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LIGHT-WEIGHT SELF-STRESSED SYSTEMS OF TENSEGRITY

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ABSTRACT

The word tensegrity is a contraction of tensional integrity. In simple structural terms, tensegrity systems are self-stressed pin-jointed networks. Each node receives at least one strut (compression member) and three cables (tension members). Tension members are thus prestressed against adjoining compression members. This is a pure form of tensegrity where only compression and tension members co-exist to form free-standing structures requiring minimum anchorage system compared with conventional types of structures. Double layer tensegrity systems are interesting because the compression members are relatively short, making the network quite rigid and compact. In the non-prestressed state, the system could be easily deployed. The present paper reviews limited research so far conducted at Coventry University on double layer tensegrity networks. It also reviews future directions in research into this fascinating field that has yet to be fully explored and exploited to find proper applications for it in the civil engineering discipline.

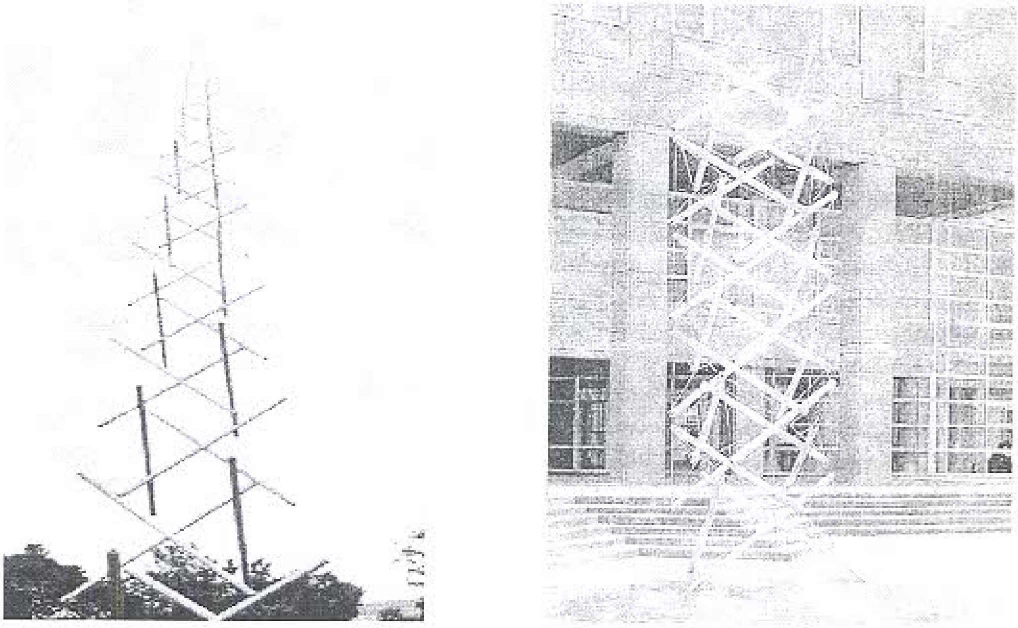
Keywords: tensegrity, tensional integrity, grids, self-stressed, lightweight.

1. INTRODUCTION

Tensegrity, a contraction for tensional integrity, is a fascinating concept developed by sculptor Kenneth Snelson [1], [2] (Fig 1) and later patented and explored by Buckminster Fuller [3]. Since then, these structures did not stop posing intriguing and interesting questions to mathematicians, architects, and engineers alike. The concept of tensegrity relies on using a suspension of discontinuous compression, which effectively acts as a stiffening system, in a continuous tension system.

To date some work has been done with the aim of understanding these structures from geometry point of view but also from an engineering viewpoint (structure and its mechanics). However, the main problem is to find applications of the system in practical terms as to its suitability in construction.

Over the years, researchers have attempted to find a suitable definition to the system, but the characteristic that is unique to tensegrity is the fact that they are lightweight self-stressed and self-supported systems. It must be stated that, while the cables are obviously rectilinear, the struts, however, don't have to, they could be rectilinear but they could also be curved for example (although this would introduce bending in the struts because of the eccentric loading). Work undertaken to understand their structural performance has been conducted by Emmerich [4], Motro [5] and [6], and Hanaor [7] and [8] among others. However, there is still a lot to be achieved before tensegrity could compete with traditional structures.



