Tensegrity : from Art to Structural Engineering

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Summary

Tensegrity can be considered as an innovative structural concept. Its development was initially largely linked with artistic activities. Following parallel design processes, most notably for the early stages, Art and Structural Engineering end up in an Art of Structural Engineering in case of Tensegrity systems. For them the coupling between Forms and Forces is very tight, and some examples testify this relation that can be studied within the framework of the theory of the systems, by advancing the notion of relational structure. The time of realizations is arrived, three of them are displayed: sculptures by Kenneth Snelson, double layer tensegrity grids ("Tensarch" project) and foldable footbridges.

Keywords: *tensegrity; art; structural engineering; relational structure; forms; forces.*

Introduction

Even if the objectives of artists and civil engineers are quite different, their processes have common features, mainly during the early design stages. Moreover artists are pioneers in some innovative structural compositions. This is particularly true for Tensegrity, and this article illustrates this fact. Beginning with the relation between Art and Structural Engineering, between artists and engineers, we develop then some of the main characteristics linked with the structural morphology of tensegrity systems. The third part is devoted to the description of examples of realized and projected tensegrity systems.

Art and Structural Engineering, Art of Structural engineering

1.1 Art and structural engineering - Pevsner and Xenakis: from constructivism to Pavilion Philips in Brussels

Constructivism is an artistic movement born in Russia at the beginning of the XX° century. This movement proclaims a geometrical construction of the space, using especially elements such as the circle, the rectangle and the straight line. This way of thinking adapts itself also well to the sculpture as to the design even in the architecture. Rodchenko, one of the constructivists, claimed in January 1921 (Lodder)

"All new approaches to art arise from technology and engineering and move towards organization and construction".

Artists and engineers are indistinctly members of this group. Vladimir Grigorievitch Choukhov developed and achieved several hyperbolic towers. Vladimir Choukhov, involved in the field of steel structures design (Figure 1-A) is one of the first to develop practical methods of calculation of the efforts and the elastic deformations of the beams, the shells and the membranes. His design is based on ruled surfaces.

Following the same geometrical principle Antoine Pevsner realized many sculptures based on ruled surfaces (Figure 1-B). Such artistic achievements opened the way to double curved surfaces generated by straight lines.

In 1958, for the Universal Exhibition in Brussels, Yannis Xenakis designed the so-called "Pavilion Philips". Yannis Xenakis, mathematician, musician and architect worked with Le Corbusier. What we want to underline is the formal analogy between this Pavilion and the

sculptures presented by Pevsner. It is obvious that the geometrical design, based on ruled surfaces (Figure 2-A) is clearly in the line of Pevsner's sculptures. The sketch of Figure 2-B, even if difficult to be read, is by Xenakis himself, the third illustration (Figure 2-C) represents the completed structure.

A  B 

Figure 1: Constructivism, A-Hyperbolic Tower Moscou 1922 (Choukhov) B-Developable surface. (Pevsner)

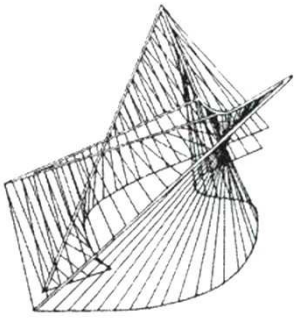
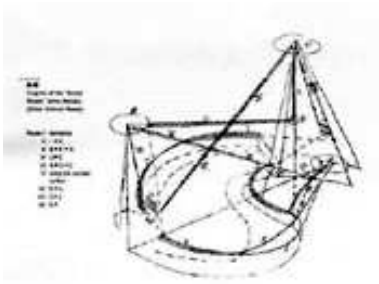
A  B  C 

Figure 2: Pavilion Philips: A Ruled surface - B Sketch by Xenakis - C Realization

It is interesting to note that the double negative curvature surfaces result from the assembly of double negative -curved paving stones poured on sand on the ground of a rough dimension of 1 m 50 aside. These paving stones are 5 cms in thickness; they are supported by a double network of pre-stressed cables.

1.1.1 Structural art

Some engineers brought up their practice at the level of the art. Several were celebrated during the exhibition The Art of Engineer, Builder, Contractor, Inventor, held in Paris 1997 (Picon).

"The Tower and the Bridge" (Billington), has as subtitle "The New Art of Structural Engineering". In this book many famous engineers are presented in their artistic way of designing: Thomas Telford and Gustave Eiffel, Robert Maillart, Felix Candela and Heinz Isler among others. Let Billington speak about this structural art:

"The conservative, plodding, hip-booted technicians might be, as the architect Le Corbusier said, "healthy and virile, active and useful, balance and happy in their work, but only the architect, by his arrangement of forms realizes an order which is a pure creation of his spirit…it is then that we experience the sense of beauty". The belief that the happy engineer, like the noble savage, gives us useful things but only the architect can make them into art is one that ignores the centrality of aesthetics to the structural artist"

Following this affirmation he describes the three "dimensions of structure": scientific, social and

symbolic. The symbolic dimension is closely related to aesthetics. These classical virtues **Firmitas**, **Utilitas**, **Venustas** enhanced by Vitruve could appear as an old history without any interest. Nevertheless if "Venustas" is recognized as one of the characteristics of artistic manifestation, some engineers practiced a real art.

