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Tensegrity Structures for the Hellenic Maritime Museum

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Abstract

Tensegrity structures composed of masts and cables bear similarities and carry metaphoric associations to nautical equipment and structures. Such metaphors have suggested the use of the tensegrity concept in the design of the lightweight structures for the Hellenic Maritime Museum. Two different types of lightweight structures have been studied. At an early design stage scaled models of existing tensegrity configurations were considered, and subsequently several new tensegrity configurations have been developed and studied. Morphological variations of tensegrity structures that occur from the assembly of new units have also been studied. A canopy structure composed of prismatic tensegrity units of irregular geometry with an attached membrane and a large space enclosing tensegrity structure have been developed. The paper presents and discusses the configuration of the two tensegrity structures for the maritime museum and the challenges encountered in their geometric & structural design.

Keywords: tensegrity structures, self tensioned cable-strut structures, membrane structures.

1. Introduction

Tensegrity structures composed of masts and cables and defined as “kinematically indeterminate systems are reconfigurable systems in which all parts coexist in a dynamic equilibrium” (Hanaor, [1]). Since tensioned cables and masts are not only the basic structural components but also the identifiable features of self-tensioned cable-strut structures in general, tensegrities bear similarities and carry metaphoric associations to nautical equipment and structures. Such metaphors have suggested the use of the tensegrity concept in the design of the lightweight structures for the Hellenic Maritime Museum, the construction of which is scheduled to start in 2010. A plan of the museum design can be seen in Figure 1.

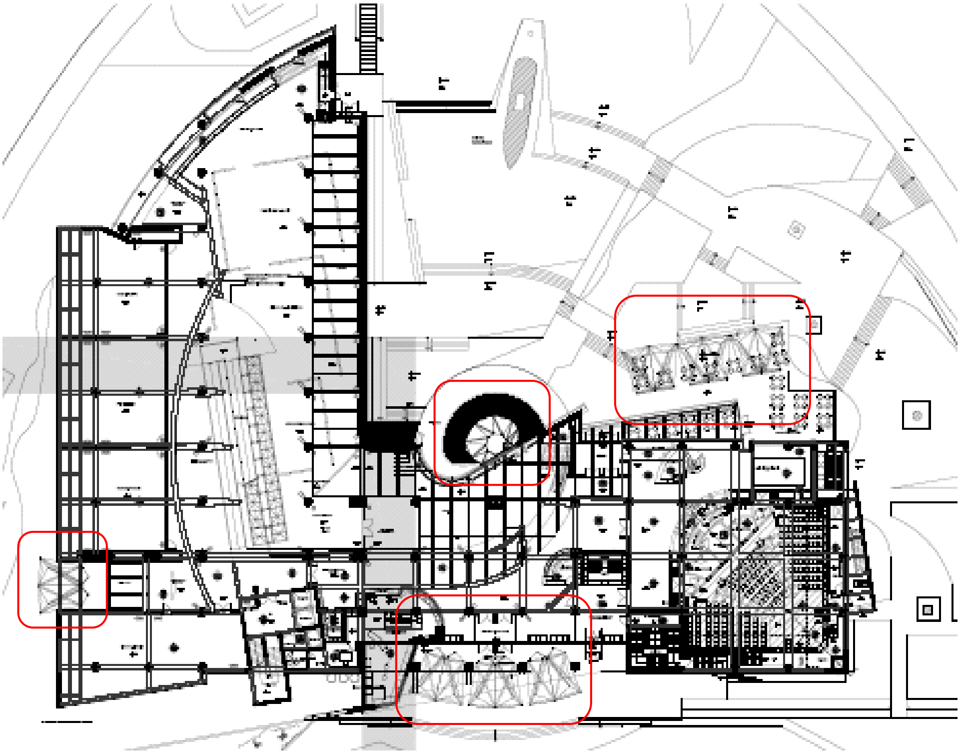

Figure 1. Plan of the Hellenic Maritime Museum

The architectural preliminary design of the Hellenic Maritime Museum received the first award in a national architectural competition and will be built at a scenic gulf on the coastal region of Athens, Greece.

