Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

Tensegrity workshop: designing (the) building process

Maria K. VRONTISSI

Adjunct Lecturer, Department of Architecture, University of Thessaly
Pedion Areos, Volos 38334, Greece
mvrontis@arch.uth.gr

Abstract

This article presents the full-scale tensegrity structures that were built in a student workshop at the Department of Architecture at the University of Thessaly in spring 2007; projects included typical tensegrity forms to industrial design or small-scale architecture structures. Objectives and constraints are described, the trial-and-error approach is illustrated. Design explorations, construction investigations and experimentation with the implementation process are presented. The methodological approach is discussed to emphasize the constructive contribution of tensegrity systems in design education, their inherent characteristics and complexities of related processes touching fundamental issues in contemporary design discourse.

Keywords: Tensegrity systems, small-scale structures, non-linear design process, multi-disciplinarity, 3d-model, design-built workshop, trial-and error.

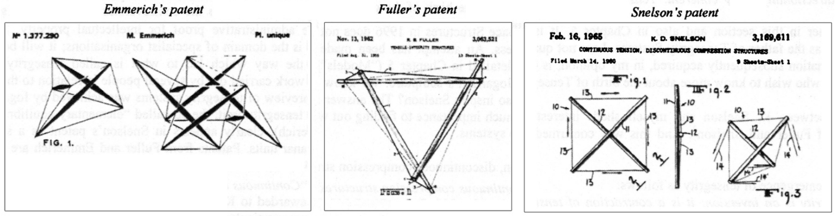


Figure 1: Tensegrity patents by Emmerich, Fuller, Snelson (adapted from Motro [8])

1. Introduction – tensegrity applications

For the past fifty years, the concept of tensegrity, named after Fuller's patent of 'tensile integrity' [5], attracts the attention of engineers, scientists and artists, while tensegrity systems, described by Fuller as ' islands of compression in an ocean of tension', never cease to produce sentiments of surprise and wonder. According to Motro's 'extended definition' [8], 'tensegrity system is a system in a stable self-equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components.'

The work of tensegrity pioneers Emmerich [3], Fuller [4] and Snelson [13] (figure 1) has instigated further research, theoretical or experimental, in fields ranging from mathematics (Connelly and Back [1]), to biology (Ingber [7]) and natural studies, from art to mechanical and structural engineering. The application of tensegrity systems in design fields has been investigated for the past three decades, with built examples ranging from industrial design to architecture, such as the 'Blur' building for the 2002 Swiss Expo by architects Diller+Scofidio [2] and structural engineers Passera & Pedretti. Motro [9] and his research group 'Conception en structures' at LMGC, Universite de Montpellier II, have been extensively engaged in research on possible application of tensegrity principles in building structures, current research focusing on form-finding methods, mechanical behavior, dynamic controls, folding possibilities, as well as technological studies on node assemblies.

2. The workshop: objectives, constraints and methodology

In design education, the captivating first impact of tensegrity systems on students (see Gomez [6]) is often confronted with practical limitations usually discouraging applications. Inclusive applied research on tensegrity systems entails extensive mathematic background, thorough structural knowledge and technical experience, due to the inherent complexities, related technologies and processes. As a result, attempts in architectural education employ a rather intuitive approach, usually based on and finally confined to physical in scale models, approach inherent to design culture. A method to develop a initial familiarity with this type of structures, facilitate design explorations, proceed to implementation and allow for full-scale experimentation in order to get to know and start dealing also with the technical aspects, is yet to be outlined.

