OVERVIEW OF TENSEGRITY – I: BASIC STRUCTURES

Yogesh Deepak Bansod*, Deepesh Nandanwar**, Jiří Burša*

The tensegrity framework consists of both compression members (struts) and tensile members (tendons) in a specific topology stabilized by induced prestress. Tensegrity plays a vital role in technological advancement of mankind in many fields ranging from architecture to biology. In Part I of this two-part article, we have reviewed topological classification of elementary cells of tensegrity structures including rhombic, circuit and Z type configuration. Further, different types of tensegrities created on the basis of these configurations are studied and analysed, for instance Tensegrity prism, Diamond tensegrity, and Zig-zag tensegrity. The Part II focuses on applications of the tensegrity principle in construction of double layer high frequency tensegrity spheres.

Keywords: *tensegrity, struts, tendons, prestress, configuration*

1. Introduction

The technique used in constructions by architects around the world is based on holding the structure with the help of its weight and continuity of stresses induced basically in compression. For example, each component of a stone dome or bridge is pulled by tension acting downward through the structure, but the compressive continuity is still in charge of sustaining most of the load. On the other hand, tensegrity architecture represents a totally different principle with tension continuity and compression discontinuity. Tensegrities represent a system of ‘equilibrated omnidirectional stresses’ [1] and they don’t need any support and are self-equilibrated as well as pre-stressed. The theory of tensegrity structures is well known in civil engineering or statuary while in other engineering branches the potential of these structures is not yet fully explored. This paper summarizes the up to date knowledge on tensegrity structures and presents some of their non-conventional applications in computational design and modelling in various technical fields.

2. Features of tensegrity

Fuller [2] coined the term ‘tensegrity’ by combining two words ‘Tensional + Integrity’; it means the integrity of a structure consisting of tension and compression components. His definition of tensegrity structures was ‘A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space’. If we apply this definition in broader sense, then the entire universe can be viewed as a tensegrity structure. Planetary systems at a space level or atomic systems at a microstructural level, all of them consist of discontinuous compressed members; for instance, planets (spheres) are connected by gravitational (tensional) forces

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that symbolize tensile members. It is evident, that this definition is too broad, and a more precise one is needed.

K. Snelson [3] describes tensegrity as a closed structural system composed of a set of three or more slender compression struts within a network of tensioned tendons, the combined parts mutually supportive in a way, that the struts do not touch one another, but press outwardly against nodal points (vertices) in the tension network to form a firm, triangulated, prestressed, tension and compression unit. In short, he defined tensegrity as discontinuous compression, continuous tension structures [4]. Probably the most complete definition of tensegrity structures is presented in [5] as 'Tensegrity is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in a way that the compressed members (usually known as bars/struts) do not touch each other and the prestressed tensioned members (usually known as cables/tendons) delineate the system spatially'. In living nature, tensegrity structures can be found as a governing principle in many biological systems ranging from cells [6] to tissues and organ systems [7]. For instance, musculo-skeletal system can be understood as a tensegrity structure [8]. Some of the recent studies show that DNA molecules and cell cytoskeleton can also be viewed as tensegrity based stable structures [6, 9]. In technology, tensegrity principle is used widely in buidling new structures, shelters (see Fig. 1) bridges, etc.

