Tensegrity Structures of Helical Shape:

A Parametric Approach

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Abstract: *Tensegrity grids composed of tensegrity units that form double layer cable nets of single or double curvature can find applications in architecture as surface structures. In this paper a parametric process for the geometric configuration and representation of double layer tensegrity structures of helical shape is discussed. Departing from the geometric construction process, an algorithm that facilitates the parametric description of helical tensegrity structures has been developed. The algorithm reflects the interdependence of all parameters involved in the design of helical tensegrity structures and has been integrated into a software application that enables the automatic generation of virtual models of helical configurations in a graphic environment.*

Keywords: *Modular tensegrity structures; helical surface structures; double layer tensegrity grids.*

Tensegrity surfaces of regular geometry: Research developments and challenges

Tensegrity structures defined as self-stressed systems composed of tension and compression members (Hanaor, 1998) have attracted the interest of scientist and artists for several decades. Engineers and architects have contributed to the understanding of their mechanical and structural behavior and the development of formal typologies of tensegrity units and tensegrity network configurations Yet, their real world applications are still limited. Their intriguing and complex geometry, which is actually one of their most appealing features, is also responsible for difficulties in their structural design and the exploration of new morphologies and working configurations. Their graphical representation also due to their complex form, poses additional challenges to their study and real world application.

Tensegrity grids composed of tensegrity units that form double layer cable nets held apart by a set of disconnected rigid members is probably the most promising tensegrity configuration for architectural applications. General directions for the development of double layer tensegrity networks which occur from the assembly of tensegrity units of regular geometry have been established by pioneer researchers in the field over a decade ago (Hanaor, 1998, Motro 1992). Yet the actual geometric issues that would allow designers to explore various surface configurations were not addressed at the time.

The authors in their earlier work have placed emphasis on solving problems related to the geometric design and representation of double layer grids

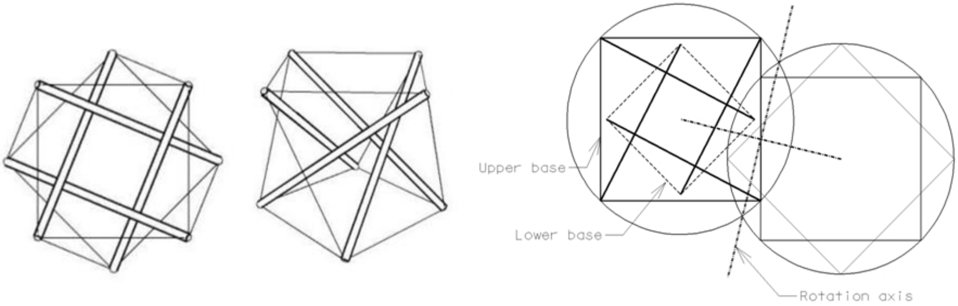

Figure 1
A typical tensegrity unit of square base and geometric principles that apply to unit adjacency (upper and lower cable bases of the two units overlap)

composed of tensegrity units of regular geometry. A relatively recent technological application also developed by one of the authors that proposes a method that makes possible the construction of double layer tensegrity structures of regular geometry from the on-site rapid assembly of deployable and re-usable identical tensegrity units (Liapi 2002). Determining the geometry that ensured the space packing of tensegrity units on a double layer surface of regular geometry was central to the development of the technology and led to methods that apply to both the design and the representation of double layer regular tensegrity grids (Figure 1). (Liapi 2001, Liapi and Kim 2004).

The developed processes have been incorporated into a multi-parameter geometric problem. The parametric description of tensegrity structures is based on the Interdependence of a) unit size and proportions, b) structure size and curvature, c) number of units and d) upper and lower base overlap. Based on this an algorithmic description of the allowed geometries has been developed. A common feature in most of these structures is that their spatial geometry is not "a priori" given, and their equilibrium depends on the topological and geometric relationships of the composing struts and cables, as well as on all the applied forces and loads. Cable-strut structures typically stiffen and acquire their functional configuration by cable tensioning, which usually involves tedious on-site processes. For this reason the design algorithms have been integrated with analysis procedures into an interactive software application that automatically generates the initial and final geometry of a double layer modular tensegrity surface in a graphical environment. Domical, vaulted and slab configurations are the geometries currently