1.1.2 Morphology in question

There is always a close relationship between the resulting morphology of a design process and the personality of the designer. This personality cannot be explicitly expressed, but every form is somewhat the visible result of this invisible content.

The external appearance is insufficient to conclude, and it is a matter of fact that, for instance, in the case of the Millau Viaduct (Figure 3), known as Foster's project, the resulting morphology is strongly related to Michel Virlogeux's work. We can perhaps claim that Michel Virlogeux has been the soul of this project. The soul assesses the expression of the designer through the resulting morphology among other parameters. At the beginning of the process there is at least one symbolic choice that is not related to scientific or social dimensions. Michel Virlogeux said that in this case the main idea was to design a viaduct not to span the river Tarn, but to span the entire valley.

Figure 3: Millau Viaduct – Foster and Virlogeux

1.1.3 Which way to Art of Structural Engineering?

Nowadays, the scientific aspects of design are helped by the increasing power of available numerical tools, but if designers can use them at the different stages of the process, since the initial idea to the realization of the project, they cannot reduce their work to manipulation of tools. They are now freer for expressing their own personality by a continuous process, and as artists can experiment, they may simulate by prototypes and numerical modeling the continuous materialization of their project. If the design process in structural engineering is governed by the scientific dimension, true designers do not provide the same solution to a given problem. Their own experience and way of thinking are conditioning the quality of their proposal. There are many differences with classical manifestations of art like size of construction and the necessity of permanence in terms of security, but the mental process is of the same kind. Similarly training conditions are also very important, and common training with artists and architects may contribute to increase the level of their art of engineering.

We evoked at the beginning of this paper the role of Constructivism. A true and free dialog between architects, engineers and artists was clearly fruitful in places where they worked together like the Bauhaus or Black Mountain College inviting designers to exchange their thoughts for a better mutual understanding.

In Black Mountain College (Figure 4), where Snelson was sculptor student in 1948, the experimentation was the main adopted principle as it can be understood by reading the essay by

Diaz . Again, like for the famous Bauhaus, cross pollination between creative people creates the best condition for improving the experience of every one, and enriching his knowledge gained by very separate practices that have in common creativity and artistic attitude in common. Generally engineers who shared this kind of training have more chance to reach the Art of Structural Engineering.

Figure 4: Buckminster Fuller teaching at Black Moutain College.

Structural morphology of tensegrity systems

Tensegrity systems constitute a very interesting example in between artistic expressions and structural engineering. They are characterized by a strong coupling between forms and forces. We provide in the following sections the main geometrical features of these systems by a description of their structural morphology.

1.2 From “Simplex” to complex cells

The problem of form finding is central in the study of tensegrity systems. Since the very beginning of their creation, by Snelson who realized the concept that has been enounced by Fuller, the definition of cells catches the interest of the designers. The following paragraphs illustrate the simplest system, the so-called “simplex” and the last complex systems which are actually designed. This is a way from simplicity to complexity with a set of several models: physical models, “form-models” based on polyhedra, “force-models” mainly based either on force density or on dynamic relaxation.

1.2.1 The “Double-X” and the simplest cell

The basic idea, for explaining the design of the first tensegrity cell with nine cables and three struts is contained in X-shape which is an assembly of two struts and four cables the whole system being in self equilibrium. By cutting one of the four cables of the X-shape, the remaining system acts like an hydraulic jack along the direction of this cable (we called it the “strut-effect” since it is equivalent to a strut under compression) (Figure 5).

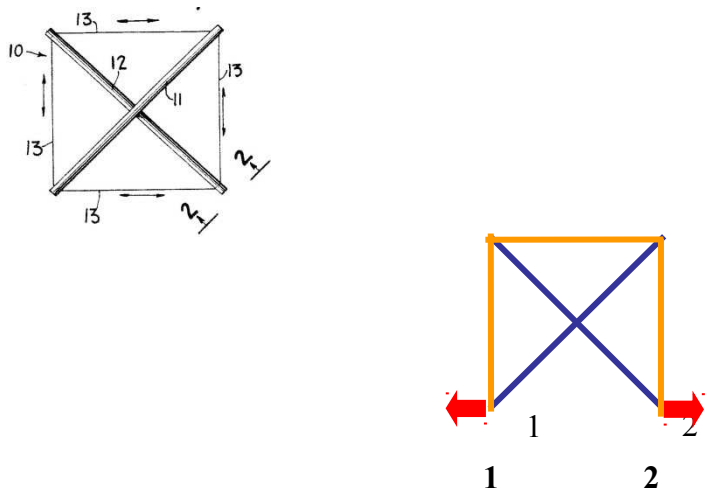


Figure 5: "Strut-effect" along direction 1-2

This idea was used by Kenneth Snelson after a specific work on the assembly of components by mean of a rhombus of cables (Motro : "one to another" and "one to the next" sculptures have opened the way to the "Double-X". In this third sculpture, we can see that Snelson assembled two "X-shapes" with a rhombus of cables in-between. Several other cables were added in order to prevent a motion of the "X-shapes" out of their own plane. The next step was to assemble three "X-shapes" together using again three rhombuses of cables. This assembly theoretically ends up with twelve cables, but three of them are common to two rhombuses: nine cables only remained. Each of the three "X-shape" played the role of a strut. This assembly was finally composed of nine cables and three struts and constituted the simplest tensegrity system which could be realized in three- dimensional space. Some authors call it the "simplex" (Figure 6).