The awarded design included several systems of lightweight structures which, for the competition stage were only developed at a schematic level. The most important lightweight structures that had to be studied are the following: a) A system of lightweight structures that will create a canopy over the museum's main entry facing East. These structures are expected to mark the visitors' doorstep while protecting them from the strong summer sun and autumn precipitations. At the same time it is desirable that they will not entirely obstruct the view to the clear blue sky of Attica. These lightweight structures need to be consistent with the main design features of the museum, while, at the same time, should attract the attention of the visitor as a structural form that bears symbolic associations to the museum's subject matter. A variation of this system will be also utilized to cover from sun and rain the outdoors café areas on the museum's courtyard. b) A different type of a lightweight cable-strut structure had to be designed to form a tall self-supported space enclosing structure at the west entry of the museum that leads to the bay and is seen from the entire gulf area. The function of this structure is primarily symbolic; it marks the transition from the water-front to the museum. The structure in plan projects over a swallow water pool that the visitors walking towards the bay have to cross through.

For these two systems of specified structures that resulted from the museum's building programme, the concept of tensegrity, the basic components of which, as already mentioned, bear similarities and visual associations to masts and cables encountered in naval structures and equipment, were given serious consideration.

The configuration of the lightweight structures that have been designed for the maritime museum of Greece and the challenges encountered in their geometric & structural design are discussed in the following sections.

The location of each one of the proposed lightweight structures for the Hellenic Maritime Museum is indicated with a red block on the museum plan in Figure 1.

2. The design process: from the initial design to the final configuration

Departing from the assumption that tensegrity was the most appropriate concept for the museum's lightweight structures, mainly because of its morphological characteristics, a search through existing configurations was first conducted.

The two types of lightweight structures were different in many aspects, i.e. the first had to be a space covering structure, while the second had to enclose an actual space that the visitors have to pass through. Thus a different approach in searching tensegrity configurations had to be taken in each instance. For this reason the approach taken for each one of the structures is discussed separately in the two sections that follow.

2.1. Space covering structure for the museum's main entry

A canopy type of structure that will overhang the museum's main entry had to be designed**.** The canopy structure, as shown on the plan in Figure 1, forms a curved canopy overhanging six meters beyond the glass façade. The canopy is composed of three modules that fit between the four entry columns. The three modules are symmetrically placed with respect to the central axis of the entry columns, are aligned on the vertical dimension, and form a regular curve on the horizontal direction.

For the specified application, tensegrity units of known configurations (Hanaor [1], Micheletti et al.[6], Motro [7], Wang [9]) were first considered. Regular configuration that respected the spatial constrains set by the columns, the roof-slab, the minimum and maximum allowable height of the structure, etc, have been studied but did not seem to provide any interesting design solution. Subsequently new unit configurations like the one illustrated in the photograph of a physical model at the upper right corner of Figure 2, were developed and their potential for the specific application has been examined.

Taking into account that each one of the three units will have to fit between each pair of columns, and that the units, when placed next to each other, need to form a smooth curve, in addition to the other spatial constraints that need to conform to, a polygonal shape in plan projection was deemed from the beginning as the most appropriate. Scaled physical models provided an invaluable method for studying new configurations. After a number of trials with new modules, several structures of pentagonal shape in plan that better responded to the spatial requirements and constraints were developed by following a rather heuristic approach. Additionally configurations of composite units defined here as units that occurred from the assembly of tensegrity prisms were explored.

It is known (Hanaor [1]) that a regular tensegrity prism of triangular base is composed of a) two cable bases that form equilateral triangles which lie on parallel planes and which are rotated with regard to each other at a 30 degrees angle- the angular rotation derives from the condition for the stability of the structure- , b) three compression members that connect the corresponding angles of the cable bases, and c) three cables which also connect the vertices of the two triangles.

