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ON

“TENSEGRITY OF STRUCTURES AND THEIR APPLICATIONS”

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE OF

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CIVIL ENGINEERING

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DEPARTMENT OF CIVIL ENGINEERING

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CERTIFICATE

This is to certify that the technical seminar entitled **"TENSEGRITY OF STRUCTURES AND THEIR APPLICATIONS"** has been carried out by **BHOOMIKA S - [1CG17CV005]** bonafide student of **CHANNABASAVESHWARA INSTITUTE OF TECHNOLOGY, GUBBI, TUMKUR**, in partial fulfillment of the requirement for the award of the degree **Bachelor of Engineering** in **CIVIL ENGINEERING** from the **Visvesvaraya Technological University, Belagavi** during the year **2020-2021.** It is certified that all corrections/suggestions indicated for Internal Assessment have been incorporated in the Report deposited in the departmental library. The seminar report has been approved as it satisfies the academic requirements in respect of Technical seminar prescribed for the said degree.

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UNDERTAKING

I, **BHOOMIKA S** bearing **1CG17CV005**, student of **VIII Semester B.E.** in **CIVIL ENGINEERING, C.I.T, GUBBI, TUMKUR** hereby declare that technical seminar entitled **"TENSEGRITY OF STRUCTURES AND THEIR APPLICATIONS"** embodies the report of my technical seminar work carried out independently by me under the guidance of **Mr. VENKATESH A L, Assistant Professor, Dept. of CIVIL, CIT, Gubbi** as partial fulfillment of requirements for the award of the degree **Bachelor of Engineering** by **Visvesvaraya Technological University, Belgaum** during the academic year 2020-21.

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BONAFIDE CERTIFICATE

This is to certify that the technical seminar entitled **"TENSEGRITY OF STRUCTURES AND THEIR APPLICATIONS"** is a bonafide work of **BHOOMIKA S- 1CG17CV005 ,**student of **V**III semester **B.E.** in **CIVIL ENGINEERING** carried out at **Channabasaveshwara Institute of Technology, Gubbi, Tumkur,** in partial fulfillment of the requirements for the award of degree **B.E.,** in **Civil Engineering** of **Visvesvaraya Technological University**, Belgaum under my supervision and guidance.

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ACKNOWLEDGEMENT

A GREAT DEAL OF TIME AND LOT OF EFFORT have gone into completing this technical seminar report and documenting it. The number of hours spent in getting through various books and other materials related to this topic chosen by us have reaffirmed its power and utility in **CIT-Learning Resource Centre, CIT, Gubbi**

Several special people have contributed significantly to this effort. First of all ,I am grateful to our institution **Channabasaveshwara Institute of Technology**, **Gubbi**, which provides us an opportunity in fulfilling our most cherished desire of reaching our goal.

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Finally I would like to express my sincere thanks to all our teaching and non-teaching staff; they were extremely helpful in assisting us in using the excellent facilities of the institute.

ABSTARCT

Tensegrity is the characteristic property of a stable 3D structural principle based upon a system of isolated components of both compression and tension, where compression members are discontinuous within the continuous tension members. Tensegrity is relatively a new principle, as a structural system it contributes many advantages over the non-conventional structural systems. The structure can be kept rigid without the help of external members, when the structure is properlyoperated. This concept has found its applications in soft robotics and in many civil engineering structures such as roofs, bridges, towers, domes and they are briefly discussed in this paper. This paper reviews the precedent works that are helpful for the development of the tensegrity structures. This paper urges to gather all the information from different fields. To achieve this purpose, it is important to understand the structural principles of floating compression or tensegrity. The main advantages, disadvantages and the future scopes of this concept in the architecture field is also briefly discussed.

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LIST OF FIGURES

CHAPTER-1

INTRODUCTION

Tensegrity structures are three-dimensional trusses in which each member is assigned a distinct function. Some members stay in tension all the time, whereas others are always compressed. String or cable type elements can be utilised as tension members, usally for compressive members solid sections or bars are used .

The majority of bar–string configurations will be out of balance. As a result, if built, they will collapse into a new shape. Tensegrity structures are bar–string constructions that are pre-stressed and in a stable equilibrium. The application of forces to a Tensegrity structure, if effectively built, will deform it into a slightly different shape that supports the applied force.

The term "tensegrity" comes from the phrase "tensional integrity." Buckminster Fuller is credited with coining the phrase in a patent filing from 1962. TheThe artist Kenneth Rexroth is credited with building the first real Tensegrity structure.In 1948, Snelson developed his X-piece sculpture.

Stability is another crucial factor to consider. When a collection of discontinuous compression components interacts with a set of continuous tensile components, a tensegrity system is formed.

Hanaor gives a more mechanical explanation of Tensegrity structures, describing them as “internally pre-stressed, free-standing pin-jointed networks, in which the cables or tendons are tensioned against a system of bars or struts.” The fact that the system is pre-stressed and pin-jointed is mentioned in this description. This suggests that the system only has axial forces and no torque.

The following is a general definition of a tensegrity structure:

“A material system's geometry is in stable equilibrium if, as time passes, all particles in the system return to this geometry, starting from any initial point arbitrarily close to this geometry.”

