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An Introduction to Tensegrity Structures

Bhrigu Joshi [a], Feras Al-Hakkak [b *]
[a] Department of Civil Engineering, ITM University, Gurgaon, Haryana, India
[b] Department of Mechanical Engineering, ITM University, Gurgaon, Haryana, India

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Abstract

Tensegrity structures are a new class of structures which are light weight, deployable, energy efficient, and highly controllable. A tensegrity structure is a paradigm of continuous pull (tension) and discontinuous push (compression). These structures essentially consist of struts (bars) and strings attached to the end of the bars, which are all loaded axially and do not receive bending moments. The objective of this review paper is to understand the basic principles on which a tensegrity system is based. For thispurpose, the definitions given by various researchers in the field of tensegrity are introduced. Then, characteristics, advantages and disadvantages of these structures are discussed in detail, followed by a review of few simple tensegrity structures. Various applications of tensegrity structures in the fields of architecture, engineering and deployable structures, robotics, and biomechanics are also introduced.

1. Introduction

Tensegrity is a relatively new field of study in which simultaneous discoveries were made around 1950's. Buckminster Fuller [1, 2] coined the term Tensegrity as a conjunction of Tension and Integrity [3]. He is widely regarded as one of the pioneers of the field of tensegrity.

Fuller described tensegrity structures as "islands of compression in an ocean of tension" [4]. A more detailed definition given in 2003 [5] by Motro is: "A tensegrity is a system in stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components". Thus tensegrity structures can be considered a paradigm of a continuous pull and a discontinuous push which complement each other producing the integrity of push and pull.

Tensegrity structures essentially consist of bars (struts), and strings which are attached to the ends of the bars. The bars are always in compression whereas the strings are always in tension. They are lightweight, adaptable, deployable, and space efficient structures in which the struts appear to be floating in the air.

Kenneth Snelson was perhaps the first to build a 3-D tensegrity system. Fig. 1 shows the "X piece", which the first tensegrity system is made by Snelson in 1948, a wooden structure in which the two pieces are not in contact with each other and are stabilized by a set of tension members (strings). Figures 2 and 3 show two more of Snelson's tensegrity sculptures

Buckminster Fuller states that "All structures, properly understood from the solar system to the atom are tensegrity structures and also that universe is Omni tensional integrity". The extensive existence of tensegrity structures around us is also suggested by Ingber [6, 7, 8] who considers the principles of tensegrity to be the building fundamentals of life. Research has also revealed that a small amount of energy is needed to bring about a change in their shape. Hence, tensegrity structures, a relatively new field of study has recently become an important topic of research and discussion in many fields of academia.

Over the last few decades, tensegrity structures have been widely researched by engineers and researchers all over the world through disciplines of architecture, civil engineering, aerospace engineering, biology, robotics and many more. As Motro [5] has stated, these structures can truly be considered as the "structures of future".

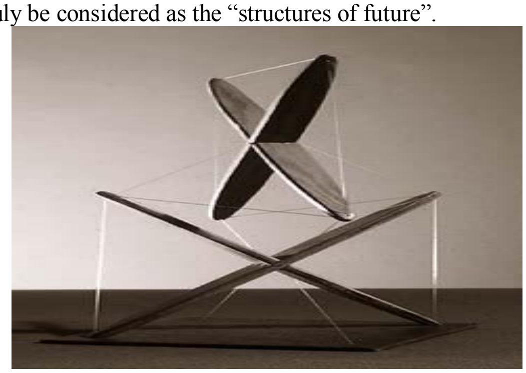
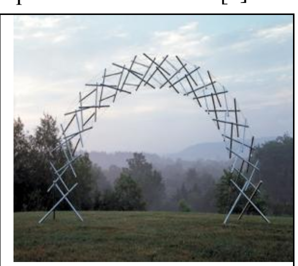


Fig: 1. Kenneth Snelson's "X piece" made in 1948 [9]

	
Fig: 1. Needle Tower II by Kenneth Snelson [**Error! Reference source not found.**]	**Fig: 2.** Rainbow Arch by Kenneth Snelson, [**Error! Reference source not found.**]

Corresponding Author,
E-mail address: feras@itmindia.edu
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2. A Brief History of Tensegrity Structures

It is believed that the first person who made a structure reminiscent of the principles of tensegrity was Ioganson Karl, a Russian artist, who made a structure comprising of 3 struts, 7 tension cables and one cable to change the shape of the structure in 1920 [5, 10].