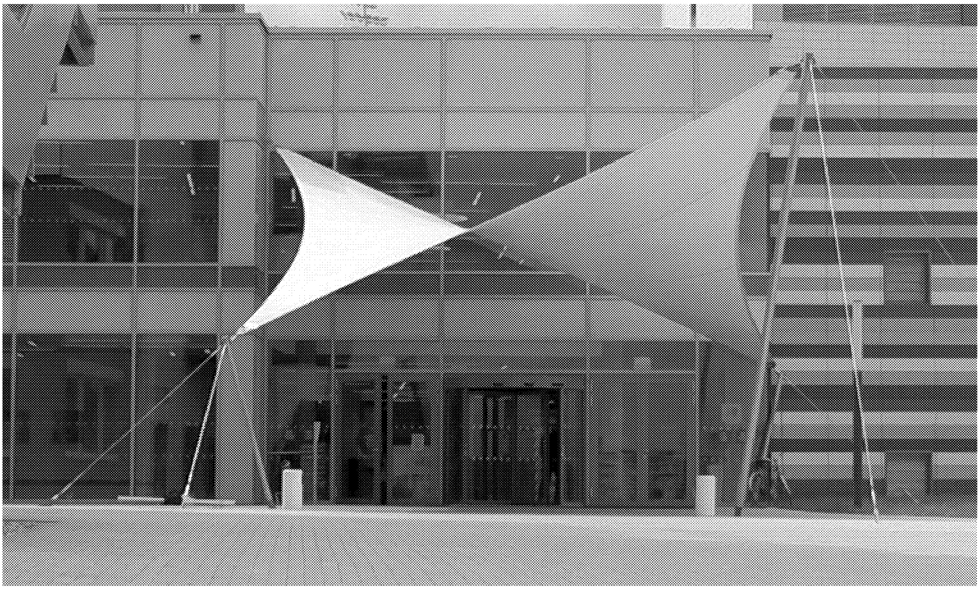

Fig.1: A tensegrity shelter built at Brno University of Technology, Brno

Apart from above, it is used for the development of advanced materials, smart materials [10, 11] and deployable devices for aerospace technology [12]. On the other hand, some natural structures (for istance, spider web) and man made structures (such as bicycle wheels or multi cable domes – Olympics stadium in Seoul (1986), etc.) can not be truly considered as tensegrity structures because their compressive members are in mutual contact; in Snelson words, they don't have floating compression system [3].

2.1. Characteristics of tensegrities

Characteristics of tensegrities can be summarized as follows:

a) They have a *higher load-bearing capacity with similar weight.*
b) They are *light weight* in comparison to other structures with similar resistance.
c) 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.
d) They are *enantiomorphic* i.e. exist as right and left-handed mirror pairs [13].
e) Elementary *tensegrity modules* can be used (such as masts, grids, ropes, rings etc.) to make more complex tensegrity structures.
f) Higher the pre-stress, stiffer the structure would be, i.e. its *load bearing capacity increases with the increasing pre-stress* [14]. The degree of tension of the pre-stressed components is directly proportional to the amount of space they occupy [15].
g) 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 [1].
h) 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.
j) 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.*
k) 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.
l) 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 [16].
m) The tensegrities are commonly modelled *with frictionless joints, and the self-weight of cables and struts is neglected.*

2.2. Advantages of tensegrity over conventional (continuous) structures

a) As the load is distributed in whole structure there are *no critical points of weakness* [16].
b) They *don't suffer any kind of torsion and buckling* due to space arrangement and short length of compression members [1].
c) *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.
d) 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* [10, 11].
e) They can be *extended endlessly through adding elementary structures.*
f) Construction of structures using tensegrity principle *makes it highly resilient* and, at the same time, *very economical.*

2.3. Disadvantages of tensegrity over conventional (continuous) structures

a) If the structure becomes too large it faces a *problem of bar congestion* (i.e. the struts start running into or touching each other) [17].
b) They show relatively *high deflections and low material efficiency* as compared to with conventional continuous structures [17].
c) *Fabrication complexity* is a major barrier in developing floating compression structures [5].
d) *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.
e) At *large constructions* the structure cannot withstand loads higher than the critical, related to its dimensions and prestress [17].