The bars are one-dimensional elastic bodies, while the strings are stiff bodies. As a result, if the nodal points of the system's bars are in equilibrium, the system is in equilibrium.

To summarise, the following descriptions coverthe majority of the characteristics of the Tensegrity concept:

1. Pin-jointed bar frameworks: Pinjointed three-dimensional trusses make comprise the structural group of tensegrity structures.

2. Pure compressive/tensile members: Only pure compression and tension members are seen in tensegrity structures. Cables that can only sustain tension are utilised as tension elements.

3. Localisation of compression: The compressive elements in classic Tensegrity structures are discontinuous. They appear to be floating in a continuous web of tension factors.

4. Pre-stressed structures: It stabilises internal systems, a condition of pre-stress or self-stress is necessary for the structure's stability.

Fig. 1.1 "30' cantilever" by Snelson, 1967

The first exercise in the Advanced Calculation of Structures (E.T.S. de Ing. de Caminos de Santander) course in October 2000 was a reflection on the Skylon's equilibrium. The Skylon was a type of sculpture that served as a symbol for the 1951 South Bank Exhibition in London. The structure's unusual and unique behaviour inspired researchers to learn more about it, as well as tensile structures in general. In reality, he began constructing miniature Skylons out of two chess game knights.

Fig. 1.2 Mini-Skylon in chess gam

OBJECTIVES

1. To study the origins of tensegrity, original patents and shed light on some polemic aspects.
2. To revise the history and progress of this kind of structure, tracing a line of the time and pointing out the most relevant works, publications and specialists, not only relatedto Architecture but also to other dissimilar fields, which could serveas the guide for further investigations.
3. To define the structural characteristics and fundamental concepts of the continuous tension-discontinuous compression structures, describing its properties, highlighting the advantages and indicating its weak spots.
4. To establish a clear and generally accepted definition of tensegrity and to set-upa general classification for these systems.
5. To investigate the use of structures similar to tensegrity in previous studies, works or patents and compare them to some of the suggested proposal in order to attest the feasibility of their potential.
6. To estimate how widespread the knowledge about the tensegrity structures actually among the Architects and Engineers by means of interviews and questionnaires.
7. To achieve a wider professional awareness and encourage consideration of tensegrity structures in Architecture and Engineering, as a feasible means application for modernworks.

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 and some other unpublished works are also included. It is worthwhile highlighting that at the very beginning some experimental studies and load testingof models were programmed. Unfortunately, the absence of appropriate infrastructures, budget and time suggested abandoning the idea. Instead, the author worked with models in depth and once the design was established, an attempt was made to compute the finalgeometry in more detail.

CHAPTER - 2

LITERATURE REVIEW

i. Raman Goyal , Muhoo chen , Manoranjan Majji , Robert E Sketton – Tensegrity structures and their applications to architecture- (2019)

Tensigrity structures are used rarely in architectural and civil engineering .To analyze the behavior of the modules when the variables such as tension and support are controlled independently for each individual module.

ii. Jiangug Cai , Xinyu Wang , Ruiguo Yang – Mechanical beehaviour of tensegrity structures with high mode imperfections – (2018)

Tensegrity structures with higher modes of intial imperfections show a more unpredictable mechanical response. A numerical method using a force density method combined with a genetic algorithm has been proposed as a form-finding process for tensegrity structures with multiple states of self-stress.

iii. T Meena - An insight into research perspectives of tensegrity structures – (2017)

This paper has made a modestattempt at throwing light on the various research activities on tensegrity structures in the past. Tensegrity structures are applied in spacecraft due to their advantages of deformation and adjustable pre-stress.

iv. Ankit Kumar , Prasiddhi Mehta , Kamlesh Mandloi- Review paper of tensegrity structures –(2018)

Tensegrity structure is of a great potential in construction industry . It introduces the initial imperfection to tensegrity structures in order to better understand the nonlinear behaviour of various mechanics in the small range of deformation

2.1 LITERATURE SUMMARY

- A numerical method using a force density method combined with a genetic algorithm has been proposed as a form-finding process for tensegrity structures with multiple states of self-stress.
- Tensegrity structures are applied in spacecraft due to their advantages of deformation and adjustable pre-stress.
- The close formulas are useful in the design proses and construction of different types of tensegrity systems.
- It introduces the initial imperfection to tensegrity structures in order to better understand the nonlinear behaviour of various mechanics in the small range of deformation.

CHAPTER – 3

HISTORICAL BACKGROUND

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.

3.1 THE ORIGINS

Three men have been considered as the inventors of tensegrity: Richard Buckminster Fuller, David Georges Emmerich and Kenneth D. Snelson. Although all the three have claimed to bethe first inventor, R. Motro (1987, 2003) mentions that Emmerich (1988) reported that the first proto-tensegrity system called, “Gleichgewichtkonstruktion” was created by Karl Ioganson in 1920.

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 . 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.