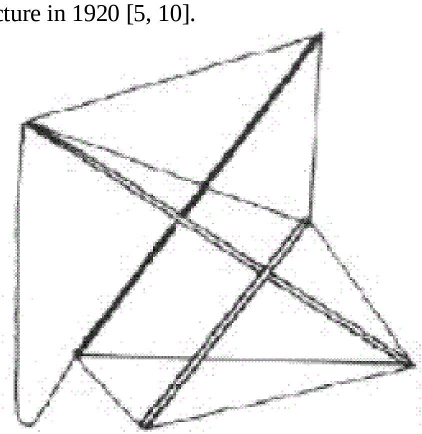


Fig: 4. Ioganson Sculpture-Structure [10]

In 1950's, simultaneous discoveries in the field of tensegrity were made by Kenneth Snelson and Buckminster Fuller in the United States and David Georges Emmerich in France [5]. David Georges Emmerich, an engineer and architect by profession, developed tensegrity systems based on prism. Emmerich and Fuller applied for patents between 1959 & 1964, and Snelson patents date back to 1965. In this way, these three people are considered as the fathers of the field of tensegrity structures.

In 1948 Kenneth Snelson made his X piece, a 3-D tensegrity structure. He also built the "Needle Tower II" in 1971, a huge structure which is kept at Kroller Muller Museum, Otterlo, Netherlands. Snelson directed his work towards the artistic development of tensegrity sculptures whereas Fuller oriented his research towards the analytical side.

Since the 1960s, lot of research work has been conducted on mathematical and structural aspects of tensegrity structures, among which the most highly cited works belong to Rene Motro and Robert Skelton. Motro has given an accurate definition based on the ones given by the pioneers, and has extended the work to the field of civil engineering structures. Skelton has extended Motro's work and given the most widely accepted definition of these structures, and has taken these structures to the field of robotics and mechanisms.

The scope of application of tensegrity structures in various fields can be understood by the latest research being carried by NASA, where a deployable tensegrity robot is being developed to be sent for planetary exploration [11]. In a totally different field of cellular biology, twenty years of research has shown that cells are tensegrity structures [12].

3. Definitions

Buckminster Fuller [1,2] coined the term Tensegrity as a conjunction of Tension and Integrity [3]. He described tensegrity structures as "islands of compression in an ocean of tension" [4]. He further explained: "the word tensegrity is an invention; it is a contraction of tensional integrity… tension is omni-directionally coherent. Tensegrity is an inherently non-redundant confluence of optimum structural factors. Tensegrity structures are pure pneumatic and can accomplish visibly differentiated tension compression inter functioning in the same manner that is accomplished by pneumatic structures, at the sub visible level of energy events" [13].

Kenneth Snelson defines tensegrity systems as follows: "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." [14].

Motro, a professor of civil engineering in Montpellier University, has extended the definition of tensegrity given by the pioneers as follows: "A tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components." Motro's definition encompasses the previous definitions with a higher mathematical clarity.

Robert Skelton's definition of a tensegrity system, which is currently the cited definition in the engineering fields, is as follows [15]: "A Class k tensegrity structure is a stable equilibrium of axially loaded elements, with a maximum of k compressive members connected at the node(s)." According to Skelton, a tensegrity structure can be named using symbols as "C" for compression members and "T" for tension members. For example, a tensegrity structure with four tension and two compression members can be called a C2T4 tensegrity [15].

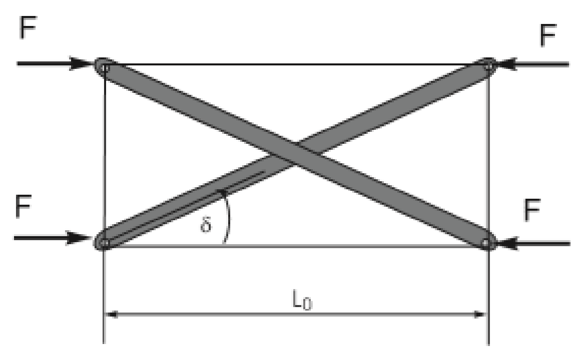


Fig: 5. Class 1 Tensegrity C2T4 [15]

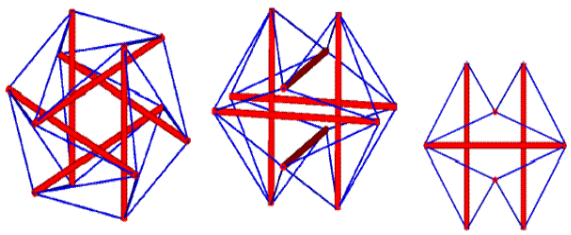
As the origins of tensegrity have been a topic of controversy, and it is a relatively new field of study, currently none of the definitions have been universally accepted. Usage of this term in various disciplines has been according to more than one definition, and that is why it is very important to know the various definitions and the differences among them.

4. Simple Examples of Tensegrity Systems

Tensegrity structures can have complex shapes and many tensile and compressive members. However, in this section we will review few simple examples of these structures to get an idea how they work.