(a) (b)

(a) "The needle tower, Kroller Museum, Holland" (Courtesy of Kenneth Snelson)
(b) "Equilateral quivering tower, Osaka, Japan" (Courtesy of Kenneth Snelson)

Figure 1 Examples of tensegrity

Some of the problems hindering the use of this fascinating system are:

(i) *large deflections as compared with conventional forms of construction even for relatively small loading;*

(ii) *difficulty in pre-determining with precision the initial geometry of the structure (dependent on the level of pre-stress present);*

(iii) *complexity of the fabrication process, this is exasperated by the difficulty in connecting all the different elements together without introducing bending forces in the struts (maintaining pin-jointed connections);*

(iv) *congestion of elements especially for large structures (such as for space enclosing purposes); absence of adequate software and design tools which again make the use of the system a difficult task (analysis would require large-deformation numerical methods);*

(v) *difficulty of covering the system because of the geometry it generates;*

(vi) *lack of understanding of failure mechanisms for such systems.*

(vii) *there is a lack of knowledge on the failure mechanisms of such systems, mainly as concerns progressive failure. How would the structure respond if say one of the cables break or one of the struts fail?*

Therefore, it seems that a lot needs to be done on the structural behaviour side of the subject.

2. NATURAL TENSEGRITY

Tensegrity is part many natural processes and is present even in our own human body as noticed by Levin in his address to the North American Academy of Manipulative Medecine [9]. Levin noted how the support system of the spine, and indeed the remainder of the body as well, is a function of continuous tension (muscles and ligaments) and a suspension of discontinuous compression (the skeleton). He suggested that the mechanics of the human anatomy could be modelled and analysed as a tensegrity system. He even suggested a total rethinking of concepts so far used in biomechanics.

On the other hand, Ingber [10] discovered how living cells use a form of geodesic architecture, known as tensegrity, to organise their molecular scaffolds into porous 3D forms that simultaneously provide high mechanical strength and enhanced flexibility. It is also said that the methane molecule, one of the most basic organic substances, has in itself the physical shape and properties of a tensegrity structure. Such systems are omnidirectional and are stable in any direction independent of gravity. It is becoming increasingly evident that tensegrity when applied to biological systems could have many advantages.

3. SOME ANALYSIS AND DESIGN CONSIDERATIONS

Fuller stated that the apparent behaviour of geodesic tensegrity is similar to that of a pneumatic structure (Fig 2) [3]. Motro and Raducanu also describe tensegrity as a system of "discrete pneumatic systems" [11]. Of course the reality is that the behaviour of tensegrity systems is very complex, since such systems can undergo very large deformations for quite small loading. The response of a tensegrity system to loading is function of:

- the magnitude of the load
- structure configuration
- rigidity of the individual components (rods and cables)
- and the level of prestress

The shape of the original structures may change so much even for small loads that such structures are referred to as kinematically indeterminate (they are also internally statically indeterminate structures since each node would have at least one rod connected to it and three cables – a consideration of compatibility requirements is, therefore, required). It is therefore expected that a large-displacements analysis approach be adopted in analysing such structures. Since even the initial geometry is not knows (since it is dependent on the level of pre-stress present in the structure), a form-finding procedure will be very difficult to carry-out as is the case with membrane and cable structures. An iterative procedure could be followed. Alternatively, and thanks to advances in computer numerical software, it is possible to model and predict the geometry of the initial structure and to undertake detailed large-deformation analysis (geometric non-linearity) for a given loading arrangement [12]. The displacements at the nodes as well as the forces in the cables and the rods could also be obtained with ease.

A condition of self-stressing of the network is that the topology at a given node is such that at least three cables and one strut meet. In addition the compressive element (strut) should lie in space within the solid angle defined by the three tensile elements (cables). These conditions are necessary but not sufficient on their own [5].

