Tensegrity Structures in Science, Technique and Art.

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Introduction

The word tensegrity was introduced by R. Buckminster Fuller. It arose by contraction of **tens**ional int**egrity**. Tensegrity describes a structural principle in which the integrity and shape of structure is guaranteed by finitely closed tensional network (e.g. network of cables) and compressions (e.g. firm struts) are local islands.

Tensegrity structures can accomplish visibly differentiated tension-compression interfunctioning in the similar manner as pneumatic structures (e.g. football or gas filled autotires).

Fuller´s prime investigation in the field of synergic geometry was important for understanding and exploiting the tensegrity structures called geodesic domes . Sculptures of Kenneth Snelson show how compression members can provide rigidity, while remaining separate, not touching one another, held in stasis only by means of tensed cables.

Prof. Donald Ingber was the first, who suggested that tensegrity is basic principal in architecture of living creatures, and in intra- and intercellular communication, which is called mechanotransduction.

A key word research of "Tensegrity" in the ISI Web of Science turned up 120 articles written in the past six years, compared to 34 in the prior decade and therefore it appears that the idea of tensegrity is on its way up, but it is necessary to say that not everyone loves it.

R. Buckminster Fuller: Geodesic dome.

It is hard to believe that well known architect, engineer, mathematician, inventor, poet and cosmologist R.B. Fuller was in 1927 prepared to through himself into the freezing waters of Lake Michigan, because his child had died, he was bankrupt, discredited and jobless. Luckily, in the last minute, he decided not to commit suicide. Over the next fifty four years he was successfully trying to prove, that his ideas may help to human society.

As early as in 1959, "Newsweek" reported, that Fuller predicted the conquest of poverty by the year 2000 and almost 20 years later, the National Academy of Sciences confirmed Fullers prediction. Fuller himself believed that humanity´s major problems can be solved through the highest technology. His slogan: ”More and more life support for everybody, with less and less resources became a central principle of his practical philosophy.

R.B.Fuller was awarded 25 U.S. patents, wrote 28 books and circled the globe 57 times, reaching millions through his public lectures, interviews and courses. He made his mark in areas of architecture, urban development and design, mathematics, physics, industry, technology, philosophy, religion, naturalism, numerology, art and literature. He is best known for the development of synergetics and invention of geodesic dome. S.E. Morrison said about his book Synergetics-Exploitation in the Geometry of Thinking (Coliner Books Macmillan Publishing Company): “Synergetics is Fuller´s most important and most readable book. I predict that it will become one of the classics of science along with Darwin´s book The Origin of the Species”. A.C.Clark generalized this idea by saying: “This book is his bible, the distilled wisdom of a life time spent contemplating the Universe from angles and directions never before suspected. It will be a source of endless inspiration and stimulus to those engaged in the most urgent task of our time – the effort to save spaceship Earth from disaster.”

Concepts of architecture are rooted in the Egyptian, Greek and Roman ideas of fighting the compression forces of gravity with massive blocks of stone. It is only in recent history that we started to understand, that tension forces can play a significant role in the integrity of various buildings. Brooklyn Bridge (length 3460 feet), Golden Gate (8981 feet) and Akashi Kaikyo (12828 feet) are the most famous examples of bridges in which steel cable wire together with pillars help to carry the main body of bridge.

Fuller´s domes demonstrate a step further. There are over 300 000 of them, spread from tropical areas up to the Arctic Zone. Weather stations withstand winds up to 180 mph. Domes have given shelter to families in Africa at a cost originally about 350 $ per dome and recently less then 200 $. Fuller is probably most famous for his 20 story dome housing-the U.S. Pavilion at Montreal, Phytotron in Louisiana and project of the largest dome (diameter: 3 km, hight 1.6 km) for enclosure of Manhattan. This dome would cover buildings from the East River to Hudson at 42nd Street. It would weight about 4000 tonnes. A fleet of the large Sikorsky helicopters could fly all segments into position in 3 months at a cost of $ 200 million. Costs of the heating and air conditioning would be dramatically reduced and the savings to the city in snow removal costs alone would pay for this dome in ten years, calculated Fuller in order to support this controversial proposal. Who knows, may be that now, after destruction of “Twins”, the project will be interesting, even from different point of view. The largest completed geodesic dome is Georgia Dome. It is covering football stadium. This building is one of the recent world miracles. Diameter of this building is 840 feet.