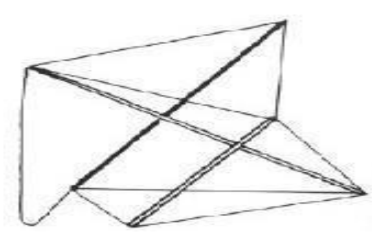

Fig. 3.1 Structure-Sculpture by Ioganson

As Emmerich (1988) explain, the structure consists of three bars, seven chords and eight cables 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. The absence of prestress, which is one of the characteristics of tensegrity system, does not allow Ioganson"s "Structure-Sculpture" to be considered the first of this kind of structures.

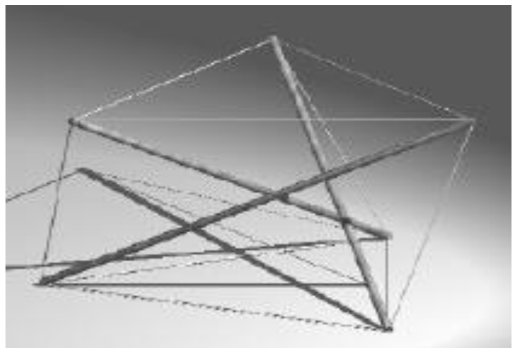

Fig. 3.2 Elementary Equilibrium or Simplex

At the same time, but independently, David Georges Emmerich (Debrecen- Hungary, 1925-1996) 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.

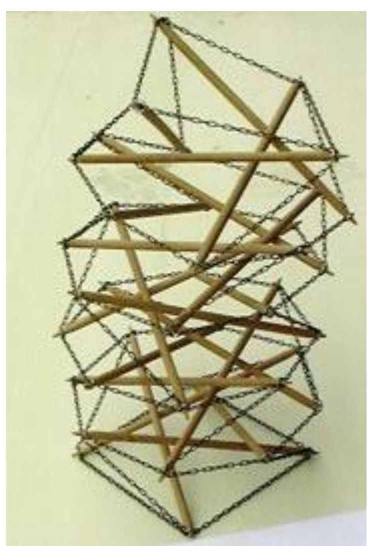

Fig. 3.3 Z3-1 mat prismatique 4B racemaiue by Emmerich

3.2 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, applying his intuitive knowledge and achieving impressive sculptures that are spread all over the world. 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.

Fig. 3.4 Dragon by K.Snelson

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. 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. 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) . 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.

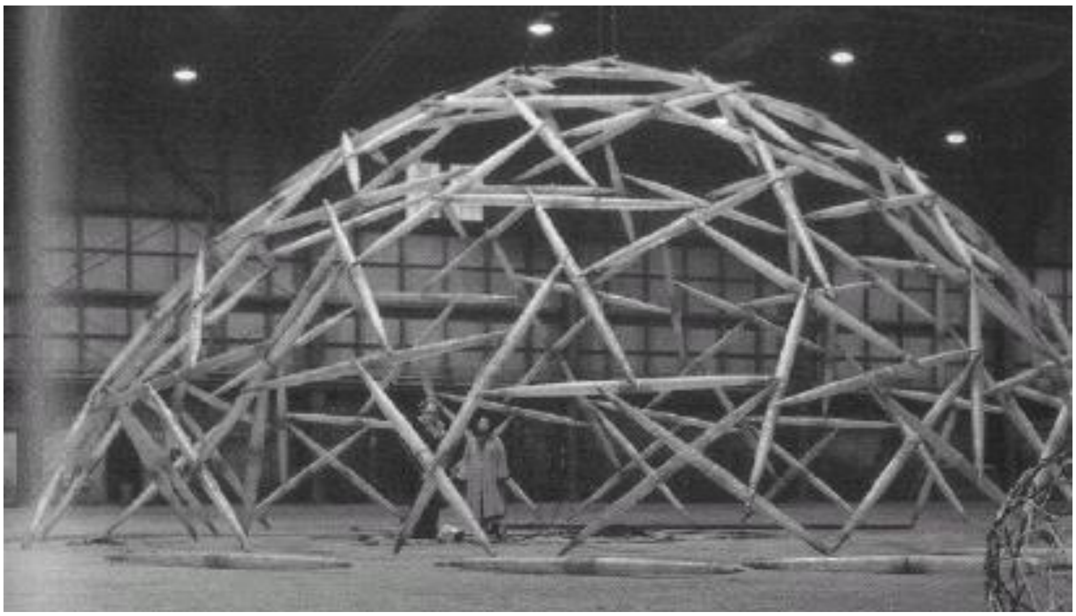

Fig. 3.5 Geodesic Tensegrity Dome by Fuller

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 (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 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 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.

Fig.3.6 U.S. Pavilion for Expo 67 by Fuller

CHAPTER-4

METHODOLOGY

René Motro, one of the most important specialists in tensegrity, started to publish his studies on the subject in 1973: Topologie design structure discretès. It was an internal note for the Laboratory of Civil Engineering of the University of Montpelier (France) about the mechanical behavior of this kind of structure.

Some years later, in 1976, Anthony Pugh and Hugh Kenner, both from 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 behavior of tensegrity under load.

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.

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.