The proposed canopy structure module is a composite unit that consists of two tensegrity units of prismatic shape. The tensegrity units though that compose the canopy module are not regular tensegrity prisms since their bases are not equilateral triangles. Respectively the lengths of the compression members and the base and side cables are not identical. The two tensegrity prisms that form the module are mirror images, that is they are similar units, one of which is dextrogyre and the other levogyre. These two prisms share a common cable and are connected at two nodes (Figure 2), one is the common vertex of the upper bases of the two units, and the other at the common vertex of the lower bases of the units. In this configuration two sets of anti-symmetric compression elements form two V-shaped members as shown in Figure 2. Accordingly each new module consists of six bars or two sets of V-shaped members, two bars symmetrically placed, and seventeen cables. This new tensegrity module has one main axis of symmetry. When the modules are in place on the museum's façade, their axis is at the horizontal direction.

A stretched membrane of pentagonal shape is then attached at the five lower nodes of the module. The membrane will be translucent so that from underneath one will be still able to perceive the geometry of the unit structure and the sky above it.

Once the form of the structure was determined with the assistance of the small scale physical models, a virtual model was constructed by measuring the lengths of the model components and estimating their angular relationship. Then the virtual model was scaled to its actual size. The dimension of the canopy module on its central axis is seven meters.

After the virtual model was developed from the dimensions taken from the physical model, the pre-stressed configuration of the canopy tensegrity module was calculated. Prestress analysis and loading analysis waere performed through a non-linear structural analysis program (NONSA) that has been developed for the analysis of double layer tensegrity networks (Liu et al. [5]). The program's strategy is to use the direct stiffness method to satisfy equilibrium, coupled with Newton's equilibrium iterations to increment and iterate non-linear geometric behavior [Tassoulas [8]). The initially assumed configurations of the structures, as shown in Figures 2, 3 and 5, were not significantly changed.

The dimensioning of the structure has been finalized after the attachment of the membrane was introduced. At this stage the FORTEN software has been utilized for the calculation of membrane stresses and for the final dimensioning of the structure members and the nodes.