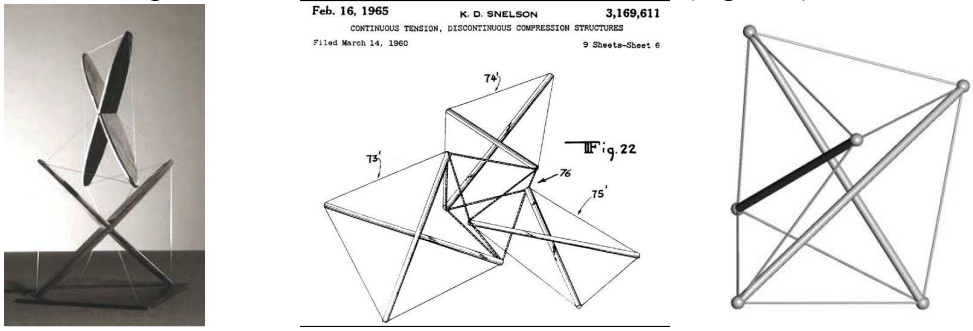


Figure 6: Double-X, Triple-X, Simplex.

1.3 Simple Systems

1.3.1 Prismatic Cells

The first attempts to create new elementary cells were based on some simple characteristics:

- Use of single straight struts as compressed components
- Use of polygonal compressed components (chains of struts)
- Choice of only one set of cable length ("c")
- Choice of only one set of strut length ("s")

The simplex, evoked in the previous paragraph, can also be seen as the result of the transformation of a straight triangular prism. The equilibrated self-stress geometry is defined by the relative rotation of the two triangular bases equal to 30° degrees (Figure 7). Clockwise and anticlockwise solutions can be used.

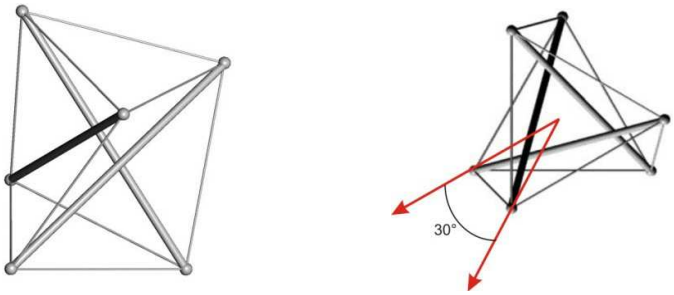


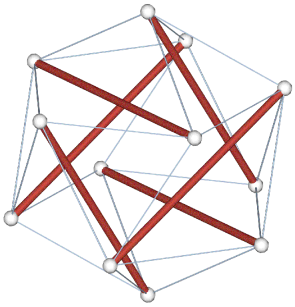
Figure 7: Equilibrium geometry

If the simplex is based on triangular straight prism, other cells can be found other straight prisms (Vassart)

1.3.2 From polyhedra to “tensypolyhedra”

When it is possible to insert struts inside regular or semi-regular polyhedra and to establish a self-stress state of equilibrium, we suggested the use of the denomination “tensypolyhedron” (Foucher). Olivier Foucher realized a comprehensive study from which I extract one example among polyhedra, which cannot be classified as tensypolyhedra. This is the so-called expanded octahedron.

This is a six strut system related to the geometry of the regular polyhedron known as icosahedron. It is possible to compute the shape resulting from the insertion of the struts. The number of cables of this tensegrity system is equal to twenty four, and it is less than the number of edges of the icosahedron (thirty).



