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Review paper

# DEVELOPMENT, CHARACTERISTICS AND COMPARATIVE STRUCTURAL ANALYSIS OF TENSEGRITY TYPE CABLE DOMES

***Aleksandra Nenadović***[1], University of Belgrade, Faculty of Architecture, Belgrade, Serbia

***Tensegrity type cable domes are three-dimensional structural configurations, prestressed inside the perimeter compression ring, in which the continuous tension throughout the roof structure is made by continuous tension cables and discontinuous compression struts. These kinds of structures can be formed like spatially triangulated networks or like networks non-triangulated in space. This paper examines some effects of network geometry on the behaviour and structural efficiency of tensegrity type cable domes. In this paper the roof cover is considered non-interactive with the supporting structure, unlike rigidly clad tensegrity type cable domes.***

***Since the main bearing elements of tensegrity type cable domes are prestressed cables, they show non-linear load deformation and rely upon geometric stiffness. A geometrically non-linear analysis of non-triangulated and triangulated structures for different load conditions was conducted employing a computer program based on the perturbation theory. The incrementally-iterative procedure, with an approximation of the stiffness matrix by combining the elastic and geometric stiffness matrix, allows detection of structural instabilities.***

***Keywords: tensegrity type cable domes, prestress, network geometry, geometrically non-linear analysis, perturbation***

## INTRODUCTION

Tensegrity type cable domes are structures that are highly convenient for large span covering owing to the fact that a comparatively small number of elements are needed to form the structure, their high prefabrication level and easy assembly. Observation of already existing tensegrity type cable domes reveals two basic approaches to the formation of these structures: Geiger's, which forms the dome as a non-triangulated spatial network, and Fuller's, that adopts the principle of spatial triangulation. This paper examines some effects of network geometry on the behaviour and structural efficiency of tensegrity type cable domes.

Campbell et al. (1994) investigated the effects of spatial network triangulation on the behaviour of tensegrity type cable domes combined with the action of a stressed fabric membrane which stabilizes them to a high degree. Since it is possible to create these systems without the roof cover as a load-bearing element, as can be seen in the first tensegrity type cable dome covered in rigid 'floating' panels (Gossen et al., 1998), this paper will analyze the behaviour and structural efficiency of triangulated and non-triangulated structures without taking into consideration the co-action of roof cover. For the purpose of this analysis, only the cable-strut network was modelled.

Since tensegrity type cable domes must fulfill the condition of equilibrium on the deformed configuration, they were analyzed by means of a software application intended for the geometrically nonlinear analysis of three-dimensional trusses. The programme is based on the perturbation theory (Levy and Spillers, 1995). The procedure applied allows for the detection of structure instability.

## DEVELOPMENT AND CHARACTERISTICS OF TENSEGRITY TYPE CABLE DOMES

The emergence of steel cables made it possible to produce structure elements of high tensile load-bearing capacity but of small cross-section. The erection of the arena in Ralley, North Carolina in 1954, fully demonstrated how steel cables could be applied in roof structures. Since that time, many structures, of various shapes and systems, have been erected featuring the cable as bearing element. Among them, those that particularly stand out are the hanging, pneumatic and tensegrity type structures. Those structures turned out to be highly economical, especially in covering large spans. Apart from having decreased the expenditure for materials, the time necessary for erection has gone down, owing to the high prefabrication level. In Serbia, an exceptional contribution to the development of primarily cable-based structures has been made by Đorđe Zloković, architect and structural

[1] Bul. kralja Aleksandra 73/II, 11 000 Beograd, Serbia
nenadovica@sezampro.rs

engineer, Professor of the Faculty of Architecture at Belgrade University and member of the Serbian Academy of Arts and Sciences.

Inspired by the idea to put the tension and compression forces within a structure into balance, some authors have developed the idea of integrally tensioned structures (Fuller, 1961). Fuller, Emmerich and Snelson patented structural systems which were fundamentally the same. The definition of tensegrity structure based on the initial patent descriptions would have been along these lines: tensegrity structures are systems established by means of interaction between discontinuous compression members and continuous tension members which, put together, form a stable shape in space. Many authors have investigated the possibilities of applying tensegrity systems in architecture, such as Vilnay, Hanaor, Pellegrino, Pugh, Emmerich and Motro (Motro, 2003). The 'tensegrity approach' has demonstrated a number of advantages over the 'non-tensegrity' approach. Separation of structure members into exclusively tensioned and exclusively compressed leads to the fact that the tensioned members may be only as light as the current technology allows it. The prevalence of light cables in the structure makes it lighter, more cost-effective and visually unobtrusive.

Some authors have focused their research towards the possibilities of tensegrity type cable domes, believing that tensegrity principles would enable bridging large spans while effectively using materials and energy (Pallasmaa, 1997). In 1964 Fuller patented his basic concept of tensegrity dome (Figure 1) after trying out numerous models.

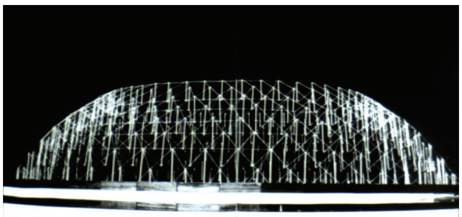

*Figure 1 – Fuller's tensegrity dome*
*Source: http://www.columbia.edu/cu/gsapp/BT/BSI/TENSEGRI/fuller.jpg*

Tensegrity domes were also the subject of research by Miodrag Nestorović (Figure 2), architect, Professor of the Faculty of Architecture at Belgrade University (Nestorović, 1994).