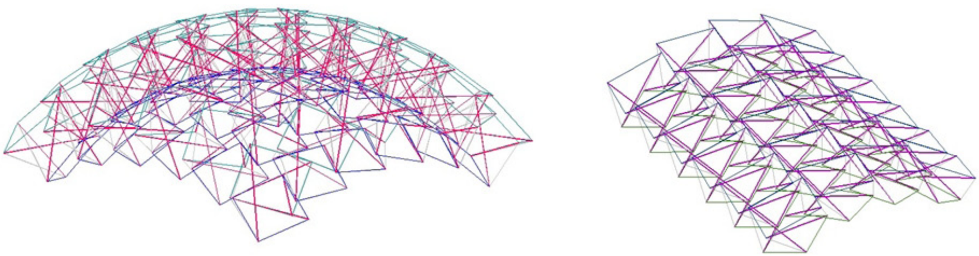

Figure 2
Double-Layer Tensegrity Networks: Spherical & cylindrical configuration.

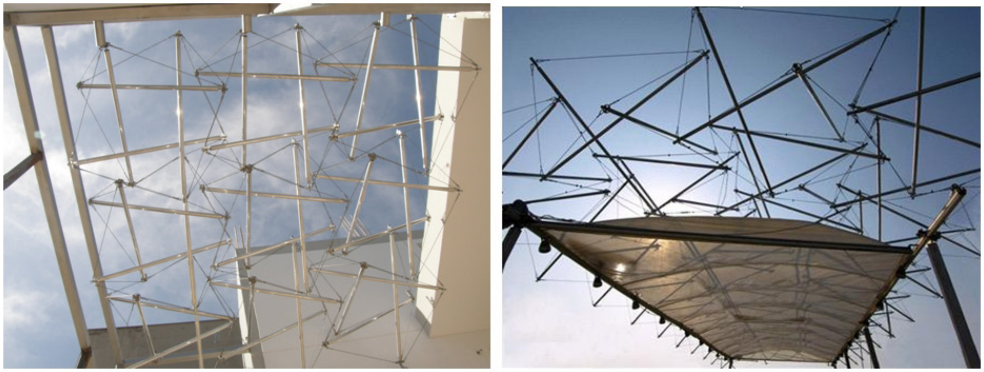

Figure 3
Real world applications of tensegrity surfaces: A patio roof of a Bank Annex in Athens Greece (2007) and an Exhibition Pavilion for "Patras Cultural Capital of Europe,", 2006 Patras, Greece

addressed (Figure 2). The same software application can generate the pre-stressed and the loaded configuration of such networks.

Real world applications of the developed modular assembly tensegrity technology and the discussed method prove the validity of the developed algorithms and the interactive software application that automatically generates the initial and final geometry of a double layer tensegrity surfaces in a graphical environment. (Figure 3)

The developed morphologies that occur from the assembly of identical units and have been studied are all of regular geometry with one or two axes of symmetry. Configurations with less regularity and which do not necessarily occur from identical tensegrity units had to be addressed in order to enrich the spectrum of potential applications of tensegrity structures.

Beyond the regular grids: Methodology and algorithmic design

Surfaces of helical shape have found a broad application in historical and contemporary structures. Examples of helical structures cover a wide morphological array. A double layer helical surface is a morphological variation that refers to a large number of applications in building design. This paper investigates the possibility of constructing a double layer helical tensegrity surface from the assembly of tensegrity modules. An attempt to develop methods for the automatic generation of their geometry in a graphical environment is also discussed.

As with regular single and double curvature configurations composed of identical units, the "space packing" of tensegrity modules on a helical surface required determining new rules, conditions and constraints based on both topological and numerical relationships. In this instance the study of the geometric constraints has shown that the construction of the surface from identical units was impossible and therefore the utilization of more than one unit types was necessary. A surface composed of rows of identical tensegrity units and columns of self similar tensegrity units of increasing dimensions was the approach taken.