4.1 Tensegrity Icosahedron

Tensegrity icosahedron consists of 6 struts and 24 edges. It is a symmetrical structure with three parallel pairs of struts. Icosahedron forms the basis of structure of carbon 60, viruses, cells and other elements in biology [16]. It is a class 1 tensegrity structure according to Skelton's definition. A Class 1 tensegrity is the one where no struts touch each other.



Fig; 6. Different Views of Icosahedron [17]

4.2 Tensegrity Cuboctahedron

It is made up of four triangular compression members and twenty four cables. At each node, 2 bars touch each other and hence it is a Class 2 tensegrity structure as per Skelton's definition and not a tensegrity structure as per Snelson's definition.

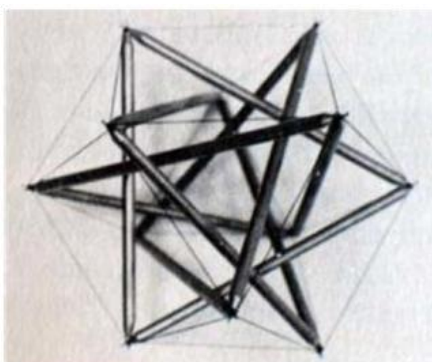
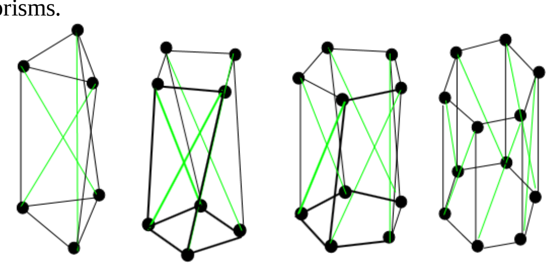


Fig: 7. Tensegrity Cuboctahedron [18]

4.3 Tensegrity Prisms

These prisms are 3-D self-stressing structures of class 1 tensegrity type. Figure 8 shows a family of tensegrity prisms.



Fig; 8. Tensegrity prisms [19]

5. Characteristics of Tensegrity Structures

- Tensegrity structures are stable structures because they can re-establish equilibrium after disturbances [20]. They are also totally independent of external forces (even gravity) because of the initial self-stress state, and do not need to be anchored to any surface [20].
- In a tensegrity structure, none of the members experience bending moments and are designed for axial loads. Hence, as compared to those structural members which are designed for bending, more reliable and accurate models can be expected [21]. Moreover, Euler's buckling load in compressive elements cannot be predicted accurately in practice as compared to the tensile strength of a member. Hence, increased use of tensile members in tensegrity structures can help to have more accurate models of the structures.
- Tensegrity structures are mass efficient [15]. Civil structures have been traditionally made with orthogonal beams, columns and plates but research has shown that this orthogonal design does not yield mass efficient design for a desired stiffness [22]. In tensegrity structures, longitudinal members are arranged in unusual patterns which are not orthogonal to achieve maximum strength with minimum mass.
- Tensegrity structures can efficiently serve as deployable structures. For this purpose, we can place pulleys at the ends of the struts and run the strings or cables through the pulleys. Then, the strings can be loosened for stacking the structure in a small space and then pulled to deploy the structure..
- Tensegrity structures are mass efficient which enables them to provide maximum strength for a given amount of material. Hence, bridges, domes etc. constructed using the principles of tensegrity may prove to be very economical.
- Tensegrity structures vibrate readily and transfer loads rapidly. Hence none of the individual members experience any stresses locally. By the virtue of this property, tensegrity structures may prove useful in absorption of seismic shocks.
- In comparison to most of the conventional structures and mechanisms, tensegrity structures can be actuated (controlled) with far smaller control energy [15].
- Pre-tensioning increases the stiffness of tensegrity structures. However, to attain high levels of stiffness, large pre-tension in the strings is required which may not be easy to implement. This is considered as the main drawback of these structures.
- The fabrication of tensegrity structures is not easy. Complex structures like spherical and domical structures may face problems in production.
- These structures are nonlinear and therefore their modeling and control needs special techniques which are still under development.

6. Applications

Tensegrity structures find applications in a variety of fields like civil engineering, architecture, mechanical engineering, aerospace, and biomechanics. A brief review of these applications is given here.

6.1 Architecture

Nowadays, material costs have been a matter of concern and as material costs go on increasing, tensegrity structures which use material more efficiently are becoming more and more attractive. Another aspect of tensegrity structures is controlled configuration change. Adaptable structures can be used to reduce damage in case of earthquakes or wind loads or can be used to modify the sunshine received inside in the building. Controllable tensegrity structures can give solutions in this regard.