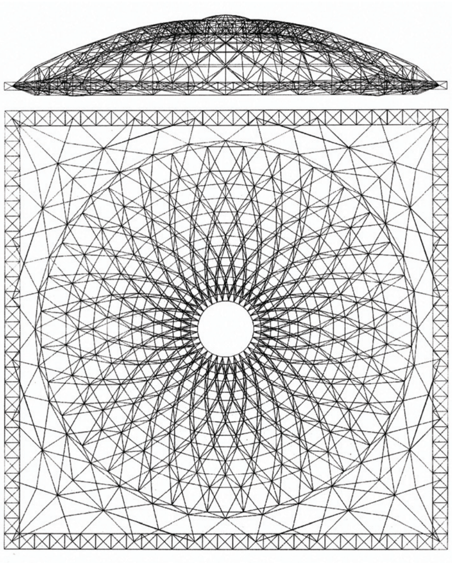

*Figure 2 – Tensegrity dome over the square plan*
*Source: Nestorović, M. (1994)*

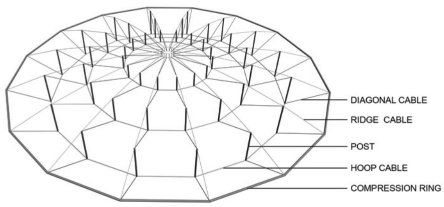


*Figure 3 – Geiger's tensegrity type Cabledome*

In 1983, Horst Berger developed a solution for the roof structure of the ''Sundome'' in St Petersburg, Florida. However, after Geiger Berger Associates split in 1983, Berger's solution was replaced by a system developed by David Geiger (Figure 3). Geiger combined Fuller's tensegrity principle with the principle of prestressed cable network formation and thus proposed a new non-triangulated spatial network. He patented the new system and called it 'Cabledome'.

The main principle underlying Geiger's cable domes is in achieving a continuous tension through the roof structure by means of continuous tension cables and discontinuous compression struts. The primary structure is formed by radial cable trusses which are rib-like and which consist of tensed ridge and diagonal cables and compressed struts. The bases of the flying struts are held by diagonal cables attached to the top of the compressed struts in the next outer ring and are mutually connected within the given radiuses by means of tension cables forming concentric hoops. These hoops assume the role that bottom chords of the radial cable trusses normally have. The concentric tension hoops relay the load effects throughout the system, thus minimizing any local effects. Changes in the tension hoops trigger a response of the entire cable-strut system. Apart from that, the tension hoops resist out-of-plane displacements of radial cable trusses nodes. The structure therefore, while resisting load, relies on geometric rather than conventional stiffness. In this way, a three-dimensional network of cables and struts is formed, prestressed within the perimeter compression ring. One of the main advantages of such a structure is that its weight by square meter of plan does not change with the increase of span. To enlarge it, it is only necessary to insert a new module in the shape of a new concentric tension hoop. Geiger's tensegrity type cable domes have proved structurally efficient in numerous large-span roofs.

Tensegrity type cable domes are cable-strut networks, prestressed within a perimeter compression ring. The fact that they rely on the continuous perimeter ring in order to close the structural system makes them different from other 'pure' tensegrity systems which are self-equilibrated.

The first large span tensegrity type cable domes were constructed in Seoul for the Olympics of 1986 (Figure 4). Two sports halls, of 120m and 93m-spans were covered by Geiger's cable domes (Geiger et al., 1986, Rastofer, 1988, Tuchman and Ho-Chul, 1986).

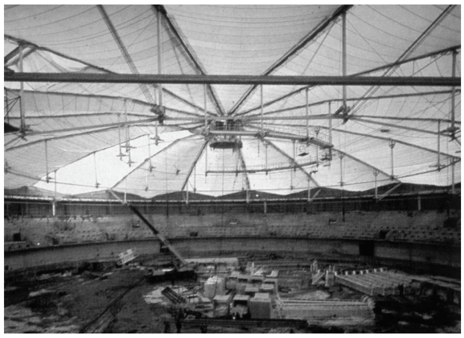

*Figure 4 – Olympic arena under construction*
*Source: http://www.columbia.edu/cu/gsapp/BT/DOMES/SEOUL/sol-43.jpg*

*Figure 5 - Olympic arena in Seoul*
*Source: http://www.atpm.com/14.10/south-korea-guam/images/Seoul%20City%20Skyline%20-%20Overlooking%20the%20Olympic%20Park%20with%20downtown%20Seoul%20in%20the%20background.jpg*

Unlike Fuller's high profile tensegrity domes, Geiger's domes display low-profile configuration (Figure 5) which decreases the wind uplift and uneven snow drifting, and significantly reduces the amount of fabric needed for roof covering.

Geiger also developed a system for the erection of tensegrity type cable domes. Tensioning of the diagonal cables and putting the hoops into their final positions is done starting from the periphery and moving to the centre of the structure (Figure 6).

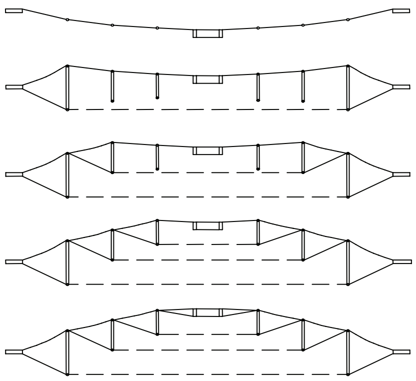

*Figure 6 - Erection sequence*

The membrane system applied in these domes belongs to the class of lightweight roof coverings, displays satisfactory thermo insulating and acoustic properties and is semi-transparent. Its overall daylight transmission is 6%, which allows for most of the daytime lighting requirements (Krstić, 2006). The membrane covering the domes consists of four separate layers: a waterproof fibreglass fabric, an insulating layer, a vapour barrier and an acoustic insulation layer that are attached to the structure. Radial valley cables are tightened to stress the membrane. In this way, the so-called 'pleated' tensile membrane is formed. The pleated tensile membrane is a system used for the first time in 1983, in the roof of the Lindsay Park Sports Centre in Calgary.

The Redbird Arena, a multipurpose arena built in 1989 as part of the Illinois State University campus, can seat 11,000 spectators and represents the first cable dome erected over an elliptical plan. The roof covering is translucent, as in the Seoul halls, and enables reduction of artificial lighting during the daytime.