Buckminster Fuller died in July 1983 leaving behind him many ideas and many followers, who were inspired enough to continue in his direction. As you can see in, geodesic domes are spherical structures in a sense that a sphere is a polydron of a plurality of trussed triangle like facets. As trussed faces multiply their chordal facet-angles become practically indistinguishable and the polyhedrons surface becomes indistinguishable from the sphere. To form a geodesic dome, grids are generally formed on the faces of a spherical icosahedron. Each face is modularly divided along its edges. The subdivision points are interconnected with 3 way omnitriangulated grid of great circle areas . Around original icosahedral vertices, there ar only 5 triangles, while around the subdivision point there ar always 6 triangles. Great circle is a spherical line, formed on a spheres surface by a plane going through a center. This line is called “geodesic”, the word from which the name geodesic dome is derived. It should be mentioned, that the shortest distance between two points in sphere surface is a geodesic line, which goes through these points. The geodesic dome of Fuller´s type is made of struts. Each strut is the chord of the sphere with its ends at greater distance from the center of the sphere than the radial distance of the mid point in the chordal strut. Plastic film is usually stretched on skeleton made of struts. Polyethylen based films under the solar exposure may serve from 2 to 5 years depending on the climate in the area. Further possible materials are tested. Covering made from panels is also as more stable, but heavier possibility. For the purpose of increased insulation and/or increased resistance to pressure a double layer domes were developed.

The main advantages of geodesis dome exploitation are the following:

- Geodesic dome may enclose a great volume of space with less material than any other type of structure
- It is stable due to its geodesic network
- It is modular and so it is easy to rebuild it, transport it and put it quickly together from parts. Nice demonstrating this point happened in Honolulu in 1957. A geodesic dome auditorium was put up so quickly, that 22 hours after the parts were delivered, a full house was comfortably seated inside by audience enjoying a concert.

- The geodesic dome offers the possibility to enclose huge space. More than 6 km^2 is the area that can be covered under the condition of present state of technology development.
- Spherical structure encloses the greatest volume with the least surface. When the diameter is double - volume increases 8 fold and surface area 4 fold.
- Spherical dome is more resistant to wind than most other shapes of buildings of the same size.
- Heat energy is more efficiently retained in large, spherical structures, than in smaller domes.
- When the radial concentric inter-spacing in double layer domes is greater than the depth of the frost penetration of the area, the heat losses (and gains) of the inner most dome is remarkably decreased.
- It is expected, that dome with small openings at the top and large openings in the ground level might be cooled in sunny hot weather by Bernoilli cooling effect.
- An increased number of vertices increase the resistance against concentrated loads from more directions.
- When any two struts 180 degrees apart around the sphere are pulled outward from one another the whole sphere expands symmetrically, while the pushing toward one another will cause symmetrical contraction.
- Domes transparent on their sunny side and opaque (inwardly reflective) on their shadow side will entrap progressively greater amounts of sun energy, i.e. they may work as energy harvesting machines.

All these properties of geodesic domes are important for their possible applications. Domes can be exploited for economic large-scale protection of storage and archaeological or agricultural construction, and refugee or hiking shelters. They may serve as structures for allowing the agriculture to escape terrestrial confines, where this is useful (e.g. dangerous areas, urban areas, flood plains). They might be used as frames over cities for environmental control, energy transformation and food protection. They can provide large-scale electrical or electromagnetic shielding, serve as barriers against flying animals or other objects, spherical superstructures for space stations, low-environmental-impact shells for musical performances, pavilions for trade shows, supports for sunscreen protection, frames for hanging plants or other objects to dry and so on. It should be mentioned that tensegrity structures, which are a pneumatic structures, performed very well during earthquakes.

It can be concluded that geodesic dome is potential to house all of humanity by giving them a simple, cheap, handy and effective technological artifact that is in agreement with Fuller´s idea doing more with less for all.

In order to be exact, it is worse to add that in fact Fuller was not the first architect, who was thinking about geodesic dome. Many years before him, in 1922, this structure was invented by Walter Bauersfeld of the Zeiss Optical Works in Jena, Germany. Since Bauersfeld used the principle merely for building a planetarium roof, whereas Fuller was awarded several patents for the dome, and he was the one, who popularized the technology and had a more comprehensive vision of the geometrical and engineering significance and advantages of the dome, he is generally accepted as the number one in this area and domes are not called Bauersfeld´s but Fuller´s.