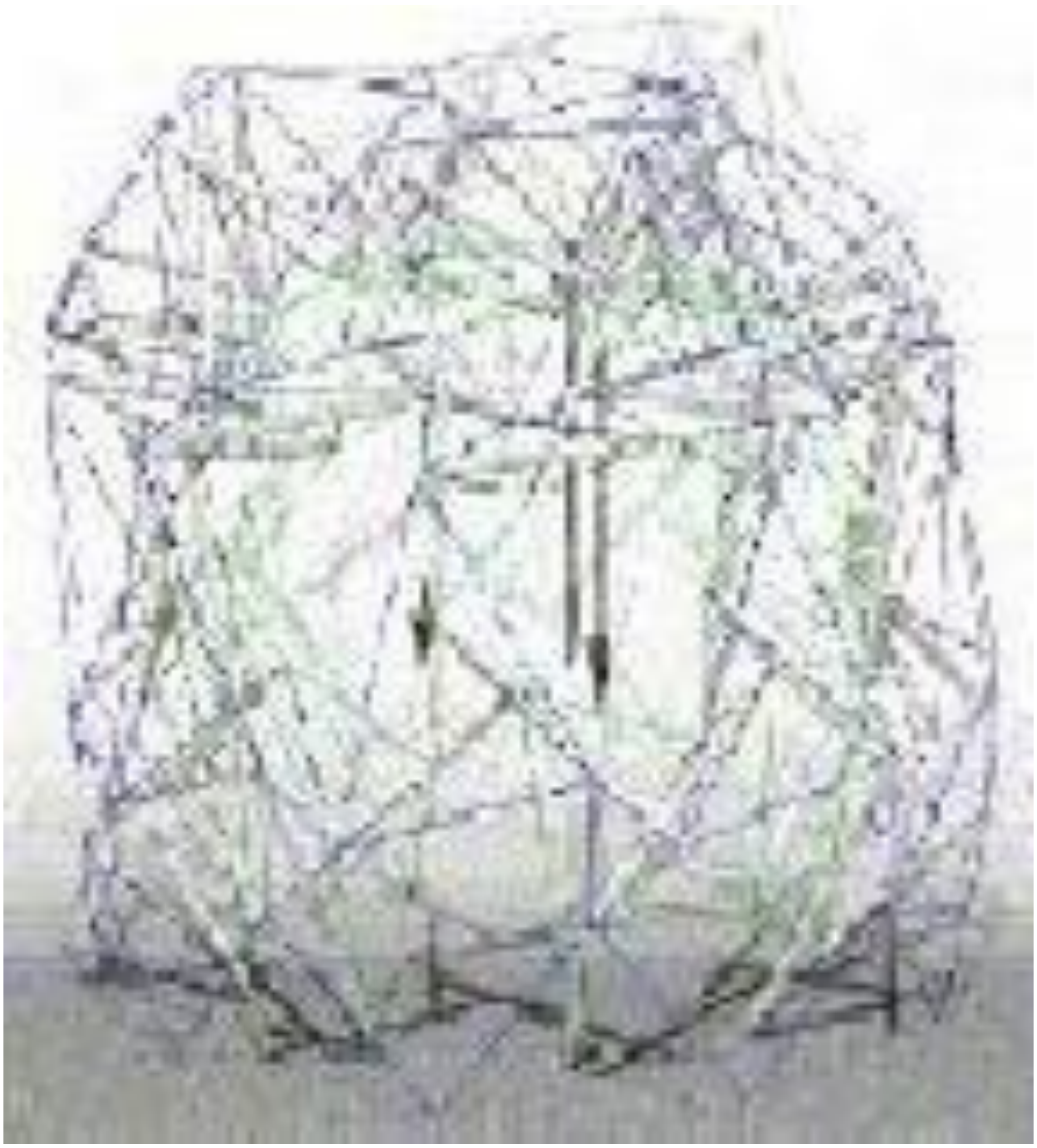

Fig.4.1 T-Octahedron Dome, Positions and effects of exogenous loads by Burkhardt

CHAPTER-5

PRECEDENTS AND KEY STUDIES

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.

5.1 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 18 th 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.

