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NON-LINEAR BEHAVIOR OF DOUBLE-LAYERED GRIDS

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Abstract

This study presents a numerical approach to an analysis of the mechanical behavior of double-layered tensegrity grids. We present a comparative study on the behavior of tensegrity grids through geometric nonlinear analysis (GNA) and combined nonlinear analysis (CNLA) (geometric and material), considering the possible effect of evolution in the elasto-plastic domain of the cable elements. The effect of the relaxation of cable on the amplification of the displacement of these grids was taken into account. The updated Lagrangian formulation, which modifies the Newton-Raphson iterative scheme with incremental loading, was adopted. We have developed a numerical computational model specific to tensegrity structures that simulates the geometric and material nonlinear behavior. The reliability of the calculation tool developed has been validated. Additionally, the results of the application of the numerical model on a grid, which was generated based on demi-cuboctahedral tensegrity cells, are presented.

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Key words

- Tensegrity,
- Double layer grids,
- Geometrical nonlinearity,
- Material nonlinearity,
- Relaxation.

1 INTRODUCTION

Double-layer tensegrity grids are spatial and tensile reticulated systems containing two parallel arrays of tension members forming top and bottom chords, the nodes of which are connected using vertical and/or inclined web members under compression and tension (Gómez-Jáuregui, 2012; Kaveh and Ghazaan, 2018). These lightweight constructive systems are frequently employed to cover large-span areas. Although Snelson (2013) was the inventor of these structures, they were first studied from a technical point of view in 1975 by Fuller, who presented most of their geometric properties (Fuller, 1982). In recent years, methods to analyze these structures have been developed, and regular and systematic research has been carried out to provide a theoretical basis for the analysis and design of these structures. Studies by (Pellegrino,1990; Pellegrino and Caladin,1986; Motro,1992; Motro et al., 1990), and Hanaor (1991) play an important role in understanding the mechanical behavior of tensile systems. In terms of behavioral studies, methods have been developed to describe the behavior of tensegrity systems in the context of large displacements (Zhang, 2013; Foroughi and Lee, 2014; Nuhoglu and Korkmaz, 2011; Feng and Guo, 2017).

Obara and Tomasik (2020) have conducted a comprehensive study focusing on a qualitative analysis of plate-like tensegrity structures constructed with modified Quartex modules. The main goal of their research was to evaluate and understand the unique properties of tensegrities, which enable control over static and dynamic parameters.

Bel Hadj Ali et al. (2021) conducted a static analysis of tensioned structures with sliding cables. They integrated friction induced by cable sliding into finite element and dynamic relaxation analysis methods using a linear complementarity approach. The study demonstrated the significance of considering sliding-induced friction through various examples, by there revealing its significant effects on the mechanical be-

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havior of the structures without impacting computation time.

Kan et al (2021) introduced an innovative approach for the mechanical analysis of clustered cable structures. Their multibody-based method, which utilizes generalized coordinates to describe the configurations of rigid bodies, departs from traditional finite element formulations; the results demonstrated that friction between the cables and bars significantly affects the mechanical behavior of a clustered cable.

The dynamic behavior of double-layer tensegrity systems has been analyzed using the time integration algorithms developed (Greco and Ferreira, 2013). Ben Kehla et al. (2020) studied the dynamic response of a pentagonal ring-based tensegrity bridge, while considering the sudden cable break selected.

A finite element formulation, based on the co-rotational approach by (Feng and Guo, 2017), was developed for geometrically nonlinear elastoplastic analyses of a classical and clustered tensegrity. Murakami (2001) derived the basic equations for static and dynamic analyses of tensegrity structures with large deformations in Eulerian and Lagrangian formulations.

Tran and Lee (2011) developed a similar study; however, instead of the incremental load method for nonlinearities, they used total and updated Lagrangian formulations to establish the equations and a variant of the Newton-Raphson method to solve them, which was similar to the approach used by (Murakami, 2001). Bel Hadj Ali and Smith (2010) developed a modified dynamic relaxation method to simulate the static response of a clustered tensegrity beam and a quasi-static deployment of a clustered tensegrity tower.

Logzit and Kebiche (2022) developed a fatigue analysis model for Geiger-type cable domes subjected to in-phase biaxial loads. They used multiaxial fatigue criteria based on the critical plane approach and formulated a specific fatigue criterion for cable domes. This model makes it possible to predict the lifetime of these structures as a function of the response in a monotonic loading mode.