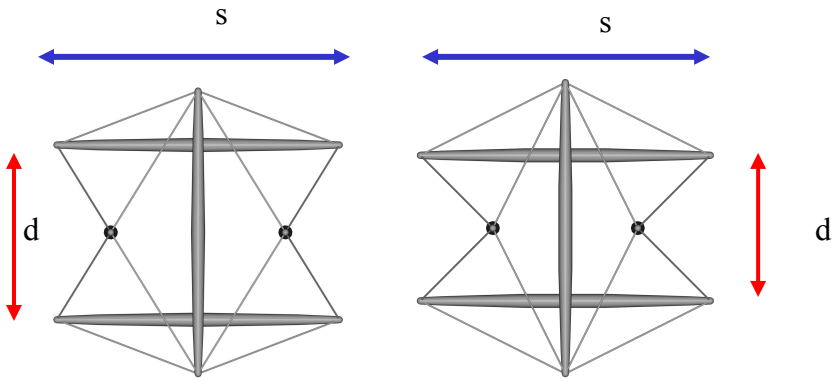
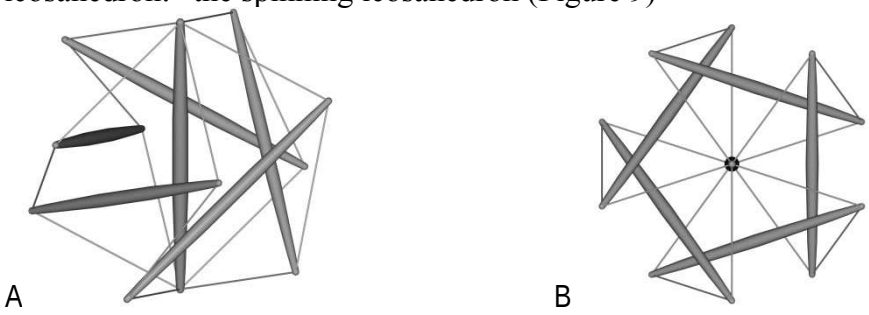


Figure 8: Comparison between icosahedron geometry and expanded octahedron geometry

We compare the regular icosahedron and the possible self-stressed geometry on basis of the ratio between the length of struts “s” and the distance between two parallel struts “d” (Figure 8). For the icosahedron this ratio is equal to approximatly1.618 (that is the “golden” ratio), for the associated tensegrity system in equilibrium (called “expanded octahedron) is equal to exactly 2. This resulting tensegrity system can be seen as the expansion of an octahedron, since there are at the end eight triangles of cables (the same as the number of triangular faces for an octahedron), and the three pairs of struts can be understood as the splitting of the three internal diagonals.

A similar result was found for the truncated tetrahedron whose geometry is not compatible with self-stress. We designed a self-stressed configuration corresponding strictly to the regular geometry of an icosahedron: “the spinning icosahedron (Figure 9)

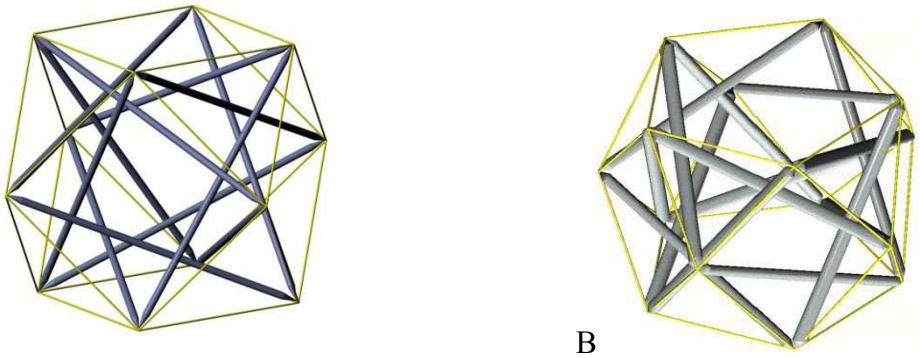


A B

Figure 9: Spinning icosahedron: perspective and in plane views

Among all tensegrity systems, some are characterized by the specific topology of their compressed components. These components are no more single struts, but strut circuit . Two examples are of interest:

- The cuboctahedron comprising four compressed interlaced triangles (Figure 10-A)
- The mono circuit tensypolyhedron (Figure 10-B). This second case is a very interesting one; the chain of fifteen struts is closed and creates a circuit which is the only compressed component. The continuum of tensioned components is a polyhedron with two pentagonal parallel faces, five quadrangular and ten triangular faces. We shall develop a study on “tensegrity rings” in a following paragraph, based on this specific cell.



A B

Figure 10: A-Cuboctahedron tensegrity system. B- Mono-circuit tensypolyhedron

1.4 Towards the complexity

1.4.1 Introduction

If the elementary cells were based on polyhedra, it became obvious that it could be interesting to design more complex systems, with many different lengths for cables and struts. Specifically, we had this need not for architectural structures, but for a specific problem in biology: the cytoskeleton of human cells can be analogically compared to tensegrity systems as far as their common mechanical behaviour is concerned. We began to work on physical models before developing a numerical method which gives some first interesting results.

1.4.2 Preliminary physical models

It is useful to begin with physical models, because it is the best way to understand the complexity of the design with all implied parameters. The first complex systems were achieved some years ago and called “clouds” (Figure11).