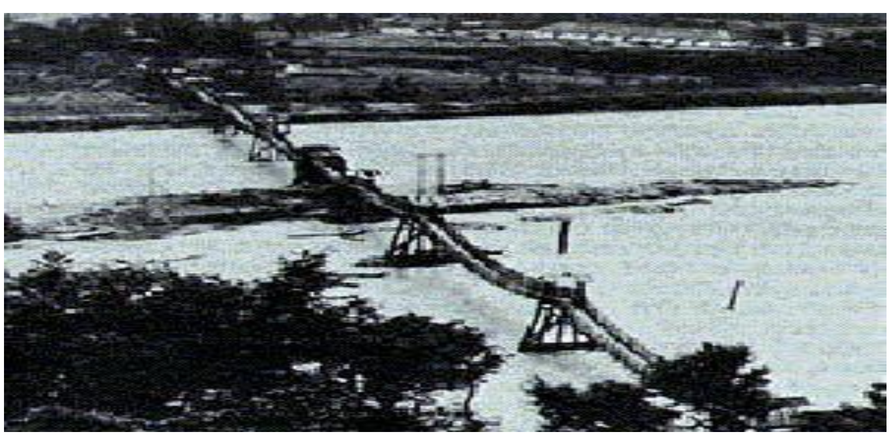

Fig. 5.1 An-Lan Bridge in Kuanshein, China

In any case, it is evident that the development of steels and other alloys lead to unpredicted outcomes in terms of resistance, weight and performances of materials, which enabled the engineers and architects to create new designs and new structural components. 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 behavior of elements under a load is different depending upon the type of load. As illustrated in figure 4.3, when a lineal element is compressed along its main axis, it has thetendency to augment its cross-section (due to Poisson‟s ratio effect) and to buckle, which means it loses its straight shape. When the same element is tensioned in the same direction, it tends to become thinner and it reaffirms its straight axe.

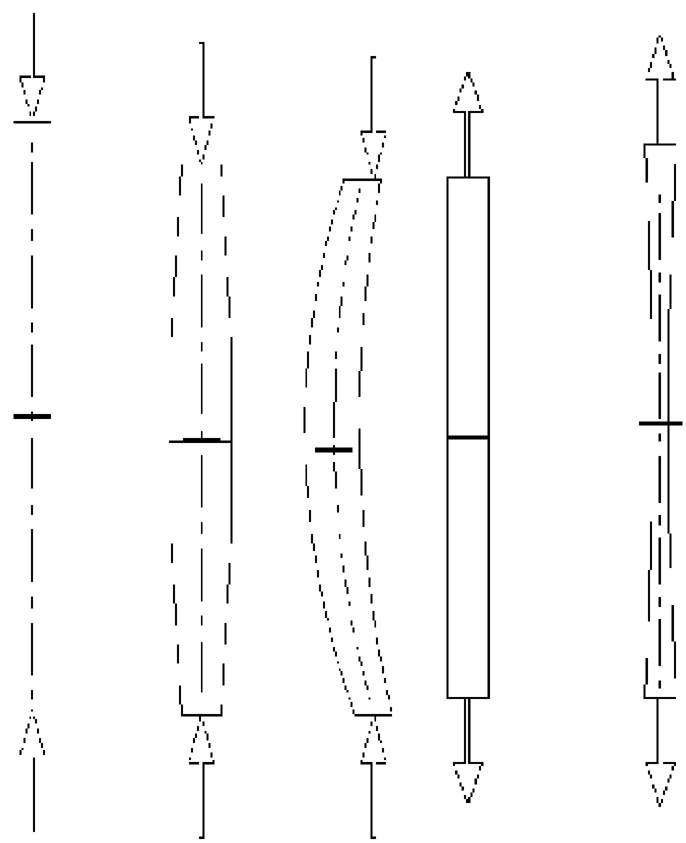

Fig. 5.2 Deformation under compression & Deformation under tension

5.2 SOME PRECEDENTS

As has just been commented on, the new materials discovered during the 19th and 20 th 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..