This article discusses the tensegrity structures that were created in a student design-built workshop at the Department of Architecture at the University of Thessaly in spring 2007. The brief called for the design and full-scale construction of several tensegrity structures to be erected in the school's courtyard. Materials, use and character of installations was to be defined. The workshop was performed by [K]onstruction Team, a voluntary student workgroup experimenting with the design and construction of small-scale structures, focusing to the material and structural characteristics of the architectural artifact and the complexities of the design process. Twenty three senior students supervised by one professor and organized in groups produced seven full-scale structures in a ten-day period. Real constraints, cost and time related, defined the final amount and scale of the installations, as well as the design and construction methods. Available means, tools and knowledge background of the students were defining parameters. Additionally, as the actual construction and mounting of the structures was expected to be performed on-site by the designing teams, demand for easy and safe mounting by an inexperienced student crew was a parameter of key importance, imposing a systematic organization of the process and calling for clear and comprehensible assembly instructions, which in turn pushed for a deeper understanding of geometric and technical characteristics.

The objective of the workshop was to provide an insight on this type of structures and introduce students to investigating construction and technical issues. Furthermore, in this particular case, the intrinsic characteristics of the structures (lightweight, flexible, portable, of demountable character, exceptionally 3-dimensional nature, geometric complexity) allowed and called for a non-linear design process, while the limited scale of the installations allowed the designing teams to keep control of all aspects. These two features gave a unique opportunity to investigate appropriate tools and working methods, experimenting with the process itself and attempting to redefine it.

In terms of methodological approach, a 3d-model based approach was suggested, encouraging a trial-and-error attitude, enhancing a non-linear process, simulating inter-disciplinary input based on 'collective' knowledge.

A brief introduction to tensegrity principles was immediately followed by an immersion exercise on building physical models of basic tensegrity modules. Construction methods were explored in two pilot structures, the so-called team projects, involving almost all students, while five discrete design proposals were developed in groups. In the group projects, the working method (based on the common characteristics of all projects and the recurring nature of concerns) was based on a model of allocating tasks, yet building a 'collective' expertise. Each group member was assigned a specific task (design, modeling, materials, detailing, assembly), each group concentrating on a specific project. Thus, every student was engaged in a double interaction; contributing specific input to the design development of a specific project within a group, exchanging information about a specific aspect of the process with the other students assigned the same task. (figure 2)

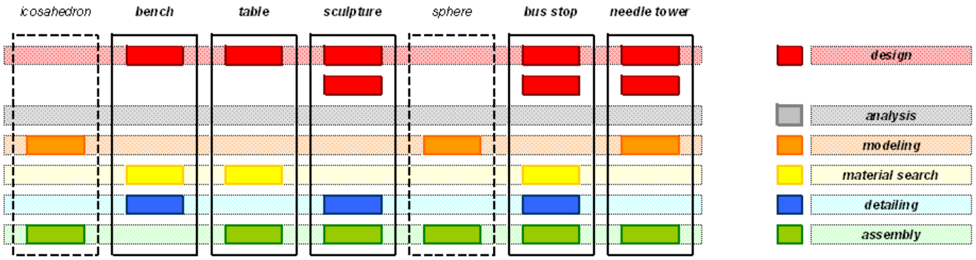


Figure 2: Simulating inter-disciplinarity; double interaction: by project or by task

As construction was progressing from the smaller to the larger structures, experience was adding up, so was self-confidence and team-spirit. For the actual mounting, all students worked together; thus, engaging in a third level of interaction; alternation of degree of responsibility ranging from full construction management, when it concerned their own design, to simple assembling tasks for the rest of the projects.

However, allocation of time, means, people and effort in each project, as well as within the whole workshop, was centrally controlled by the professor in charge, providing a 'safety-net' in order to avoid large deviations in time, reduce material waste and secure safety issues.

3. Description of projects

A number of pieces was designed ranging from typical tensegrity forms to industrial design or small-scale architecture structures.

3.1. Typical tensegrity forms

3.1.1. Icosahedron (expanded octahedron) (figure 3)

The first team project was one of the most characteristic and popular tensegrity systems. The icosahedron, or else 'icosahedric tensegrity system', also defined as 'expanded octahedron' by Pugh [10] and Motro [8], is a regular six strut, twenty-four cables, two-layer, diamond-pattern spherical system (codification n12-S6-C24-R-SS according to Motro). The struts are parallel to one another, in sets of two. Two methods of construction were tried out in physical models, either by using a supporting temporary interior cube or by using a descriptive layout diagram. Digital models were used to test given ratios of elements. For the final structure, the first method was adopted. The cardboard tubes were securely fixed (as indicated by Pugh) to a temporary carton box and the cables were added defining a diamond pattern about each strut; at the end, the box cube was dismantled and removed.

