into a reasonable building system, or even an unreasonable one, the country would be dotted with novelty shopping centers or MacDonalds supported by tensegrity golden arches since, beyond all other attributes, novelty is great for commerce. Yes, Bucky Fuller exploited his puffed up tensegrity claims shamelessly even though he knew better. By now, too, the very word has become garbled. For example the engineer Mathys Levy calls his great dome in Atlanta “tensegrity” whereas it actually is a beautifully designed giant bicycle wheel; and tension-spoke bicycle wheel with its major load-bearing rim is not tensegrity no more than is a spider web. Similarly, the Harvard microbiologist Donald Ingber invokes tensegrity as a buzzword to bolster a contested theory of cell structure. To him, a geodesic dome is synonymous with tensegrity.

I regret that this letter grew much longer than I possibly imagined when I started out, but I think it’s important for you as well as for me and for the sake of your splendid scholarship. I very much look forward to the publication of your book but I hope you have the chance to work out these problems before it goes to press.

Please let me know your purpose in choosing my 1967 stainless steel X-Piece for illustration. Out of fairness, I would much prefer you include a photo of something really representative such as “Needle Tower”, “Easy Landing” or other major piece for the benefit of those who know nothing of my work and might take it that I stopped producing way back then.

Ms Gough, I realize my discussion here sounds harsh but it isn’t meant to be hostile, only corrective. I’m sure your book will be much more complete than your thesis which, to me came across as forceful, clear and highly intelligent.

Warmest wishes for the book,

Kenneth Snelson

D.2. Correspondence with Mike Schlaich.

Asunto:	tensegrity
Para:	valentin.gomez@alumnos.unican.es
De:	m.schlaich@sbp.de
Fecha:	Wed, 7 Jul 2004 19:02:24 +0200

Estimado Valentín,

gracias por tu mail. Nosotros hemos proyectado la torre de Rostock, que con sus 62m de altura probablemente es la torre tensegrity más alta hasta ahora.

Mañana te mandamos un artículo (en aleman) sobre la estructura.

Saludos de Stuttgart, Mike Schlaich

Mike Schlaich, Dr. sc. techn.
Schlaich Bergermann und Partner
Hohenzollernstr.1, D-70178 Stuttgart
fon: +49-711-6487114
fax: +49-711-6487166
e-mail: m.schlaich@sbp.de
http://www.sbp.de

Asunto:	Antwort: Articulo Tensegrity
Para:	"VALENTIN GOMEZ JAUREGUI" <valentin.gomez@alumnos.unican.es>
De:	m.schlaich@sbp.de
Fecha:	Mon, 19 Jul 2004 14:23:05 +0200

Valentin:

La revista Alemana se llama "Stahlbau" la editora es "Ernst und Sohn" y salió en Octubre 2003:

[x] M.Schlaich: Der Messeturm in Rostock - ein Tensegrityrekord; Stahlbau 72 (2003), Heft 10, Ernst & Sohn (in German).

Para que sepas: hacía finales del año saldrá una versión inglés de este artículo en la revista: JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES: IASS.

Saludos, Mike

Mike Schlaich, Dr. sc. techn.

Asunto:	Antwort: Dissertation Tensegrity
Para:	"VALENTIN GOMEZ JAUREGUI" <valentin.gomez@alumnos.unican.es>

De:	m.schlaich@sbp.de
Fecha:	Mon, 30 Aug 2004 08:52:32 +0200

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2 APPLICATION/OCTET-STREAM 476776 bytes, "", "messeturm_IASS.pdf"

Estimado Valentin,

La torre ha sido disenada, definida y analisada completamente por Schlaich Bergermann und Partner y también nosotros propusimos en su día utilizar tensegrity. No obstante, los arquitectos eran de gran ayuda ya que nos aconsejaron y también establecieron todos los contactos con el cliente.

El coste neto (y el presupuesto) de la torre era de 500.000€. Para torres creo que tensegrity es demasiado flexible (y por lo tanto caro) para servir mucho. Te adjunto un nuevo artículo en ingles que saldrá pronto en la revista del IASS.

Saludos, Mike Schlaich

Mike Schlaich, Dr. sc. techn.

D.3. Correspondence with Arturo Ruiz de Villa.

Asunto:	Torre Tensegrity 1/2
Para:	valentin.gomez@alumnos.unican.es
De:	arturo.ruizdevilla@ono.com
Fecha:	Mon, 19 Jul 2004 11:24:45 +0200

Hola Valentín:

He recibido tu correo relativo a las estructuras tensegrity. Creo que ya lo sabes por Santiago, pero cuando estuve en Alemania con Schlaich participé en el proyecto de una torre tensegrity. También me ha comentado que habías recibido contestación de Mike Schlaich.

La torre en cuestión no es tensegrity pura, ya que está formada por 6 módulos tensegrity de 8.3 m superpuestos unos encima de otros en los que las barras comprimidas del inferior tocan las del superior. Está rematada por una antena de acero inoxidable. Tiene una altura de 61.8 m que la convierten en la más alta del mundo (por lo menos que tengamos constancia), superando una de 30 m que existe en EEUU.

Si tienes alguna duda, no dudes en preguntarme. Mejor contéstame a esta dirección.

Un saludo,

Arturo Ruiz de Villa Valdés

PD: en el siguiente mail te envío un par de fotos de la torre. La primera es mía y puedes utilizarla como quieras. Las dos últimas están tomadas de la portada de una revista y de un libro de Schlaich.

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3 IMAGE/PJPEG 1106612 bytes, "", "rostock-2.jpg"
4 IMAGE/PJPEG 1116400 bytes, "", "rostock-3.jpg"

Asunto:	Re: Torre Tensegrity Rostock
Para:	VALENTIN GOMEZ JAUREGUI <valentin.gomez@alumnos.unican.es>
De:	Arturo Ruiz de Villa Valdés <arturo.ruizdevilla@ono.com>
Fecha:	Wed, 25 Aug 2004 18:07:47 +0200

Hola Valentín:

Espero que no sea demasiado tarde, pero ahí van las respuestas:

1. Qué programas usaste para el calculo de la torre?

Para el análisis global de la estructura se calculó con el programa Sofistik realizando un cálculo no lineal (geométrico) en grandes deformaciones (teoría de tercer orden). También se realizaron modelos de elementos finitos para los detalles, tales como nudos de barras, placas de anclajes y para la aguja o antena de coronación.

2. Fue un calculo estático, o también dinámico?

Se analizaron los modos propios de vibración de la estructura y a partir de ellos se hizo un estudio aerodinámico de la influencia del viento. Este estudio reveló que dado el carácter zig-zagueante y relativamente irregular de la estructura no eran de esperar fenómenos de resonancia y acoplamiento de los vórtices turbulentos. Del mismo se obtuvo un coeficiente dinámico que permitió considerar la respuesta dinámica de la estructura frente al viento y así poder mayorar su acción (Cd = 1.3). Resumiendo fue un cálculo cuasi-estático.

3. Qué pretensado, aproximado, tienen los cables para evitar el efecto del viento? Siendo una estructura eminentemente "hueca", es tan decisivo el factor viento?

El viento y el pretensado son las dos acciones principales sobre la estructura. El viento es la acción externa principal y totalmente determinante en el diseño, pues condiciona el pretensado. La torre es tan ligera que su peso propio es despreciable frente a las otras cargas.

El pretensado se fijó de manera que bajo la carga de viento máxima en servicio (sin mayorar) ningún cable se destesara (1100 kN para los cables diagonales = aproximadamente el 30% de la carga de rotura del cable). Éste es un asunto sensible, pues tiene gran influencia en el coste y en la deformabilidad de la estructura. Cuanto mayor es el tesado inicial de los cables, mayor es la rigidez de la estructura y menores sus deformaciones. Sin embargo, no se aprecia influencia del pretensado en la seguridad global de la estructura frente a rotura de los cables, que permanece constante (mira la gráfica 8 del artículo de Mike).

Por otra parte, una estructura más flexible por efecto de los cables provoca un aumento de las flexiones de compatibilidad de las barras (que están rígidamente unidas entre ellas); con lo que si se disminuye el tesado, las tensiones en las barras aumentan.

4. Sabes cuáles son los movimientos y desplazamientos de la mentada torre?

El desplazamiento máximo de la punta de la aguja es de 1200 mm bajo las cargas máximas de viento en servicio (sin mayorar). Esta antena, como habrás visto en el artículo, es de acero inoxidable y está sujeta por seis cables anclados en los tres nudos superiores del último módulo de la torre. Estos nudos se mueven 850 mm.

5. Qué tipo de cimentación se usó para estabilizarla?

La torre está anclada en un encepado circular de hormigón que tiene un diámetro de 8 m y un canto de 1.5 m (aunque por cuestiones arquitectónicas se recreció hasta unos 2 m). La idea del encepado es colocar un peso en la base que evite literalmente que "el viento se lleve la torre por los aires", dado lo ligera que es. Este encepado se apoya en 6 pilotes de 500 mm. La estructura está anclada a la cimentación mediante barras pretensadas.

6. El diseño de la torre vino definido por la oficina de arquitectos (von Gerkan, Marg und Partner?), o vosotros la modificasteis en función de la estabilidad del diseño?

Los arquitectos querían construir una torre que sirviera de referencia y símbolo del recinto ferial junto al edificio principal de exposiciones, el "Warnow Halle". No puedo asegurarte si la idea de realizar una tensegrity fue de Schlaich o de los arquitectos. Yo creo que Mike propuso varias soluciones tensegridad y finalmente los arquitectos seleccionaron la altura y número de módulos. De lo que sí estoy seguro es de que en el proyecto constructivo sólo intervinieron en la iluminación y pavimentación del encepado y zócalos de apoyo de la torre, así como en la orientación de la torre.

Recuerdo que debido al fuerte viento que hace allí se modificó el diámetro de la torre para que tuviera más inercia. También se tuvieron que tantear diferentes diámetros de cables y barras.

7. Sabes cuál fue el presupuesto y el precio real de la torre? Crees que el factor económico es poco conveniente para este tipo de construcciones?

Espero no meter la pata con esto, creo que costó 500.000 Eur, pero mejor pregunta a Mike. La torre es, sin duda, cara pues los cables lo son y además porque exige un proceso constructivo muy preciso. También es cierto que en lugares emblemáticos como exposiciones, recintos feriales etc. son elementos muy vistosos que merecen la pena la inversión.

8. Crees que torres de este tipo podrían usarse como estaciones de repetición, antenas, receptores o similares, o las oscilaciones que sufren las harían desaconsejables?