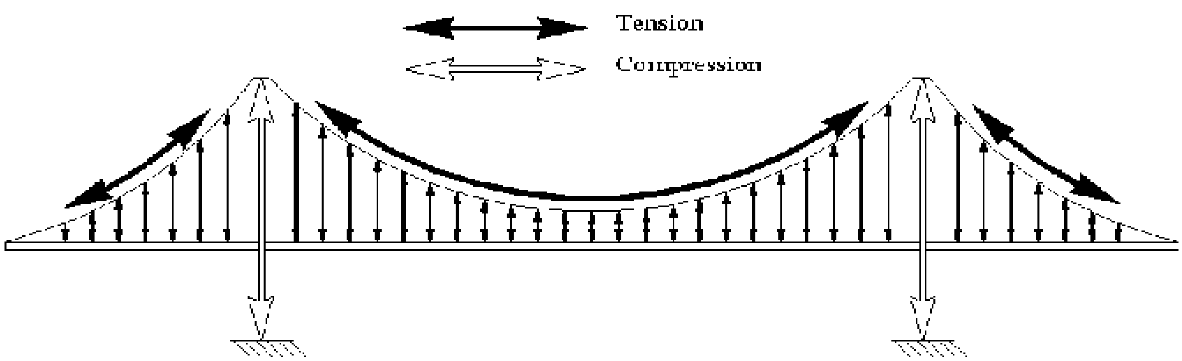

Fig. 5.3 Suspension Bridge Fundamental concepts

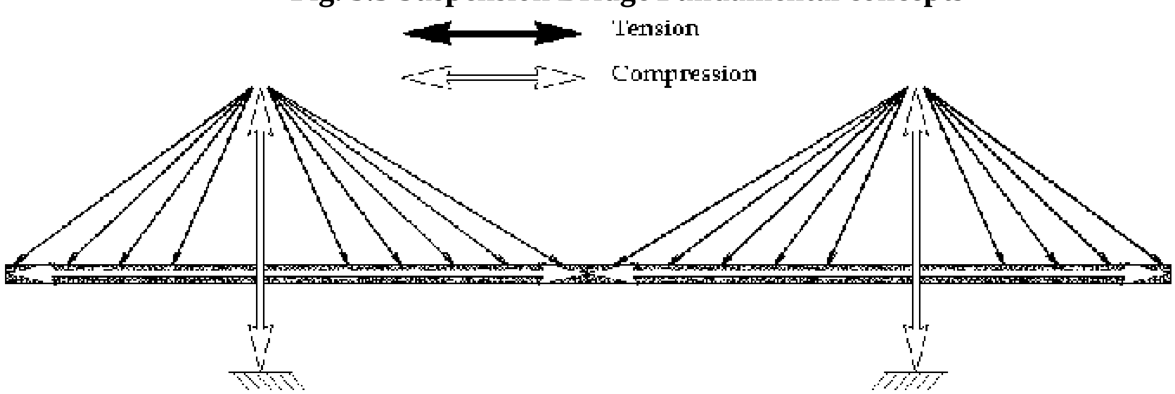

Fig. 5.4 cable-stayed Bridge Fundamental concepts

The cable-stayed bridges make use of stressed cables to support the deck and also put it undercompression. Thus the deck is prestressed and out in equilibrium. A very good example is theBarrios de Luna Bridge in Asturias (Spain), by Javier Manterola, which shows this principle perfectly in both of its two towers and main span of 440m.

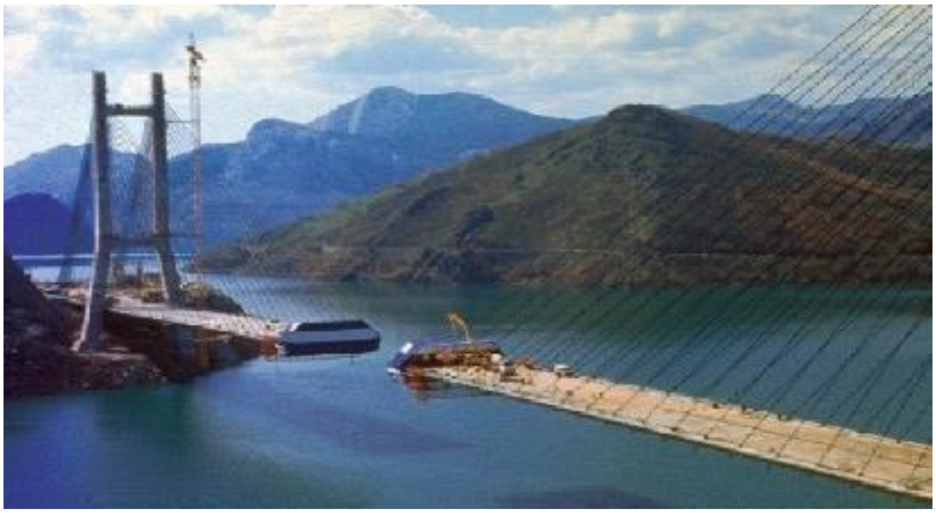

Fig. 5.5 Barrios de Luna Bridge by J. Manterola

5.2.1 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 exhibitionsgrounds. Philip Powell and Hidalgo Moya (helped and inspired by their former Felix Samuely) designed the Skylon , which was selected as the best proposal and built nearthe Dome of Discovery.

Fig. 5.6 Skylon

5.2.2 Suspended roofs and tensile structures

During the 1950s, the exploitation of cables in traction was not only improved, but also of other elements such as membranes, materials and tissues. In 1950, the State Fair Arena, at Raleigh (North Carolina) was designed by Matthew Nowicki following his intuitive concepts of suspended roofs . 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).