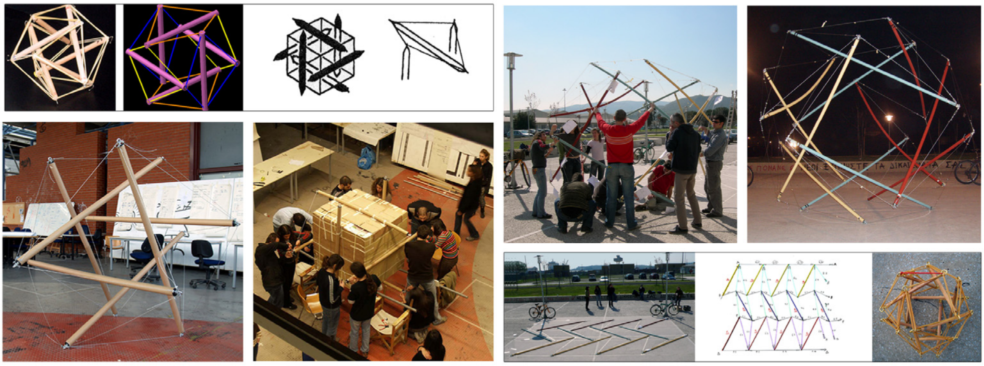


Figure 3: The two pilot projects exploring different construction methods
(students in charge: V.Karga, A.Kassimati, E.Moschonas, C.Papasarantou)

3.1.2. Sphere (expanded cuboctahedron) (figure 3)

The second team project was another quite typical tensegrity system. Usually referred to as 'expanded cuboctahedron' (as opposed to its equivalent, the Archimedean cuboctahedron, a circuit-pattern system), it is a regular three-layer diamond-pattern spherical system comprising of twelve struts and fourty-eight cables (codification n24-S12-C48-R-SS according to Motro [8]). According to Pugh [10], 'the overall figure is approximately cylindrical, tapering at top and bottom like a wooden barrel, (...) the ends of the twelve-strut figure being squares.' Digital models were used in this case too to test given ratios of elements. Construction for both the physical models and the full-scale structure was based on descriptive layout diagrams. The plastic tubes used for the struts proved to be weak in relation to their lengths for the resulting compression forces and were soon submitted to buckling deformations.

3.1.3. Tower (figure 4)

The third and most complex project on typical tensegrity geometrical forms was a tower, a variation of one of the most celebrated sculptures of Snelson, the Needle Tower [12].

According to Motro [8], this is 'a uni-dimensional system, characterized by a predominant axis, which dictates the whole geometry; (...) the aesthetics, purity and rhythm of which can not fail to surprise the visitor.(...) Its system is in fact a 'rhombic' (diamond-pattern) tensegrity system with several layers of three elements each. It can be also be considered as a superposition of expanded octahedra.' This tensegrity system is generated by the superposition of a module unit along a linear axis. In most examples, this module is a 'simplex', otherwise described as 'elementary equilibrium', 'twist unit', ' regular simplex'. 'Elementary' is composed by three compressed elements of equal length and nine tensioned elements of equal length. It is the smallest spatial system that can be built according to the so-called 'patent' definition.' (codification n6-S3-C9-R-S according to Motro [8]).