Desconozco las limitaciones de movimientos y oscilaciones de este tipo de estructuras, pero a nada que sean algo estrictas veo inviable su empleo. También es cierto que se puede recurrir a soluciones mixtas (por ejemplo la torre de Rostock no es tensegrity pura para reducir los movimientos, pues los elementos en compresión se tocan). Por otra parte, si se busca dulcificar el impacto estético de una antena puede que sean una buena solución. También podrían usarse como pararrayos en zonas urbanas.

Un saludo,

Arturo Ruiz de Villa Valdés

D.4. Correspondence with Robert W. Burkhardt.

Asunto:	Re: Tensegrity Dissertation
Para:	VALENTIN GOMEZ JAUREGUI <valentin.gomez@alumnos.unican.es>
De:	Robert W Burkhardt <bobwb@juno.com>
Fecha:	Wed, 25 Aug 2004 22:00:47 -0400

Hi Valentín,

The Gough article is the only place where I have seen a claim that Ioganson originated a tensegrity prism. I don't have a copy handy, but Figure 13 is just a picture of a reconstruction of a structure Gough (and/or collaborators) claims to have reconstructed from a picture of an exhibition. It is a standard tensegrity 3-prism exactly like the one I discuss in Section 2.2. If you read my historical essay you'll note that I also mention Emmerich who is referring to a completely different structure by Ioganson which must be what Snelson (and Rene Motro) are referring to in regard to not being pre-stressed. Certainly the prism Gough exhibits must be prestressed if only a small amount, and the one Emmerich refers to is not. Snelson admits to knowing about the Gough article and doesn't seem to contest it though when he says "far background" and puts "replicated" in quotes I sense a certain amount of skepticism. I don't know how controversial this replication is. The claim seemed reasonable to me, and the Guggenheim seemed to think it valid if they displayed the replications as such. Sorry I can't send a copy of the article, but Figure 13 is as I say, and I'd imagine you can find pictures of the constructivist exhibition elsewhere though maybe not at the resolution that would allow you to judge Gough and Koleichu's claim. Since Snelson doesn't directly contest it, you might as well treat it as valid. It's just hair splitting. As far as tensegrity is concerned, Ioganson just did that one structure and really didn't develop the form like Snelson, Emmerich and Fuller.

I'd be glad to look over your dissertation if you care to email it or whatever. If you email it and it's over 500K let me know a day ahead to expect it and what size it is. I just use a dialup connection and I'll be patient if I know it's something worthwhile. I know where to get copies of the U.S. patents on the web. The French ones I wasn't able to find, but I'm not that curious so don't bother sending them.

Bob

Asunto:	Re: These sur Tensegrite
Para:	"List for discussion of Buckminster Fuller's works" <GEODESIC@listserv.BUFFALO.EDU>
De:	Bob Burkhardt <bobwb@lycos.com>
Fecha:	Sun, 29 Aug 2004 12:38:21 -0400

Ref: http://www.channel1.com/users/bobwb/tenseg/book/cover.html

Valentín,

Yes I'd have to disagree with Snelson based on my experience. I'd agree with him as far as algebraic formulas are concerned as those have been found only for some simple structures. For the most part I think iterative techniques are necessary. I think my methodology is very general (see Section 7.2.6), accurate, efficient and allows tuning on the computer though I'd agree field work is very valuable. Many times I don't appreciate the full implications of a structure until I have it assembled and I've learned a lot by putting them together. From what he's said, I think his procedure amounts to minimizing a sum of second powers of lengths and perhaps that leads to the sturdiest structures (see the end of Section 7.2.2 in releases of July 29, 2004 or later). On the other hand, I think his tuning capability is somewhat limited, and I don't think he can make the radical sort of experiments that I can numerically. For example, see the bridge design I did recently (http://www.channel1.com/users/bobwb/synergetics/photos/x3dblprism1.html), or the X-Module arch (http://www.channel1.com/users/bobwb/synergetics/photos/x2l11chain6.html). I've found there's a sort of art to setting up the mathematical programming problem and initializing it in various settings, and I use meta-constraints (Section 7.3.6 in releases of July 16, 2004 or later) to good effect.

I sent him a copy of the first edition of my book but perhaps it didn't make much of an impression. I know he made this claim in the past, but I'm surprised if he's still saying it since there are so many engineers that say otherwise. Of course none of them has produced the array of interesting structures that he and Emmerich have. I think I've done pretty well.

I tend to state a lot of my conclusions (if I have any worthwhile ones) in the body of my exposition without reserving a special section for them. This works out for me since I think it's best to have them very close to the procedure they apply to. If you see anything you think I've omitted I'd be glad to hear about it. I'm not going to bother explicitly rebutting Snelson's claim since I think the book does that implicitly.

I don't think anyone has objected to resilience as a property of structure, but perhaps by-products of the characteristics that lead to resilience, but I'm not a civil engineer so maybe I don't understand the technical meaning of resilience. It is something like Hanaor's comment: "relatively high deflections as compared with conventional, geometrically rigid structures" (Section 1.4 comment #2). Getting effective load response is perhaps more difficult, but I think with the double-layer designs progress has been made there. My use of nylon makes the load response of my structures somewhat problematic, but I think application of less elastic material would help a lot here. I think these considerations may arise in many quarters due to the early experience with single-layer structures which were pretty wobbly although even there the deresonated tensegrity domes do pretty well I think.

It is also important to remember that tensegrity structures are prestressed and that the effect of an exogenous load on one can vary quite a bit depending on the magnitude of the prestress. Some people see this as a defect as the materials are in a sense fighting against themselves instead of just against gravity, but I see it as a virtue (prestressed concrete is pretty popular right?) since it adds so much resilience.

You found the French patents on line? I guess after all I'm curious enough that if you have electronic copies send them along thanks or best of all tell me where to find them on the net. I looked around and couldn't find anything.

Bob

Asunto:	Re: Some other points
Para:	"List for discussion of Buckminster Fuller's works" <GEODESIC@listserv.BUFFALO.EDU>
De:	Bob Burkhardt <bobwb@lycos.com>
Fecha:	Sun, 29 Aug 2004 15:13:16 -0400

Hi Valentín,

I can't say I'm familiar with other software packages. I haven't tried to distribute mine as I'm not ready to yet though I think I've set out the theory and practice behind it pretty well in my book. It would be difficult for other people to use I imagine. I may look into developing it for release after the revisions for the 2nd edition of the book are done.

My main emphasis is on design. That I think is where I would find the most difficulty getting satisfaction out of other packages. I consider tensegrities where the struts touch to be true tensegrities, and I haven't heard of anyone who rules out a structure as a tensegrity in that regard except for your allusions. I cite three fairly diverse definitions in my book, and all of them admit structures where the struts touch. I don't think the design difficulties are so great as with those where the struts don't touch and I am very interested in exploring these latter sorts unconstrained by problems with design software which I think my software allows one to do. For analysis, there may be lots of other packages out there that do the job, and I imagine my analysis theory and practice (Chapter 7 and 7.3 in particular) could benefit from the attention of a civil or mechanical engineer. I will be curious to see what you get from your software.

I think the custom extremal analysis software I use works well, but there too perhaps a commercial package could do better. But a lot of my advantage is the way I've tailored my software to apply extremal techniques specifically to tensegrity. Perhaps the main consideration for me is that the commercial packages are beyond my budget even when I've spotted one that might work. My custom-developed extremal software is somewhat generic, but the interface is closely tailored to support the tensegrity work since that's all I use it for.

This Tower of Rostock reminds me of Tristan Sterk's towers (which were at www.ofram.com though the sublink seems to have disappeared -- maybe he still has them there somewhere -- I can't find it). For a lot of the tensegrities where the struts touch I think the geometry is fairly well determined and though my extremal approach works there, simpler approaches may do very well. If you have an internet link to this guy's work, I'd be curious to see it. If it's not Tristan's work, I may not be familiar with it.

I'll see how I do with the French patents. I've been working on my French lately, but if it's inadequate I'll ask for the British patents. Thanks for sending me the French ones.

Bob

Asunto:	Re: Renders
Para:	VALENTIN GOMEZ JAUREGUI <valentin.gomez@alumnos.unican.es>
De:	Bob Burkhardt <bobwb@lycos.com>
Fecha:	Tue, 07 Sep 2004 16:46:24 -0400

Hi Val,

Looks like an interesting concept. I think I understand the stadium better than the bridge, but they both look good to me. You have an interesting approach to tensegrity. I'll try out one of the stadium modules eventually and see what I come up with. Very simple design, but it should work. Thanks for sending it along.

Bob

Asunto:	Re: Modules Figures
Para:	VALENTIN GOMEZ JAUREGUI <valentin.gomez@alumnos.unican.es>
De:	Bob Burkhardt <bobwb@lycos.com>
Fecha:	Wed, 08 Sep 2004 09:04:09 -0400

Val,

Thanks for sending these along. The lower-left view in the first picture confused me for a minute since visually two struts look combined into one. It looks like you've got a sort of deterministic tensegrity where my sorts of procedures aren't necessary to find tendon lengths. I'd think any canned software could tell you stresses etc., but mine can handle it as well although it's sometimes tricky to set up the problem so it knows what I'm talking about without running into singularities.

I did a similar thing when analyzing a Geiger dome. Your software hasn't been helpful?

The modules are folded by changing lengths of specific tendons I take it? Once you are more secure in the design, I hope you will post it on the net.

Looks good so far.

Bob

Appendix F. Questionnaire

Belfast, 18 June 2004

Dear Professor,

My name is Valentín Gómez Jáuregui, a MSc Architecture student at Queen's University Belfast. At the moment and until mid September, I am finishing my dissertation which is titled "*Tensegrity Structures and their Application to Architecture*". As you already know, these types of structures are currently being studied and experimented upon, and some specialists are attempting to apply them to functional shapes, buildings and public works. On a smaller scale, I am trying to do something similar. Throughout my thesis (you can find the table of contents on the following page), I will be carrying out theoretical and experimental research, which will also include some history of Tensegrity, the basic principles, some precedents and current examples.

However, in my opinion the views of current engineers and architects are very important and could give me a wider perspective of what I am researching now and what they may have already studied. This is the reason why I am addressing this letter to you. It would help me immensely if you could fill out the brief interview that you can find enclosed. Even if you do not know a lot about the subject, I would like to record your opinion, as it would be interesting to see how much is known about these structures in our profession. If you wish to remain anonymous, this shall be facilitated.