Geometric principles and rules that apply to tensegrity unit dimensioning and assembly

The developed method required setting first the geometric constraints and conditions that apply to the construction of helical tensegrity structures composed of rows with the same number of identical tensegrity units. That is setting the geometric boundaries with regard to unit increase ratio, and overlap conditions within which the construction of a tensegrity helical surface is possible. Then departing from the principles and rules that apply to the geometry of regular single and double curvature

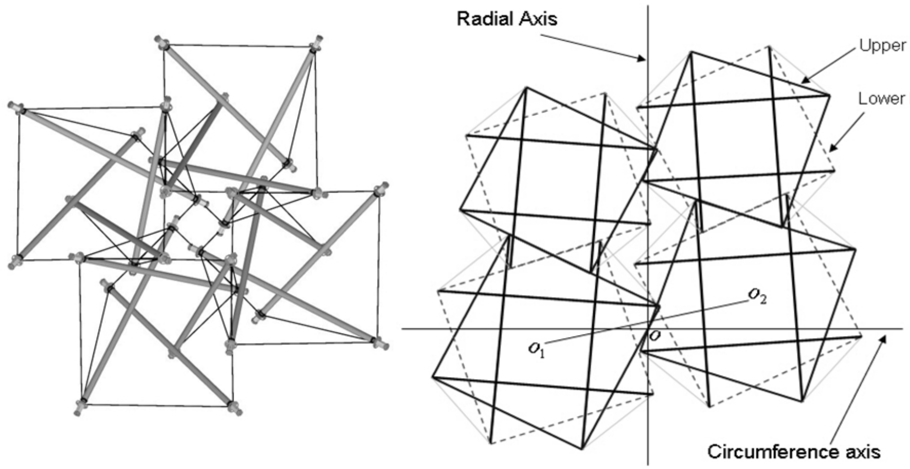

Figure 4
A spherical structure cluster composed of 4-identical units Configuration of a 4-unit cluster of a helical structure

configurations described in earlier publications (Liapi and Kim, 2004), new rules that comply to the helical surface geometry have been developed. Thus in a helical tensegrity structure, which is also a single curvature structure, the upper and the lower bases of adjacent units need to overlap along the radial direction to allow the structure to bend only one way. Unlike to the configuration of a vaulted tensegrity geometry, the sizes of the units in a helical structure along the radial direction need to be reduced proportionally. Therefore, the center points of tensegrity units in addition to being shifted, as is the case with vaulted tensegrity structures, need also to rotate. Figure 4 shows a flat configuration of a 4-unit cluster of a helical structure as compared to the configuration of 4 identical units that form a single curvature surface. On the scheme on the right only the upper bases of the tensegrity units meet.

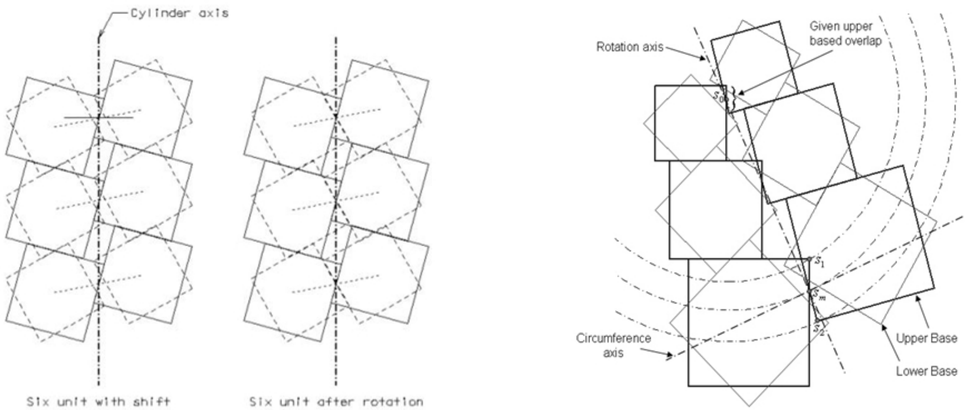

Figure 5
Configuration of a 4-unit cluster of a helical structure

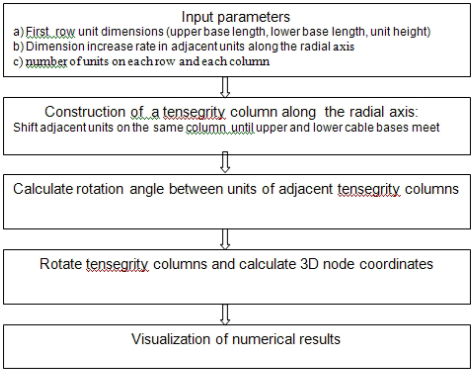

Figure 6
Steps in Helical Tensegrity Surface design Algorithm

Similarly the scheme in Figure 5 compares the process to be followed for the geometric construction of a 6 unit vaulted configuration, to the required process for the generation of a six unit helical configuration composed of sets of self-similar but not identical units.