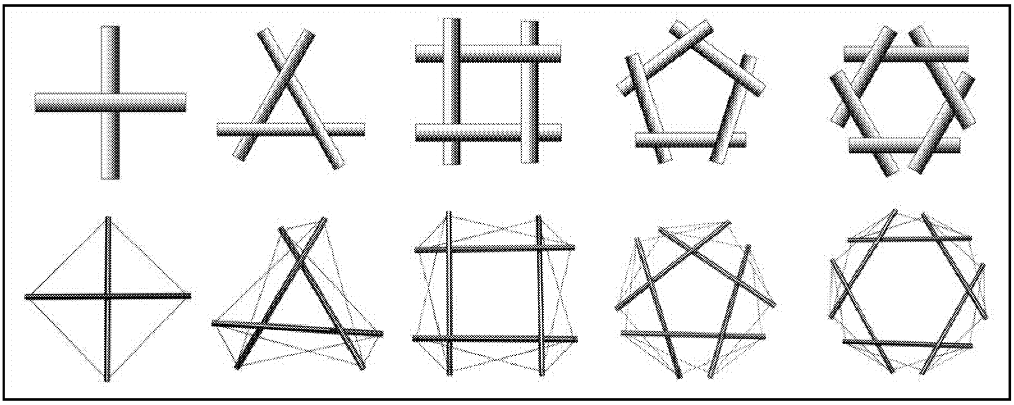

Fig.2: Primary weave cells & equivalent basic tensegrity modules (from [4])

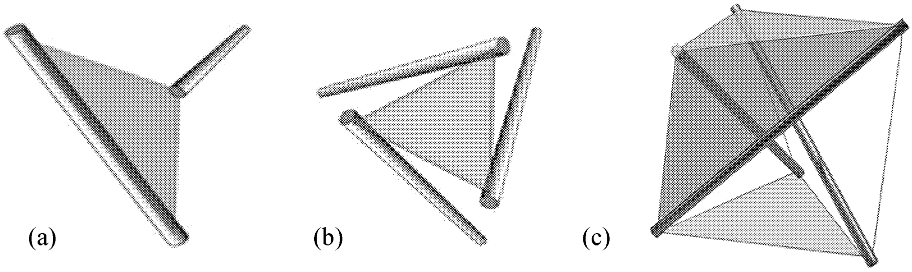

Fig.3: (a) Tension/compression triangle, (b) Tension only triangle, (c) 3 strut prism (from [3])

3. Tensegrity weaving & triangulated tension network

Snelson [4] has defined 5 basic weave cells as depicted in Fig. 2 which can be translated into basic tensegrity structures. Among these the first two geometries on the left hand side (two and three-way cross units) have total triangulation making the tensegrity structures firm. The remaining geometries are flaccid because they have less tendons than required for total triangulation (as compared to the number of struts in the weave unit). On the basis of the relative position of tendons and complexity of arrangement of struts Pugh [14] classified the basic patterns to configure tensegrity structures which were further refined by Motro [18] as a spherical system, star system, irregular system and cylindrical system. In this overview article, we have focused only on spherical systems due to their large scale application in designing tensegrity structures. Spherical systems can be further divided into rhombic, circuit and zig-zag configurations.

The triangles formed by tendons in a tensegrity network can be classified in two different ways. First, the tension/compression triangle is formed with two struts and two tendons where two cables from the end of one strut join to the two ends of a second strut as depicted in Fig. 3(a). Second, a tension only triangle can be formed with three different cables attached to three different struts as shown in Fig. 3(b). The tension/compression triangles always occur in pairs like butterfly wings, whereas tension only triangles do not (see Fig. 3(c)) [3].

4. Topological classification of elementary cells of tensegrity structures

4.1. Rhombic configuration

The name of tensegrity patterns is based on the way they are constructed (tendon patterns). In Fig. 4, each strut (blue/black colour) of a system represents the longest diagonal of a rhombus formed by four corresponding tendons (red/orange colour) and can be folded following these diagonal. Generally, this configuration corresponds to the diamond tensegrity. T-prism (section 5.1) and T-icosahedron (section 5.2) tensegrities are well known examples of the rhombic configuration where rhombus represents a non-planar quadrilateral formed by tendons [14].

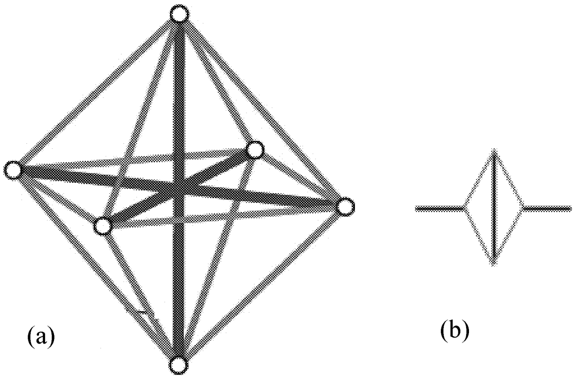

Fig.4: (a) Assembly of rhombic configuration and (b) its pattern (from [19])

4.2. Circuit configuration

In this system, the compressed members are formed by close circuits (see Fig. 5(a)) which do not comply with standard definition of tensegrity [17]. This can be constructed by closing the rhombus generated by struts and tendons of the diamond pattern tensegrity, such as T-icosahedron (see Fig. 11).