Finally, I would like to thank you in advance for your collaboration and I would be very grateful if you could reply a.s.a.p., as I'm trying to gather all my information in the next month. If you have any queries or problems with the questionnaire, please don't hesitate to contact me. If you wish to read the final work, just let me know and I will send you a text version of the thesis.

Hoping to hear from you very soon,

Yours sincerely,

Valentín Gómez Jáuregui.

Belfast (Northern Ireland)

SECTION A

Firstly, I would like to ask some simple questions about your personal details. If you do not wish to answer, please, do not feel forced to and skip the question.

1. Name:
2. Age:
3. Sex:
4. Formation
    4.1. Degree:
    4.2. Location:
    4.3. Further education:
5. Profession
    5.1. Current profession:
    5.2. Location:
    5.3. Precedent professions and locations:
6. Do you wish to remain anonymous? (In that case, any information given by you will be referenced as "*some architects/engineers/... think...*")

SECTION B

Now, I would like to ask you a few questions about general issues concerning your attitudes. Please, write Y (YES) or N (NO), in order to ask to them or, other case, write the answer that proceeds.

7. Do you usually read any publication (books, journals, etc.) related to architecture or engineering?

8. If yes, which?

9. Do you usually travel with the motivation of visiting any architectural or public work, such a building, bridge, dam, etc?

10. If yes, could you write any recent example(s)?

11. Do you usually read any other publication(s) related to other different subjects?

12. If yes, which?

SECTION C

Finally, I would like to ask you about the main subject of this letter, the Tensegrity Structures. Please, do not be troubled if you do not know a lot about the subject; I just would like to record your opinion, as it would be interesting to see how much is known about these structures in our profession.

13. Have you ever heard about Tensegrity structures before?

(Y or N – If NO, please, go to question 22)

14. What do you know about them?

15. And what personal opinion(s) have you about them?

16. Do you know any professional or specialist dedicated to work/study about Tensegrity Structures?

17. Have you ever seen any of them (in reality, not in photographs or videos)?

(Y or N – If NO, please, go to question 19)

18. If yes, where?

19. Have you ever heard about any real or practical application of this sort of structures in any architectural or engineering work?

(Y or N – If NO, please, go to question 21)

20. If yes, where?

21. Would you be able to suggest any possible application for this kind of structures (even if at first glance could seem unfeasible)?

22. Have you any other proposal, suggestion or question?

23. Would you like to receive a text version of the dissertation when it is finished?

Thank you very much for your collaboration.

Appendix G. Tensegrity Models

All the models shown in this Appendix have been made by the author in 2004 by means of "Tensegritoy" elements. Each strut is 30 cm length.

Fig. G.1.
"Tensegrity Truncated Tetrahedron"

Fig. G.2.
"Tensegrity Truncated Octahedron"

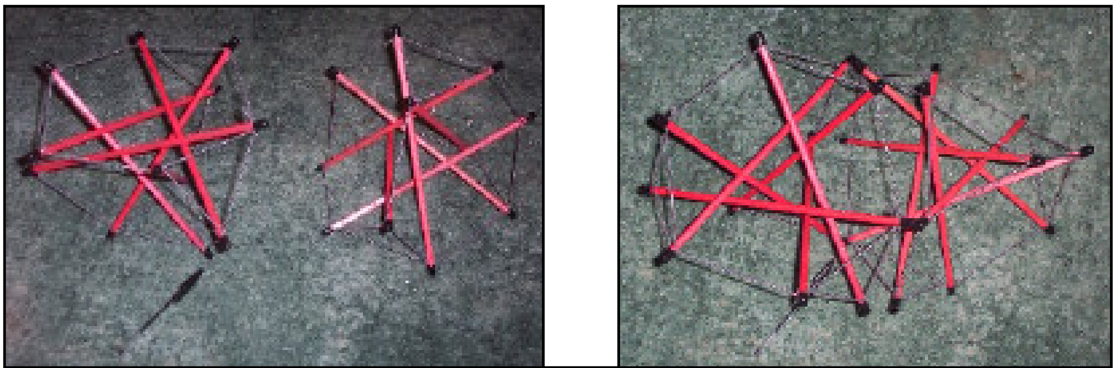

Fig. G.3. **Assembly of two Truncated Tetrahedron by strut-strut contact.**

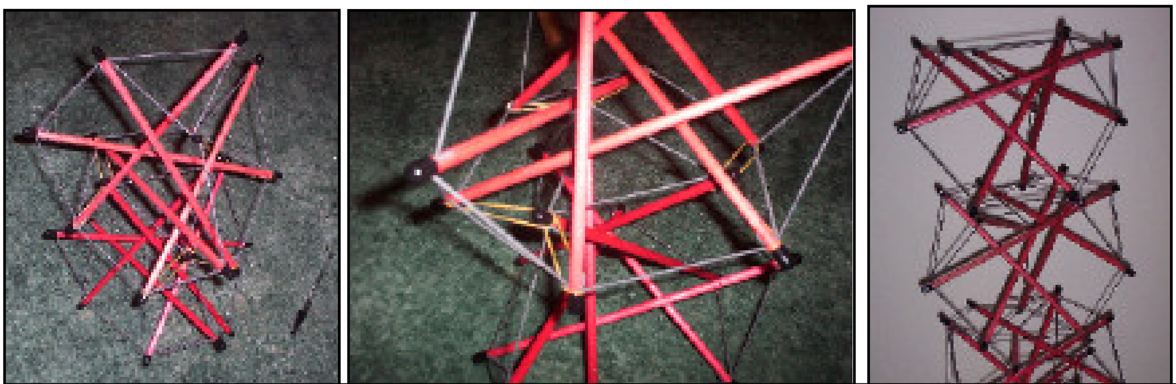

Fig. G.4. **Assembly of Truncated Tetrahedron by strut-cable contact.**

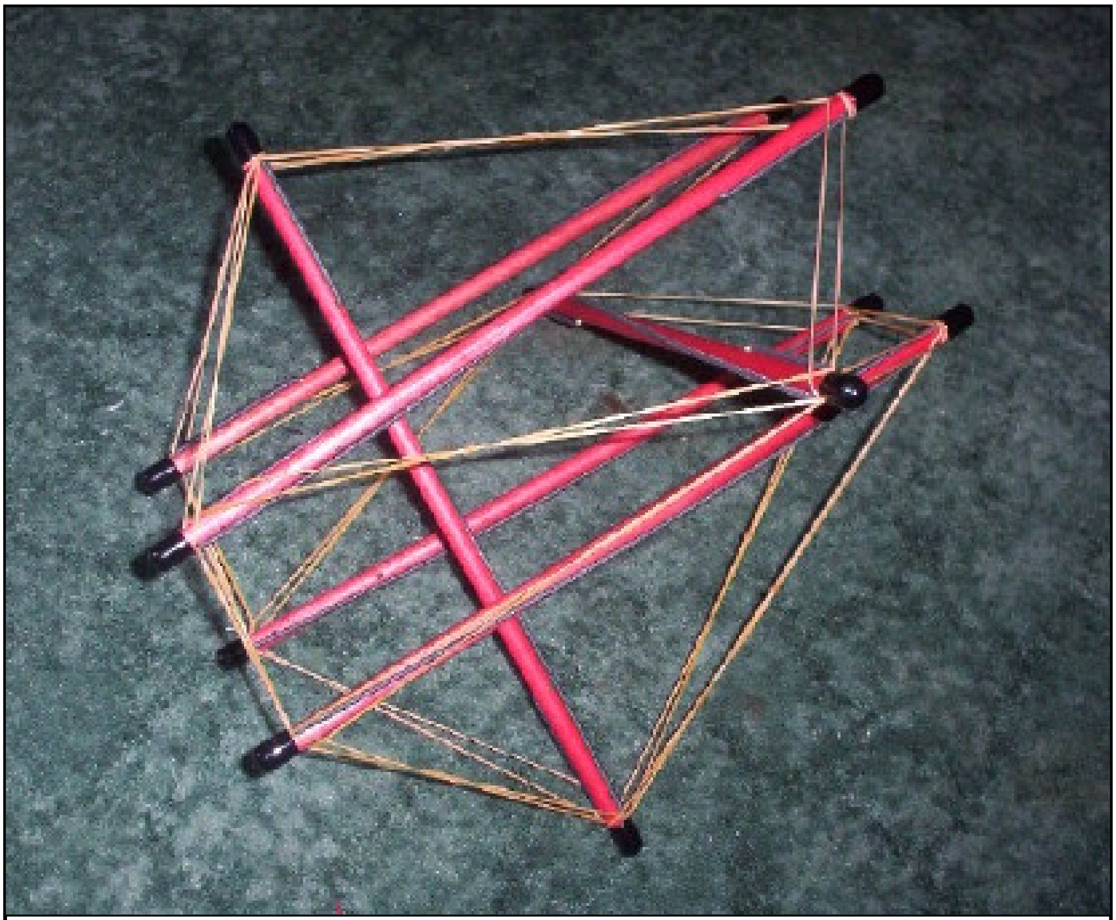

Fig. G.5.
“**Foldable Module for Stadium. Unfolded**”

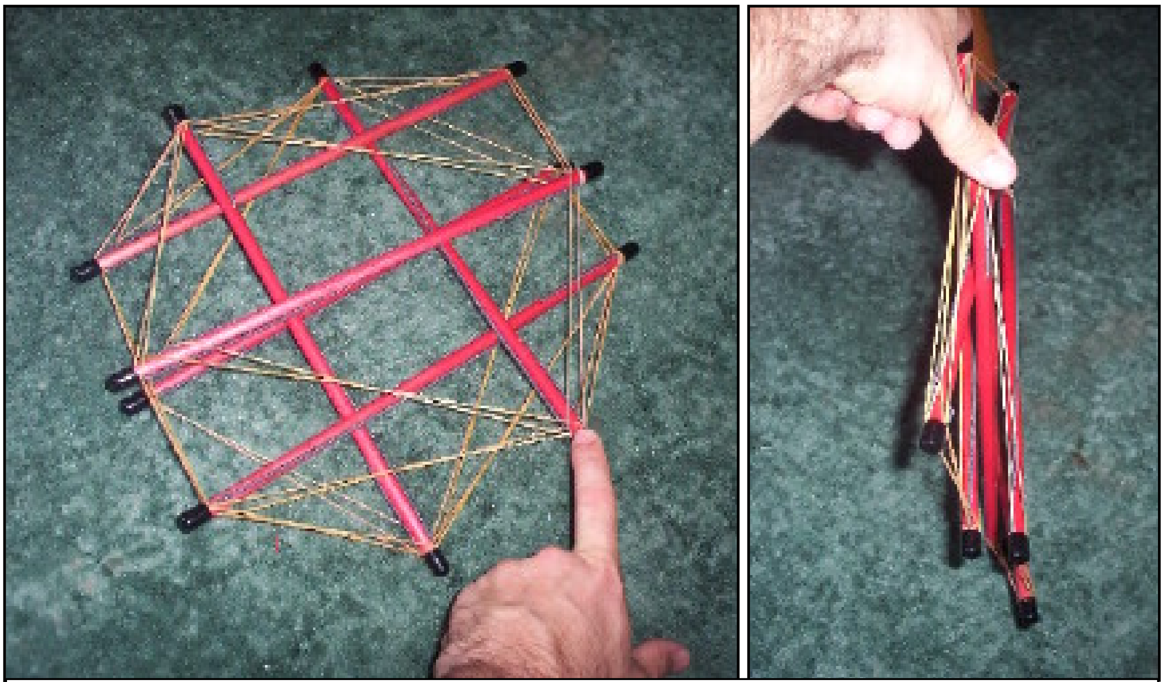

Fig. G.6. “**Foldable Module for Stadium. Folded**”