Shekastehband et al. (2012) studied the progressive collapse behavior under static loading on a tensegrity grid of (3x3x0.7). Logzit and Kebiche (2020) adopted a model based on the verification of iterative stability for a tensegrity cable dome using a geometric nonlinearity analysis.

As to the static studies carried out on these structures, we have focused on (Kebiche et al., 1999; Khellaf and Kebiche, 2013), who developed a calculation code treating geometric and combined nonlinear analyses (geometric and material) of the elements based on tensegrity modules. The code was applied to linear structures (columns or beams), where the focus was on the effect of local instabilities (slackening and plasticization of cables) on the global behavior of the structure. In addition, (Khellaf and Kebiche, 2014) studied the geometric and material nonlinear mechanical behavior of reconstructed tensile systems of hexagon-based rings by adopting the arc length driving technique imposed.

These studies aim to establish a strategy for the safe dimensioning of these innovative construction systems intended for different applications, such as covering large spaces. The present study, which is a part of these investigations, focuses on an analysis of the non-linear behavior of double sheet tensile grids. This study presents a novel numerical approach for analyzing the mechanical behavior of double-layered tensegrity grids. With their complex geometric and material nonlinear behavior, tensegrity structures have been thoroughly investigated through a comparative study utilizing both geometric nonlinear analysis (GNA) and combined nonlinear analysis (CNLA). The study accounts for the evolution in the elastoplastic domain of cable elements and for their relaxation on the displacement amplification of tensegrity grids. The motivation for this research was driven by the need to better understand tensegrity grid behavior and overcome the challenges posed by their unique nonlinear characteristics. It aims to develop and validate a specialized numerical computational model that associates material and geometric nonlinearity and demonstrates interest numerically in various tensegrity grid configurations. The interest of this model, once validated, makes possible the extension of a study to deal with more complex problems such as the phenomena of cable fatigue or buckling struts.

2 ANALYSIS METHOD

The tangential stiffness matrix of a tensile structure is derived from its equilibrium, compatibility, and ratio constitution. A numerical model has been developed to simulate and highlight the amplification of the displacements of the tensegrity plates, known for their great flexibility, considering the large deformations (plastification) and large displacements (slackening) of the cables.

2.1 Nonlinear resolution method

The nonlinear behavior of tensegrity grids (load-displacement), which is due to their great flexibility, can be amplified by the geometric or material nonlinearity of their constitutive elements (struts or cables).

The resolution method used is iteratively incremental. For an increment, a balance correction is introduced, using an iterative process. The Newton-Raphson method, which is based on a tangent stiffness matrix re-estimated at each iteration in order to reach equilibrium, is used.

The use of this method has the advantage of ensuring fairly rapid convergence with reliable results; its major drawback arises in the time spent updating the tangent stiffness matrix at each iteration.

The following figure shows an example of a non-linear process using the incremental method. The values used in the non-linear calculations are displayed:

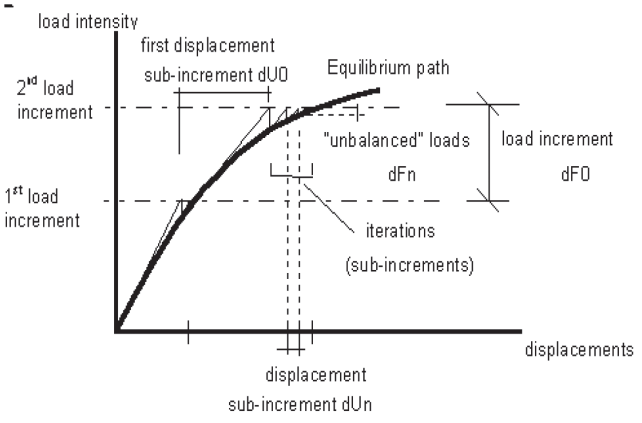


Fig. 1 *Nonlinear calculation process.*

2.1.1 Modeling of the grid elements (cables, struts)

The cable is an element that works only in traction (palisade). Owing to its non-linearity, an analysis of a structure containing cable elements requires the use of calculation algorithms defined for an analysis integrating geometric non-linearity.

The following equations were used (Khellaf and Kebiche, 2013):

$$\sigma = E_T.\varepsilon \ \ if \ \ \sigma < \sigma_y. \tag{1}$$

$$\sigma = f(\varepsilon) \ \ if \ \ \ \sigma \geq \sigma_y \tag{2}$$

where σ is the axial engineering stress; is the stress limiting the elastic behavior of the material; E_T is the elastic stiffness modulus of the material ('Young's modulus'), is the axial engineering strain; and represents the one-dimensional flow law (Khellaf and Kebiche,2014; Abedi and Shekastehband,2008). The work-hardening rule will be defined later.