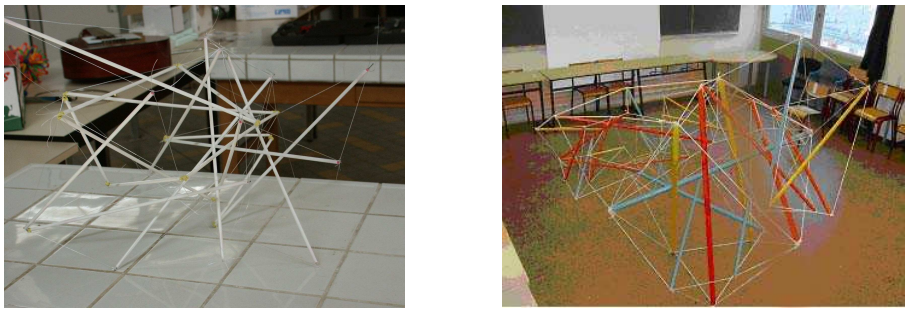


Figure 11: Clouds

1.4.3 Numerical models towards complex systems

It was necessary to model and to generalize the process through numerical methods. This work has been achieved by Zhang et al. (Zhang).

The form-finding process that we use started from an initial specification of the geometry. At the same time, self-stresses in some or all the components are also arbitrarily specified. Hence, excepted particular cases or lucky situations, the system cannot be in equilibrium. A motion of the structure is then caused by the unbalanced internal forces. The displacements are computed by using the dynamic relaxation method that is based upon the calculation of a sequence of decreasing energy peaks and leads the system to reach the steady equilibrium state.

During form-finding process, the minimum distance between two spatial line segments should be checked for avoiding contact. It is necessary especially when system geometry is complex and several algorithms for checking can be used (Eberly). If in final equilibrium state some elements touch each other (which means improper topology or geometry chosen by designer), then the topology or the geometry has to be modified until no contact is ensured. It can be done in a "slight way" by modifying stiffness values or more roughly by changing the topology.

No topology of the whole system is specified in advance for that example. The process is started from a simple system and, next, more and more struts and cables are added step by step. The computational sequence is summarized as follows: the process starts from a quadruplex (Figure 12), and another vertical strut 9-10 is added. To keep nodes 9 and 10 in equilibrium state, it is necessary to add six cables (three connected to node 9 and another three to node 10). Note that other possibilities exist for adding these new elements but we have chosen the simplest way.

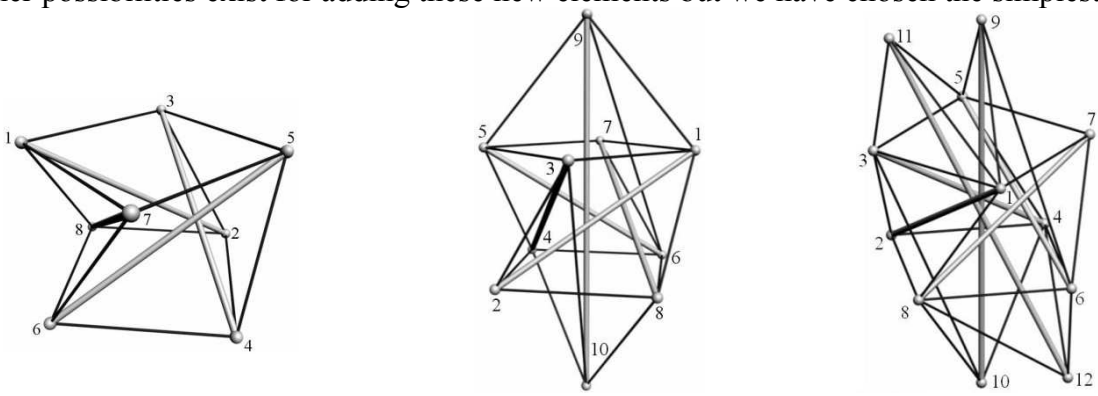


Figure 12: From four struts to six struts

Following the same procedure, three other struts (11-12; 13-14; 15-16) and eighteen-cables are added to the system step by step; the topologies are respectively shown in Figure 13.

In this example only two different lengths for the eight struts are necessary at the starting configuration. During the form-finding process, one strut following another one is added to the

system randomly. To keep this strut in stability, a certain number of cables are added to its ends. Many possibilities exist for such topology modifications and the designer can choose the more suitable solution.

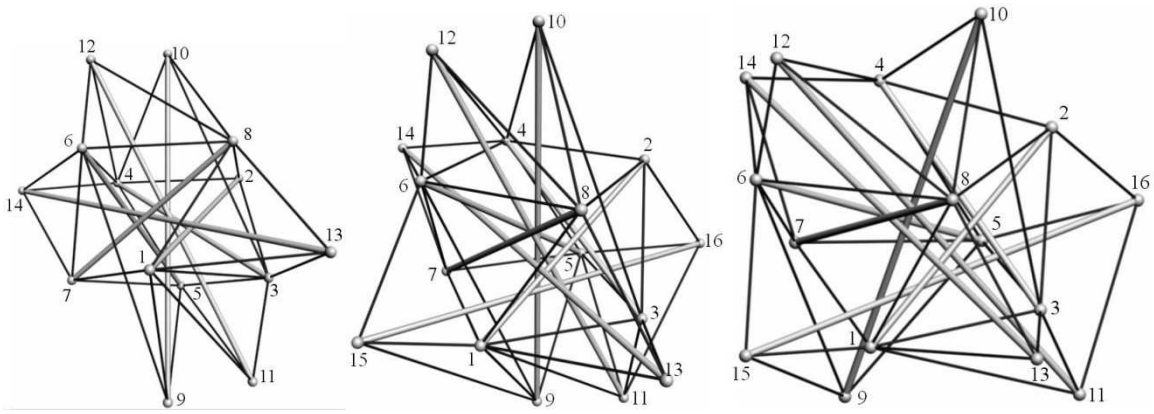


Figure 13: From seven struts to eight struts

Examples of realized and projected tensegrity systems

1.5 Kenneth Snelson, “Forces Made Visible”

Kenneth Snelson is an artist who is at the key point between art and structural engineering. Many papers have been devoted to his pioneer work in the field of tensegrity structures.