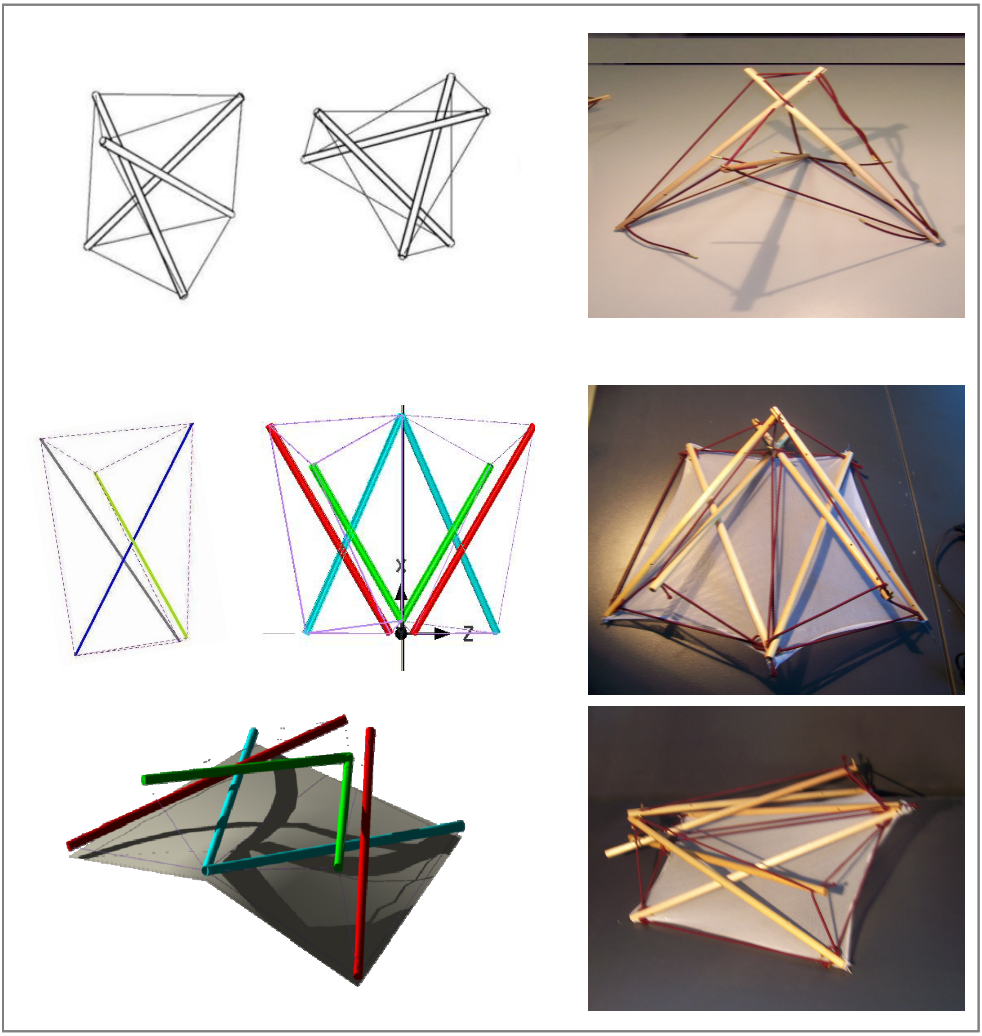

Figure 2. Canopy structure composed of two symmetrical tensegrity units of irregular geometry: views and physical models

For the construction of the canopy module tubular aluminium alloy (6005/ 160 150) members of 16 cm exterior and 15 cm interior diameter and weight of 6,57 kg/m, 8.00 mm wire cables and 3000/3000 kg in tension, UV protected, translucent membrane will be utilized**.**

Each composite tensegrity module will be attached on its adjacent columns at its outer nodes. Eventually the two disjointed bars of the module will be also connected to form a V-shaped element. The node at the vertex of this v-shaped element will be used to suspend the module from the roof slab (Figure 3).

In addition to the three modules on the museum's main facade facing east, a single module will be also placed on the northern elevation of the museum (Figure 1) this module will be attached at the two adjacent walls and the roof slab.

A variation of the canopy module is used to provide partial weather protection for an outdoor café area at the museum's courtyard. The structural frame of this module is the same as the previous one. This module has two additional horizontal bars that connect the two nodes on the smaller side of the structure with the vertical support that is fixed on the ground (Figure 4).

