ARTICLE

Tensegrities and Tensioned Structures

Mª Dolores Álvarez Elipe[*]

CEIPSO Salvador Dalí, Spain

ABSTRACT

"Push-and-pull" efficient structures have been inconceivable between XVIII centuries. It is because of the incapacity of obtain an efficient behaviour of tensioned material. Since XVIII centuries, architecture developed some structural knowledge generating novel structural forms in the architecture and engineering that were not known before. Tensegrities and tensioned structures were studied due to the knowledge of geometry and tension. Some investigations about tensegrities and tensioned structures have been developed since that moment. Tensegrities are bar and cable structures that work only in compression or tension efforts. Bars and cables are balanced, but in appearance the growth is disorderly. Most of deployable structures are based on tensegrity systems. The research is focused in presenting a summary of tensegrities and tensioned architectures that have been used in the structural design of novel patterns. The research of adequate materials to tension efforts will be crucial in this study. The investigation presents an important state of the art that provides technical solutions to apply on novel architectures based on tensegrities and tensioned structures. The research is useful to produce the current constructive solutions based on these constructive systems.

1. Introduction

The research is focused in presenting a summary of tensegrities and tensioned architectures that have been used in the structural design of novel patterns. The research of adequate materials to tension efforts will be crucial in this study.

The goal is to know any current tensegrities and tensioned architectures to know this configuration and the advantages and disadvantages of them. It is collected for the knowledge of tensegrities and tensioned structures to the artists, architects, engineers and all type of people. Relations with architecture and arts will be shown to generate the lines of work of this type of structures.

Some examples of researches of this type of structures are Shookhov, Passera, Manterola, Kenneth D. Snelson, Philip Powell and Hidalgo Moya, Francis, Nowicki, Frei Otto, Jörg Schlaich, Geiger, Motro, A.M. Watt, Levy and Weidlinger Associates, Y. Kono, Buckminster Fuller, Pugh, Kenner, Robert Burkhardt, D. Williamson, Ariel Hanaor, Nestorovic, Connelly, Back, S. Pellegrino, A.G. Tibert, W.O. Williams, R.E. Skelton, David Georges Emmerich, M. Pedretti.

Solutions for the creation of tensegrities and tensioned structures will be looked for. These solutions are characterized by their elements, which are only compressed and tensioned. These structures are not based on thrust and weight strategies. Tensegrities are focused on tensioned and equilibrate configurations. External forces as gravity

Corresponding Author:
Mª Dolores Álvarez Elipe,
CEIPSO Salvador Dalí, Spain;
Email: mdolores_500@hotmail.com

or weight not influence this type of structures.

The research is supported by geometrical and mathematical basic criteria. The questions of form are in the first topic geometric and mathematic questions. The growth questions are physic problems, because the matter reflects physic principles. Therefore, the apparition of ordered designs is a result of physicochemical processes, and as many of the principles that govern these processes are expressed in mathematical expressions, then, in the final study, the underlying mechanisms which explain the appearance of developments are based on maths.

2. Evolution of Tensegrities and Tensioned Structures

The evolution of tensegrities and tensioned constructions will be studied to generate a synthesis of the novelties than have been developed in this area. All of this is possible because of the study of some authors and some existing patents.

"Push-and-pull" efficient structures have been inconceivable between XVIII centuries. It is because of the incapacity of obtain an efficient behaviour of tensioned material. Edmonson[1] in 1987 states that until that time only the tensile strength of wood had been exploited (mainly in the construction of ships). But its tension was not comparable with the compression of the stone masonry.

But in 1851 the massive steel generation modified this criteria a lot. Steel could achieve strengths similar to masonry stone, both in compression and in tension, leading to a lot of novel situations. Edmonson[1] said that a new time of tension design was opened with the construction of the Brooklyn Bridge. According to Edmonson[1] Fuller said: "Tension is something very novel".