A new tendons-struts relationship is established by joining the struts to form the circuit pattern which gets compact in size and able to withstand greater external load compared to

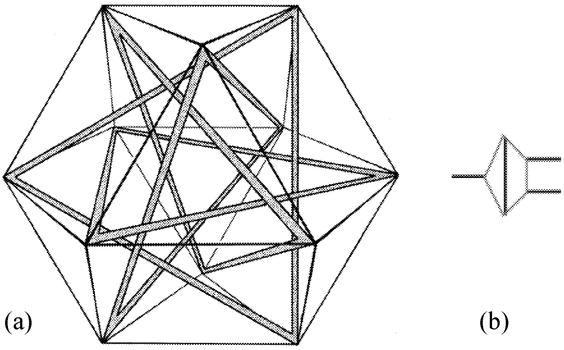

Fig.5: (a) Circuit configuration of Cuboctahedron tensegrity having 4 non-touching triangular circuits and (b) its pattern (from [20])

the tensegrity structure built using diamond pattern for the same number of struts. It was Pugh's discovery that a circuit system is more rigid than a rhombic one with the same number of struts. Several regular and semiregular polyhedra can be built using this configuration, for instance icosidodecahedron, cuboctahedron, snub cube and snub icosahedron, etc. [14]. If opposite pair of squares (created by tendons in Fig. 5(a)))are forced toward one another in a, then the whole system twists and contracts.

As shown in Fig. 5, the cuboctahedron tensegrity is composed of four circuits of three struts each (triangles) and 24 tendons defining the edges of the cuboctahedron. The equilibrium of these triangles is ensured by four hexagons of tendons, each of them being in plane with one of the triangles and connecting its apices with one apex of the other three triangles. It may be claimed that it is not a true tensegrity structure since the struts here are connected to each other but now the triangles of struts act as a single compression unit and hence, these structures can be regarded as tensegrity structures.

A rhombicuboctahedron has 8 triangular and 18 square faces. It has 24 vertices, each shared by one triangle and three squares. The tensegrity structure has 24 struts making 6 square circuits (see Fig. 6(a)) arranged in three pairs perpendicular to each other and

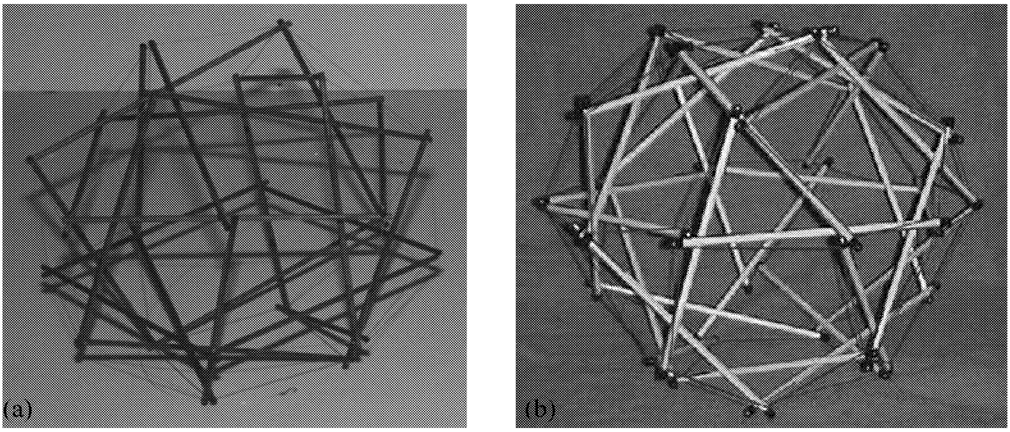

Fig.6: (a) Rhombicuboctahedron tensegrity using 6 non-touching square circuits, (b) Icosidodecahedron tensegrity from 6 non-touching pentagonal circuits (from [21])

48 tendons. Icosidodecahedron consists of twenty triangular faces and twelve pentagonal faces. It has 60 edges of the same length and 30 vertices, each of them shared by two triangles and two pentagons. The corresponding tensegrity structure based on circuit configuration has 30 struts of equal length arranged into 6 non-touching circuits of pentagons (see Fig. 6(b)) and contains 60 tendons [21].