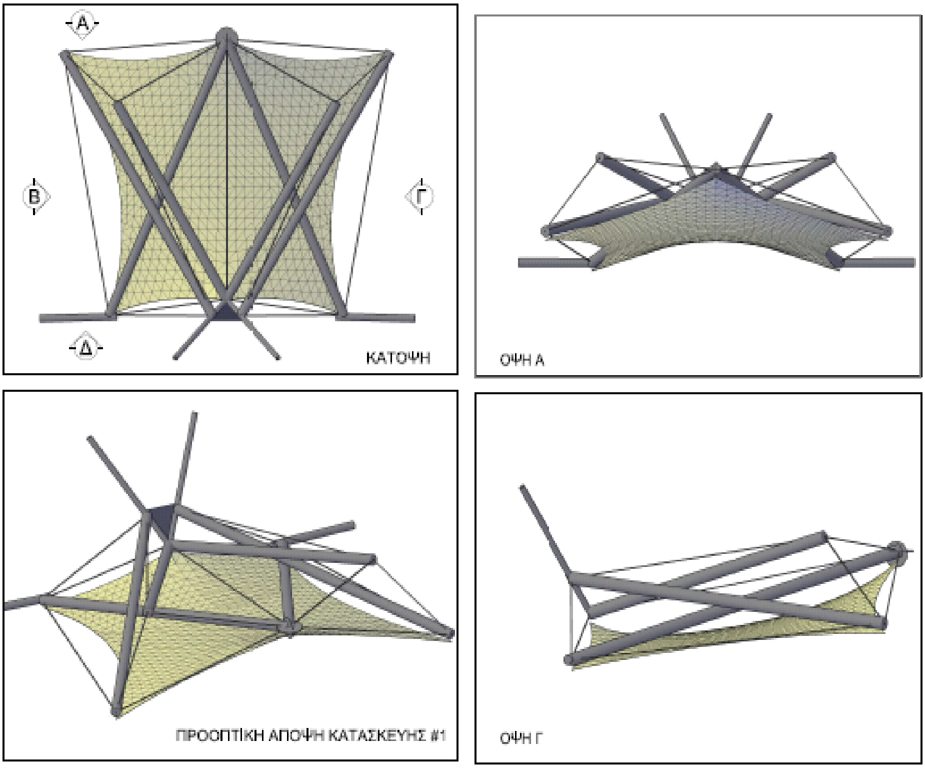

Figure 3. Canopy tensegrity structure with attached membrane

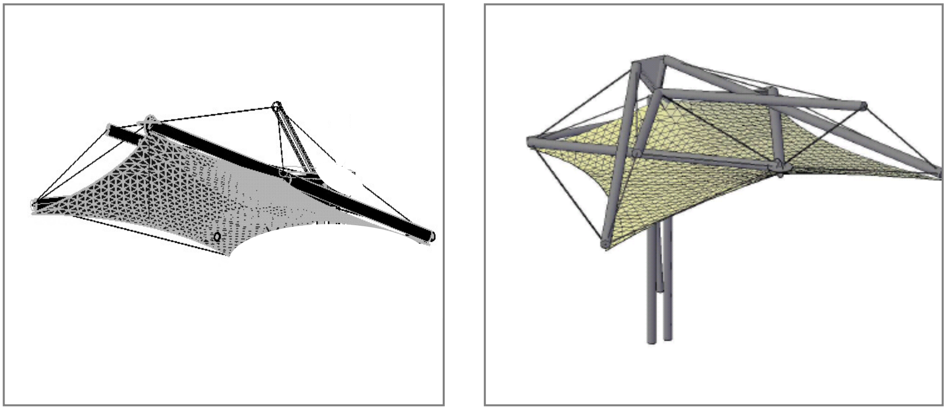

Figure 4. Canopy tensegrity structure perspective view and module variation

2.1. Self-supported space enclosing tensegrity structure at the museum's second entry

This structure is free standing and denotes the museum's west entry that overlooks the bay. This structure will be an installation that visitors will have to cross before entering or exiting the museum.

The structure consists of a single tensegrity unit the form of which is a distorted truncated pyramid. The two bases of the structure are irregular octagons. The shape of the irregular base-octagon has been dictated by specific spatial constrains such as: one of the sides of the octagonal shape had to match the door opening in terms of direction and size, while the position of the remaining vertices had to coincide with the control points that define the geometry of the spiral shape on the plan; the spiral shape marks the boundaries of the pool and thus the points through which the visitor could cross the pool and pass to the courtyard are also important and define an additional dimensional constraint for the geometry of the polygonal shape of the base of the structure.

The control points on the plan that have determined both the shape of the spiral pool and the shape of the octagonal base of the structure are indicated on the plan in Figure 5.

Another geometric constraints that had to be taken into account for the form-finding of the structure refers to one of the faces of the structure which had to be vertical, parallel to the plain of the facade wall of the museum. In addition the upper octagon had to be titled in a direction that would help the visitor that observes the museum from a distant point, to recognize the overall shape of the structure, etc. (Figure 5).

For the study of this structure, physical models have also been utilized. A tensegrity prismatic unit of regular octagonal geometry was first constructed. As it is already known, (Hanaor [1]), regular prismatic units or units of truncated regular pyramidal geometry belong to a standard tensegrity typology and consist of two parallel octagonal cable bases of different sizes, eight rigid bars, and eight diagonal cables. The rotation of the upper base of the tensegrity unit with regard to the lower one is the half of the angle of a regular octagon.