In the case of basic tensegrity prisms (see example of triangular prism, Fig 3), the relationship between the (minimum) number of tendons required (T) and the number of cables (C) is: C = 3xT

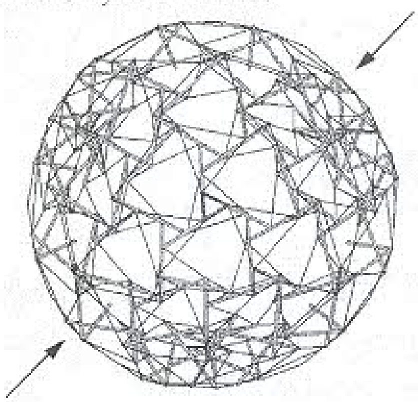
Table 1 Examples of basic tensegrity prisms

Tensegrity prism type	No. of tendons required T	No. of cables required C
Triangular	3	9
Square	4	12
Pentagonal	5	15
Hexagonal	6	18

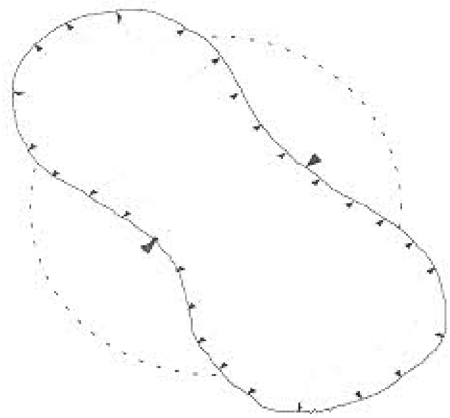
Obviously, the number of joints is always equal to twice the number of tendons, since in a pure tensegrity, at each joint, there is only one tendon and at least three cables. There is no obvious relationship for other type of tensegrity, such as tensegrity polyhedra. The relationship tendons-cables would depend on the kind of geometry generated and level of prestress required.

Like in any structural network, at each node the conditions of static equilibrium and displacement compatibility must be satisfied. It is possible to determine the number of possible states of self-stressing and independent mechanisms by determining the rank of the equilibrium matrix for the network [12]. The use of sophisticated finite element suites may solve many of the problems associated with both understanding the mechanics of tensegrity and ultimately their design requirements. Also, it is possible to use work previously undertaken on cable networks [13] and extend it to tensegrity for the development of theoretical and analytical models.

There is no doubt that the question for the future will not be how to analyse such structures but rather how to find efficient and effective usage of them as highly visible and functional structures, like any of the traditional structures known to mankind. However, it may be argued that these structures will probably find their application in some non-traditional type of civil engineering structures. Only time will tell.



(a) geodesic tensegrity



(b) pneumatic model

Figure 2 Geodesic tensegrity and model as envisaged by Fuller [3]

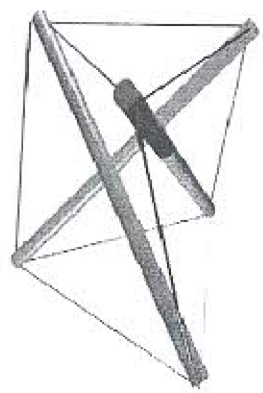
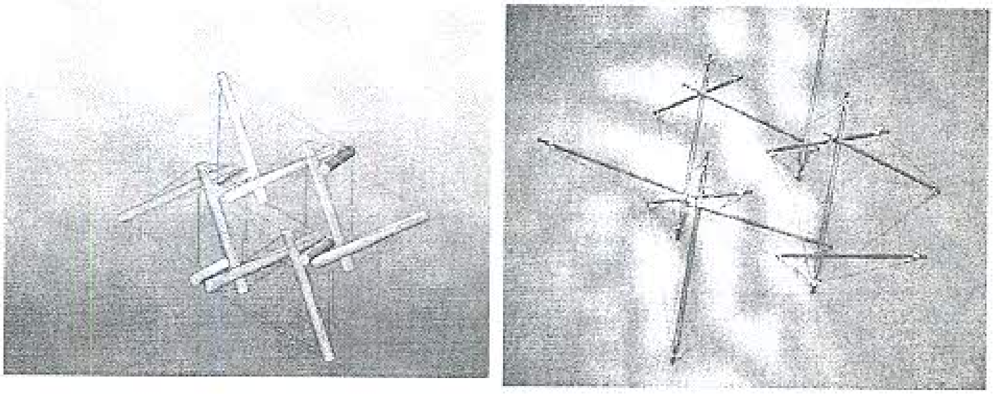