4.3. 'Z type' configuration

A 'zig-zag' configuration (also being an enantiomorphic) is obtained from the rhombic configuration as the basic structure. Both ends of any strut should be connected by three non-aligned tendons arranged to form a 'Z' shape. Truncated tetrahedron (see Fig. 7) is a classic example of Z type configuration obtained from truncated icosahedron which belongs to the class of rhombic configurations (refer sections 4.1 and 5.2).

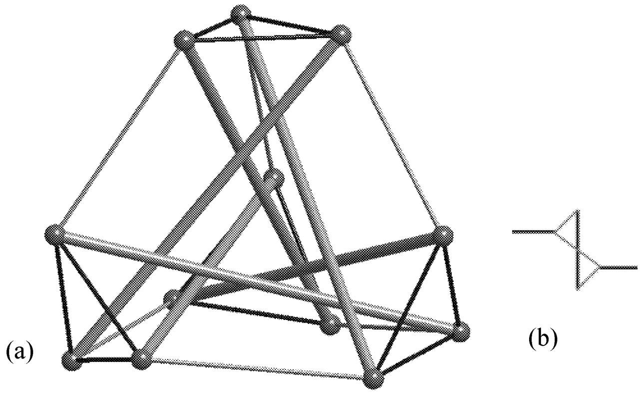

Fig. 7: (a) Truncated Tetrahedron (T-tetrahedron) using Z type configuration, (b) its pattern (from [22])

This type of configuration can be obtained by removing two tendons of the opposite sides of a non-planar rhombus of truncated icosahedron. In this way, the number of tendons is reduced and their arrangement can be changed in a way that three nonaligned tendons connecting both ends of a strut form a 'Z' shape [5]. The distortion of regular polygon may rise due to the orientation of struts that converge in each face. To obtain the perfect geometry, additional tendons can be inserted into the original system [18].

5. Types of tensegrities

The tensegrity structures are widely classified as prestressed and geodesic structures. They are divided into three main categories: Tensegrity prism, Diamond tensegrity and Zig-zag tensegrity. The X-module (see Fig. 8) build by Snelson had given birth to tensegrity principle. This simple tensegrity structure consists of two X-shaped wooden struts suspended in air by stretched nylon cables [4]. The simple kite frame is the basic prestressed tension-compression cell of X-module tensegrity structure. It consists of two crossed struts firmly held together by a girth of four tension members, because the (vector) sum of compression forces pushing out equals to the sum of tension forces pulling in. As shown in Fig. 9, the change in length of both struts and tendons i.e. change in proportion of frame is related to the variation in distribution of forces, both tension and compression.

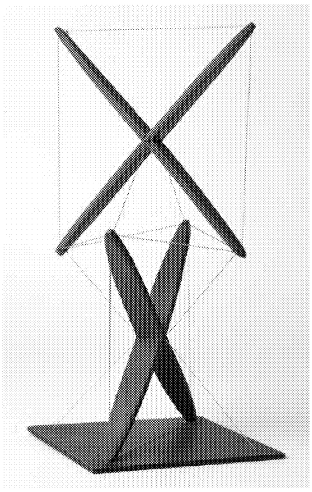

Fig.8: Wood X-module (from [4])