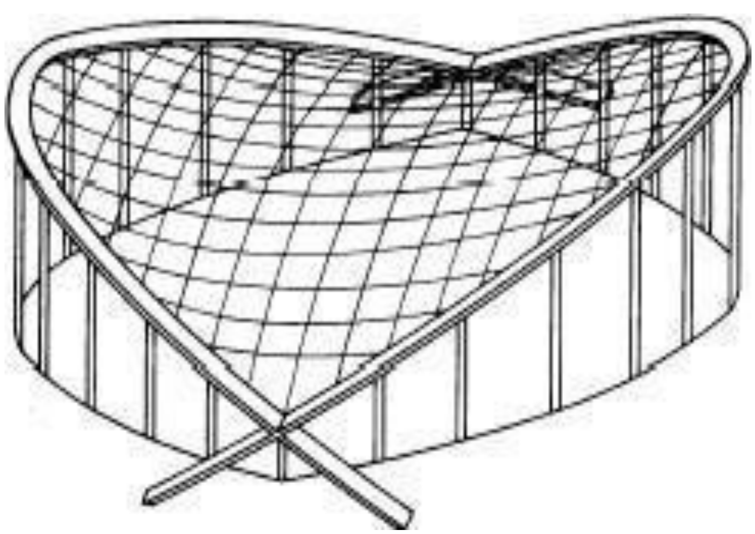

Fig. 5.7 Rayleigh Arena, by Nowicki

CHAPTER-6

TYPES OF TENSEGRITIES

6.1 TENSEGRITY PRISM (T-PRISM)

Also known as „Three struts T-prism" was invented by Karl Ioganson in Moscow in 1921 [23]. It is the simplest and therefore one of the most instructive members of the tensegrity family. The T-prism has 9 tendons and 3 struts (see Fig. 10) and belongs to a subclass of prismatoids. It has been called tensegrity prism or T-prism as it can be considered as atwisted prism consisting of two triangular faces twisted with respect to each other. Generally, these tensegrity structures are designed by keeping the lengths of one set of tendons and struts constant, and determining the lengths of another set of tendons. When one end of the prism is twisted relative to the other, the rectangular sides of the prism become non-planar quadrilaterals. Thus, two opposite angles of each quadrilateral become obtuse and acute. For structure to be stable and prestressed, the prism is twisted in such a way that the distance between the obtuse angles is least (an intermediate stage of twisting) and hence, a completely stable T-prism is formed.

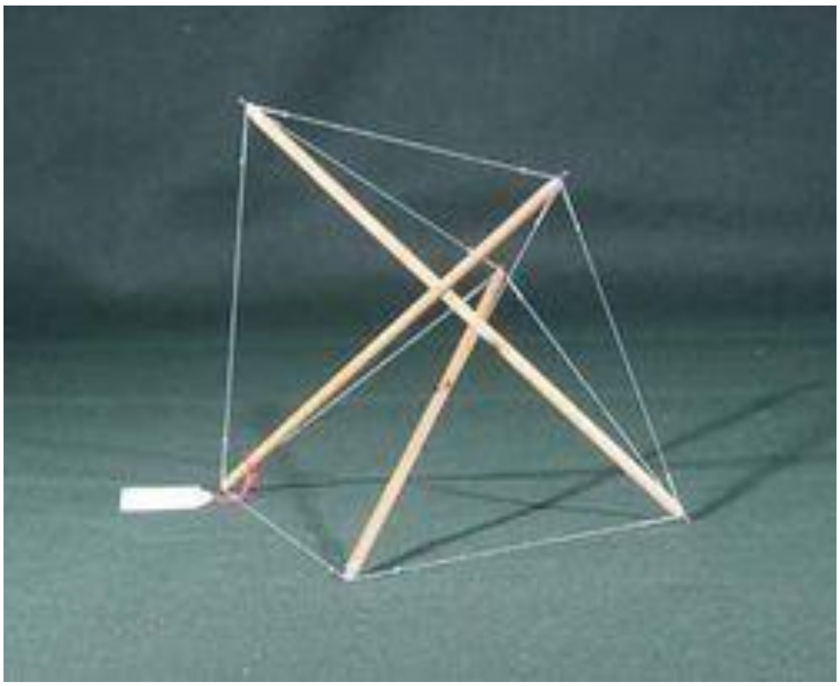

Fig. 6.1 Diamond Configuration of T-prism

6.2 DIAMOND TENSEGRITY

The tensegrity icosahedron also known as T-icosahedron depicted in Fig. 11(a) is a classic example of diamond tensegrity. These tensegrities are characterized by the fact that each triangle of tendons is connected to the adjacent one via a strut and two interconnecting tendons [17]. It was first exhibited by Buckminster Fuller [23] in 1949 and is one of a few tensegrities which exhibit mirror symmetry. This tensegrity is classified as a „diamond‟ type because each of its struts is surrounded by a diamond form of four tendons which are supported by two adjacent struts making them distinct from a Zig-zag tensegrity. It has 6 struts and 24 tendons with tendon to strut lengths ratio of 0.612.

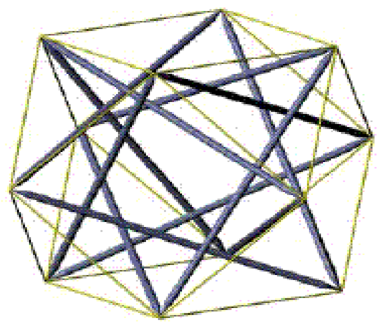

Fig. 6.2 Diamond tensegrity

6.3 ZIG-ZAG TENSEGRITY

The tensegrity tetrahedron also known as (T-tetrahedron) depicted in Fig. 15 is a classic example of diamond tensegrity developed by Francesco della Sala in 1952 [23]. The T-tetrahedron is the zig-zag counterpart of the diamond T-icosahedron (see Fig. 11). Although both structures have 6 struts, the major difference is that T-tetrahedron has four tendon triangles, whereas the T-icosahedron has eight of them.