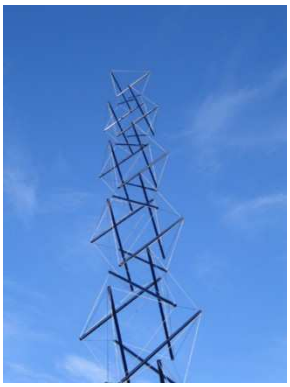
A  B 

Figure 14: Snelson sculptures A Easy Land, Boston – B Tensegrity Tower

In 2009 Snelson had an exhibition in Marlborough Gallery, Chelsea, New York. The title was “Kenneth Snelson Forces Made Visible”, and this is also the title of the book edited for this opportunity (Hartney): the best title for the work of this artist who is able to make forces visible. Forces are a mechanical concept useful for engineers who want to size their structures and they are by nature invisible. On the other hand forms are visible and measurable, and they are the product of the artistic process. Why forces are made visible? Some key-points may be put forwards:

By differentiating clearly cables and struts, Snelson’s sculptures provide information on whether tension or compression is present. This is not the same for classical reticulate systems.

If the level of tension and/or compression can be qualitatively evaluated according to the external diameter size of components, it is insufficient since this level is depending upon the material, and the thickness of tubes, or the arrangement of cables.

The very specific structural composition surprises and fascinates everyone seeing them for the first time: struts seem to float in the air. And this is also a key point, since people, and engineers

more than the others, are surprised by this new kind of flow of forces. They are used to gravity effects, and in this case gravity seems to be absent. The artist provokes interrogations by submitting an unknown process for transmitting forces.

Last but not least: art is a source of emotional feeling. In case of tensegrity systems people feel that at every end of each strut, cables contribute to the equilibrium. And it cannot be possible without an amount of stress of tension in cables, and compression in struts: struts are "lifted" inside the structure by a continuum of cables. But of course it is not easy to understand how all these forces are distributed; we only know that the whole is in equilibrium, stressed and stable

Finally it can be said that the artistic work by Snelson obliges the structural engineers to question their structural approach, and to enrich it.

1.6 Tensarch Project

1.6.1 Introduction

Between 1998 and 2000, a project of a tensegrity system has been realized with the financial support of the industrial firm Ferrari. The resulting prototype is a flat double layer grid, rectangular in plane and covering an area of more than 80 square meters, with a self-weight of 12 kg per square meter.

The challenge was to demonstrate that beyond an apparent complexity it was possible to build tensegrity systems in the same way as other space structures. Several studies were undertaken and they concerned: conceptual design, sizing for usual conditions, study of sensitivity to manufacturing imperfections, node design, self-stress implementation policy, and finally realization.

1.6.2 Main stages of the project

The whole project is described in a contract report (Raducanu et al.), and the structural composition was patented (Raducanu et al.)

We began the work by an initial thought about the design process: avoiding the usual agglomeration of cells (Figure 15-A), and we developed the concept of extender (Figure 15-B).

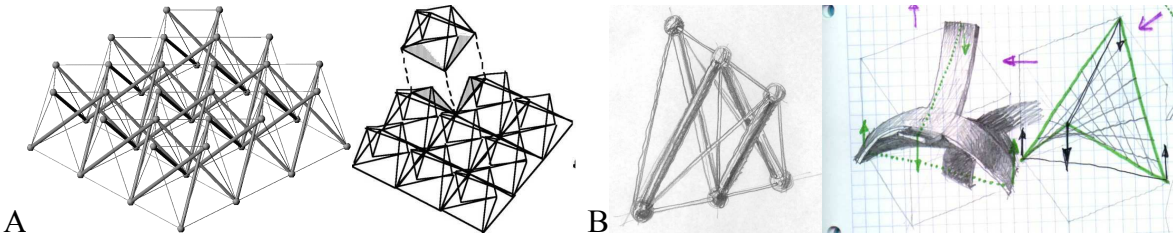


*Figure 15: **A**-Previous design principle : agglomeration **B-**. Extender principle*

This led us to several structural compositions, whose some possible networks are illustrated by Figure 16.