The Florida Suncoast Dome was built in 1990 in St Petersburg, Florida. It seats 43,000 visitors. Its unique translucent fibreglass membrane covers the world's largest 'Cabledome' (Figure 7). This structure covers a roof span of 225m. It comprises four tension hoops. A low profile roof configuration has allowed for minimal fabric costs.

At night, a translucent roof covering gives the effect of the 'fifth facade' when the lights are on – which is illustrated by the Tao-Yuan Coiunty Arena built in 1994 in Taiwan (Figure 8). The arena is multipurpose, designed to host sports events and entertainment performances alike. The circular plan of the arena and a wish to secure as much daylight as possible led the design towards the tensegrity type cable dome.

The cable dome spans 120m employing three tension hoops. The structure has been designed to enable quick erection. The whole cable-strut network was preassembled on the ground, and then lifted to the given height and stressed. The roof was completely engineered, fabricated and erected in fourteen months.

The relative flexibility of Geiger cable domes to asymmetric loading was a decisive factor in using the stressed membranes as roof covering in those first structures. Apart from that, the development of the system was motivated by the wish to keep the membrane covering but to develop a structure that would replace the vulnerable large-span air-supported roofs. The membrane covering was widely in use for its light weight and translucency, especially in

*Figure 7 - Florida Suncoast Dome*
*Source: http://www.columbia.edu/cu/gsapp/BT/DOMES/TIMELN/suncoast/sun-06.jpg*

*Figure 8 - Tao-Yuan County Arena*
*Source: http://www.taiyokogyo.co.jp/img/lgr/mk_371.jpg*

sports halls which required a considerable amount of daylight, as venues of athlethic competition. However, it turned out that rigid cladding of such structures was also a choice, especially in those cases where membrane covering was not desirable for reasons of adequacy or cost-effectiveness. The erection of the first rigidly clad cable dome began in 1994, in North Carolina, where the authorities decided to build an athletic hall to seat 13,000 spectators (Gossen et al., 1998). The project architects developed a circular plan of 99.7m in diameter. A number of roof structures had been taken into consideration and analyzed before the 'Cabledome' cable-strut network was selected. The tensegrity type cable dome offered the best combination of architectural features and cost-effectiveness.

The roof consists of three tension hoops. The roof is segmented radially into 18 pieces. In this design, the typical arrangement of 'Cabledome' elements is somewhat modified (Figure 9). The perimeter compression ring is a conical truss. The top chord of the perimeter compression ring anchors the diagonals and the bottom chord anchors the ridge cables. The cable network is non-triangulated in the central zone of the dome, while it is partially triangulated in the outer compression ring zone by doubling the ridge cables.

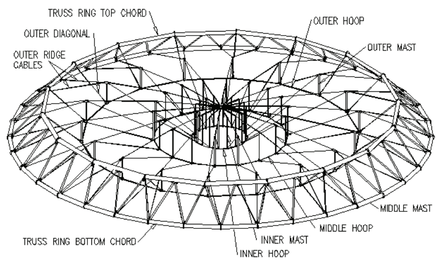


*Figure 9 – Axonometry of the roof structure*
*Source: http://www.geigerengineers.com/images/techfigs/roofdiagramfig1.gif*

The relatively flexible structure is covered by non-transparent rigid panels instead of the translucent membrane. The panels, made of steel frames, are supported by the cable-strut network. The support points of the roof panels are angular nodes which coincide with the position of compressed struts. The nodes are designed in such a way to allow for the rotation in the radial and circumferential direction. The panels 'float' on the cable-strut network and follow the distortion of its geometry caused by loading. The entire cable-strut network was assembled on the ground and then lifted and put into place. Finally the system was prestressed. The roof panels were mounted last.

In 1992, Georgia Dome was erected in Atlanta, USA. The oval stadium, that can seat 70,500 visitors, was designed and built in thirty months. Apart from sports events, this 'megastructure' hosts fairs, conferences, multimedia concerts and political conventions (Figures 10a and 10b).

*Figure 10a - Georgia Dome interior view*
*Source: http://www.columbia.edu/cu/gsapp/BT/DOMES/GEORGIA/1018-52.jpg*

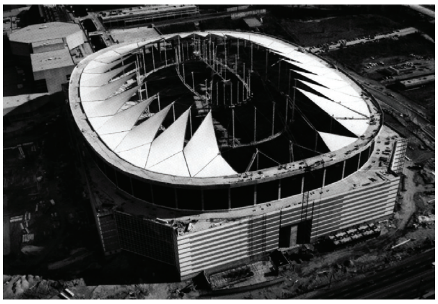

*Figure 10b - Georgia Dome exterior view*
*Source: http://www.columbia.edu/cu/gsapp/BT/DOMES/GEORGIA/geo-21.jpg*

The tensegrity type cable dome, patented as the 'Tenstar Dome', was formed as a triangulated spatial network over an oval plan, 240 x 192m of span and represents the world's largest structure of its kind (Castro and Levy; 1992, Levy 1994; Terry, 1994). The continuous tension through the roof structure was achieved by means of continuous tension cables and discontinuous compression struts. The primary structural system consists of tensed ridge and diagonal cables and compressed struts. The bottoms of the compressed struts are borne by diagonal cables attached to the tops of the compressed struts in the next outer ring and are interconnected by tensed cables that form concentric hoops. These tension hoops assume the role that bottom chords of the radial cable trusses normally have. In this way, a three-dimensional structural configuration was made, which is prestressed within the compressed perimeter ring. Unlike the Geiger system, this one is triangulated in space. This solution follows Fuller's principle of spatial triangulation (Figures 11 and 12).