It seems to be very common situation, that new things have to be invented several fold, before they get generally accepted. Let me mention that Mendel´s discoveries of the basic rules of genetics in 19th century had the similar history.

The buckyball

The Platonic bodies have often served as patterns, and hydrocarbons had already been synthesized as tetrahedral, cubic or dodecahedral structures.

Buckminsterfullerene or the buckyball for short, discovered in the early 1985 is a new form of carbon. The name of it is the tribut to the designer of the geodesic dome in Montreal (1967) which has exactly the same structure, e.i. “truncated icosahedron cage” with 12 pentagonal and 20 hexagonal surfaces and 60 atoms of carbon in vertices. The same pattern has a European football. Before this discovery, there were only six known crystalline forms of carbon. The slippery, soft and gray material called graphite and rigid crystalline stone, diamond are the main ones. All bonds are to another carbon atom. When compressed to 70 % of its volume, it becomes more then twice as hard as diamond. Fullerens can serve as a conductor. insulator, semiconductor or superconductor. Fully hydrogenated fuzzy ball would create a slicker substance than teflon. Fully fluorinated buckyball would create the slickest molecular lubricant. A pure buckyball is an insulator, while it becomes a superconductor with the addition of a few atoms, including potassium. Buckyball stretched out to form tube, creates a fiber even stronger, then a graphite fiber. In addition, it was demonstrated, that fullerenes can be turned into diamonds at low temperatures.

It is not surprising, that the Royal Swedish Academy of Sciences has decided to award the 1996 Nobel Prize in chemistry to professor Robert F. Curl, Jr. (Rice University, Houston, U.S.A.), Professor Sir Harold W. Croto (University of Sussex, Brighton, U.K.) and professor Richard E. Smalley (Rice University) for the principal discoveries in this field. It should be mentioned, that fullerenes are not pure artifacts, which arise only under conditions of chemical laboratories. Later they were discovered also in the nature.

Snelson´s towers and exoskeleton

Kenneth Snelson attended one of the Dymaxion Seminars of B. Fuller at Black Mountain in 1948. Deeply inspired Snelson then worked on his own in Oregon in the fall of 1948. When he returned to Black Mountain College he had ready his first prototype of tensegrity structure which I shall call Snelson´s type of tensegrity structures. Snelson´s sculptures show more clearly than geodesic domes, that compression members may be held in stasis only by means of tensed cables, e.i. discontinuous compression is held by continuous tension. Fuller saw the significance of Snelson´s work, he coined the neologism "tensegrity" soon after Snelson shared his discovery with him, and incorporated Snelson´s concept into his sinergetics. Unfortunately, over time, Fuller stopped crediting Snelson for making a crucial contribution to synergetics and this fault caused a permanent rift between them. Snelson´s towers and exoskeletons made of cables and rods are the monuments of tensegrity idea of tensegrity in many towns and museums all over the world.

In addition, personal contacts and friendship with Ken Snelson caused that concept of living tensegrity structures, was formulated by Dr. Ingber from Departments of Pathology and Surgery, Children´s Hospital and Harvard Medical School, Boston MA, U.S.A. The simplest tensegrity structure of Snelson´s type containing 3 sticks became the building unit for construction of double –layer geodesic domes, which have the better properties than original Fullers monolayer structures, which are made of triangles. Snelson´s sculpture, Needle Tower 2, from Kroller Museum in Otterlo, Holland, was the first tensegrity structure I have ever seen. It fascinated me so much, that I decided to follow Snelson´s ideas and tried to develop it further, particularly in the direction to mobile tensegrity structures, hierarchical tensegrity structures and structures build of bow-like unites. Only two bow rods are enough to make a threedimensional tensegrity structure, while minimally three straight rods are necessary for such construction. In addition I have focussed on constructing so called "internets", structures, based on tensegrity principle, with more cables then is necessarily required for stabilizing the construction.

Bow-tensegrity structures

The first is represented by two opposite bows, the second is formed by two the same-side bow and the third is combination of straight rod and bow. When central bow or rod is prolonged the number of “perpendicular” bows may be increased. Even the simplest tensegrity structure may serve as carrier of net. Internet structures have several interesting features that I have exploited in my sculptures.

The first interesting property is the illusion of movement in the sculpture of the “internet” type. “Moiré pattern” is generated by two sets of ropes, which do not cross each other, because they do not lie in the same plane. However, there is an illusion of crossness in such structures. The “knots” move when we walk around the sculpture. The most shocking is the fact that “knots” are moving e.g. up, when we walk from left to right and down, when we walk in opposite direction.