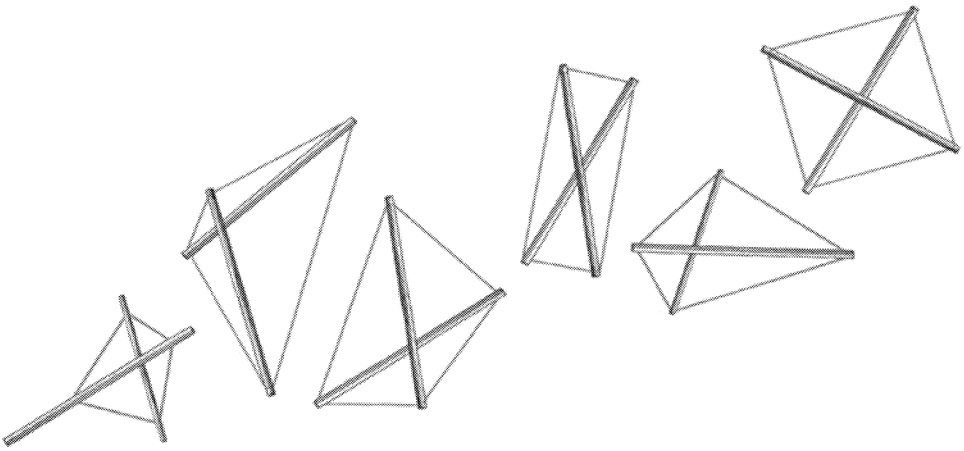

Fig.9: Kite frame shape in various proportions (from [3])

It is a quasi-tensegrity structure because it is planar (2D), and the struts touch each other. If any one of the tendons is removed, then the blank side will work as a compressed component; this is called as 'strut effect'. This basic principle is required to design various elementary components of two layer and three layer tensegrity systems. The lengths of the four tendons and the lengths of the two struts determine the shape of the kite frame (see Fig. 9) [13].

5.1. 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 a twisted prism consisting of two triangular faces twisted with respect to each other. Generally, these

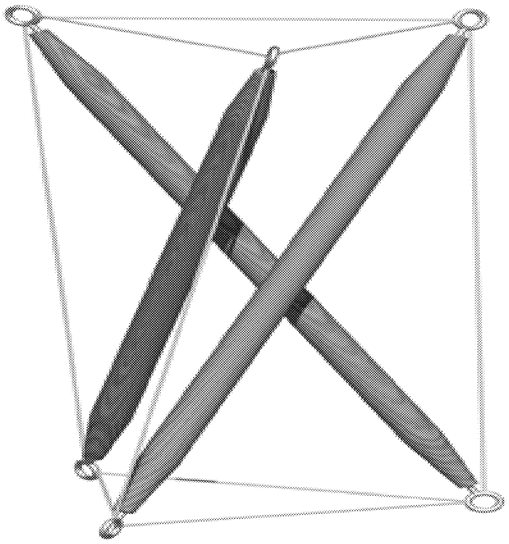

Fig.10: Diamond Configuration of T-prism (from [1])

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 [17].

5.2. 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 [14].

If the quadrilaterals nested with struts are changed to squares then the tendons form a cuboctahedron network. Fig. 11(b) illustrates the change in system of tendons from an octahedral arrangement (with each strut doubled-up by presence of two struts in the identical position) to cuboctahedron and back. Small arrows indicate the direction of movement of the struts and of the corresponding pair of opposite points of the quadrilateral as the tendon system goes through transformations [17].

Opening the octahedral structure carefully from one end gives a single layer diamond structure as depicted Fig. 12(a). New tensegrity structures with spherical symmetry can be generated by addition of new layers of struts and tendons and joining both ends of each layer. Planar views of tensegrity systems based on this approach are depicted in Fig. 13 and Fig. 14.