The development of steels and other alloys led to unpredictable results in terms of strength, weight and material performance. This allowed architects and engineers to develop novel structural designs. These novel materials decrease the cross section of the materials and, consequently, their weight. They also served to increase the strength of the elements.

But the behaviour of components when they are loaded is different depending of the type of the load. When a lineal element is compressed along this principal axe it generally increases its cross section (by Poisson ratio effect). This element also warps, losing its straight shape. In the other hand, the component tends to thin and it also "firms" its straight axis, if it is tensioned in its principal axe. By this reason, the innovation in materials is essential to the future of pre-stressed structures, in which their tensioned elements must resist better the tensile efforts.

Some constructions were designed to take advantage of the latest studies and adopt their most useful characteristics, specially their tension resistance. As Tibert said [2], the first wire roof structures were developed in 1896 by the Russian engineer V. G. Shookhov. He constructed four suspended ceilings pavilions in the Nizjny-Novgorod exposition (Russia). Along the 1930 decade many other designs were proved after this first attempt, but they did not suppose relevant examples.

Aside from suspension bridges, a few other patterns of bridges raised the value of stress to the same importance that compression had had in previous centuries. For example the cable-stayed bridges were used in the tensioned wires that maintain the cover in compression. By this way, the cover is pre-tensioned and put in equilibrium. A great example is the bridge of the Barrios of Luna in Asturias (Spain), of Javier Manterola, that works in its two towers and in the principal section of 440 m this principle.

The South Bank Exhibition Festival in Britain was in London three years after the discovery of the tensegrity, in 1951. With the festival, a concourse was organized to build a "Vertical Feature", a basic element in international expositions. Philip Powell and Hidalgo Moya (inspired and helped by their trainer Felix Samuely) developed the Skylon that was chosen like the winning project and was erected close to the Discovery Dome.

Many authors like Burstow[3] and Cruickshank[4] claim that this vertical construction was a sculpture without functional proposes. However, this needle was converted in the attractive of the festival. It was a beacon of social and technological potential and a reference to future engineers and architects. The needle of 300 foots of higher was a body coated of aluminium shaped like a cigar suspended by just three almost invisible cables. It seems float up 40 foots upon the floor. The structure was constructed with a series of pre-stressed steel cables and three lowered poles.

As Moya said, "By an amazing stroke of genius (Felix Samuely) organized a hydraulic jacks system under the three smaller needles. When all the construction was assembled, he pumped these hydraulic jacks and raised the pylons. This one put tensions or tractions in all cables and did that all became a stressed structure. It reduced the number of necessary wires to anchor the Skylon and it halved the amount of oscillation in the structure. This lack of support made the structure look tremendously dangerous. It seems not have enough cables to hold it, which became enormously exciting" [4]. The cause of the sensation of not having enough cables to hold the element in the same form that a dirigible was because of the stable equilibrium obtain by this special configuration.

Francis [5] presented a diagram that explains the stability condition of a post sustained by tensioned wires. When one cable is joined to the floor, the point in which the other cable be kept will influence the equilibrium of the strut. If it is fixed in a point under the level of the strut, it will collapse. If it does it at the same level, the pole is in an unstable balance (any displacement will cause it to fall). Conversely, if it is held at a point above ground level, the set is in stable equilibrium. In other words, when there is any movement to this situation, it tends to return to the vertical position. The diagram of the Skylon is similar. In fact, the conditioning factors for the balance of a strut in a three-dimensional structure influence the place of application of the ends of the cables that fix it.

In 1950 years, the use of wires in tension was perfected, but also that of other parts such as materials, membranes and fabrics. In 1950, the State Fair Arena, in Raleigh (North Carolina) was design by Matthew Nowicki following its basic ideas of suspended ceilings. That same year, a German architecture student had a brief look at the drawings and plans during an exchange trip to the US, and he was completely fascinated by the novel idea. As a result, he started a systematic research that was defended as his doctoral thesis in 1952. His name was Frei Otto and it was the first complete documentation about suspended ceilings [2,6].