Figure 3 Triangular tensegrity prism

4. DOUBLE LAYER TENSEGRITY GRID (DLTG)

The DLTG is a special concept of tensegrity systems. In a DLTG, the bars (struts) are confined between two parallel layers of tendons (ties). A natural way of constructing DLTG's is by means of joining together tensegrity prisms or truncated pyramids. The grid is effectively made of an outer and an inner layer of tendons interconnected by struts and additional tendons. Models of double layer tensegrity domes have already been built by Burkhardt [14]. An experimental investigation (probably the first of its nature?) on a type of a double-layer tensegrity grid supported on 6 columns was carried out by Kono *et. al.* in Japan [15]. This work showed clear evidence of hysteresis. The work is quite promising since it is the first evidence of use of tensegrity for a proper structure. Current work at Coventry concentrates on studying double layer tensegrity systems and some simple models have been built (Fig 4) to assist with understanding the geometry and mechanics of the system. This will in turn assist in the preparation of a numerical and analytical model.



(a) computer model (b) physical model

Figure 4 Grid studied at Coventry University

The Formian software [16] is used to generate the grids that can then be transferred to a finite element (FE) software for analysis. The use of FE is a powerful way of in simulating the behaviour and easing the understanding of tensegrity systems. In turn, the design and construction of tensegrity structures will eventually become a normal routine once fabrication and assembly technology have become more capable of dealing with complexities (especially those resulting from making the connections) caused by such systems.

The flowchart shown in Figure 5 the process used in researching into tensegrity. Research is still in its early stages and it is hoped that progress will lead to the development of an integrated view encompassing geometry gene-ration, design, fabrication, and construction.

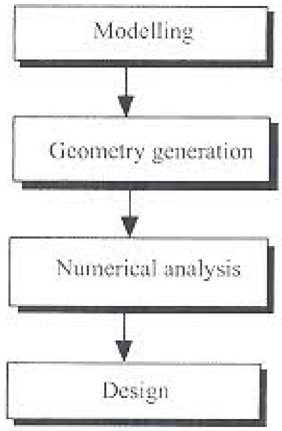


Figure 5 Methodology adopted

Typically, the analysis of tensegrity structures consist of two phases:
(i) form finding;
(ii) load analysis of the prestressed geometry.

DLTGs constructed of tensegrity prisms (i.e. flat) do not involve shape finding as the pre-stressed geometry is defined by the pre-stressed geometry of the individual units [17].

An intermediate analytical phase, exploring internal mechanisms, state of prestress and the extent of non-linearity of the prestressed geometry can be introduced in the analysis [18]. Figure 6 shows the self-stress state of the grid being described.

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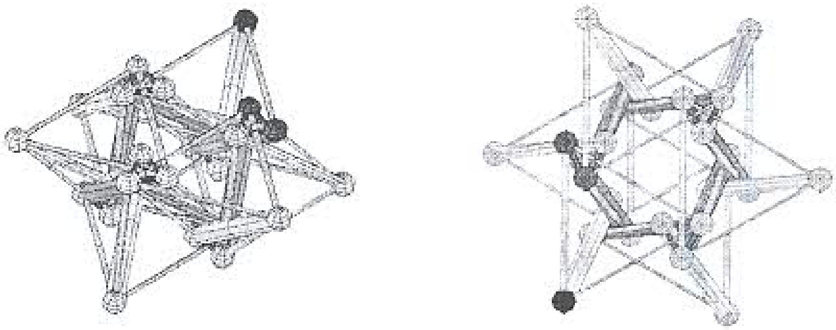

Figure 6 Self-stress state in the grid.

Elsevier Science Publishers, 1984.

16. A. Hanaor, Double Layer Tensegrity Grids: Geometric Configuration and Behaviour, Edited by H. Nooshin, Studies in Space Structures, Multiscience, 1991.
17. S. Pellegrino and C.R. Calladine, Matrix analysis of statically and kinematically indeterminate frame-works, *International Journal of Solids and Structures*, **22**(1986)409-428.