Study of conglomerations for the Pyramidal Roof

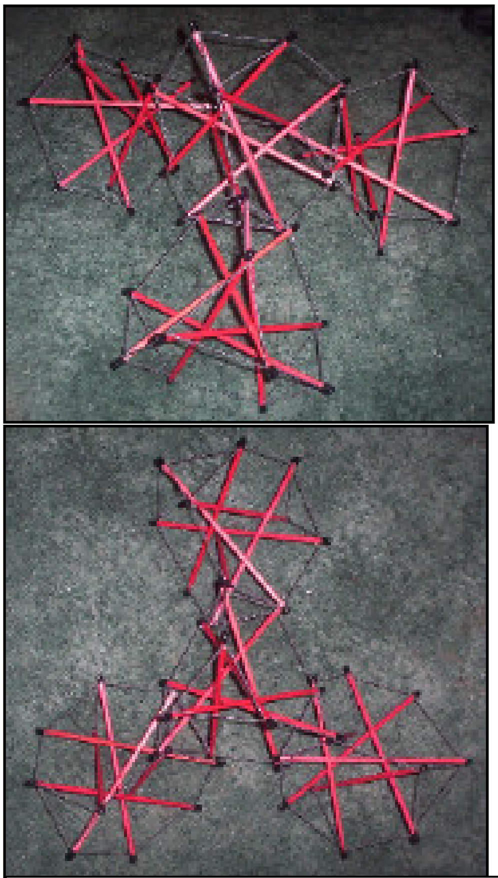

Fig. G.7. **Option 1**
“**Assembly of three Truntated Tetrahedra**”

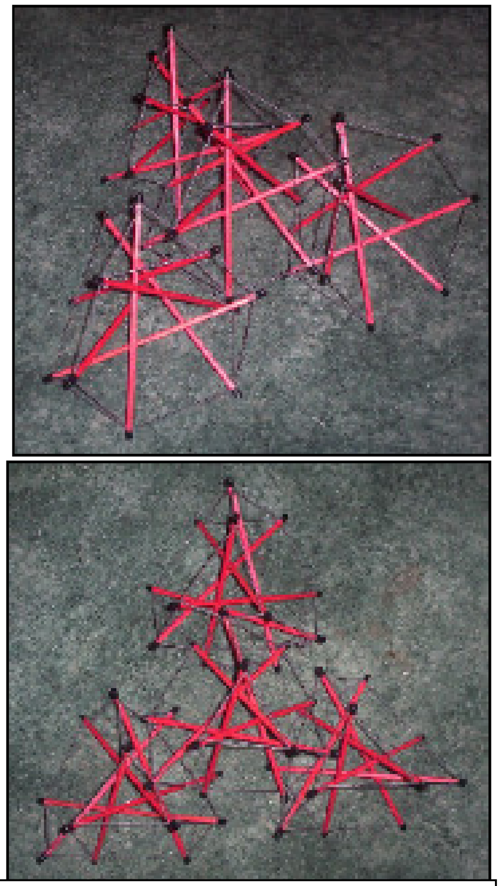

Fig. G.8. **Option 2**
“**Assembly of three Truntated Tetrahedra**”

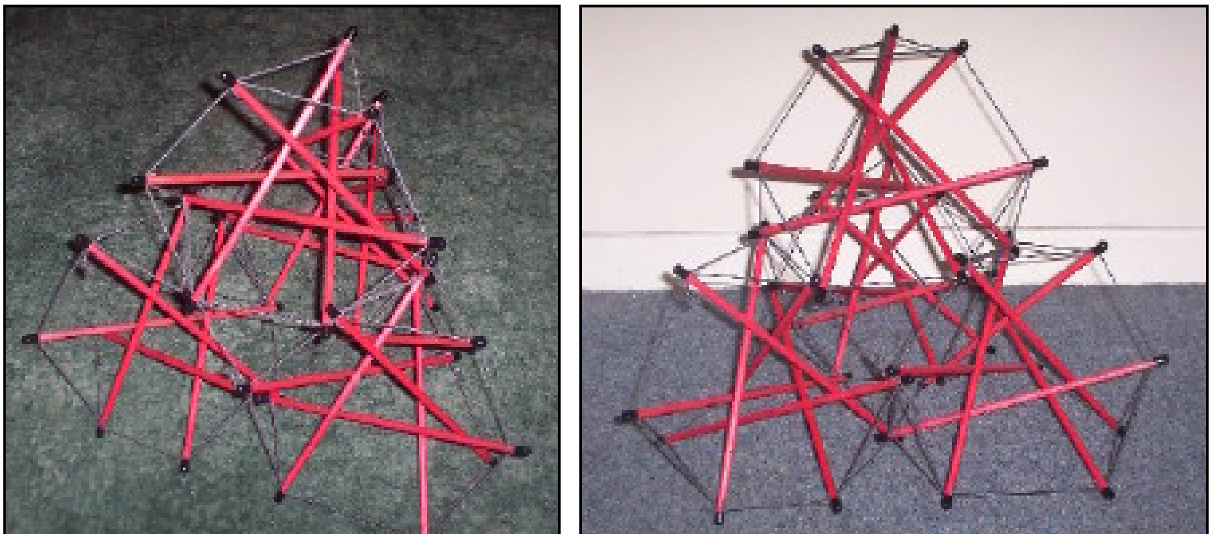

Fig. G.9. **Option 3 (Chosen)** “**Assembly of three Truntated Tetrahedra**”