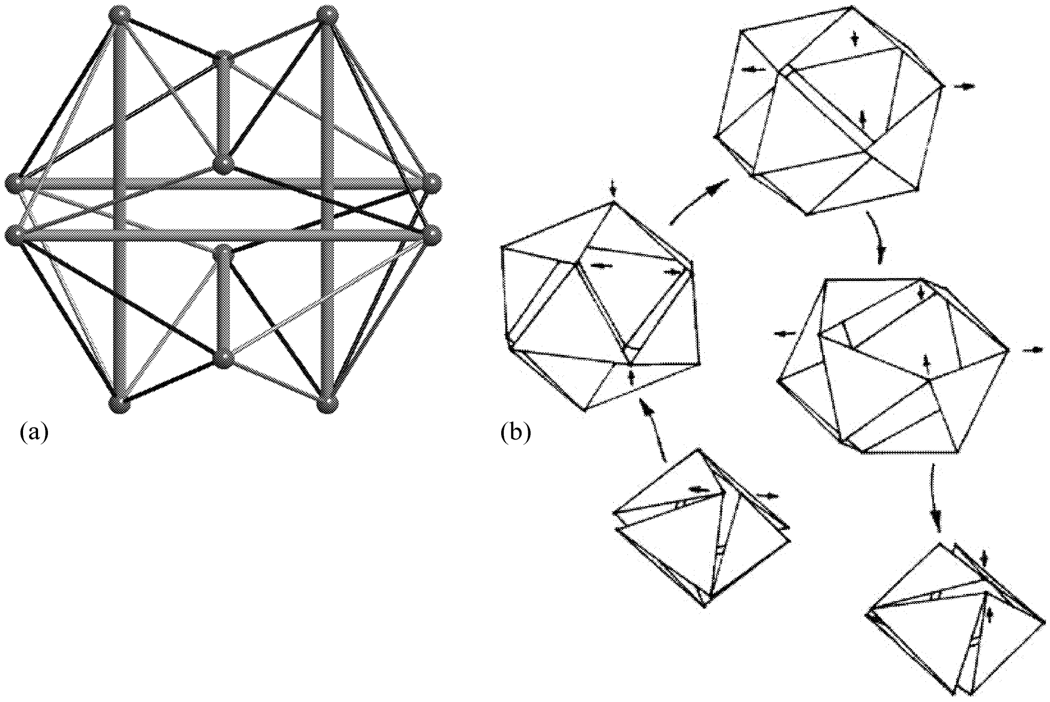

Fig.11: (a) T-icosahedron and (b) its corresponding transformation from and back to doubled-up octahedron (from [17])

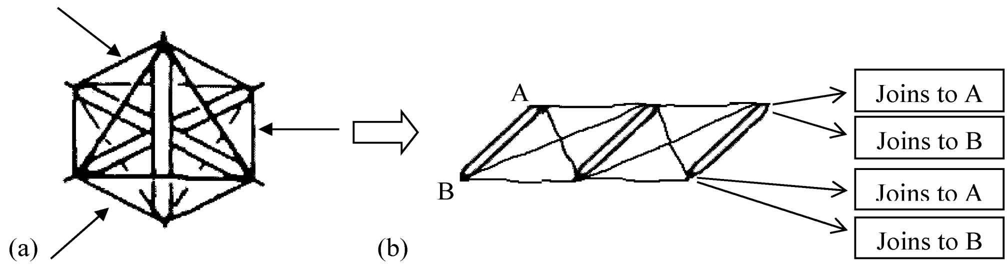

Fig.12: (a) Octahedral structure (b) planar view of corresponding 3-struts single layer tensegrity system (modified from [14])

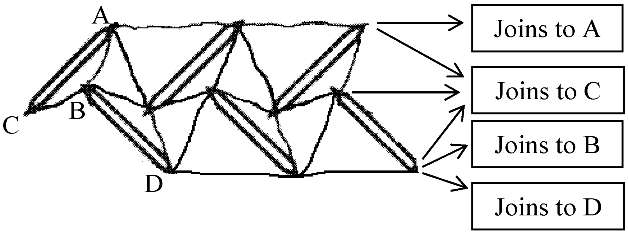

Fig.13: Planar view of 6-struts two layer tensegrity system (modified from [14])

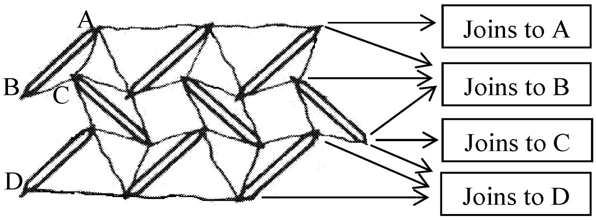

Fig.14: Planar view of 9-struts three-layer tensegrity system (modified from [14])

5.3. 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.