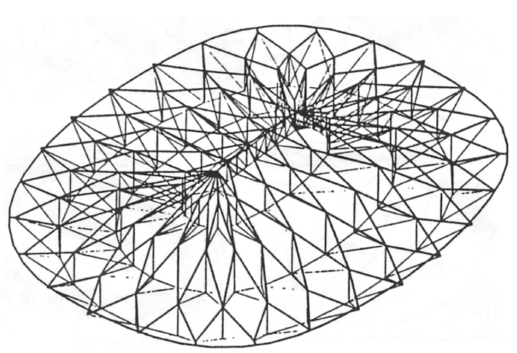

*Figure 11 - Axonometry of the roof structure*
*http://www.columbia.edu/cu/gsapp/BT/DOMES/GEORGIA/geo-23.jpg*

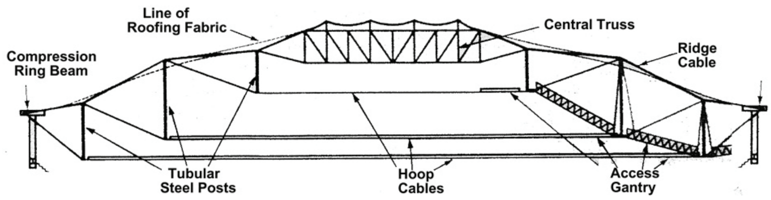


*Figure 12 – Roof structure section*
*Source: http://www.columbia.edu/cu/gsapp/BT/DOMES/GEORGIA/geo-41.jpg*

The structure is clad in diamond shaped panels of PTFE coated glass fibre membrane that follow the geometry of the network. Structural components, joints, steel pipes for compressed struts and steel cables were prefabricated which significantly reduced erection time.

## COMPARATIVE GEOMETRICALLY NONLINEAR STRUCTURAL ANALYSIS OF TWO TYPES OF TENSEGRITY TYPE CABLE DOMES

In tensegrity type cable domes, prestressed cables are the primary loadbearing elements, thus their non-linear behaviour due to load action is expected, as well as their reliance on geometric stiffness. Since structures of this type need to fulfil the condition of equilibrium upon a deformed configuration, the analysis of the structures was conducted by means of a software application for geometrically nonlinear analysis of three-dimensional trusses, based on the perturbation theory (Levy and Spillers, 1995). Instead of directly solving non-linear equations, they were being linearized by the application of the incremental approach. Load was determined by a system of consecutive steps, where the final structure configuration at a given step was taken for an initial approximation for the next step. At each step, i.e. within each increment, the geometrically non-linear analysis was reduced to the application of Newton's iterative method to the equations describing perturbation conditions, with the approximation of the stiffness matrix by combining the elastic and geometric stiffness matrix. A quantitative analysis of the combined system stiffness matrices allowed for the detection of structure instabilities. During the incremental-iterative solution procedure, the determinant of the system matrix is monitored. When this determinant goes to zero (singular stiffness matrix) the structure is said to be unstable. Conventional analytical methods for system instability prediction could not be applied to structures of this type.

In this paper, the computer program for geometrically nonlinear analysis of three-dimensional trusses - P3-TR3DNL was used for the analysis of structures. This program was given on a disk as an integral part of the book "Analysis of geometrically nonlinear structures", written by Robert Levy and William R. Spillers, 1995. The original computer program was partially adapted (reprogrammed) for the needs of the analysis, so the different modulus of elasticity-E of the cables and struts could be taken into account.

Two analogous models (Figures 13a and 13b), based on the basic premises of these structures, were formed for the needs of comparative structural analysis of non-triangulated and triangulated tensegrity type cable dome for different load conditions (Nenadović, 2004). The network geometry was

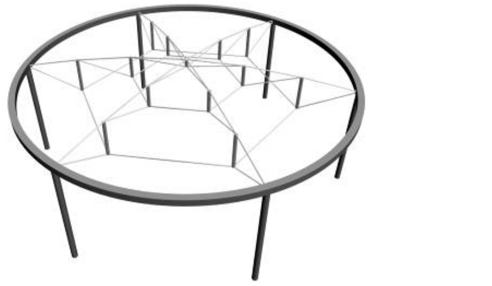

*Figure 13a - Non-triangulated tensegrity type cable dome model*

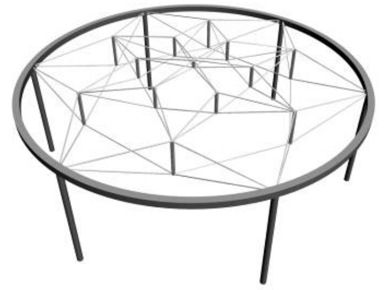

*Figure 13b - Triangulated tensegrity type cable dome mode*

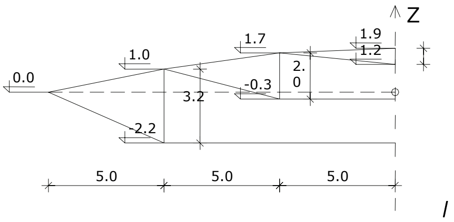


*Figure 14 – Cross-section of tensegrity type cable dome model*

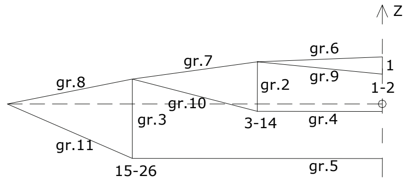


*Figure 15 – Groups of elements and nodes*

established in such a way that it resembled already constructed tensegrity type cable domes. This yielded in low profile domes in both cases (Figure 14). Both domes were formed as two-hoop configurations. Either model was developed as a cable-strut network, i.e. a three-dimensional truss. The cables could only take tension forces. The loads were given only at the system nodes. Both models were developed and analyzed without taking into consideration interaction with the roof cover.

The structures were analyzed for prestressing of the cable network and for different combinations of snow, wind and temperature loads. The prestress introduced into the structure, which carried dead load only, was determined relative to the condition that cables had to remain tightened for all load conditions and relative to the defined deformability expressed as allowed deflection under the most unfavourable load conditions. During the geometrically non-linear analysis of the structures, the software application reported the possible structure instability under various load conditions.