Study of masts for the Lightning Rod

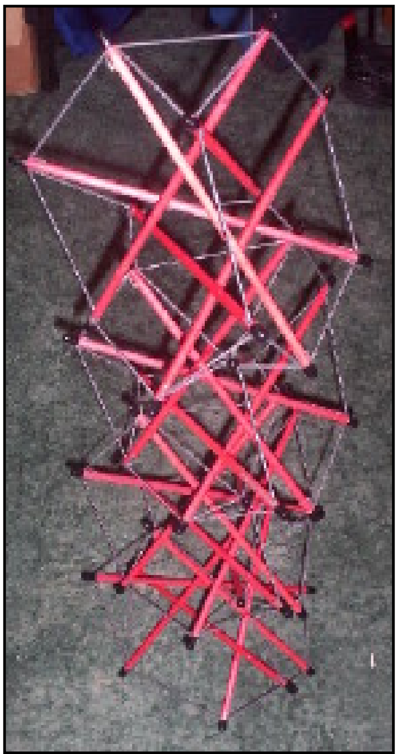

Fig. G.10.
“**Study of masts**”
Upper perspective

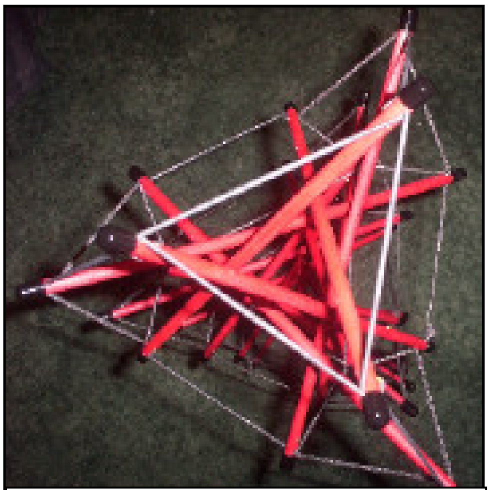

Fig. G.11.
“**Study of masts**” Upper perspective

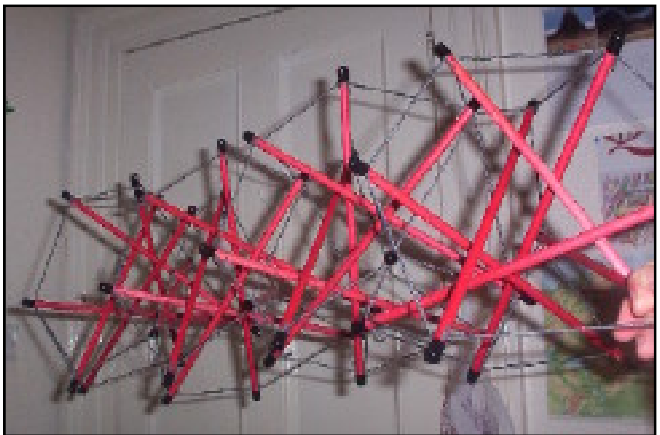

Fig. G.12.
“**Study of masts**” Horizontal disposition

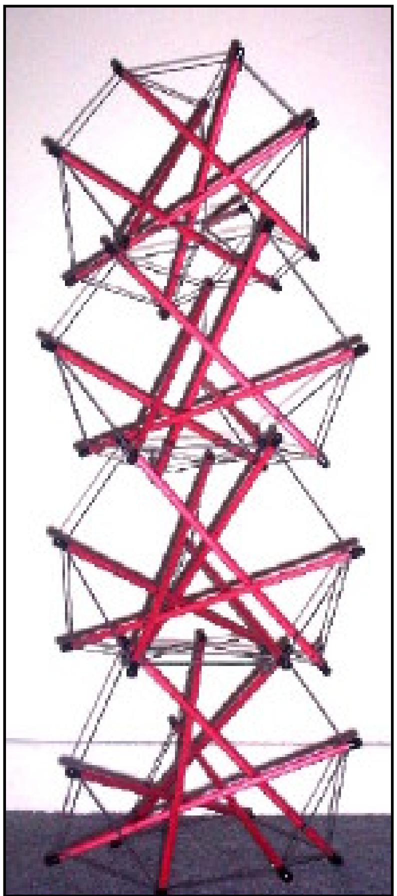

Fig. G.13.
“**Study of masts**”
Frontal view

Generation of domes from a Tensegrity Truncated Icosahedron

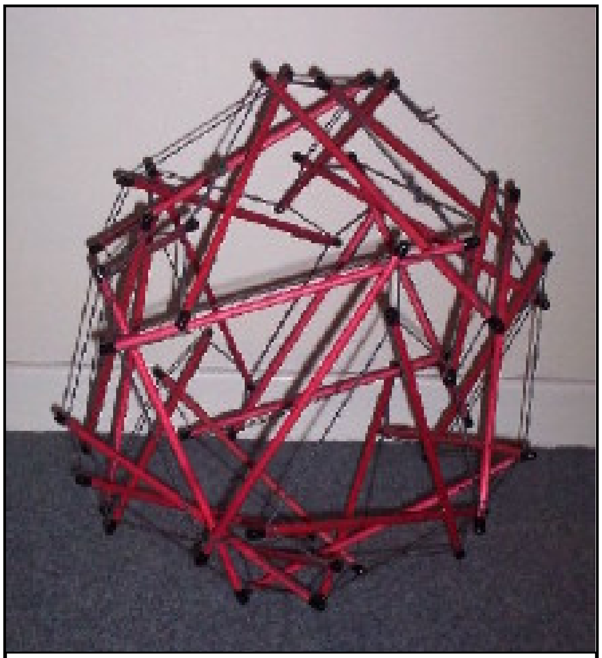

Fig. G.14.
"**Tensegrity Truncated Icosahedron**"
Model made by the author (2004)

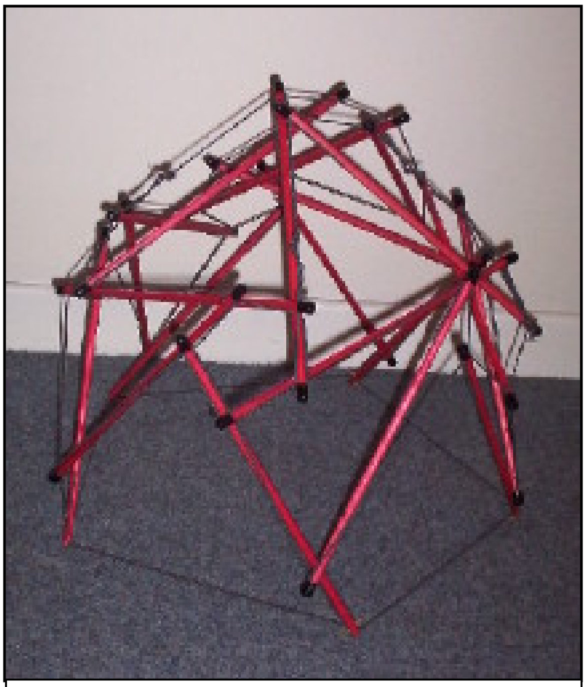

Fig. G.15.
"**Dome from Truncated Icosahedron**" (1/2)
Model made by the author (2004)

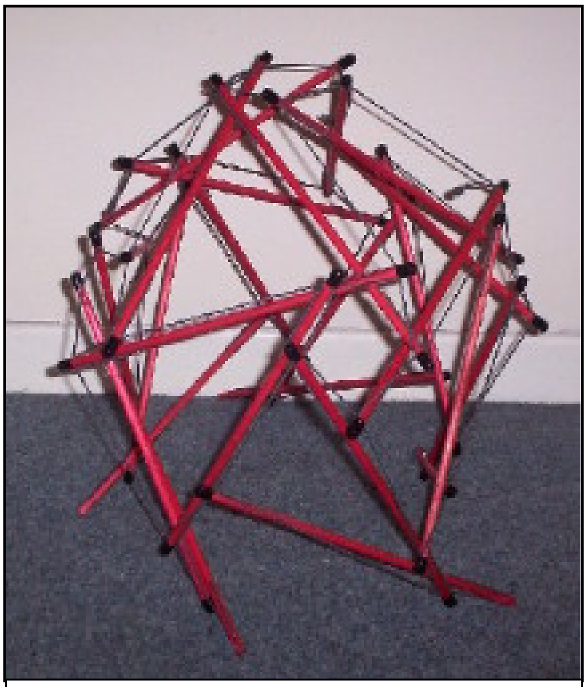

Fig. G.16.
"**Dome from Truncated Icosahedron**"(3/4)
Model made by the author (2004)

Appendix H. Plans and renders

Index:

1. Tensegrity dome from the Truncated Icosahedron
2. Lightning rod from the Helix Tower
3. Roofing for Stadiums by assembly of modules
4. Tensegrity pyramidal roof from Truncated
5. Footbridge by assembly of modules