As to **struts**, which are assumed to have a perfect elastic plastic behavior, the constitutive law is:

$$f(\varepsilon) = \sigma_y \tag{3}$$

3 VALIDATIONS OF THE CALCULATION MODEL

3.1 Validation using numerical results from ANSYS

In this section, we validate our simulation results by comparing the simulation results obtained using commercial software (ANSYS V20.2) with the results of the calculation model developed.

Geometric and mechanical characteristics of the grid

All the geometric and mechanical characteristics as well as the values of the initial self-stressing applied to the elements composing the structure (bars and cables) of the grid are specified in Table 1.

The nodal loads were applied as shown in Fig. 2. For practical realization conditions, we assumed that all the peripheral nodes on the bottom sheet of the grid were fixed according to the X, Y, and Z directions (Fig.2).

The vertical displacements (Z_{mean}) of the central nodes (6,7,10, and 11) as a function of the increasing load applied are plotted in Fig. 3. As shown in Fig. 2, the results were compared with those obtained using the ANSYSV20.2 software and were found to be in perfect agreement.

3.2 Validation using experimental results

To confirm the reliability of the simulation model developed, a comparison with the data obtained from experimental tests carried out on a double-layer tensegrity grid was performed.

Geometric specifications of the grid tested

An experimental study was conducted by (Shekastehband et al., 2012) on a tensile grid consisting of nine modules in a demi-cuboctahedron (3 m × 3 m × 0.7 m). The module and the assembled structure are shown in Fig.5, and the material properties are presented in Table 2. The grid was composed of 132 elements, including 36 compressed struts (steel tubes) and 96 tensioned cables (steel), which were connected through the nodes, as shown in Fig. 5.

Tab. 1 *Geometric and Mechanical Characteristics of Cables and Struts Elements*

Group	Component Type	Initial yield stress σy (daN/cm²)	E (daN/cm²)	A (cm²)	Critical buckling stress (daN/cm²)	Initial tension (daN)
1	struts	2350	2000000	3.25	1116.9	-1469.64
2	Base cables	4800	400000	0.28	-	600.0
3	Upper and braced cables	4800	400000	0.28	-	848.52
4	common cables	4800	400000	0.56	-	848.52