The Development Centre for Light Construction was founded by him five years later in Berlin and, in 1964; it was included in the Light Surface Structures Institute at the University of Stuttgart, to further increase research in tensioned architecture. Therefore, some important works that exploit the tension characteristics of the materials (principally steel, but also polyurethane, PVC, fibreglass, cotton-polyester blend, polyester, acrylic panels...) were developed. Within these works was a four-prop tent such as the Bundesgartenschau Music Pavilion, Kassel (Germany) in 1955, the first large cloth-covered wire mesh, the German pavilion at the 1967 Montreal World's Fair and the known 1972 Munich Olympic Stadium, the structure of which was calculated by Jörg Schlaich.

For example, Pugh in 1976 [7] built a dome done with wood struts and plastic skin. The plastic skin was the component in tension that supports the compressed elements of the structure.

W. O. Williams [8] said that the term "tensegrity" was being used to some type of pin-connected construction in which some of the strut components are tensioned cables or compression-only bars. The "Cable domes" or the "Bicycle wheel domes", designed by David Geiger [9], are examples of this type of structures. Since this moment, some domes have been erected with this principle. They have a group of radial tensegrity girders attached by an outer ring in compression, and converge to an inner ring to fix all of them.

Although some engineers and architects include these cover constructions within the tensegrities, Motro [10] say that they are false tensegrities, as they have a compressed limb member. In fact, although Geiger did not point out directly to Buckminster Fuller, it must be remembered that Fuller in 1964 [11] patented an alike type of construction that was called later "Aspension" by him.

The first wire domes were design by Geiger to the Seúl Olympic Games (1986), followed by the Redbird Arena in Illinois, the first oval wire dome (1988), the Florida Suncoast Dome in Saint Petersburg (1988), and The Tayouan Arena in Taiwan (1993). In fact, the biggest dome in the world until today, that is a one of this family, is the Atlanta Georgia Dome (1992) of Levy and Weidlinger Associates.

It should be pointed out about the "tensegrity" definition, essential to consider any structures like real or false tensegrities. Gómez [12] in his thesis published in 2004 defined the tensegrities as a structural principle based on the use of isolated components under compression inside a continuous tension set. The members that work under compression (generally struts or bars) don't touch each other, and the tensioned members (usually cables or tendons) draw the spatial configuration.

According to Gómez [12], the inventors of the tensegrities have been three men: Richard Buckminster Fuller, David Georges Emmerich and Kenneth D. Snelson[1]. Emmerich reported the first system of proto-tensegrity, said "Elemental equilibrium" o "Simplex", with three bars and nine cables. Fuller and K. D. Snelson, independently of David Georges Emmerich, studied different types of geometric models considered tensegrity structures.
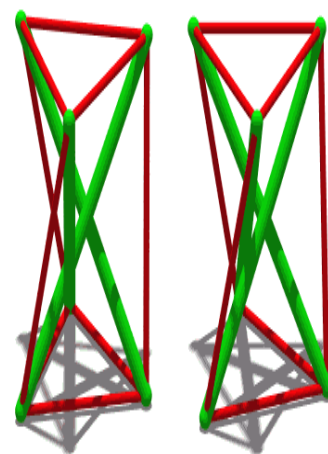
Figure 1. "Elementary Equilibrium" or "Simplex", David Georges Emmerich

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1 As note, they are mentioned chronologically according their conceived patents: Fuller-13 Nov 1962; Emmerich-28 Sep 1964; Snelson-16 Feb 1965.