With the numerous research works conducted by civil engineers and architect all over the world, it is now possible to mathematically model and design tensegrity structures for architectural applications. Hence, tensegrity bridges and roofs are now a reality [23, 24].

Fig: 9. Kurilpa bridge in Brisbane Australia built in 2009 [25]

In domical configuration, tensegrity structures can be used for fabrication of very large scale structures, for various purposes such as large scale electrical or electromagnetic shielding, green house for plant and food production, exclusion or containment of birds over agricultural fields, etc.

Tensegrity structures are deployable. Therefore, they can be used for disaster-stricken areas, setting up field hospitals, temporary shelters, etc.

As tensegrity structures are extremely resilient and transfer loads very rapidly, they could withstand large structural shocks and earthquakes.

Tensegrity structures provide superior resistance to external loads as compared to the conventional rigid concrete structures. Therefore, they can serve as an environmental friendly alternative to concrete construction.

6.2 Robotics

Deployablitiy, low weight, low energy requirement, and high controllability of tensegrity structures has made them a viable option in the field of deployable robots. These robots particularly can be used for exploratory missions where it is not easy or safe for human beings to reach. An example of these robots is the SuperBall [11], a deployable tensegrity robot under development by NASA for planetary explorations.

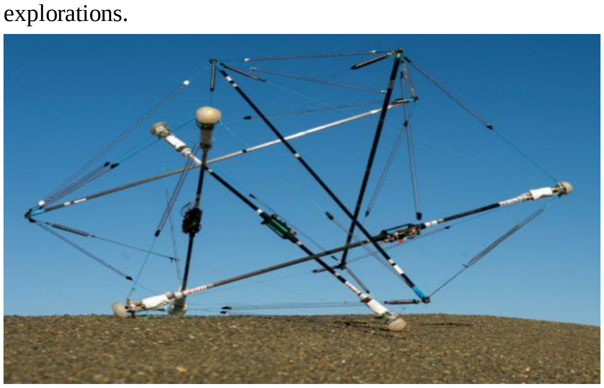


Fig: 10. "SuperBall" an Icosohedron Deployable Tensegrity Robot under Development in NASA [26]

6.3 Biology

One of the most interesting applications of tensegrity structures is found in the field of anatomy. Twenty years of research by Donald Ingber and his colleagues in Harvard University has shown that cells are not fluid filled sacs, but dynamic network with a tensegrity structure. The responses of cells to mechanical stimuli are best explained if they are modeled as tensegrity structures [6, 7, 8].

On the gross anatomy level, the theory of biotensegrity [16, 27] states that the body is made on the principles of tensegrity structures, in the sense that body joints carry compression forces via fascia, ligaments, and tendons and not via direct compression of the joint surfaces. Although this theory is still under debate, it is strongly supported by certain computational and experimental evidences [28, 29].

6.4 Other applications

Some more examples of the applications of tensegrity structures are as follows:

- Light weight shells for pavilions for expositions and trade shows, entrances to events, etc.
- Tensegrity Towers can be used as Lightning conductors. In situations where large displacements are not a matter of concern or considerable displacements are acceptable, tensegrity towers can be employed to support antennas, receptors, radio transmitters, mobile telephone transmitters, etc.
- Foldable reflector antennas and masts for large retractable appendages in spacecraft.
- Tensegrity systems can be used to make economical furniture like chairs, tables, lamps etc.

7. Conclusion

This review paper focused on understanding the definitions, characteristics and applications of tensegrity structures. A tensegrity system is a special case of a truss in which structural members have special functions. All the members in a tensegrity structure are axially loaded and none of the individual members experience bending moment. Tensegrity structures offer superior resistance to external loads as compared to conventional rigid structures with comparable mass. These structures are lightweight, deployable and mass efficient. Since the longitudinal structural members of a tensegrity system are arranged in non-conventional (not orthogonal) patterns, maximum mass efficiency is achieved having maximum strength with minimal mass. This characteristic of tensegrity structures makes them a potential alternative for conventional rigid structures with an added advantage of being deployable.

One of the most significant characteristics of tensegrity structures is deployability. Tensegrity structures are easily tunable and have a great potential to serve as an integration of structural design and efficient control. These structures are also space efficient. Deployability makes tensegrity structures viable options in disaster management, esp. in remote and hard-to-reach areas.

Researchers in the field of biology and biomechanics tensegrity suggest that tensegrity is the structure of choice in the nature. Similarly, tensegrities are slowly emerging as an alternative for conventional structures in architecture, engineering, aerospace, and other fields of engineering.

Excessive deformations under heavy loading and current lack of analytical tools to study and design tensegrity structures are among the major hindrances in large scale use of these structures. Methods of their easy fabrication need to be developed and further experimental and analytical research is required. These issues are currently the subjects of extensive research all over the globe.

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