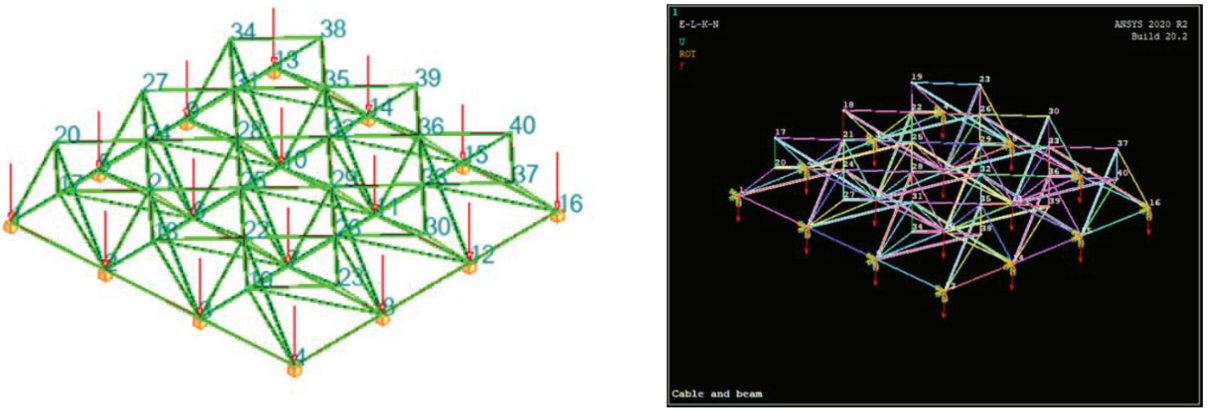


Fig. 2 *Geometry and loading of the 9-module double-layer grid*

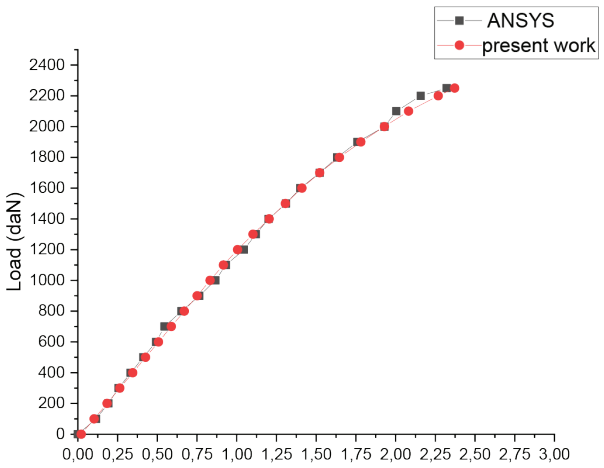


Fig. 3 *Average z displacements of nodes (6,7,10,11) in the Z direction.*

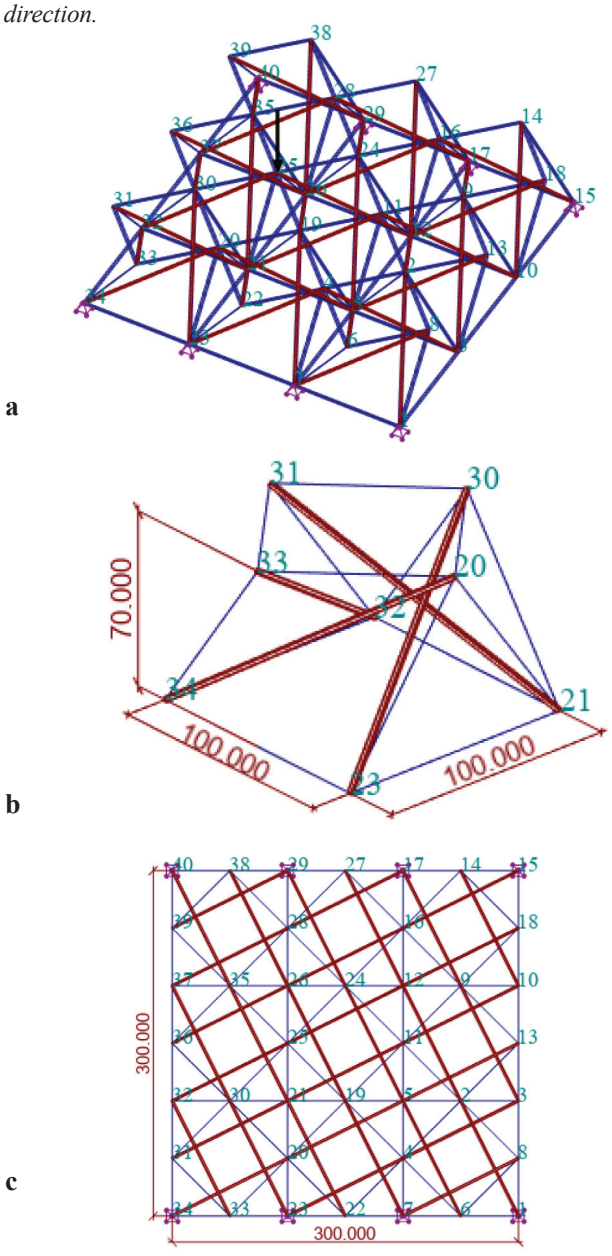


Fig. 5 *Regularly arranged tensegrity grid composed of 36 spacers and 96 cables. a) Perspective view. b) The quadruplex module .c) Plan view.*

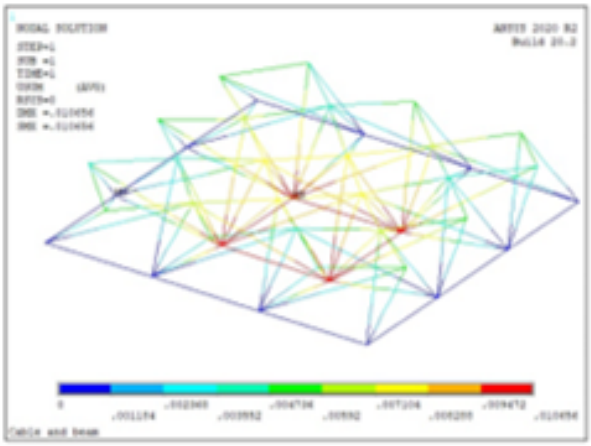


Fig. 4 *Displacement of nodes obtained by Ansys under load 1200 daN.*

The load was applied on Node 25 (Fig.5). Nodes 1, 7, 23, 34, 15, 17, 29, and 40, were blocked along the X and Y directions, as shown in Fig. 5. The experimental investigation was carried out under a load control; there was therefore no control on the displacements.