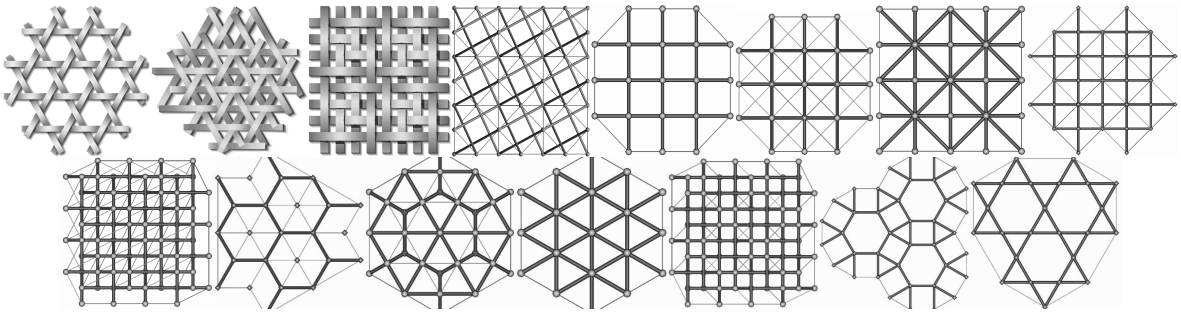


Figure 16: Possible Networks

All are in the spirit of weaving process. Among the possibilities we chose five of them and build models at scale 1/5°. Simultaneously we made some numerical computations related to mechanical behaviour and self-stress identification, according to Eurocode 3 specifications. Self-weight and active loads are those which are really used in identical constructive situations for space structures.

We first assembled the two cable layers (Figure 17) before inserting the struts, the vertical ties and the peripheral cables according to the composition given in Figure 18. The whole grid was then put on a small wall. This work was achieved by two men in two days, knowing that they also made a very rigorous identification of every part.

Figure 18: Building the grid

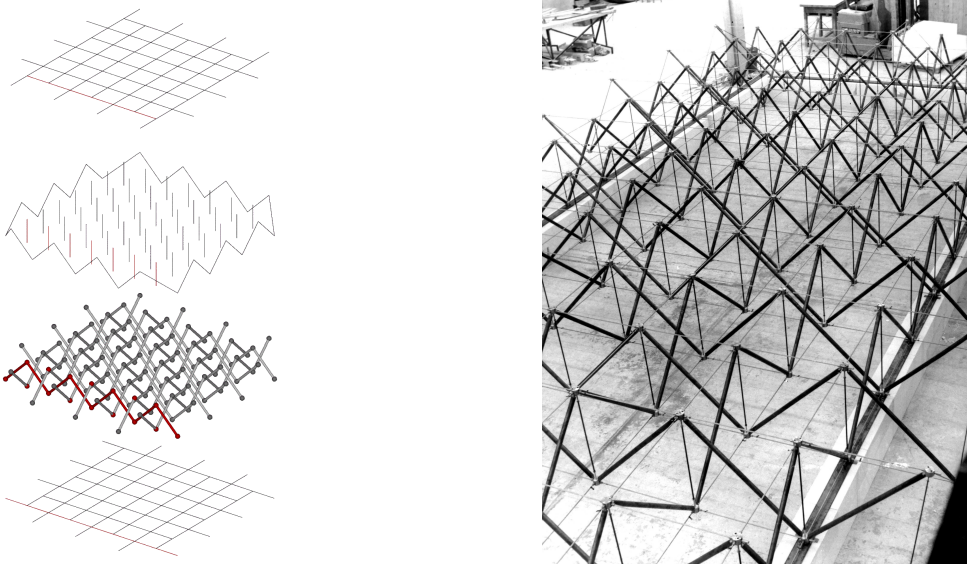


Figure 19: Exploded view of the grid and its realization

1.6.3 Conclusion

The main objective of our project was to prove the feasibility of tensegrity double layer grids. By the way we learned many other lessons from this experience. A first one concerns the definition of tensegrity that we could approach physically when we saw the grid “inflated” by means of cables. The denomination “discrete pneumatic structures” that we used for tensegrity systems seems to be very well adapted.

During the initial stages of the design process, a new design mode, based on weaving analogy, has been developed and we only used one of the projects, the simplest one. Other structural

compositions have to be explored since some of them which have been numerically tested seem to be stiffer than the one we built, even if its rigidity was satisfying.

It is known that the difficulty in case of initial stressed systems is to satisfy both shape and mechanical requirements in terms of stresses. With our experiment we could check that the geometric goal is easily reached since the beginning of the process and is not affected by self-stress variations. As far as self-stress is concerned we could adjust its level and repartition with a very good precision. This was a first step toward applications of tensegrity, but we know how many improvements can be achieved specifically with other material than steel.

1.7 The "Hollow Rope"

1.7.1 "Tensegrity rings"

Since the whole components of the cell called "Mono circuit tensypolyhedron" (Figure 10-B) cables and struts are inside a hollow tube shape, these tensegrity cells are grouped under the denomination "tensegrity rings" (Figure 20).