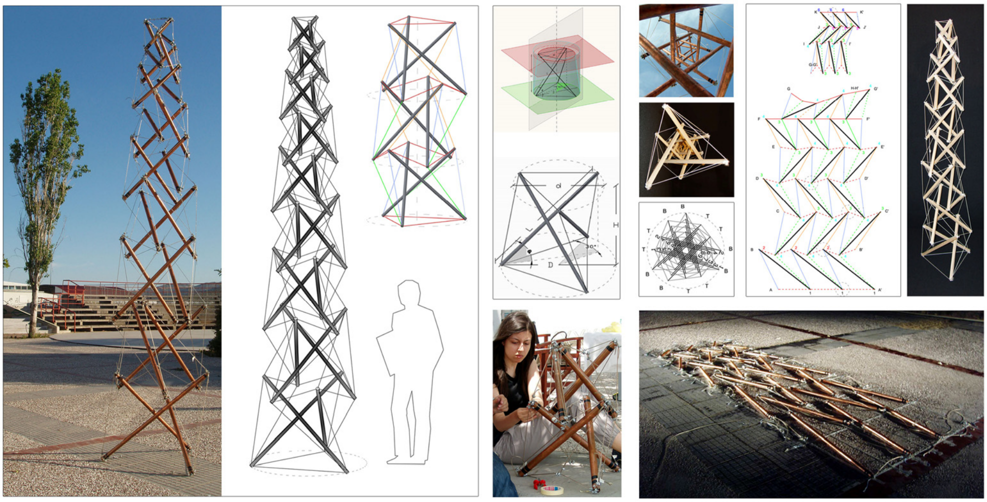


Figure 4: Tower (S.Bagiartaki, P.Doudessis, E.Kostopoulou, N.Theodoulou)

Once Snelson's Needle Tower principles had been understood, several variations were investigated. Changes included overall dimensions, amount, proportions and overlap of subsequent levels, lengths of struts, form of the module unit (length of struts, type of polygon, orientation of 'twist angle', circumscribing figure). A modified 'simplex' was attempted as the base module unit; deriving from the basic prismatic configuration by slightly varying the dimensions of the two base triangles; that is, a module inscribed in a cone instead of a cylinder. One more parameter was introduced; size of modules was proportionally reduced in subsequent levels.

Variations were compared on physical models in 1:10 or 1:20 scale (using balsa pieces and cord) in terms of aesthetics, assembly method and overall stability. No form-finding methods and analytical tools were used. Subsequent digital 3d-models helped to define and fine-tune dimensions of all elements. However, the first full-scale trial failed as the 'twist angle' principle was not carefully taken into account and the proposed variation resulted in a non-stable configuration. Experimental approach wasn't enough and further readings were necessary. A full-scale trial of the final configuration was conducted by first assembling the upper three levels of the system before proceeding to the final assembly. Besides, this 1:1 scale mock-up, served as an experimental guide to define the assembly sequence of cables, as the density of conveying elements was high (4-5 pieces), especially for the smaller units.

The final variation, 4.0m high, consists of nine partly overlapping levels, composed of conical-prismatic units of decreasing size, based on a three-strut module, with alternating 'levogyre' and 'dextrogyre' units. The struts, made of copper tubes, have a varying length ranging from 1.20-0.40m, while PVC coated wire rope is used for the cables.

3.2. Art explorations

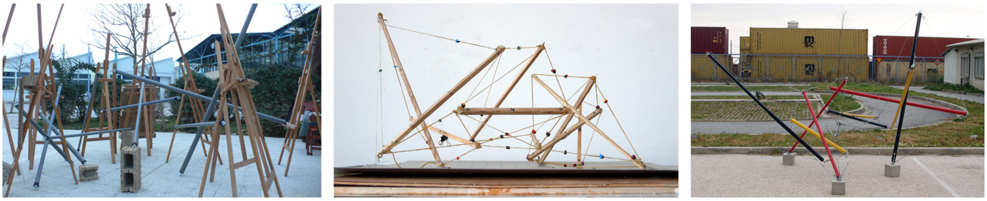


Figure 5: Sculpture (S.Chatzichristos, Y.Rammos, M.Salehi, K.Tsakiris)

3.2.1. Sculpture (figure 5)

Inspired by 'Audrey I' [12], a small sculpture by Snelson, this project is a rather intuitive artistic search to produce the effect of floating struts. Ten plastic tubes of varying length have been used for the strut elements. Initial rough attempts with physical models were refined by using a precise space grid and detailed identification system to record coordinates of the small-scale model and 'translate' them into the full-scale structure. During the assembly process a temporary supporting system was used to maintain the struts in their final position, while the thirty-two cables were connected. Small concrete base-foundations were used to ensure stability of the structure against wind for outdoor use.