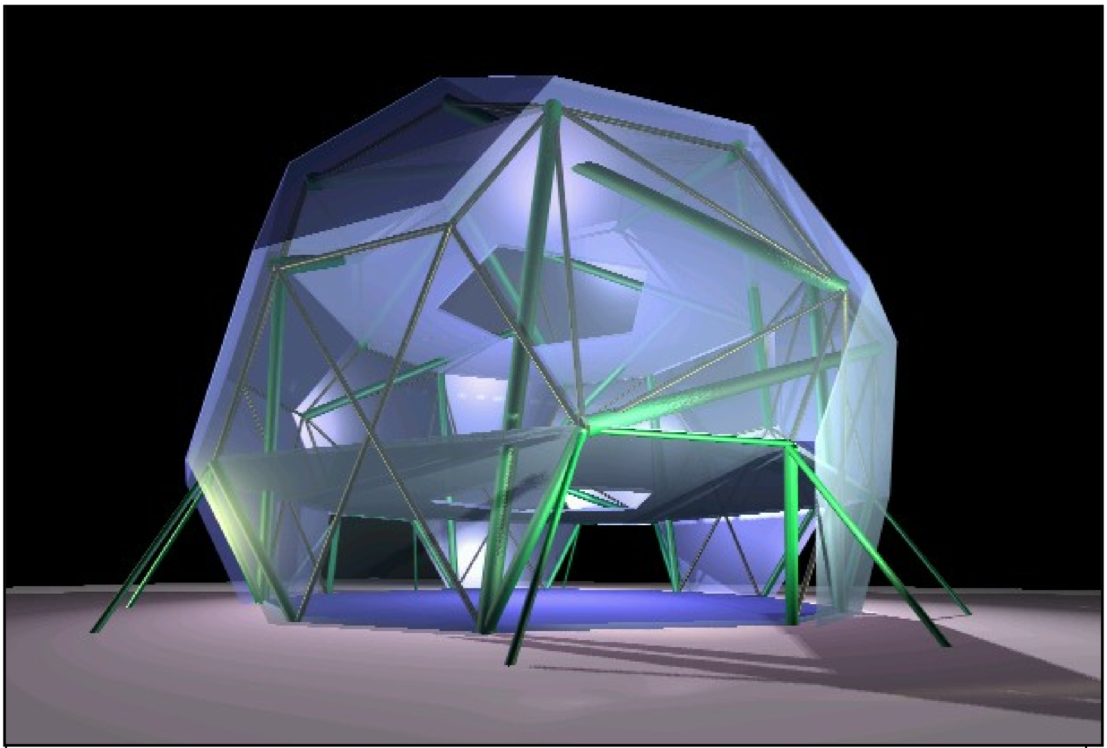

Fig. H.1.Dome from **Tensegrity Truncated Icosahedron**

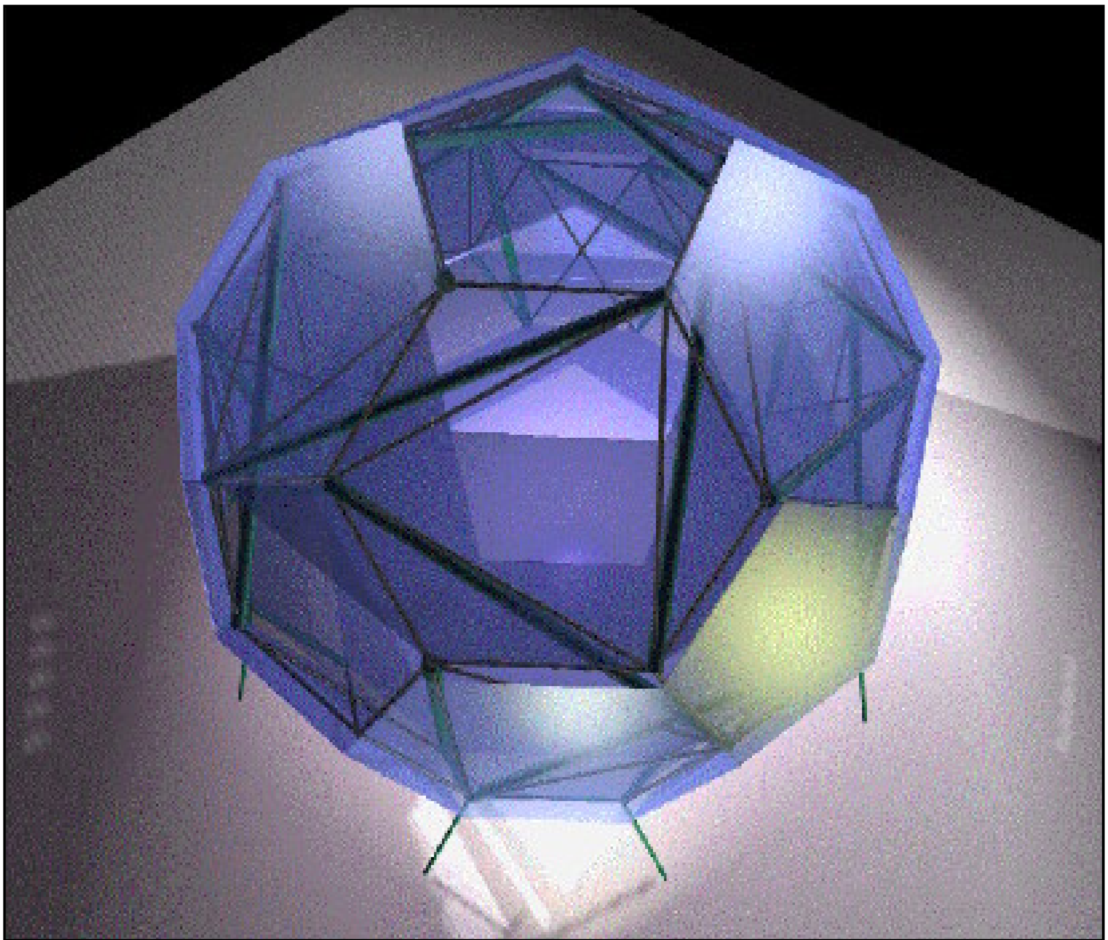

Fig. H.2.Dome from **Tensegrity Truncated Icosahedron**

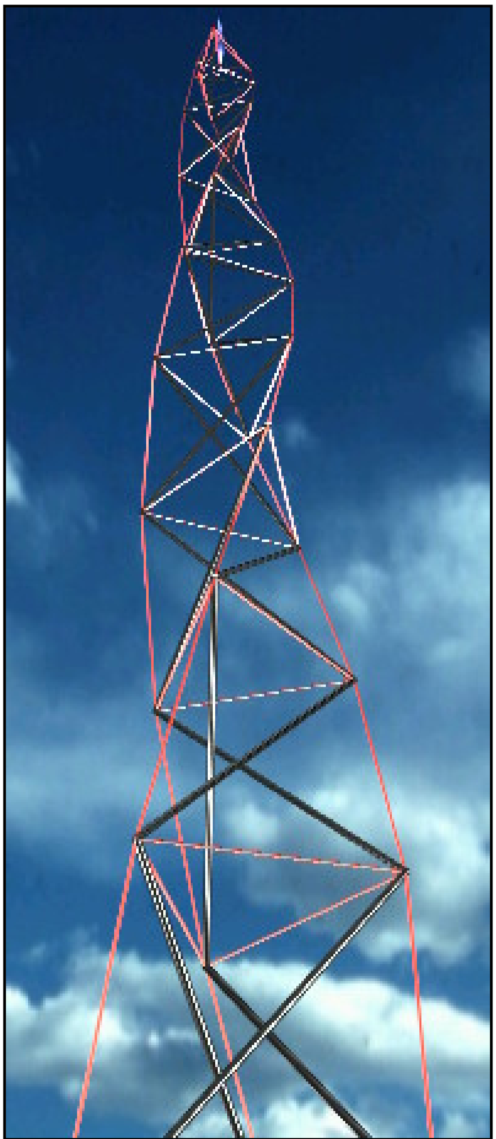

Fig. H.3. **Lightning Rod.**
Perspective from below

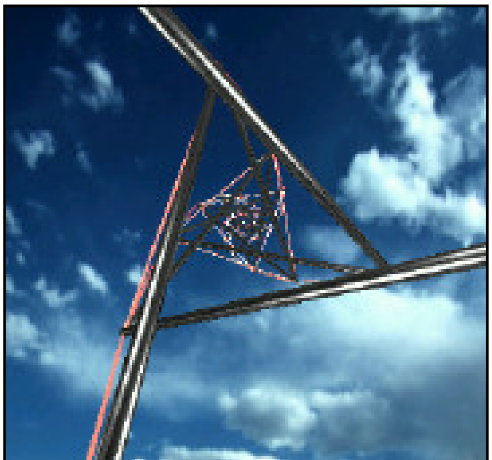

Fig. H.4. **Lightning Rod.**
Perspective from below

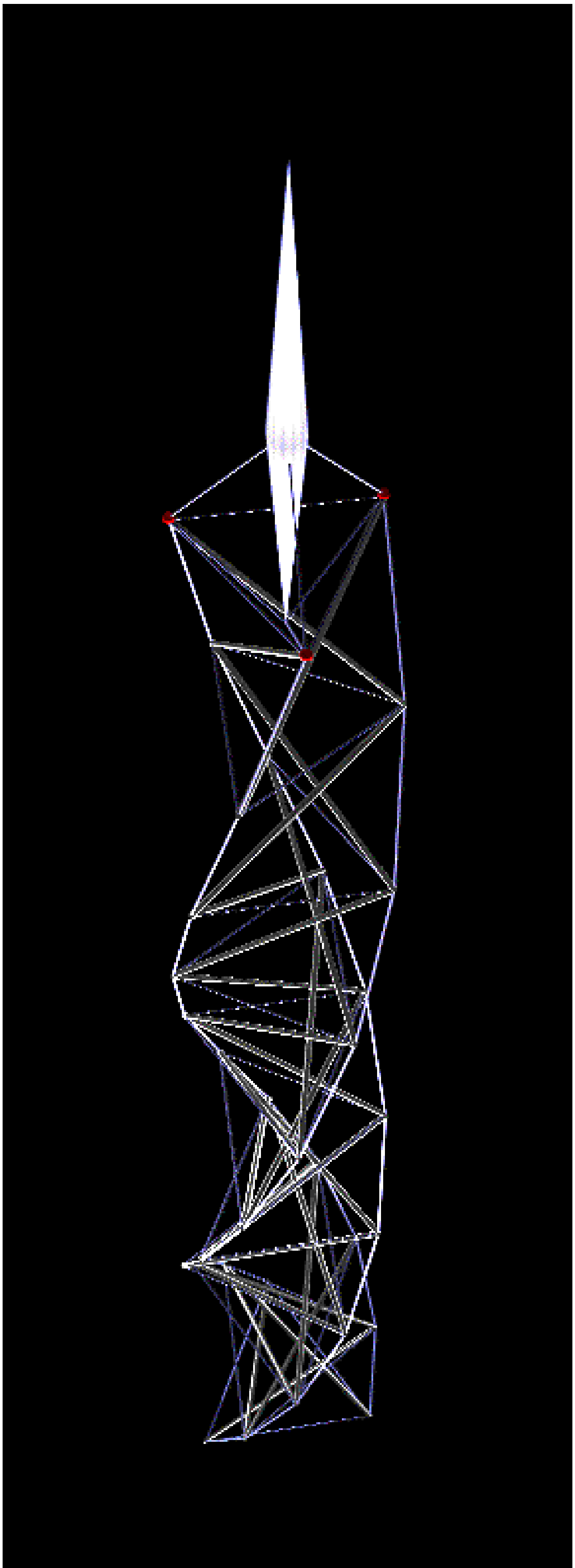

Fig. H.5.**Lightning Rod. Perspective from above**

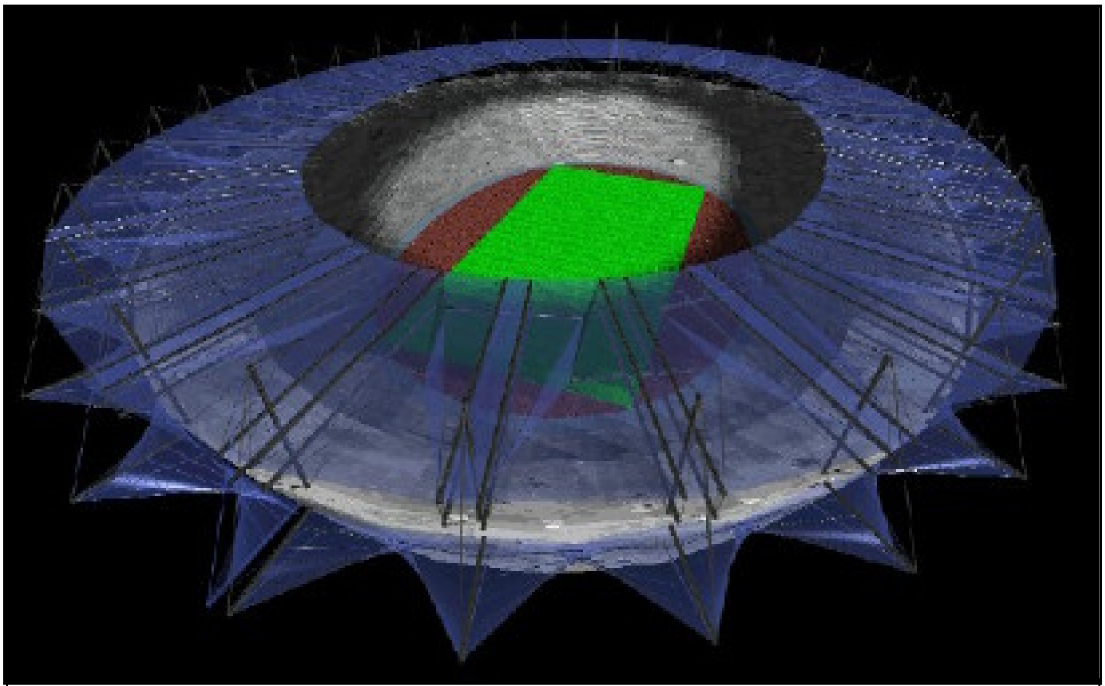