The developed processes are incorporated into an analytic geometry problem that reflects the interdependence of all parameters involved in the design of the structure. An algorithmic description of these processes that allows for the parametric description of helical tensegrity structures has also been developed and shown in *figure 6* . By varying the values of each one of the parameters one can get a feeling of the effect of the changes in unit proportions and size, connection pattern etc. on the final configuration of the double layer structure.

To facilitate both design and construction of such structures, a spatial visualization system, which integrates algorithms for initial form generation, geometric parameters that simulate construction stiffening processes, and appropriate structural analysis methods has been considered. The system will render feasible the exploration of alternate configurations with various levels of pre-stress and will display initial and final configuration of the structure, as well as structural analysis data visualization. Geometric Design and Analysis Methodology on which the system is based is shown in Figure7.

The design algorithm that has been integrated into an interactive software application involves a step by step process that generates first the flat configuration of the double layer tensegrity surface and then, by applying the condition of space packing, the final configuration is derived. The algorithms make possible the automatic generation of virtual

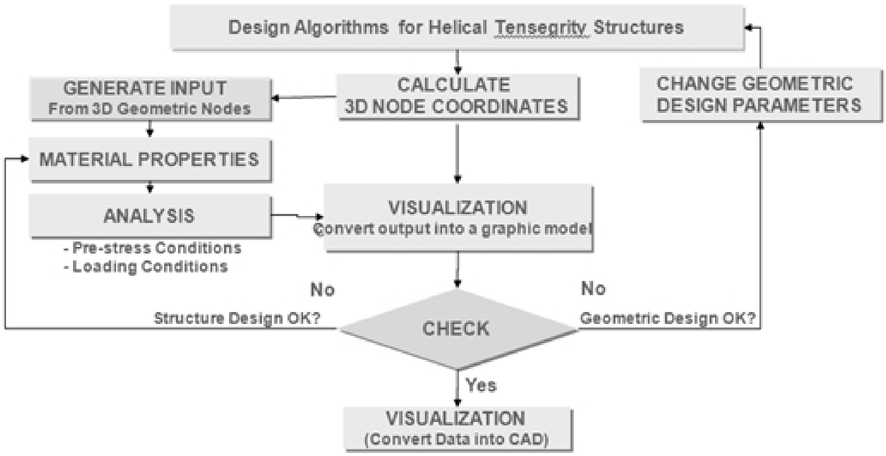

Figure 7
Geometric Design and Analysis Methodology of Helical Tensegrity networks

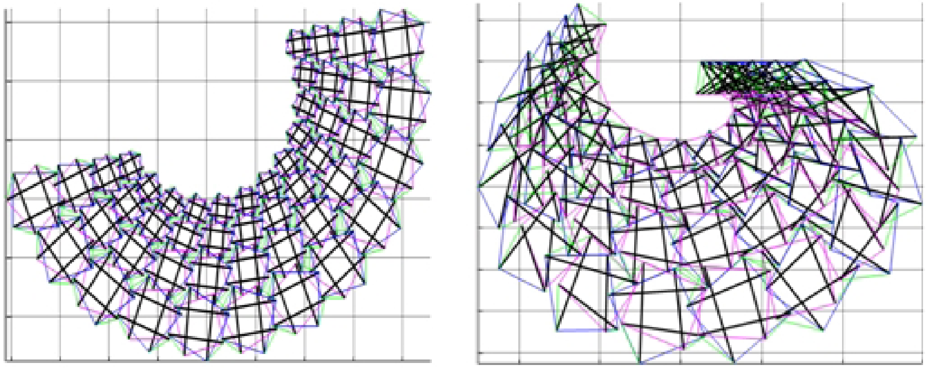

Figure 8
Parametric generation of the geometry of a structure composed of 4 rows of 12 identical units each: Top view before unit rotation and top view of the correct configuration

models of alternate configurations in a graphical environment (Figure 8). That further facilitates the morphological study and exploration of helical tensegrity networks. The integration into the system is in progress but no problem is anticipated since a similar system that integrates structural analysis for the study of tensegrity networks of regular geometry is already complete and fully functional is fully functional for is still to be completed.

As a conclusion the helical tensegrity configurations that occur from self similar but not necessarily identical has been investigated and have been successful integrated into a design algorithm that automatically generates their geometry.

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