For the groups of load-bearing elements in non-triangulated and triangulated structure, from 1-gr.11 (figure 15), comparative maximum force graphs are given for the analyzed load conditions. For the nodes of non-triangulated and triangulated structure, the comparative maximal horizontal and vertical displacement graphs are given for the analyzed load conditions (nodes 1-2 – in the central zone; nodes 3-14 – the inner tension hoop; nodes 15-26 – the outer tension hoop).

Loads:

- Dead load – g=0.25 kN/m$^2$
- Snow load – s=0.75 kN/m$^2$
- Wind load – w=0.9 kN/m$^2$
- qw'=-0.63 kN/m$^2$ Gz=2.0 qw = - 1.26 kN/m$^2$
- Thermal load $\Delta t = \pm 30°$

Load conditions:

- LC-0 – dead load and prestress without fabric membrane

This load case is used as the input condition for load conditions I through IX

- LC-I - LC-0/snow load
- LC-II - LC-0/asymmetrical snow load
- LC-III - LC-0/wind load
- LC-IV - LC-0/temperature decrease
- LC-V - LC-0/temperature decrease / snow load
- LC-VI -LC-0/temperature decrease/asymmetrical snow load
- LC-VII - LC-0/temperature decrease/wind load
- LC-VIII - LC-0/temperature increase
- LC-IX - LC-0/temperature increase/wind load

## Influence of the network geometry on the behavior and structural efficiency of tensegrity type cable domes

***Prestress level – LC-0***

The prestress level in the triangulated structure is 15% higher than in the non-triangulated structure.

***Initial (referent) stress intensity and stress distribution after prestressing – LC-0*** (Figure 16)

In the triangulated structure, a differential distribution of stress was noted, i.e. a differential force flow from the periphery towards the structure's centre. While the non-triangulated structure was characterized by practically linear dependence in the increase of tension forces from the centre towards the periphery, the tension force flow in the triangulated structure was significantly disturbed in the outer tension hoop zone. The prestressing forces in the triangulated structure, which were significantly higher in this zone than in the non-triangulated structure, decreased rapidly toward the central zone. In spite of the higher intensity of initial prestress, the prestress, i.e. stiffness, was lower in the central zone of the triangulated structure. It was obvious that the triangulated network geometry partially impeded the distribution of the initial prestress, which was particularly reflected on the lower prestress in the central zone.

***Horizontal and vertical displacements after initial prestressing – referent position***

The referent position of the nodes in deformed structures, measured in comparison to the span, was slightly changed (0.3 – 1.2%) after the introduction of initial prestress.

***Force intensity in load-bearing elements – stress distribution – load conditions I – IX***

The effect of network geometry on the structure sensitivity for different load conditions was analyzed. The structure sensitivity was defined as the relation between the maximum force values for the given load conditions and the maximum force values for the basic load case (LC-0) in different element groups. Besides the comparative analysis of structure sensitivity, the relation between the stress intensity was analyzed, as well as the stress distribution after loading.

Comparative maximum force graphs for the analyzed load conditions I - IX in different groups of load-bearing elements are given for both the triangulated and non-triangulated cable domes (Figures 17-25).