Tab. 2 *Mechanical properties of elements used in the tensegrity model*

Element		Initial yield stress [daN/cm^2]	Elasticity module [daN/cm^2]	Element Section [cm^2]
Struts		3450	2040000	2.07240
cables	Type 1	13500	1250000	0.50240
	Type 2	13800	1370000	0.50240
	Type 3	16400	1930000	0.50240

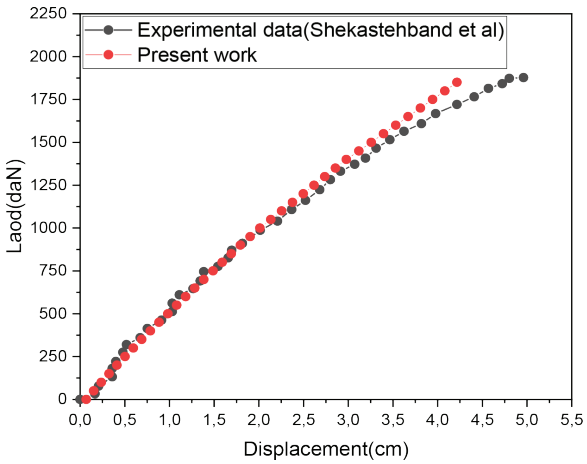


Fig. 6 *Behavior curve at node 25*

Figure 6 shows the experimental and numerical load-deformation responses of the tensile grid at Node 25. The Z-displacements of Node 25 are plotted as a function of the increasing load applied.

Discussion

It can be seen from Fig. 6 that the experimental and numerical values obtained from the present model are very close. The table below shows the maximum divergence (%) between the two calculation methods:

Load P(daN)	1850
$Z_{\text{numerical value}}$(cm)	4.21589
$Z_{\text{experimental value}}$(cm)	4.64265
Difference	10%

This small difference may be owing to some imperfections, such as the application of initial tensions at the cables and possible looseness at the connection nodes in the experimental execution.

4 APPLICATION

4.1 4x4 Tensegrity grid

This section describes the application of a proposed code for the analysis of a 4 x 4 double-ply quadruplex tensile grid under a bending load (Fig. 7). The results are presented as the evolution of the displacements of the stressed nodes as a function of the external loads. The Elastic and elastoplastic deformations are studied as a function of the external loads.

4.1.1 *Geometric and material specifications of the grid*

Fig. 7 shows a square (4 x 4) plane tension grid generated based on 16 quadruplex cells. It is composed of 65 nodes, 64 struts, and 168 cables. The nodal coordinate, mechanical characteristics, and self-tension vector of the grid are given in Tables 4, 5, and 6, respectively.

Tab. 3 *Nodal coordinates (cm) of a quadruplex*

Node	X[cm]	Y[cm]	Z[cm]
1	0	0	0
2	0	100	0
3	0	50	50
4	50	0	50
5	50	100	50
6	100	0	0
7	100	100	0
8	100	50	50

For practical purposes, we assumed that all the peripheral nodes on the bottom sheet of the grid were fixed along the X, Y, and Z directions. The vertical load 'F' was applied as shown in Fig. 8.

Fig. 9 shows the load-displacement curves for the NEA and NEPA of the tensile grid (4x4) (Fig.8). The displacements were measured in cm at Node 13 in the center of the plate. The effect of the cable slack was taken into account for both types of analyses. The purpose of this study was to highlight the impact of the material nonlinear behavior of cables on the amplification of the maximum displacements of the structure.

It should be noted from Fig. 9 that the behavior of the grid in **NEA** presents a barely detectable non-linearity. The divergence between the two curves starts from the load at F=850daN. When this load reaches its maximum value at F=1300 daN, the difference between the displacements corresponding to the two types of analysis is approximately 1 cm.