3.3. Industrial and architectural design applications

3.3.1. CoffeeTable (figure 6)

This structure is basically a reproduction of Snelson's sculpture 'Proto Newport' [12]. Studies focused on understanding the overall geometry, defining lengths of elements, exploring technical issues concerning cable assemblies and node detailing. Proposing a valid mounting method, e.g. a method to ensure relative position of struts, while the cables were connected, proved to be the most difficult task, especially because it was decided to use continuous loops for certain groups of cables. After an unsuccessful attempt, final solution included the use of a sort of formwork, comprising of a set of two base surfaces, to stabilize strut ends. Copper circular tubes were used for the struts, while a circular glass or steel plate was proposed for the top surface. This system could be studied as an assembly of basic modules.

Figure 6: Coffee Table (A.Nikolopoulou, A.Ntovas , T.Tousas)

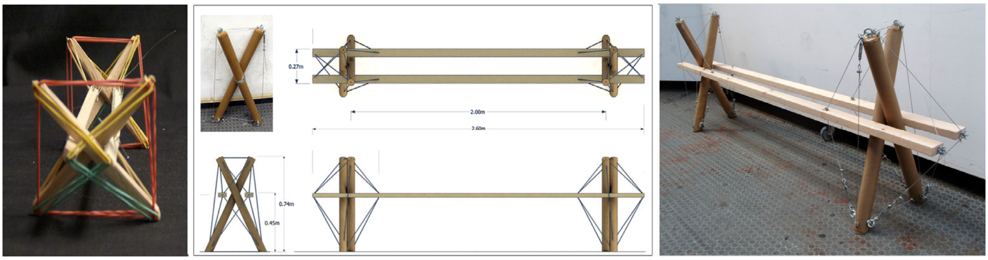


Figure 7: Bench (A.Chronas, M.Kokkinos, P.Nikolakis)

3.3.2. Bench (figure 7)

Snelson's sculpture 'Double Cross Bar' [12] was the inspiration for this project. The reference figure led to the proposed use and several alternatives were explored in physical models. For the full-scale structure cardboard tubes were used as supporting elements, while a couple of timber beams formed the horizontal 'seating'. Issues of relative stabilization of strut elements during cable assembly were, here also, present, to a smaller extent though, as the system was assembled in sets of two, forming 2d-configurations. Though the final structure was not purely a tensegrity structure, neither by configuration, nor by its proposed use (the main timber beams subjected to bending when used for seating, and, thus, force equilibrium within the elements is modified by external actions), the object proposed an interesting design route for further explorations, in terms of use and materials, and was definitely one of the most enjoyed in subsequent exhibitions.

3.3.3. BusStop (figure 8)

The structure called bus-stop was the largest in scale, heavier in terms of material use, more complex to assemble and last one to set in place. Several outdoor sculptures by Snelson were studied (namely ‘Avenue K’, ‘Sun River’, ‘Flat Out’ [12]) before this ‘architectural’ application was developed in small-scale models. The relatively large scale, the outdoor location and the end use called for a heavier structure with differentiated characteristics in terms of necessary strengths (choice of material and cross-section), weather protection, assembly precision and safety precautions. Steel hollow sections were used, treated for outdoor use, while special provision was made for the cable assemblies; galvanized wire rope of increased diameter, double wire rope clips per node, eye and eye type turnbuckles. Studies have been made to ensure overall stability against over turning and strut cross-sections were oversized to increase overall weight. While this structure too was a rather extended variation of a tensegrity system, this project attempted a tensegrity application of increasing interest from the design scope.