The aesthetic and sculptural aspect is chosen by Snelson to focus his work. He did not want lot complications with physics and mathematics. He knew the difficulty applying tensegritical principles by his artistic background. This development facilitated him the development of a lot of diverse asymmetric and not typical configurations[1]. The construction of tensegritical systems requires a slim and delicate technical that he has been improved during years, too. The actual process which Snelson erect his works is a science and an art by itself. Actually, as Fox established[13], he is the only people able to engineer these constructions.
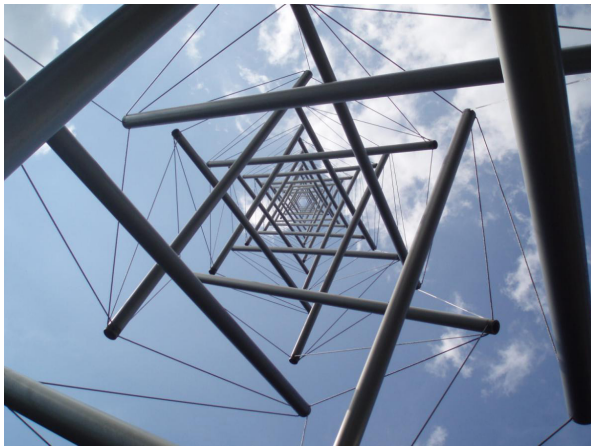

Figure 2. Needle Tower II in the Kröller-Müller Museum in Holland, Kenneth Snelson (1969)

With another perspective, Emmerich and Fuller chose alternative paths, investigating the alternative tensegrity typologies, specially one-dimensional and spherical types like needles. The principal work tools of them were the empiric experiments and the used models. They wanted the application in engineering and architecture in contrast with Snelson.

Right after, looking at the Snelson sculpture, the Massachusetts researcher investigated some simple developments and generated a classification for tensegritic needles, characterized by vertical surfaces of three, four, five and six sides respectively[14]. He developed the "six isolated bars icosahedron" (expanded octahedron)[2] too. Consequently, his investigation was studied by others developing types of tensegrity like the "balance vector" (cuboctahedron), the "tensegritical sphere of 30 isolated bars" (icosahedron), the "isolated six bar tetrahedron" (truncated tetrahedron) and the "octa-tensegrity of three isolated bars". Consequently, a hierarchy of the first tensegrity models was developed, and the principles of compression of the universal tensegrity structures were close.

1 See web page of Kenneth Snelson (www.kennethsnelson.net)
2 In quotation marks, denomination of Fuller
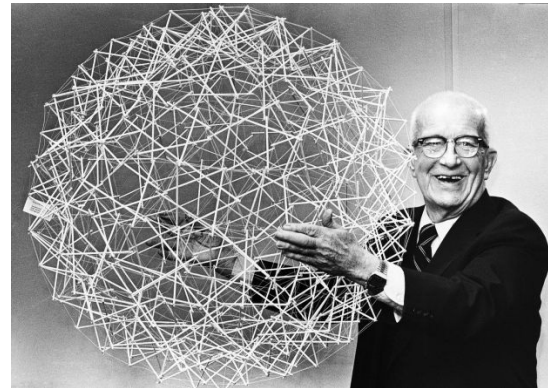
Figure 3. Buckminster Fuller holding a geodesic tensegrity sphere

Thus, Buckminster Fuller was investigating for novel developments, applications, and construction methodologies. He realized some proves of designing tensegrity geodesic domes (figure 3) (although since they were not triangulated they were not stable), and he patented[3] many of his studies in relation with this area[15,16]. But the last enforcement of the tensegrities was not as satisfying as it was believed to be. He never produced the tensegrity dome that was able of coat a great city, as he had supposed. He also had to construct the Expo Montreal Bubble in 1967 like a geodesic dome, but without use tensegrity knowledge by budget and time causes.

From now on, many researches interested in the work of Fuller began to study his novel constructive system, trying to find some uses for engineering and architecture. In 1973, René Motro, for sure a very good expert in tensegrities actually, started to publish his research in this area: Topologie des structures discrètes. Incidence sur leur comportement mécanique. Autotendant icosaédrique[12]. It was an internal archive to the Civil Engineering Laboratory of the Montpellier University (France) about the mechanical behaviour of this type of structures. Henceforth, this laboratory and engineering became the reference in investigation on tensegrities.