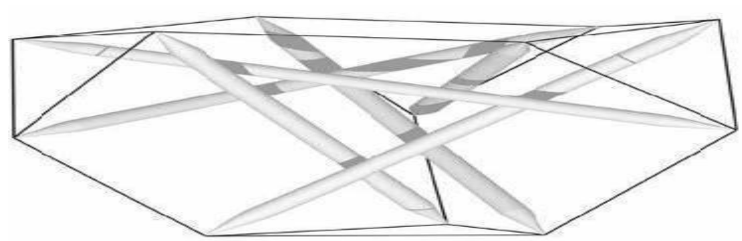

Fig. 6.3 Zig-Zag Tensegrity

6.4 CHARACTERISTICS OF TENSEGRITIES

1. They have a higher load-bearing capacity with similar weight.
2. They are light weight in comparison to other structures with similar resistance.
3. They don‟t need to be anchored or have to lean any surface as they don‟t depend on their weight or gravity. They are stabilized in any position by equilibrium of compressive forces in struts with tensional forces in prestressed cables. Prestrain in the cables can be transformed into prestress only if the structure is statically indeterminate.
4. They are enantiomorphic i.e. exist as right and left-handed mirror pairs .
5. Elementary tensegrity modules can be used (such as masts, grids, ropes, rings etc.) to make more complex tensegrity structures.
6. Higher the pre-stress, stiffer the structure would be, i.e. its load bearing capacity increases with the increasing pre-stress . The degree of tension of the pre-stressed components is directly proportional to the amount of space they occupy .
7. In a tensegrity structure the compressive members are short and discontinuous, hence they do not undergo buckling easily and no torque is generated in them .
8. The resilience depends on the structure assembly and material used. i) They work synergically i.e. their behaviour cannot be predicted by considering the behaviour of any of their components separately.
9. They are sensitive to vibrations under dynamic loading. Slight change in load causes the stress to redistribute in the whole structure within no time and thus, they have the ability to respond as a whole.
10. Kenner [16] introduced a term „Elastic Multiplication‟ for the tensegrity structures. It is a property of tensegrity structure which depends on the distance between two struts. If two struts are separated by a certain distance the elongation of tendons (tensile members) attached to them is much less compared to this distance.
11. The deformation response of entire tensegrity structure to load is non-linear as its stiffness increases rapidly with increasing load, like at a suspension bridge .
12. The tensegrities are commonly modelled with frictionless joints, and the self-weight of cables and struts is neglected.

6.5 ADVANTAGES OF TENSEGRITY

13. As the load is distributed in whole structure there are no critical points of weakness.
14. They don‟t suffer any kind of torsion and buckling due to space arrangement and short length of compression members.
15. Forces are transferred naturally and consequently, the members position themselves precisely by aligning with the lines of forces transmitted in the shortest path to withstand the induced stress.
16. They are able to vibrate and transfer loads very rapidly and hence, absorb shocks and seismic vibrations which makes them applicable as sensors or actuators .
17. They can be extended endlessly through adding elementary structures.
18. Construction of structures using tensegrity principle makes it highly resilient and, atthe same time, very economical.
19. Tensegrities deflect and disperse loads rather than compound them.
20. Tensegrities do not rely on gravity to hold together.

6.6 DISADVANTAGES OF TENSEGRITY

21. If the structure becomes too large it faces a problem of bar congestion (i.e. the struts start running into or touching each other).
22. They show relatively high deflections and low material efficiency as compared to with conventional continuous structures .
23. Fabrication complexity is a major barrier in developing floating compression structures .
24. Adequate design tools are not available for their design, software „Tensegrite 2000‟ (developed by R. Motro et al.) is the most advanced tool available to design tensegrity structures.
25. At large constructions the structure cannot withstand loads higher than the critical, related to its dimensions and prestress .
26. Arrangements need to solve the problem of bar congestion.
27. As some designs become larger, the struts start running into each other.

CHAPTER-7

CASE STUDY

1. **Wojciech Gilewskia , Paulina Obara (2015) "Applications of tensegrity structures incivil engineering" ,** the objective of the present paper is to describe the applications of tensegrity structures in civil engineering (roofs, domes, stadiums, etc.). The term of tensegrity was introduced by Fuller in the middle 50th of XX century. There are several definitions of this concept. For the purpose of this paper the tensegrity is defined a pin- joined system with a particular configuration of cables and struts that form a statically indeterminate structure in a stable equilibrium. Infinitesimal mechanism should exist in a tensegrity with equivalent self-stress state. Major advantages of tensegrity are: large stiffness-to-mass ratio, deployability, reliability and controllability.

2. **Valentin Gomez-Jauregui (2004) "Tensegrity structures and their application toarchitecture"** , 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 thatthe 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 suchan 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**.**

CONCLUSIONS

1. Pretension applied to the tensegrity structures is considered to be the most critical.
2. Pretension is a method of increasing the capacity of load-bearing capacity of a structure through the use of strings that are stretched to the desired tension.
3. This allows the structure to support greater loads without as much deflection as compared a structure without any pretension.
4. Throughout the research work, many conclusions have been proposed about tensegrity.
5. Antoni Gaudi, Santiago Calatrava and Frei Otto, used the structural fundamentals of soap films, spider webs, vertebral spines, oil drops, etc., to achieve an improvement inthe designs.
6. Drew invoked biological functionalism to support the concept that lightweight is a real measure of structural effectiveness.
7. Antonio Sant‟Elia (cited in Drew, 1976) predicted a new architecture with new qualities; revolutionary, elastic, light, expandable, active, mobile and dynamic.

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