Figure 8: Bus Stop (F.Adrimi,H.Helidonaki, P.Kanellopoulou, M.Koulogeorgiou, M.Mavri)

4. The implementation process: allocating tasks

4.1. The modeling

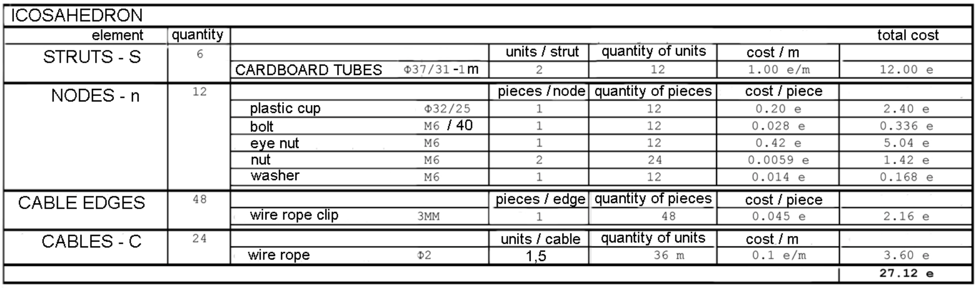
While the traditional methods (paper based design) and representation tools (sketches, 2d drawings,…) proved to be inadequate, the 3d-model was the only and interactive basis for design studies. The 3d-model was used in several versions, each version contributing a specific, yet somehow interactive, information component, indicating behavior patterns and suggesting possible alterations; data sheets to describe coordinates and calculate mathematical relationships between elements, digital models to geometrically refine forms, physical models to understand overall configuration and ‘sense’ force distribution, and, ultimately, 1:1 scale mock-ups (figure 4) to deal with complex 3d details, define assembly lengths and node configurations and decide upon assembly sequence, as well as construction management diagrams to guide the mounting process.

4.2. The analysis

Preliminary sizing (cross-section material, type and dimensions) was performed based on intuition, rules-of-thumb or on-site testing; no analytical methods were used. The 1:1 scale mock-up proved to be the only available experimentation tool to understand the physical characteristics of the architectural form, while the specific digital model was inadequate for testing purposes, as it contained no information about materials and cross-sections, force equilibrium and stress distribution, being basically a static descriptive representation tool unable to simulate structural and material behavior.

4.3. The materials

A list of possible materials was formed according to market availability, cost and processing possibilities; dimensions of possible strut end components being a decisive parameter. Proposed materials included cardboard (37dia.x3mm) or plastic tubes (50dia.x2.5mm, 40dia.x2.5mm, 32dia.3.5mm), wood beams (100mmx60mm), steel (76dia.x2mm, 42dia.x1.5mm) and copper (35dia.x1mm) circular hollow sections for struts and galvanized wire rope (2-3mm dia.) for the cables. Rough material and cost estimates were produced, defining quantities of struts, cables and nodes per project based on initial configurations parametrically described. Final tables present full data. (figure 9) Cost of projects ranged from 30€ to 150 €.



ICOSAHEDRON							
element	quantity						total cost
STRUTS - S	6			units / strut	quantity of units	cost / m	
		CARDBOARD TUBES	Φ37/31 -1m	2	12	1.00 e/m	12.00 e
NODES - n	12			pieces / node	quantity of pieces	cost / piece	
		plastic cup	Φ32/25	1	12	0.20 e	2.40 e
		bolt	M6 / 40	1	12	0.028 e	0.336 e
		eye nut	M6	1	12	0.42 e	5.04 e
		nut	M6	2	24	0.0059 e	1.42 e
		washer	M6	1	12	0.014 e	0.168 e
CABLE EDGES	48			pieces / edge	quantity of pieces	cost / piece	
		wire rope clip	3MM	1	48	0.045 e	2.16 e
CABLES - C	24			units / cable	quantity of units	cost / m	
		wire rope	Φ2	1,5	36 m	0.1 e/m	3.60 e
							27.12 e