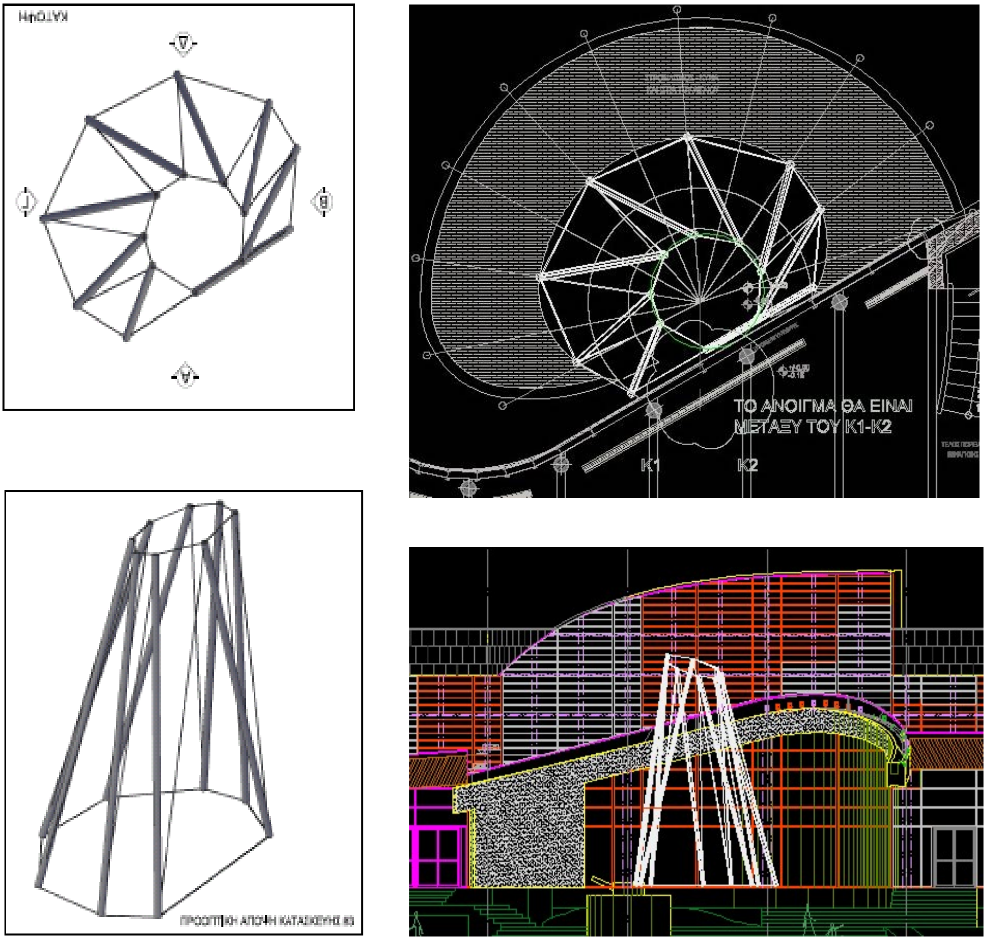

Figure 5: Self-supported space enclosing tensegrity structure at the museum's entry

In the proposed space enclosing structure though, the cable base couldn't be a regular polygon, and the respective cable lengths on each base are not identical; similarly the diagonal cables are not identical either. The length of the rigid bars is on purpose kept identical which imposes an additional constraint to the design.

To achieve a tensegrity configuration with such features, the initial model of regular geometry, constructed with elastic bands and identical wooden dowels, was proven to be very helpful. By following a rather heuristic approach, the model was systematically modified so that the geometric constraints were gradually met. Specifically the dimensions of the octagonal cable base were set first at the desired dimensions. Then one of the cable sides was changed to be perpendicular to the base plane.

After these main geometric constraints were met, by shortening or elongating the side cables and the cables of the upper octagonal base, and by applying a relatively equal amount of tension on each cable, various configurations were derived by simply letting the model stabilize itself. The initial design of this structure was thus achieved with the assistance of small scale physical models. Then, by repeating the process followed for the study of the tensegrity canopy module, that is by measuring the model components' lengths and estimating their angular relationship, a virtual model was constructed. Then the model was scaled to the actual size which will be over eleven meters high.