Fig. H.6.**Roofing for elliptical Stadium. . Perspective from outside**

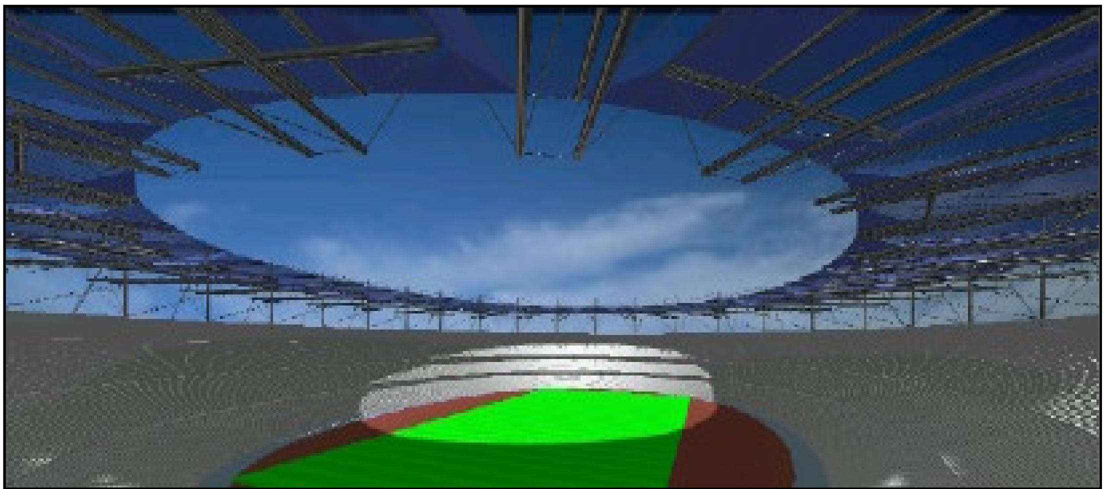

Fig. H.7. **Roofing for elliptical Stadium. Perspective from inside**

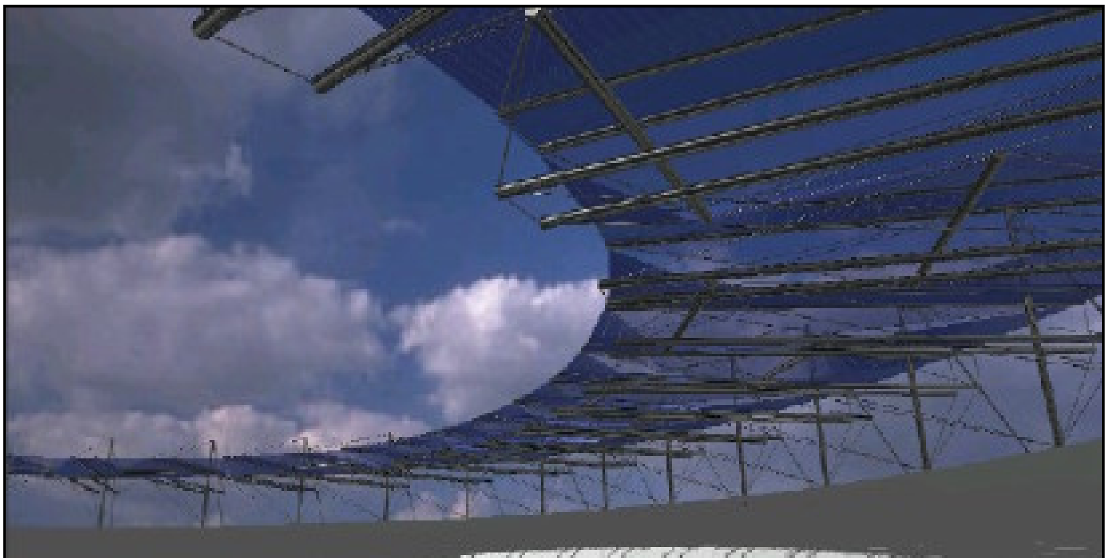

Fig. H.8. **Roofing for elliptical Stadium. Perspective from inside**

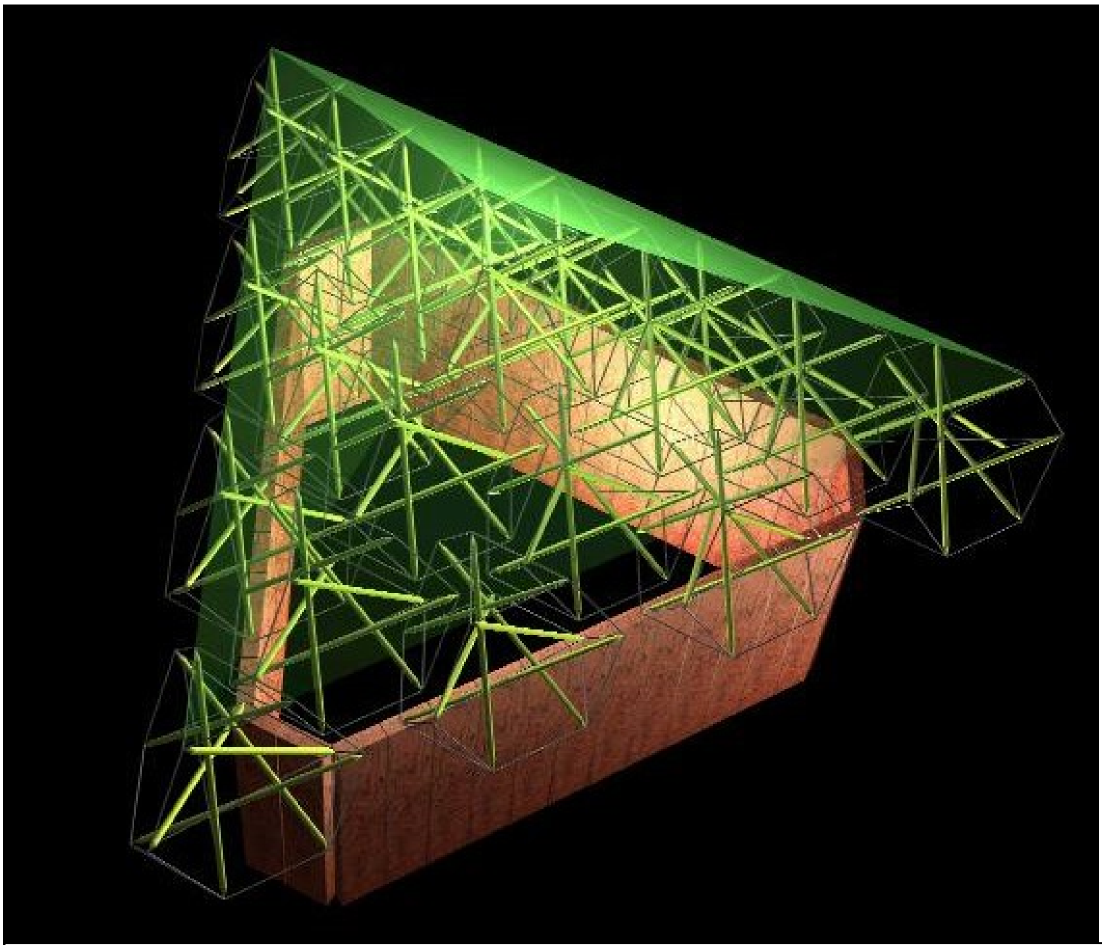

Fig. H.9.**Pyramidal roof from assembly of Truncated Tetrahedra**

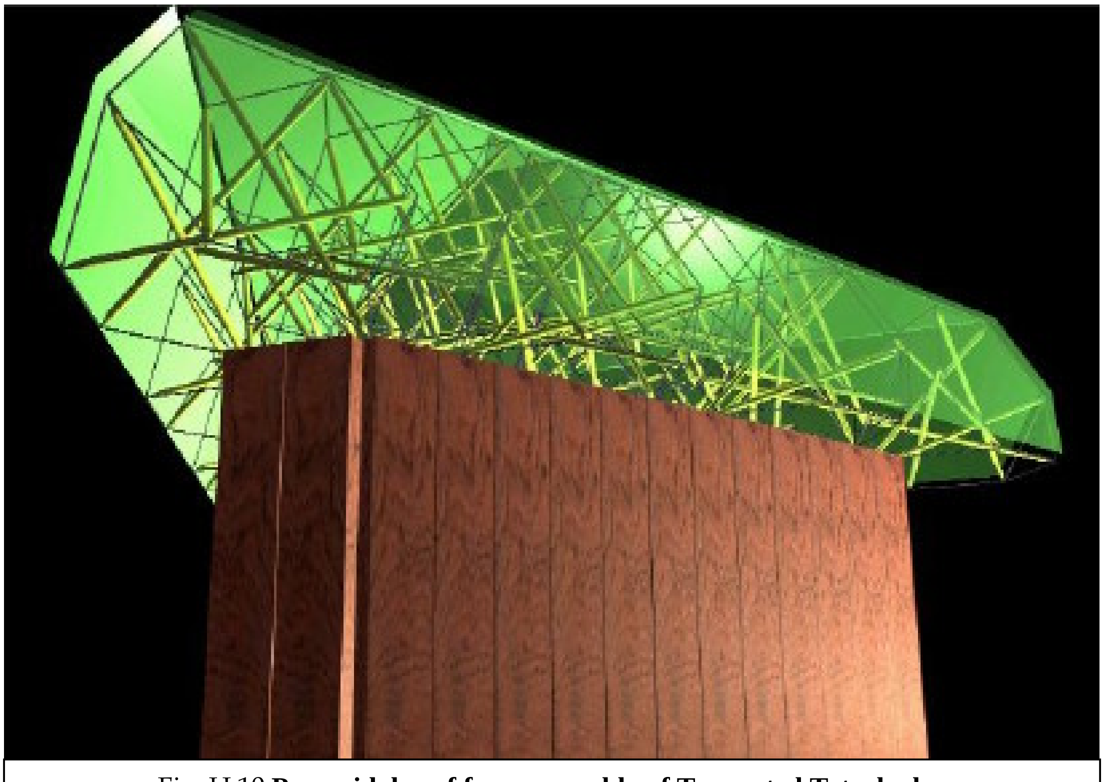

Fig. H.10.**Pyramidal roof from assembly of Truncated Tetrahedra**

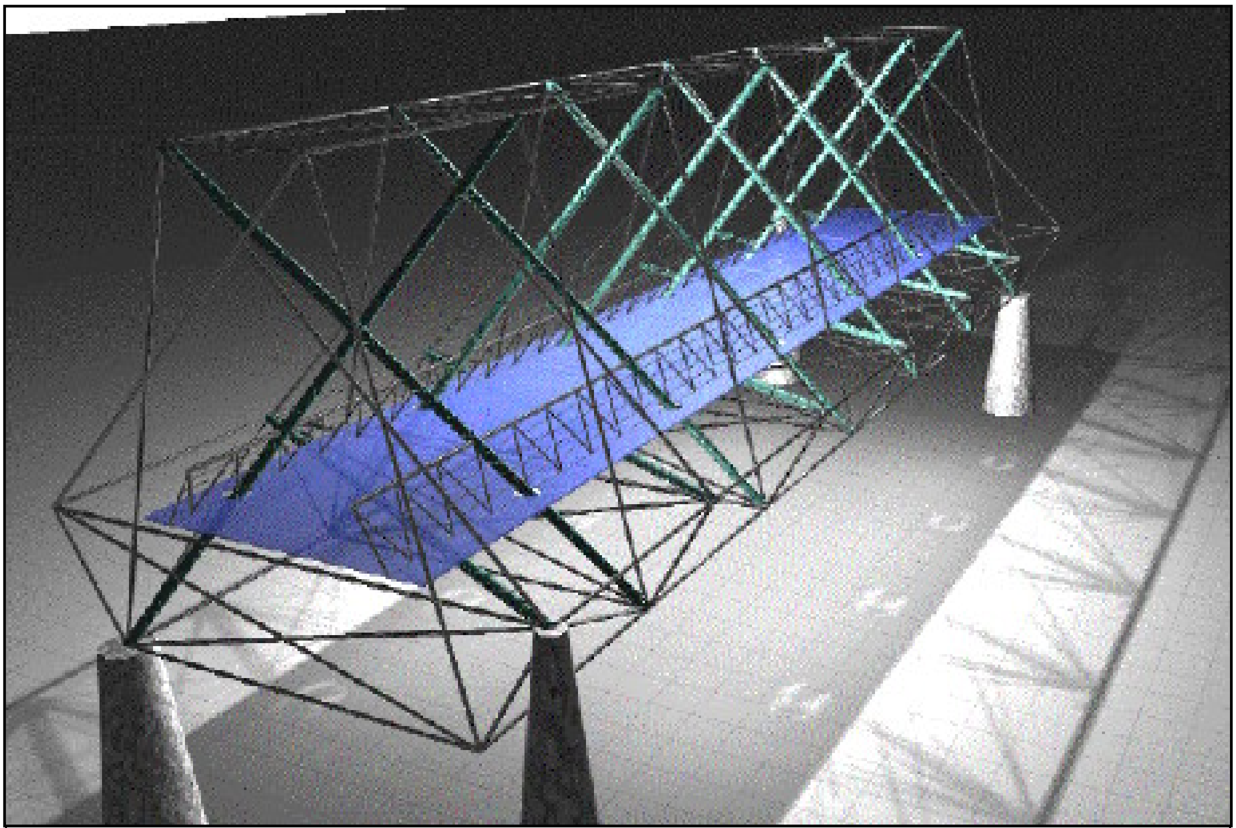