Figure 9: Typical table presenting full data and cost per project

Figure 10: Node configurations according strut material and actual location

4.4. The detailing

The pin-joined nodes of tensegrity structures added one more degree of freedom to the process, disconnecting detailing issues from a linear process and allowing for investigations on node configurations to start and develop in parallel with design explorations. Several alternatives have been studied for the node components and assembly according the strut material, the amount of conveying cables and the actual location of the node (base nodes demanded a separate solution). (figure 10)

Basic node configuration consisted of a plate component (steel plate or plastic/ copper cup), eye bolt or eye nut, bolt(s) and washer(s); the plate component wasn't needed in the case of wood beams. In certain cases (especially for copper tubes) an alternative was proposed; using a standard shackle connected to a thread bolt fastened with a couple of nuts through the strut end; in the assembly process, opening the shackle to connect pre-assembled cables proved to be quite practical. Basic cable configuration included typical rigging hardware; galvanized wire rope, a couple of wire rope clips, standard shackle and simple hook and eye type turnbuckle.

4.5. The designs

Design novel tensegrity systems from scratch was neither the goal nor a possibility for a ten-day student workshop. Design investigations derived from well-known tensegrity typologies or developed variations of precedents, namely sculptures chosen from Snelson's work [12] (also see Schodek [11]). Even so, students enthusiasm and commitment was compensated by the problem-solving process of understanding given geometries and find ways to reproduce them, as well as designing the actual implementation process. (figure 11)

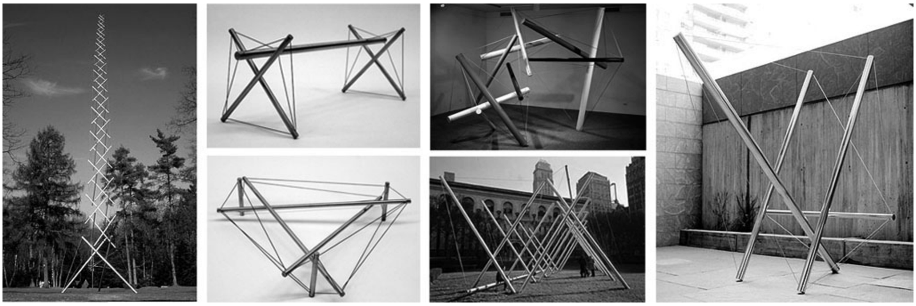


Figure 11: Precedents chosen by students from K.Snelson's work

4.6. The construction process - assembly sequence

Designing the implementation process proved to be the most challenging part.

Processing of elements included cutting, piercing, joining or welding struts, mounting nodes assemblies and preparing cable sets; finally, tagging all pieces. Pre-assembly of cable sets was selected as a standard procedure for precision and safety purposes. For mounting purposes, certain sets of cables were unified to form a continuous network.

Two basic construction methods were proposed during the immersion exercise, developed and tested on the team projects.(figure 3) a) Direct mounting using a space-grid and a secondary supporting system to ensure relative strut positions during cable assembly. Tasks included definition of space grid, design and construction of the supporting system, precise positioning of struts according to given coordinates, assembly of cables at resulting lengths, and, finally, removal of supporting system and fine-tuning of cable lengths using turnbuckles, b) Two-steps mounting starting with assembly in flat using according layout diagram to provide relative positioning of elements. Once the optimum layout diagram was established, all the elements were laid out flat (struts first, cables next), then the end parts were connected to form the 3D figure. Certain cables needed to be adjusted to final (pre-marked) lengths and remainders to be removed before final cable length fine-tuning.

The optimum 2d layout diagram was generated from the basic one, according given S/C ratio and based on optimization of cable length traces: seeking the maximum amount of cables straight to final length C, the minimum number of loose cables to be tightened to final length when assembly is complete, and, finally, the least, none if possible, number of elongated cables to be shortened (at pre-marked points) to final length at the mounting phase.