Many years after, Pugh and Kenner (1976), both of the California University (Berkeley), continued their investigation by diverse paths. In one hand, Pugh wrote "An Introduction to Tensegrity"[7] that is important because of the diversity of types that it explains and its strict typology and classification. In the other hand, Kenner wrote "Geodesic Math and How to Use It"[17] that explains the calculus "for any degree of accuracy", the relevant aspects of the geometry of the geodesic and tensegritic structures (angles and lengths of the bar pattern) and investigates

3 Casually, while Fuller was patenting his "geodesic domes" in 1954 (US 2,682,235), Emmerich patented the "stereometric domes" in 1967 (US 3,341,989).

their potential. Although this last research focuses more in geometry and mathematics, it doesn't focus in the loaded tensegrity behaviour.

Along 1980 years, many researches strove in developing the open investigation of their ancestors. Robert Burkhardt (figure 4) developed an exhaustive research and he corresponded with Fuller [18] to know more about the geometrical and mathematical principles of the tensegrities. The final goal 20 years after is a useful, complete and continuously reviewed "practical guide to tensegrity design" [19]. The researcher Ariel Hanaor [20] developed the principal two-dimensional sets of self-balancing elemental cells. Nestorovic [21] proposed a metallic dome of integrated tension. Recently, some works have been added to this field of knowledge.
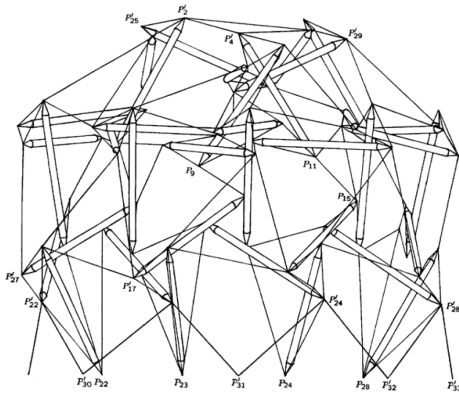

Figure 4. T-Octahedron Dome (lateral view), Burkhardt

Connelly and Back [22,23] have looked for finding an adequate generalized three-dimensional relationship for tensegrities. They have produced a detailed classification according to symmetry and stability typology rules of tensegrities, with many tensegrities that not had been seen before. They did it by the use of tools based on representation theory, mathematics of group theory and computer capacities.

Other authors (A.G. Tibert, S. Pellegrino, A.M. Watt, D. Williamson, W.O. Williams, R.E. Skelton, Passera, Y. Kono, M. Pedretti...) have also developed the physic, mathematics (since a geometric, topologic and algebraic point) and mechanisms of the tensegrity constructions. But apart from the mentioned authors, and Motro and his group in Montpellier, there are not a lot of investigations looking for the application of this novel knowledge to any area particularly.

Recently Peter Testa has developed the Carbon Tower (figure 5), first carbon fiber tower based on the concept of tensegrity: it is an interesting development with tensioned and compressed elements, but the concept of skein is applied in order to do more resistant the structure getting a pre-compression.

Figure 5. Carbon Tower, Testa

The Arena stadium (figure 6) also changes the structural concept, when putting a bicycle wheel frame as cover, in which the external edge is compressed, and the central ring and the radios are tensioned.
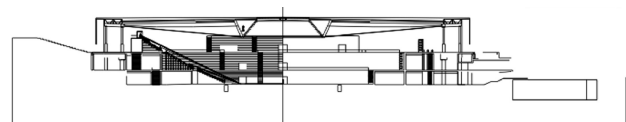