Fig. H.11. **Footbridge from assembly of "Simplex" modules**

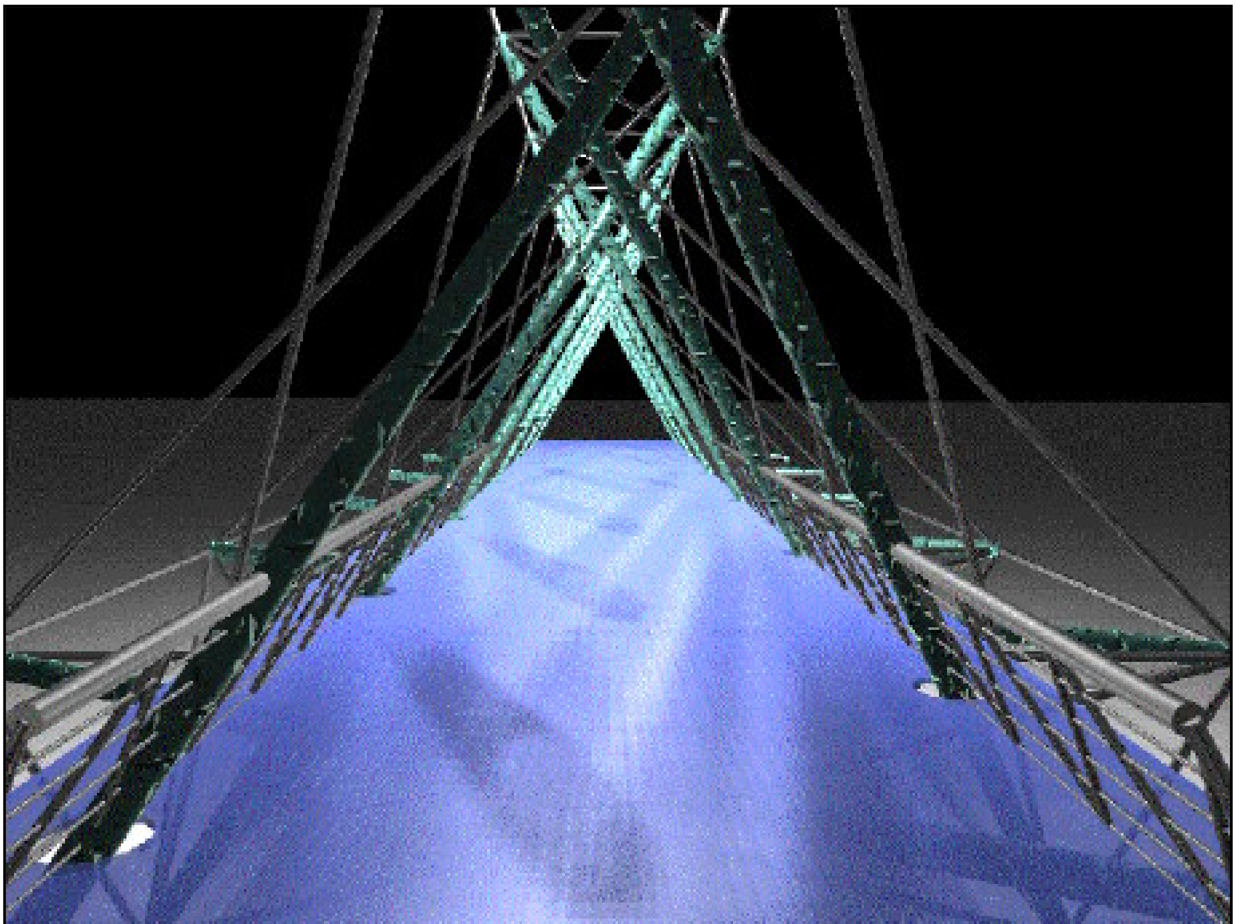

Fig. H.12. **Footbridge from assembly of "Simplex" modules**

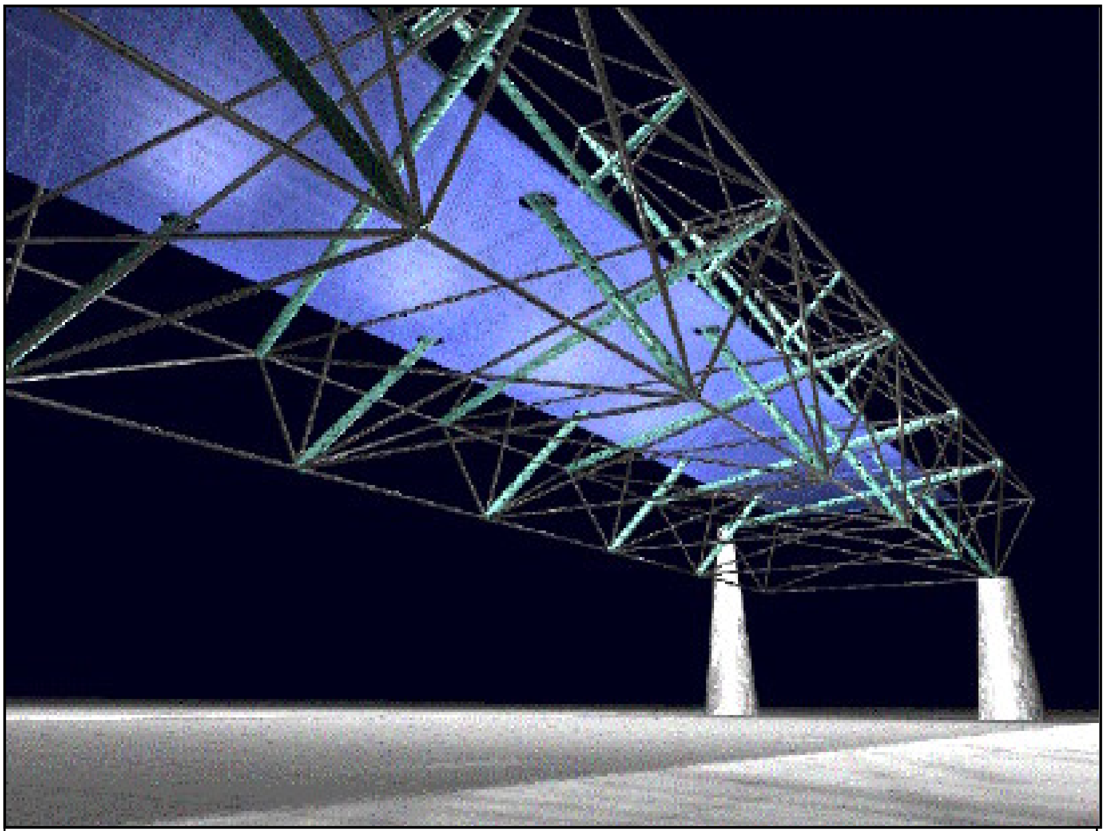

Fig. H.13. **Footbridge from assembly of "Simplex" modules**

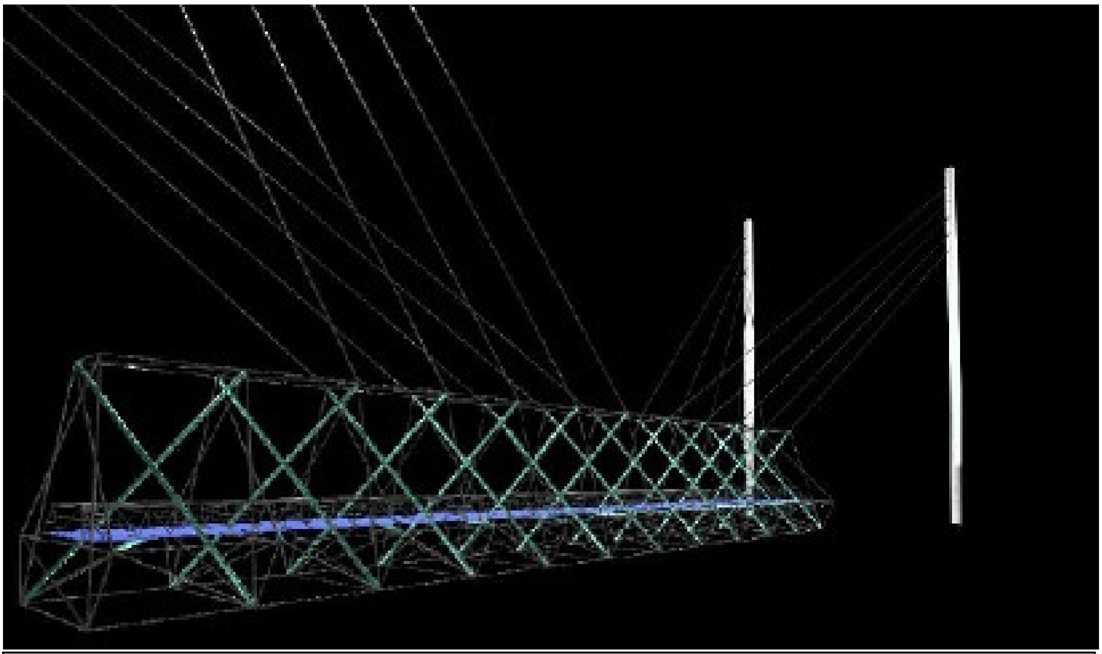

Fig. H.14. **Footbridge from assembly of "Simplex" modules**

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The items of the bibliography are in order by subjects as follows:

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