5. Conclusions – Further work

Primary objective of this workshop was to provide an insight on this type of structures and introduce students to investigating construction and technical issues by encouraging a trial-and-error approach. Though this methodology can by no means substitute for an inclusive approach, the actual implementation of the projects suggests their ability to fit within the concept of structural tensegrity in exploring possible design applications.

From an educational standpoint, the design-built workshop is a module giving students a unique chance to experience the whole design series from concept to realization, revealing the importance of experimentation for the design development. Tensegrity systems offer a unique opportunity in design education to explore tools and methods and experiment with the design and construction process itself, their implementation touching fundamental issues in contemporary design discourse: non-linear process, inter-disciplinarity, the 3d-model as an inclusive design tool, representation and simulation methods and tools.

In a research framework, several considerations arise as a base for further investigations. In a more inclusive approach, form-finding methods [14] and tools would be required in order for form and shape to fulfill stability requirements; in addition, analytic studies and lab experiments would be needed to precisely size elements. The use of an inclusive 3d-model, for simulation rather than representation purposes, would be most helpful. Especially in the case of systems-module assemblies (such as the Needle Tower), a parametric approach could be explored for geometric studies. Finally, additional investigations on node assemblies would be suggested in developing a more systematic approach.

Acknowledgements

This workshop was realized thanks to the support of the Department of Architecture, University of Thessaly, the personal encouragement of the Dean, Professor P.Lazaridis, and the vigorous participation of the students of [K]onstruction Team. The projects were realized thanks to the materials donated by the Cooperative Society of Magnesia Plumbers, Gamaletsos Brothers Steel Products, G.Kolliopoulos Woodshop, PERSICA Carpets, FIORE Printing Services and the architectural office of D.Filippitzis and Associates. Further documentation is accessible at http://www.arch.uth.gr/sites/tensegrities/

References

[1] Connelly R. and Back A., Mathematics and tensegrity. *American Scientist*, 1998; 86 (2); 142-151.

[2] Diller E. and Scofidio R., *Blur: the Making of Nothing*, Harry N. Abrams, 2002.

[3] Emmerich D.G., Emmerich on self-tensioning structures. *International Journal of Space Structures*, 1996; 11 (1&2); 29-36.

[4] Fuller R.B., Tensegrity. *Portfolio and Art News Annual*, 1961; 4; 112-127.

[5] Fuller R.B., *Tensile-Integrity Structures*, United States patent No. 3,063,521, November 13, 1962.

[6] Gomez J.V., *Tensegridad: Estructuras Tensegriticas en Ciencia y Arte*, Servicio de Publicationes de la Universidad de Cantabria, 2007; studied from: Gomez J.V., *Tensegrity Structures and Their Applications in Architecture*, Master's Thesis, Queen's University, School of Architecture, 2004.

[7] Ingber D.E., The architecture of life. *Scientific American*, 1998; 278 (1); 48-57.

[8] Motro R., *Tensegrity: Structural Systems for the Future*, Butterworth-Heinemann, 2006.

[9] Motro R., Tensegrity systems : state of art. *International Journal of Space Structures (Special Issue on Tensegrity Systems)*, Motro R. (guest editor), 1992; 7 (2).

[10] Pugh A., *An Introduction to Tensegrity*, University of California Press, 1976.

[11] Schodek D.L., *Structure in Sculpture*, M.I.T. Press, 1993.

[12] Snelson K., *Kenneth Snelson*, official website; http://www.kennethsnelson.net/

[13] Snelson K., Snelson on the tensegrity invention. *International Journal of Space Structures*, 1965; 11 (1 & 2); 43-48.

[14] Tibert A.G. and Pellegrino S., Review of form-finding methods for tensegrity structures. *International Journal of Space Structures*, 2003; 18 (4); 209-223.