Basic tensegrity structure (theme) is covered by net in which individual ropes interconnect different points on the rods. Differences in algorithm of connecting points on bows cause the differences in both, the form of the sculpture and the way how it moves. There is some similarity between sets of such sculptures and variants on a theme in music.

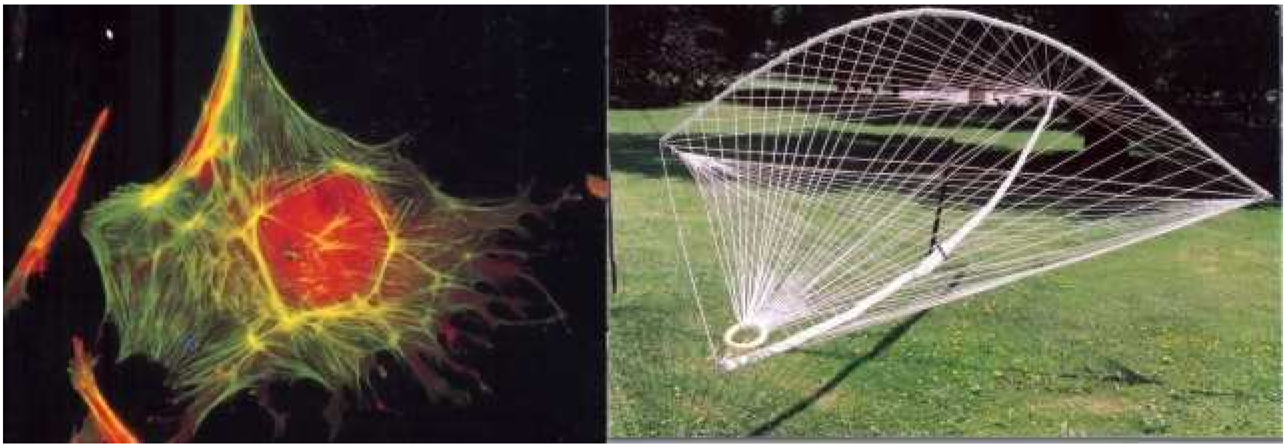
When ropes are painted with different colours, e.g. white and green, and the background of the sculpture is green grass, green part of the net will on the other hand be invisible against the white wall, white net will became invisible. Due to this effect we may see different form of internet structure depending on the place from which the sculpture is observed.

Beside these illusions the real movement of parts of the tensegrity structures may be used in order to reach the special effect. As an example may serve my sculpture called “Pack for dreams”. Nonmoving white spheres are placed in icosahedral vertices and above you can see several spheres on elastic wires. In dark background including black icosahedral rods disappear and due to the relative change of positions of moving and nonmoving spheres all white spheres appear to move.

A new model of living cell

Since 1993 when the tensegrity model of cell structure was described the scientific view of cell architecture and mechanoregulation improved so much that Donald E. Ingber decided to write a new two-part article in order to introduce a revisited tensegrity-model of cell which is placed in context of new advances in our understanding of this problem that have been made over the past decade. In the first part he described how this building system may provide a structural basis for the hierarchical organization of living systems from a molecule to organism. In the second part he focused on how these networks influence information on processing networks. It is well known that eukaryotic cells are not parcels filled with liquid protoplasm in which several cell organelles are in floating. They contain an intricate framework, the cytoskeleton that is composed of interconnected microfilaments, microtubules and intermediate filaments. These filaments both generate and resist mechanical loads and they are also responsible for the ability to resist shape distortion, function as tracks for movement of organelles, orient many enzymes and substrates to their destinations, and respond to mechanical forces and to changes of cell shape.

The cellular tensegrity model proposes that the whole cell is a tensegrity structure.



The cellular tensegrity model

Tensional forces are born by microfilaments and intermediate filaments and these forces are balanced by internal microtubule struts and extracellular matrix (ECM) adhesions. However, in different structural contexts individual filaments can have either tension or compression dual function. The tensional prestress that stabilized the whole cell is generated usually by the contractile actomyosin apparatus. Beside ECM osmotic forces acting on the cell membrane, forces exerted by filament polymerization and cytoskeletal network directly beneath the plasma membrane contribute to the whole architectural system.