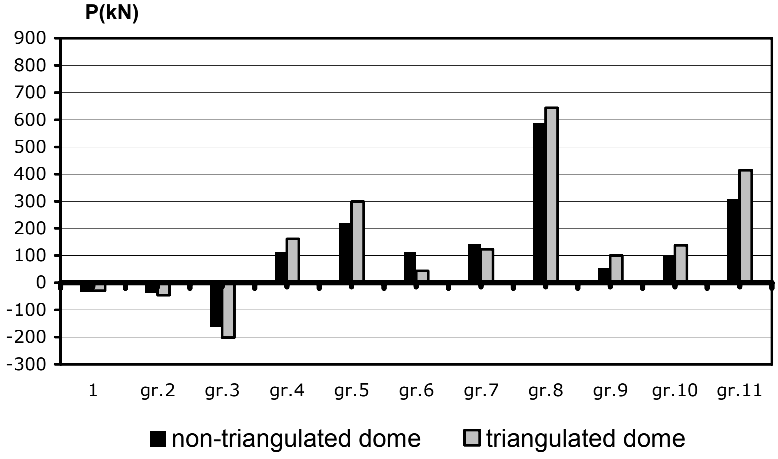


*Figure 16 – LC-0*

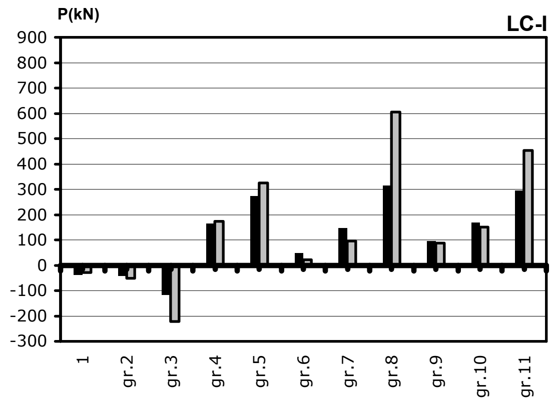


*Figure 17 – LC-I*

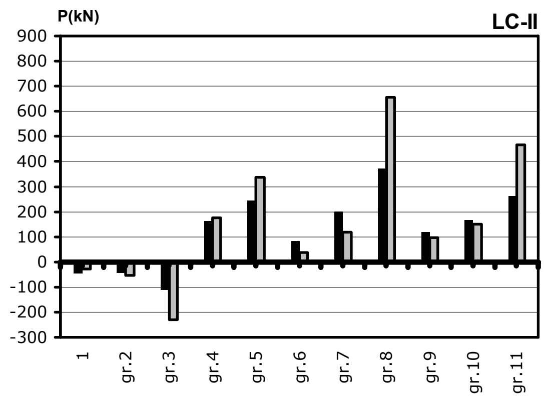


*Figure 18 – LC-II*

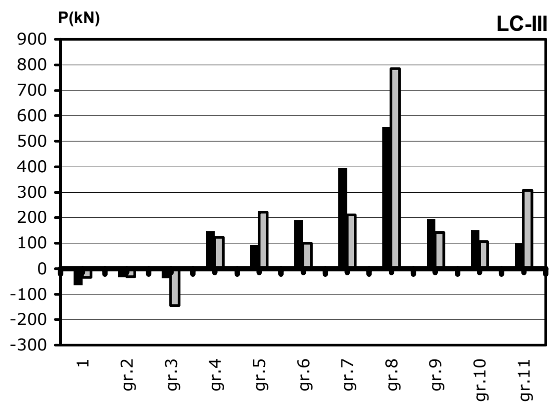


*Figure 19 – LC-III*

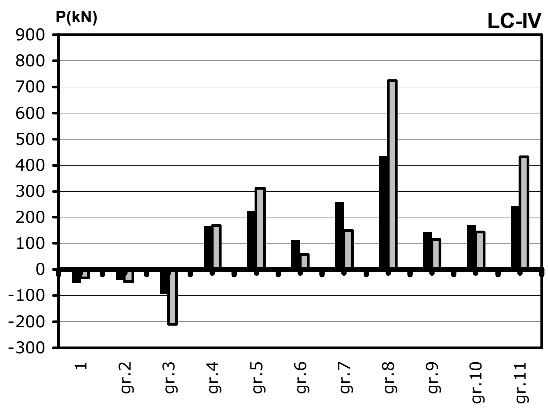


*Figure 20 – LC-IV*

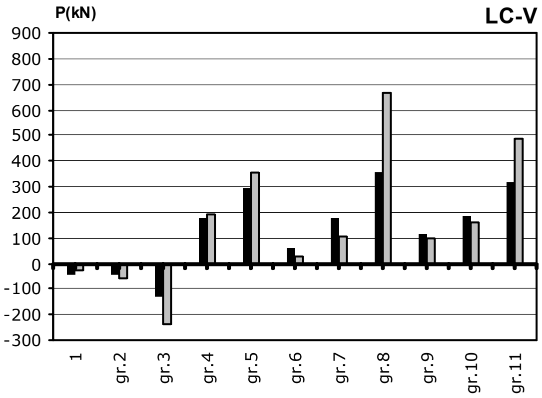


*Figure 21 – LC-V*

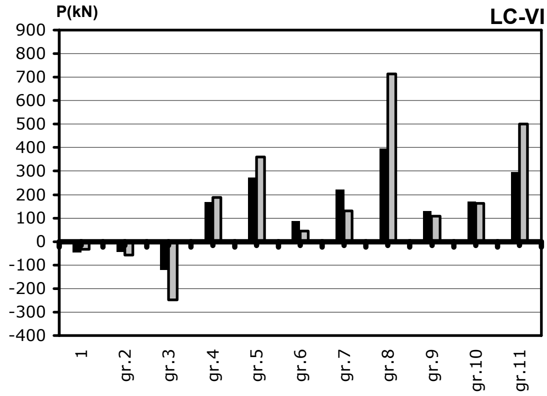


*Figure 22 – LC-VI*

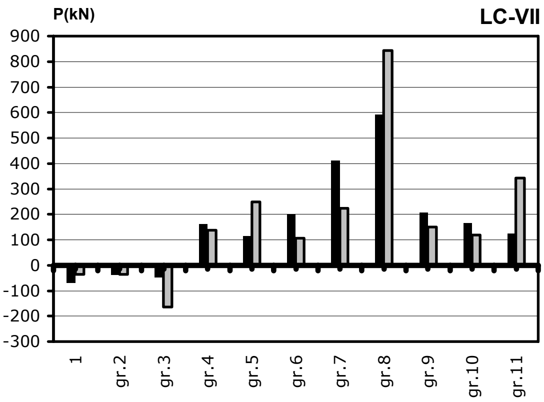


*Figure 23 – LC-VII*

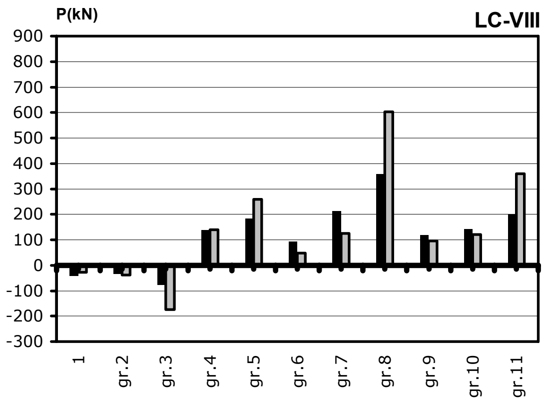


*Figure 24 – LC-VIII*

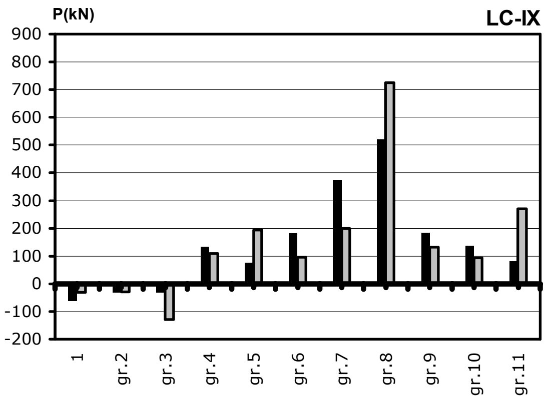


*Figure 25 – LC-IX*

LC–I – On the whole, the triangulated structure was less sensitive to snow load than the non-triangulated one. The triangulated structure showed a higher sensitivity to the given snow load only within the central zone, in which there was a significant drop in the prestress of ridge cables.