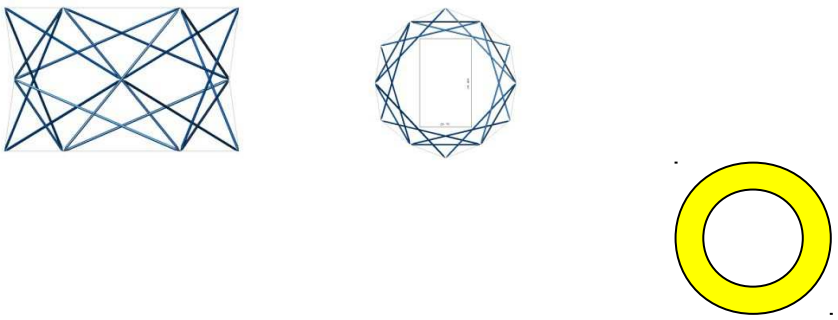


Figure 20: Tensegrity ring

It is simple to act on the geometrical parameters, namely the height of the cell, the interior radius and the exterior radius in order to meet some criteria of architectural type. At this stage only regular systems have been studied, but there is no doubt that other possibilities are opened in the field of irregular shapes. Many physical models were built and we checked their foldability which is a very important feature of tensegrity rings.

1.7.2 The "hollow rope"

The simplest application is to add several tensegrity units by their basis creating so a kind of "hollow rope". The units can be identical or not in terms of height. If the two bases are not parallel, new curved mean fibber are created. The idea of "hollow rope" was soon described with other structural compositions, which did not rely on tensegrity principle. Robert Le Ricolais, and also Maraldi developed their own solutions.

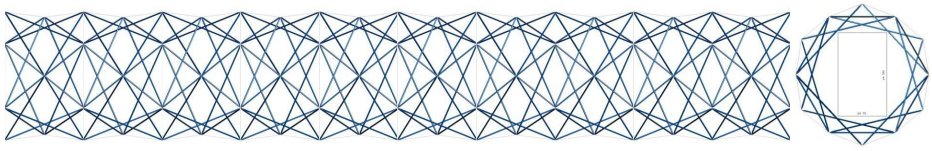


Figure 21: The "hollow rope"

Several parameters can be adjusted. According to the size of the global system, and to an appropriate size of tubes and cables, a pedestrian bridge can be designed on this structural composition, since the inner free space could receive the walking floor.

1.7.3 Foldable tensegrity rings

Figure 22: Physical model for a foldable tensegrity ring

These first studies on rings provided the roots for more intensive research, which is carried on in our laboratory. The foldability of these rings has been tested on more sophisticated models.

Conclusion

Tensegrity is a major innovation in terms of structural composition. Richard Buckminster Fuller dreamed of a concept of "Islands of Compression in an Ocean of Tensions". Kenneth Snelson, by his artistic work, materialized the concept in fascinating sculptures. Engineers provided the mechanical models for the understanding of their behaviour: self-stress, mechanisms, foldability. Designers began to benefit of this innovative system by building masts (Rostock Tower in Germany), grids (Clouds in Swiss Expo 2002) and designing footbridges. The way is open for a wide use of tensegrity principle.

References

Lodder C., "The Transition to Constructivism". *The Great Utopia. The Russian and Soviet Avant-Garde*, 1915-1932, Exhibition. Guggenheim Museum, 1992.

Picon A. (supervised by). Exhibition « *L'art de l'Ingénieur, constructeur, entrepreneur, inventeur* » Catalog. Centre Georges Pompidou, Paris, Editions du Moniteur, 1997

Billington D.P., "*The Tower and the Bridge*", The New Art of Structural Engineering, Princeton University Press, 1983

Diaz E., "Experiment, Expression and the paradox of Black Mountain College", ISBN 0-907738-78-8, Kettle's Yard Arnolfi, 2008

Motro R, "*Tensegrity: Structural Systems for the future*". Hermes Penton Sciences. 2003 - ISBN 1903996376 (UK).

Vassart N., Motro R.,. "Multi parameter Form finding Method. Application to Tensegrity Systems". R., *International Journal of Space Structures*. Special Issue on Form finding of Tension Systems. Vol.14.N°2. 1999. 131-146.

Foucher O., "*Polyèdres et Tenségrité*", Master Thesis, Université Montpellier II, 2001.

Motro R., "Structural Morphology of Tensegrity Systems", *Meccanica*, Springer, 2011, 46, pp 27-40.

Zhang Li, Maurin B., Motro R.,"Form-Finding of non regular tensegrity systems", (IJSS) ASCE. (2006) *Journal of Structural Engineering*, vol.132, 4, 1435-1440.

Eberly D. "*Distance between two line segments in 3D*". Magic Software Inc., 1999.

Hartney E., "*Kenneth Snelson - Forces made visible*", Hard press editions, 2009

Raducanu V., Motro R. "Système constructif et architecture : cas des systèmes de tenségrité" *Contrat SLA/LMGC/Ferrari*. Rapport Final. September 2001

Raducanu V., Motro R., "*Composition structurale de systèmes de tenségrité*" Société de Tissage et Enduction Serge Ferrari, déposé le 16 Mars 2001 sous le numéro 0104 822.