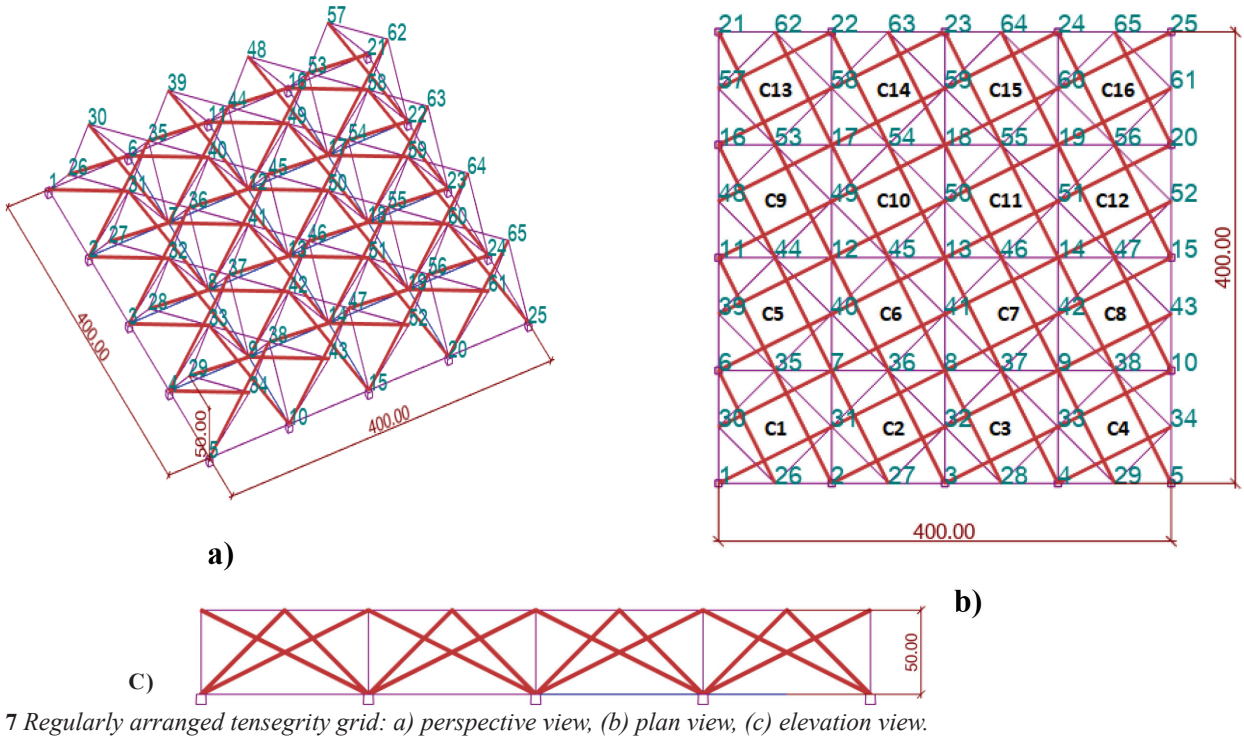


Fig. 7 *Regularly arranged tensegrity grid: a) perspective view, (b) plan view, (c) elevation view.*

Tab. 4. *Geometric and mechanical characteristics of cable and bar elements*

Group	Component Type	Initial yield stress σy (daN/cm²)	E (daN/cm²)	A (cm²)	(daN/cm²)	Critical buckling stress (daN/cm²)
1	Struts	2350	2,000,000	3.25	2350	1116.9
2	Base cables	4800	400,000	0.28	4800	-
3	Upper and braced cables	4800	400,000	0.28	4800	-

Tab. 5 *Initial Self-Stress Values Used in (daN)*

Nature of Element	S1(daN)
struts	-1469.64
Base cables	600.0
Upper and braced cables	848.52
Ordinary cables	848.52

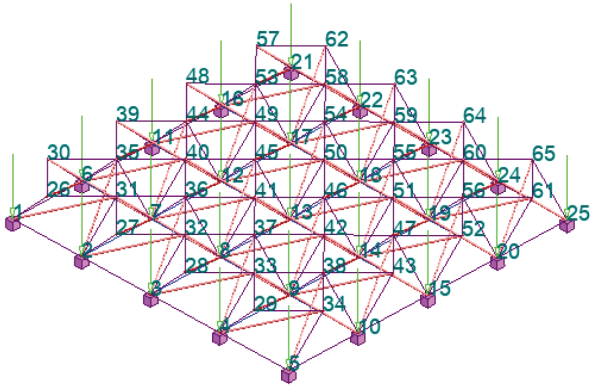


Fig. 8 *Geometry and loading of the tensegrity grid.*

Therefore, it can be concluded that the effect of the cable plasticization on the increase in grid flexibility is certain.