After the virtual model was developed, the method used for the pre-stressed configuration and the load analysis of the tensegrity canopy module has been applied for determining the final configuration of the octagonal tensegrity structure. It was determined that the same material that will be used for the construction of the canopy structure can be used for the construction of the octagonal structure as well.

3. Assembly and erection considerations

For the construction of both structures, a rapid assembly and erection method that applies to tensegrity modules of regular geometry and to tensegrity networks composed of tensegrity modules , and which is a major feature of a tensegrity structures technology (Liapi [3]) will be utilized. According to the above technology for the easy, on site assembly of the structures, a concept of deployable modules will be considered (Liapi [4]). This technology facilitates the transportation to the site, fast assembly, and erection of the proposed lightweight structures.

A problem that the tall space enclosing structure of pyramidal shape could create is that, when fixed in its place, the lower base cables could interfere with the visitors' path through the structure to the courtyard. This has suggested further changes to the configuration of the structures. Two of the base cables will be removed after the structure is fixed in its permanent position. Accordingly the tensegrity structure will be first assembled and prestressed on site, then each base node will be attached on the ground at its permanent location, and finally after all nodes are fixed in place, the two cables will be removed.

The study of the details of the nodes in both structures are of particular importance. In the tensegrity canopy module, in addition to holding the diagonal and base cables on the contraction bars, are also expected to allow the structure to get attached to the adjacent columns and to the roof slab. At the same time the nodes should allow the cable-ends to freely rotate around each bar axis so that the structure will be easily assembled and pre-stressed before being fixed in place. Similarly the details of the nodes of the space confining structure are also expected to allow the structure to get attached to the ground.

4. Conclusion

The paper presents and discusses the configuration of new tensegrity modules and structures for the Hellenic Maritime museum. The challenges encountered in the geometric design process suggested the use of physical models. For the final configuration additional form finding methods had to be utilized, yet the initially assumed configurations of the structures was not significantly altered. The method to be used for the assembly and erection of these structures has also been given serious consideration and has an important effect on the design of the joints at the nodes. The approach taken, that is a systematic exploration of various tensegrity configurations, with the assistance of small scale physical models, has been an effective one and has led to the two new tensegrity structures. These because of their morphology and materials, are expected to bear symbolic associations to the visitors of the Maritime Museum's subject-matter.

References

[1] Hanaor, A., Aspects of Design of Double-Layer Tensegrity Domes, *International Journal of Space Structures*, 1992; 7(2), 101-103.

[2] S.G. Liu, K.A. Liapi, J.L. Tassoulas

[3] Liapi, K.A, A Novel Portable and Collapsible Tensegrity Unit for the Rapid Assembly of Tensegrity Networks, in *Fifth International Conference on Space Structures*, University of Surrey, 2002, pp 39-46.

[4] Liapi, K.A., Tensegrity Unit,Structure and Method for Construction, US Patent:#5119-07202, 5/28/2002

[5] Liu, S.G., Liapi, K.A., Tassoulas J.L., The Effects of Static Loading And Support Conditions on the Performance of Double Layer Vaulted Tensegrity Structures, in *IASS 2004. Shell and Spatial Structures from Models to Realization*, Motro R (ed.), Editions de l'Esperou, 2004.

[6] Micheletti. A.,Nicotra, V., Podio-Guidugli, P. Tensegrity Modules for Cable-Strut Systems, in *IASS 2004. Shell and Spatial Structures from Models to Realization*, Motro R (ed.), Editions de l'Esperou, 2004.

[7] Motro, R Tensegrity Systems: the state of the art. *International Journal of Space Structures,* 1992,7 (2): 75-83.

[8] Tassoulas, J.L., Implementation of Tensegrity Analysis in NONSA0, unpublished.

[9] Wang, B.B., Cable-Strut Grids Made of Prisms, in *IASS 2004. Shell and Spatial Structures from Models to Realization*, Motro R (ed.), Editions de l'Esperou, 2004.