Figure 6. Madrid Arena stadium, Cano Lasso studio

Note: Roof structure design by Julio Martínez Calzón

In bar structures, apart from the forces, we have to pay attention to deformations: the solution of angular deformation that has the Berlin Bank of Ghery (figure 7) consist in a tensioned bar system.
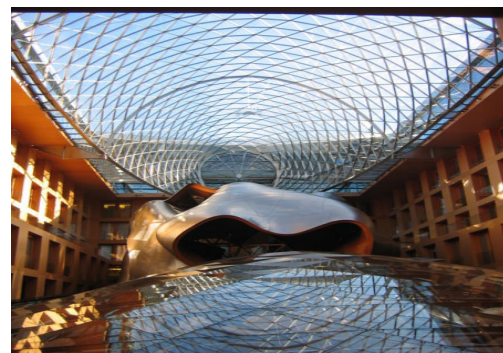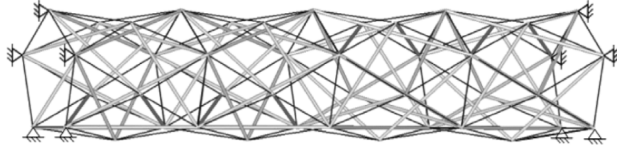

Figure 7. DZ Bank, Pariser Platz, Berlin, Frank O Gehry

Landolf Rhode-Barbarigos, Nicolas Veuve, Nizar Bel Hadj Ali, René Motro and Ian F. C. Smith develop a tensegrity system of pedestrian bridge (figure 8), which deployment requires employing active cables to adjust simultaneously the degrees of freedom of the structure.

Figure 8. Boundary conditions of the limit of the tensegrity bridge, Landolf Rhode-Barbarigos, Nicolas Veuve, Nizar Bel Hadj Ali, René Motro and Ian F. C.

Josep Llorens, V. Gómez-Jauregui, C. Manchado y C. Otero, Paolo Beccarelli, Guglielmo Carra y Roberto Maffei, Carolina M. Stevenson Rodríguez, Ana Cocho-Bermejo, InA Sin and SeungDeog Kim are researches interested actually in tensegrity structures. All of them realize theoretical researches in an academic context.

3. Discussion

A tensegrity is a structural set in which three or more components are compressed by tensioned elements. Tensile components create space between compression components and it creates a triangulate pattern that maintains the forces in perfect equilibrium. This means that tensegrity not depends of thrust and weight strategies. Tensegrity depends of patterns with tensions in equilibrium. They are not based on external forces as a gravity and weight.

Tensegrity constructions are capable of generating a general behaviour like something global. All concrete loads are equally distributed and received for the global set. When the load is increased, its stiffness is increased too.

The principal structural property of the tensegrities is their lightweight when they are compared with designs of approximately the same resistance. They possess great carrying capacity in comparison with other designs of similar weight.

The tensegrities have self-balance. They do not require anchoring or fixing to conserve their geometry and shape. They have stability in all positions.

When the pre-stressing of a tensegrity configuration is higher, its resistant capacity and bearing capacity will be higher.

As the compression components are no continuous, they act locally. They also are resistant to torsion and buckling because of the small section of their elements.

The synergy is a property of the tensegrities. From the behaviour of their separate elements is not supposed the behaviour of the set.

The links and the materiality influence the rigidity of the design.

Natural principles influence the tensegrities designs. One example of this is the cell, which cytoskeleton has the same behaviour that wires and bars in tensegrities design. The cell receives stiffness and shape of the cytoskeleton, which balances the stresses.

To finish, it should be noted that some of the presented deployable constructions base their principles on tensegrity configurations.

4. Conclusion

A tensegrity is a wires and bars design that only generates forces of tension and compression. Equilibrium between wires and bars is produced. Apparently the design has a disordered growth.

The advantages and disadvantages of the tensegrity designs are:

Advantages:

(1) There are no local weak points..

(2) Materials can be used economically and cost-effectively.

(3) Tensegrities usually have no buckling or torsion stresses.

(4) It is possible to generate more complex sets by the assembly simpler systems.

(5) For big-scale designs, the building process can be carried out without scaffolding. The construction works as a scaffold by itself.

(6) To change the configuration in folding designs, very little energy is required.

Disadvantages:

(1) The tensegrities have yet to solve the bar congestion problem. When the size grows, their components begin to interfere with each other.

(2) Compared to traditional geometrically rigid designs a relatively low material efficiency and high degree of deformations are observed.