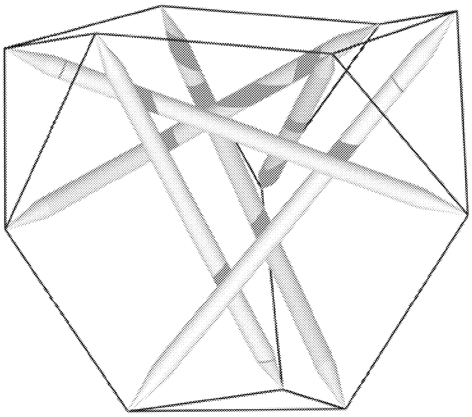

Fig.15: T-Tetrahedron (Z type configuration) (from [17])

In general, zig-zag structures with Z type configuration are simpler and less rigid due to their lower number of tendons than their diamond counterparts with rhombic configuration [17].

6. Conclusion

In this part-I of the overview article, the authors have introduced the tensegrity principle and its unique features over conventional solid structures. Further, the topological classification of elementary cells (tendon patterns) and tensegrities based on these types of cells were presented here. The tensegrity structures have a wide range of applications specifically in structural engineering such as domes, bridges, and towers, as well as in biological sciences for computational modelling of human anatomy, eukaryotic cells, etc. The tensegrity principle based computational model of smooth muscle cell cytoskeleton is depicted in Fig. 16. It has been developed at Brno University of Technology as a part of simulation study of different mechanical tests of eukaryotic cells [24]. The lines in purple colour symbolise cables (microfilaments) being in tension, the green ones are struts (microtubules) loaded in compression and the red ones are bars (intermediate filaments) acting as pretensed springs. In Part II of this article high frequency double layer spherical tensegrity structures will be discussed.

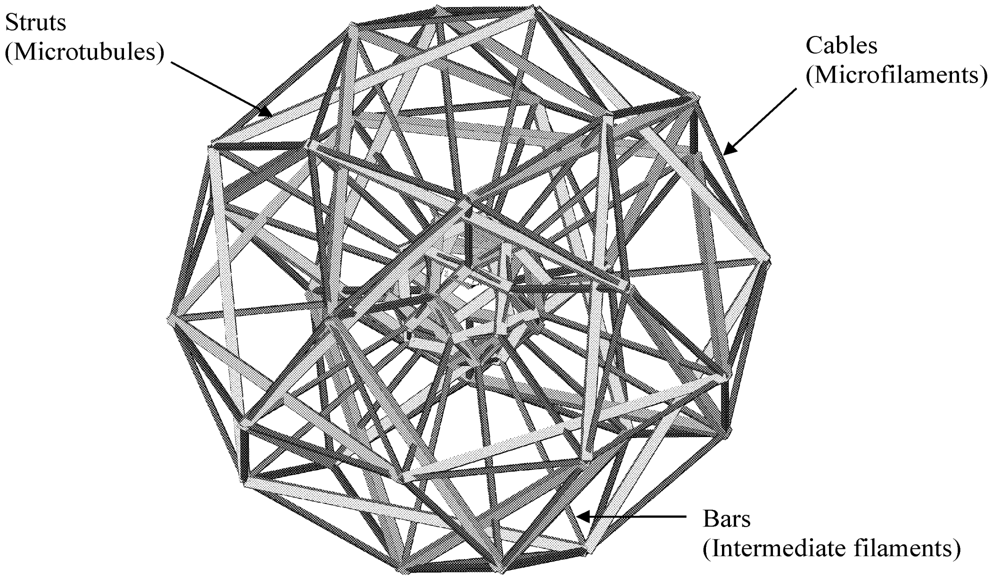

Fig.16: Computational model of smooth muscle cell cytoskeleton based on icosidodecahedron tensegrity (from [24])

Acknowledgement

This work was supported by financial means from the Ministry of Education, Youth and Sports within the support programme 'National Sustainability Programme I' through project NETME CENTRE PLUS (LO1202) and by Czech Science Foundation project number 13-16304S.

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Received in editor's office: November 6, 2014
Approved for publishing: December 6, 2014