LC–II – On the whole, the non-triangulated structure was less sensitive to an asymmetrical snow load than the triangulated one. The non-triangulated structure showed a higher sensitivity to the given load only in the zone between the perimeter compression ring and the outer tension hoop, where a lesser drop in the tension force intensity in ridge cables was noted.

LC–III – On the whole, the triangulated structure was less sensitive to wind load than the non-triangulated one. The triangulated structure showed a higher sensitivity to the given load only in the zone of the inner tension hoop, where a decrease in tension force was noted, which was reflected as a lower prestress in the central zone.

LC–IV – The structures analyzed showed similar sensitivity to temperature decrease.

LC–V – Sensitivity of the analyzed structures to temperature decrease and snow load varied depending on the system zone that was analyzed. The sensitivity of the non-triangulated structure increased from the centre towards the perimeter compression ring, while the situation was reversed in the triangulated structure.

LC–VI – The non-triangulated structure was less sensitive to temperature decrease and asymmetrical snow load than the triangulated structure.

LC–VII – On the whole, the triangulated structure is less sensitive to temperature decrease and wind load than the non-triangulated structure. The triangulated structure showed a higher sensitivity only in the zone of the inner tension hoop, where a decrease in tension force was noted and which was reflected as a lower prestress in the central zone.

LC–VIII – The triangulated structure was slightly less sensitive to temperature increase than the non-triangulated structure.

LC–IX – Sensitivity of the analyzed structures to temperature increase and wind load varied depending on the system zone analyzed. The sensitivity of the non-triangulated structure increased from the centre towards the perimeter compression ring, while the situation was reversed in the triangulated structure.

The distribution of stress in the given structures after the application of load did not change significantly relative to the basic load case; it changed only in the non-triangulated structure after the application of wind load, after temperature decrease and wind load and after temperature increase and wind load, where a significant decrease in tension force intensity in the outer tension hoop, as well as a linear decrease in tension force intensity in diagonal cables from the centre towards the periphery of the structure was noted.

However, in spite of the noted differences in structural sensitivity and stress distribution after the given load application, it should be noted that the maximum force values in the load-bearing elements of the non-triangulated and triangulated structure were present at the same load cases: at temperature decrease and snow load, a temperature decrease and asymmetrical snow load, and at temperature decrease and wind load.

***Vertical and horizontal displacements – load conditions I – IX***

For different load conditions, the effect of network geometry on structure displacement relative to the referent position was analyzed, i.e. the effect of network geometry on structural stiffness was analyzed.

Comparative maximum vertical displacement graphs are given for different node groups of non-triangulated and triangulated cable domes, for given load conditions I – IX (Figures 26, 27 and 28).

Comparative maximum horizontal displacement graphs are given for different node groups of non-triangulated and triangulated cable domes, for given load conditions I –IX (Figure 29, 30 and31).

LC-I - At snow load, the triangulated structure proved stiffer than the non-triangulated one in the zones of the outer and inner tension hoops, while the non-triangulated structure proved slightly stiffer in the central zone.

LC–II – At asymmetrical snow load, the triangulated structure was significantly stiffer than the non-triangulated one.

LC–III – At wind load, the triangulated structure proved stiffer than the non-triangulated one in the zones of inner and outer tension hoops. In the central zone, the triangulated structure proved slightly less stiff than the non-triangulated structure.

LC–IV – At temperature decrease, both structures proved similarly stiff. The triangular structure was slightly less stiff in the central zone, while in the zones of outer and inner tension hoops it proved slightly stiffer than the non-triangulated structure.

LC–V – At temperature decrease and snow load, the triangulated structure proved stiffer than the non-triangulated one, in the zones of inner and outer tension hoops, while in the central zone both structures had the same stiffness.

LC–VI – At temperature decrease and asymmetrical snow load, the triangulated structure proved vertically stiffer than the non-triangulated structure. However, in the central zone and in the zone of inner tension hoop, the triangulated structure showed higher deformability in horizontal direction than the non-traingulated one. It is only in the zone of the outer tension hoop that the triangulated structure showed greater horizontal stiffness.

LC–VII – At temperature decrease and wind load, the triangulated structure proved stiffer than the non-triangulated one in the zones of inner and outer tension hoops. In the central zone, the triangulated structure proved slightly less stiff than the non-triangulated one.

LC–VIII - At temperature increase, the triangulated structure proved stiffer than the non-triangulated structure.

LC–IX – At temperature increase and wind load, the triangulated structure was stiffer than the non-triangulated one in the zones of inner and outer tension hoops. In the central zone, the triangulated structure was slightly less stiff than the non-triangulated one.

However, in spite of the noted differences in the system stiffness at different load conditions, it should be pointed out that the maximum horizontal displacements in triangulated and non-triangulated structure occurred at asymmetrical snow load, and maximum vertical displacements occurred at temperature increase and wind load.

***Load-bearing elements weight – material consumption***

The overall load-bearing elements weight (steel pipes and steel cables) of the non-triangulated structure was 56% lesser than that of the triangulated one.