(3) The complex manufacture of these structures is an impediment to their development.

(4) To maintain the self-tensioning state, it is necessary to submit them to a pre-stressed state which would need big efforts for their stability, especially for those of big size.

References

[1] Edmondson, A. C. A Fuller Explanation: The Synergetic Geometry of R. Buckminster Fuller. Cambridge, Mass, (USA): Birkhäuser Boston, 1987.

[2] Tibert, G. Numerical Analyses of Cable Roof Structures. Unpublished Licentiate thesis. Royal Institute of Technology, Stockholm (Sweden), 1999.

[3] Burstow, R. Symbols for '51, the Royal Festival Hall, Skylon and Sculptures for the Festival of Britain, The Ballroom, Main Foyer, Royal Festival Hall, London, 1996.

[4] Cruickshank, D. The 1951 Dome of Discovery, London. The Architectural Review, 1995, 197.1175: 80-85.

[5] Francis, A.J. Introducing Structures. Oxford: Pergammon Press, 1980.

[6] Drew, P. Frei Otto. Form and structure. London: Crosby Lockwood Staples, 1976.

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

[8] Williams, W.O. A Primer on the Mechanics of Tensegrity Structures. Pittsburgh (USA), 2003.

[9] Geiger, D.H. Roof structure. U.S. Patent No. 4,736,553, 1988.

[10] Motro, R. Tensegrity: Structural Systems for the Future. London: Kogan Page Science, 2003.

[11] Fuller, R.B. Suspension Building, U.S. Patent No. 3, 1964, 139: 957.

[12] GÓMEZ, V. Tensegrity Structures and their Application to Architecture. Tesis Doctoral. School of Architecture, Queen's University, Belfast, 2004.

[13] FOX, H. N. Portrait of an Atomist. Catalog Essay for Kenneth Snelson Exhibition at Hirshhorn Museum and Sculpture Garden, Smithsonian Institution, Washington, D.C., Junio - Agosto, 1981. Also avaliable in:
http://www.kennethsnelson.net/icons/art.htm

[14] Fuller, R.B. Tensegrity. Portfolio and Art News Annual, 1961, 4: 112-127+144+148. Also avaliable in:
http://www.rwgrayprojects.com/rbfnotes/fpapers/tensegrity/tenseg01.html

[15] Fuller, R.B. Octahedronal building truss, U.S. Patent No. 3,354,591, 1967.

[16] Fuller, R.B. Non-symmetrical tensegrity, U.S. Patent No. 3,866,366, 1975.

[17] Kenner, H. Geodesic Math and How to Use It, Berkeley, California: University of California Press, 1976.

[18] Fuller, R.B. Correspondence with Robert Burkhardt, Enero 29 -Marzo 18, 1982. También disponible en http://www.bfi.org/burkhardt/section1.html

[19] Burkhardt, R.W. A practical guide to tensegrity design, [on-line], Cambridge (USA), 1994-2017. Avaliable in:
http://www.channel1.com/users/bobwb/tenseg/book/cover.html Last access 27 of may of 2017

[20] Hanaor, A. Preliminary Investigation of Double-Layer Tensegrities. H.V. Topping, ed., Proceedings of International Conference on the Design and Construction of Non-conventional Structures (Vol.2), Edinburgh, Scotland: Civil-Comp Press, 1987.

[21] Nestorovic, M. Metallic Integrally Tensioned (Tensegrity) Cupola. H.V. Topping, ed., Proceedings of International Conference on the Design and Construction of Non-conventional Structures, Edinburgh, Scotland: Civil-Comp Press, 1987, 2.

[22] Connelly, R., Back, A. Mathematics and Tensegrity. American Scientist. 1998a, 86(2).

[23] Connelly, R., Back, A. Catalogue of Symmetric Tensegrities, [online], Cornell University, Ithaca (USA), 1998b.
http://mathlab.cit.cornell.edu/visualization/tenseg/in_progress/short_top.html Last access 28 of may of 2017