Figures 10 and 11 show a comparison between the variations in the internal tension in Cables 137 and 77 of the grid for **NEA and NEPA.** The two figures show that there is a difference in the internal forces. For **NEP**A, Cable 137 relaxed at F= 850 daN, while for **NEA** the same cable relaxed at F=900daN (Fig. 10).

In figures 12, 13, 14, and 15 and Table 6, we have attempted to present the NEPA of the response of the grid during bend-ing, considering the evolution of the internal forces in the ca-ble and bar elements of Modules C_1 (corner module) and C_2 (central module).

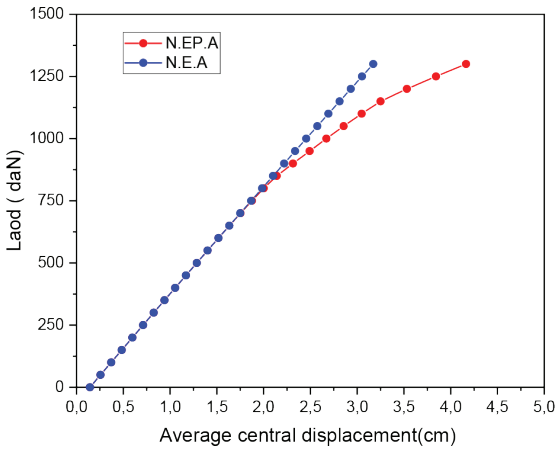


Fig. 9 *Comparison of elastic and elastoplastic behavior under flexion.*

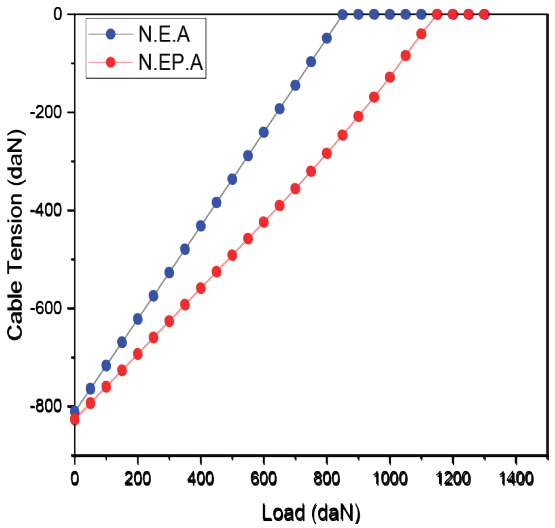


Fig. 10 *Tension in Cable 137.*

Tab. 6 *Analysis of the variation of internal forces in the struts and cables at the center and corners of the 4X4 grid based on the demi-cuboctahedron.*

	Corner area (Module C1)	Central zone (Module C6)
Cable states	Only one cable was released (slack cable). Most of the cables in the module displayed an almost constant development of tension. Cable K, whose tension increased visibly and approached the breaking point, was a spacer cable (Fig.10).	Three cables were released (top and bottom sheet cable). The release of Cables D, G, and F caused a rapid increase in tension in the other cables of the module. Cable B approached breaking tension (T=2100daN) (Fig.11).
Status of the struts	In Fig.12, we can clearly see the effect of slackening the cables (F=1150daN) on the increase in compression in struts C and D	The compression in the four bars showed an increasing beam influenced mainly by the loss of Cables D, G, and F through relaxation under F=1150daN.
	which shows that the internal forces are too far from the value of critical buckling force equal to 3629.925 daN, in both NEA and NEPA.	

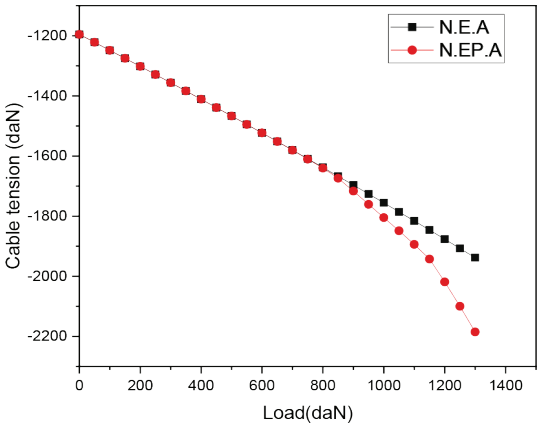


Fig. 11 *Tension in Cable 77.*

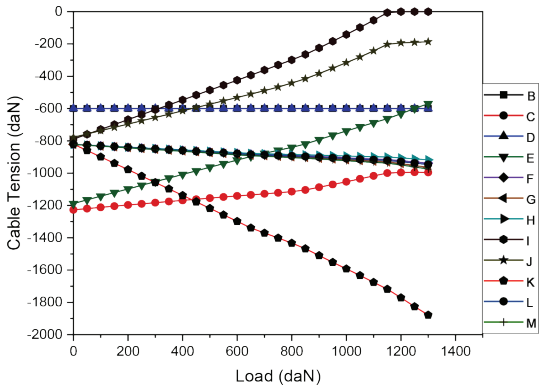


Fig. 12 *Variation of Tension Forces in Cable Elements of Cell C1 Considering an N.EP. A*