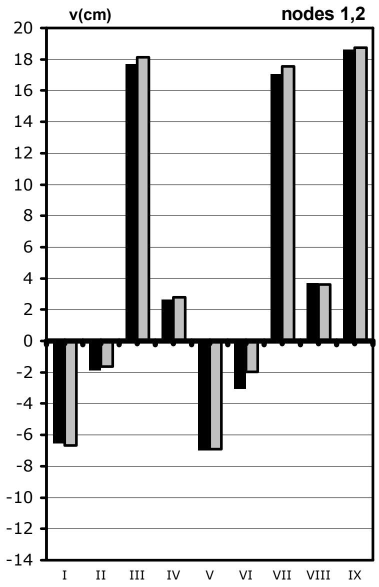


*Figure 26 – Maximum vertical displacements – nodes 1, 2*

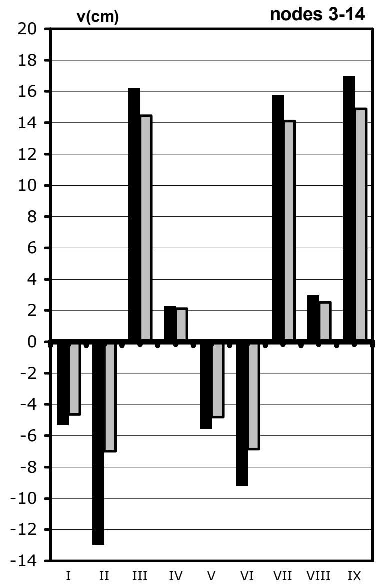


*Figure 27 – Maximum vertical displacements - nodes 3-14*

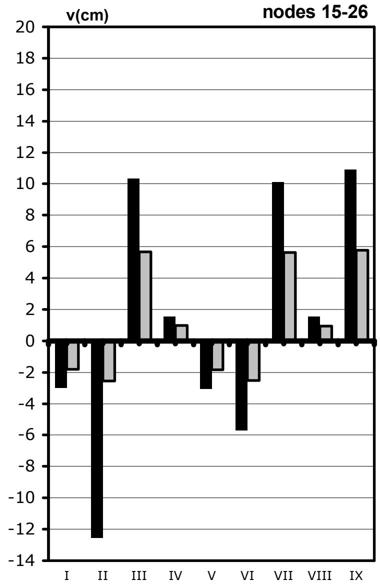


*Figure 28 – Maximum vertical displacements – nodes 15-26*

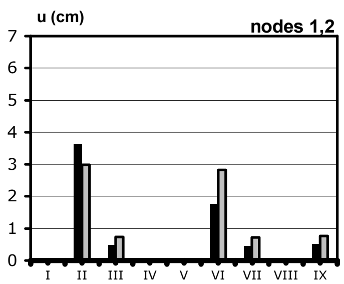


*Figure 29 – Maximum horizontal displacements – nodes 1, 2*

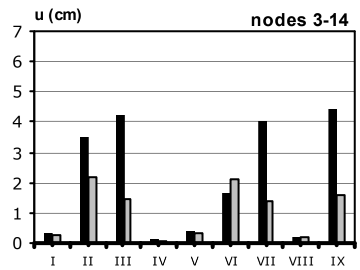


*Figure 30 – Maximum horizontal displacements - nodes 3-14*

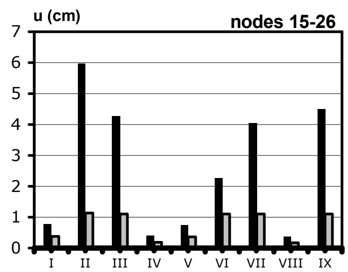


*Figure 31 – Maximum horizontal displacements - nodes 15-26*

### *Maximum support reactions – load conditions I – IX*

Maximum vertical support reactions for the non-triangulated structure show relatively lower intensity, bearing in mind lesser overall weight of the network load-bearing elements. This allows for the formation of a secondary structure with a smaller cross-section of the bearing elements. The maximum horizontal support reactions in the radial direction were 25% lower in intensity than the respective support reactions within the triangulated structure. This allows for the formation of the perimeter compression ring and secondary structure of the lesser cross section.

## CONCLUSION

On the basis of a geometrically non-linear comparative analysis of triangulated and non-triangulated tensegrity cable domes, it can be noted that the introduction and distribution of prestress in the triangulated structure appeared to be partially impeded, which particularly reflects itself on the lesser prestressing of the central zone. The sensitivity of the analyzed structures varied under different load conditions and between different systems zones under analysis. Within the triangulated structure there was a greater number of occurrences of central zone sensitivity, which was a result of its lesser prestressing following the introduction of initial prestress. The stress distribution within the given structures, following the application of different loads, did not change significantly relative to the basic load case, except in the non-triangulated structure where, upon the application of wind load, a significant decrease in tension forces in the outer tension hoop occurred, as well as a linear decrease in tension force intensity in diagonal cables from the centre towards the periphery of the structure.

On the whole, the triangulated structure appeared to be stiffer than the non-triangulated structure. However, in its central zone, a significant decrease in stiffness occured due to its lesser prestress (in spite of the greater intensity of initial prestressing forces), to the degree where the maximum vertical displacement of the structure nodes in this zone, in the majority of cases, proved to be higher than in the non-triangulated structure. It should be noted that those displacements were also related to the defined deformability of the system. In non-triangulated structure, greater horizontal displacements of nodes occurred. The non-triangulated structure would require less material for its construction, as well as for construction of the perimeter compressed ring and secondary structure.

Significant decreases in the tension force intensity in the outer tension hoop and diagonal cables of the non-triangulated structure, especially at asymmetric load action and with comparatively great horizontal displacements, showed that this network geometry has its disadvantages, especially in rigid roof cladding solutions. Geiger's 'pleated' roof membrane that is applied in tensegrity type cable domes is system based on the interaction of the membrane fabric and cable-strut network in bearing the load. The membrane has a stabilizing effect on the structure, but is flexible enough to follow its displacements. Unlike membrane fabric, rigid roof panels 'float' upon the load-bearing structure, i.e. the cable-strut network, and do not exert the stabilizing effect of the membrane fabric. In such cases, the structure experiences significant displacements. In order to control the displacement, especially horizontal displacements of non-triangulated structure in case of rigid sheet cladding, it is possible to intervene with the network geometry by introducing partial triangulation in the critical zone. The example of a successful combination of the triangulated and non-triuangulated network is the first realized rigidly clad tensegrity cable dome, where the network is partially triangulated in the zone of the outer tension hoop, while in the inner tension hoop zone it respects and follows the geometry of Geiger's non-triangulated network, which enables a higher prestressing level and a higher stiffness in the central zone.

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