Biophysical studies with isolated microfilaments and microtubules revealed that former are better at resisting tension, whereas hollow microtubules are more effective at withstanding compression. They are rigid and straight when in solution, whereas isolated microfilaments and intermediate filaments are usually bent. This is consistent with the rule that tension straightens and compression buckles or bends. In addition, tensegrity model was supported by showing that cells be have mechanically as discrete networks and not as a mechanical viscoelastic continuum. Tensegrity differs from conventional models of the cell in the answer on application of local stress on cell-membrane. It may result in direct deformation of the whole structure depending on the cytoskeleton network. Magnetic twisting-cytometry shows that when controlled mechanical stresses are applied directly to cell-surface receptors (to receptor-bound magnetic microbeads) these receptors provide greater degree of mechanical coupling across the cell surface than other transmembrane molecules. By disrupting filaments we could inhibit integrin-dependent stiffening response. Forces transmitted by integrins to microfilaments in the focal adhesion, apparently can be passed to microtubules at distant sites as so these different filament-networks must be interconnected inside living cell. Thus, the cellular response to stress depends on cooperative interactions between all these cytoskeletal filament systems.

Both cell and nuclear shape stability is dependent on cytoskeletal tension (prestress) modulating actomyosin-based contractility using drugs, varying transmembrane osmotic forces and further effects results in immediate changes in cell shape stability.

Tensegrity models of nucleate cells composed of struts and tensed cables exhibit similar responses. Cytoskeletal tension appears to be a criticaů determinant of cell and nuclear shape stability independently on transmembrane osmotic forces. In addition continuous transmition of tension from cytoskeleton to both the nucleus and EMC receptors is critical for cell shape stability.

Some argue that cytoskeleton is like a network of muscles tendons and ligaments without bones. Where are the compression elements? Cell shape in tissue depends on the ability of ECM anchoring to withstand compression, but it only helps the internal compression struts to refine cell shape. This situation reminds a camp tent. Surface membrane is made stiff by placing it under tension. It can be accomplished by various means: pushing up tend poles. Pulling membrane against fixed tent pegs in the ground and/or tethering the membrane to an overlying tree branch. The last action is complementary to the first one. If you disrupt the microtubules (tent poles), their function is transferred to the cell adhesive anchors (tree branches). If tension elements are chemically disrupted (microfilaments or intermediate filaments) cell tractional forces exerted on ECM adhesion decrease. The ability of individual microtubules to resist buckling when compressed is greatly enhanced by presence of lateral tensile connections.

Mathematical formulation of the tensegrity theory led to the following predictions:

1. The stiffness of the model (or cell) will increase as prestress is raised

2. At any given prestress, stiffness will increase linearly with increasing stretch force (applied stress). These and further predictions turned to be true in connection with cell architecture.

Simple tensegrity models of the cell have been very useful, but the reality appears to be more complex. This fact calls for “multimodular” tensegrity structure. This means that cell is composed of multiple smaller tensegrity modules that are linked by similar rules of tensional integrity. These points are critical, because disruption of one element in a simple tensegrity will produce a total collapse, while in the case of multimodular system only one modul will collapse and the structure whole cell will be relatively untouched. Another important feature of multimodular structure is its stability during continuous turnover of its elements.

Cellular tensegrity model takes into account the hierarchical features of multicellular organism. Organisms are constructed as tiers of systems within systems. The bones and muscles, whole organs, cells and muscles make the main steps in the hierarchy. The architecture of each part is based on the tensegrity structure. This fact can be demonstrated by showing the isolated part as relatively stable shaped objects. In addition, mitotic spindle that holds chromosomes in position and helps their separation during mitosis is a prestressed tensegrity cage. Cytoskeleton submembraneous cytoskeleton nuclear matrix and mitotic spindle may act independently, but when mechanically coupled they function as one integrated, hierarchical tensegrity system. Tensegrity forces balance to stabilize also the elongated forms of membrane projections, to create filopodia at the leading adge of migratory cells extensions in sperm? Cross-linking of filaments in large bundles greatly increases stiffness of the complex structure. Thus, microfilaments, which normally bear tension in the cell, can act also as compression struts when organized in this manner.

Geodesic forms of tensegrity also occur at molecular level. Most impressive examples of these forms are hexagonal arrangements of basement membrane proteins, polyhedral enzyme complexes, clatrin-coated transport vehicles, viral capsides, lipid miceles, individual proteins, RNA and DNA molecules.

You can see that tensegrity structures are everywhere. Once you may see huge artificial tensegrity-constructions and in another time you may find molecular tensegrity-microstructures.