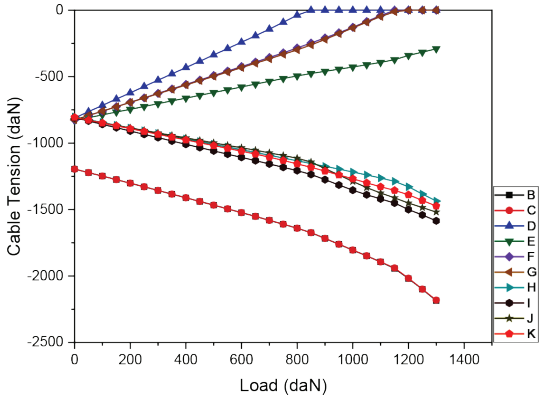


Fig. 13 *Variation of Tension Forces in Cable Elements of Cell C6 Considering an N.EP. A*

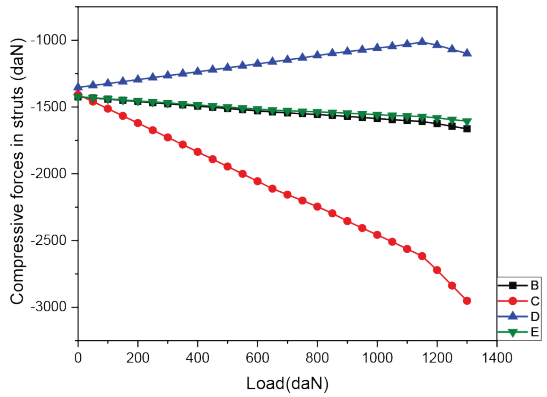


Fig. 14. *Variation of compression in the struts of cell C1 considering an N.EP.A*

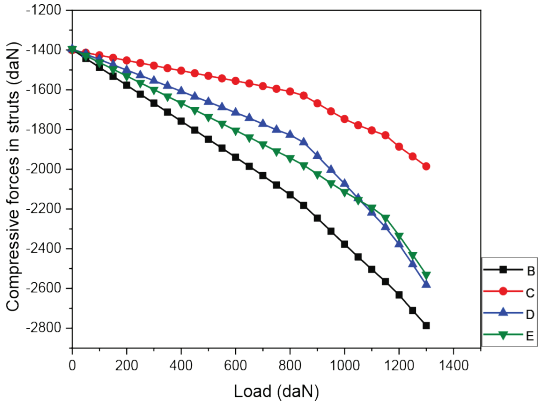


Fig. 15. *Variation of compression in the struts of cell C6 considering an N.EP.A*

5 CONCLUSION

A numerical method implemented in a computer program has been proposed for an inelastic analysis of a large deflection of tensegrity systems. The Newton-Raphson iterative solution method in the updated Lagrangian formulation was adopted, taking into account the geometric and material nonlinearities. Two types of analyses, i.e.s NEA and NEPA, are proposed.

The results obtained were validated experimentally and through the ANSYS commercial software; the validity and efficiency of the proposed method have been illustrated using numerical examples. The elastic and elasto-plastic responses of a double-layer quadruplex tensegrity grid were studied using the proposed formulation.

The proposed program plots the responses of the quadruplex double-layer tensegrity grid of the quadruplex module under external loads. From the numerical results obtained, the following conclusions can be drawn:

– The proposed program can accurately predict the geometric and material nonlinear behavior of tensegrity systems using both updated Lagrangian descriptions.

–The inclusion of a geometric non-linear analysis has generated a decrease in internal stresses. This suggests an optimization in the dimensioning of the structural elements (weight optimization).

–The results of the code we developed, which is specific to tensegrity structures in geometric and material nonlinearities, are in agreement with the results obtained from the commercial ANSYS software and the experimental work by Shekastehband et al. (2013).

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