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Scientific Paper

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Design, Fabrication and Construction of a Deployable Double-Layer Tensegrity Grid

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Abstract

Deployable Double-Layer Tensegrity Grids (DDLTGs) are pre-stressed spatial frames containing two networks of tensile members forming the top and bottom chords in the form of tessellations, the nodes of which are linked by vertical and/or inclined web members in compression (usually struts) and/or in tension (usually cables), in such a way that these structures are able to be folded and unfolded.

This paper presents a procedure to design, fabricate, build and fold a light and inexpensive DDLTG composed of tensegrity modules Quastrut-S. A prototype 4x4 m grid structure was constructed, in a short timeframe, to allow the structural behavior and deployability of the DDLTG to be tested. In its folded configuration, the perimeter of the structure is less than 180 cm. The structure can therefore be easily stored, transported and erected within a short timeframe, allowing it to be used as a temporary shelter, exhibition roof structure, etc.

Keywords: Tensegrity, Grid, Double-Layer, Deployable, Structure, Construction

1 Introduction

1.1. Tensegrity structures

Tensegrity is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in such a way that the compressed members (usually bars or struts) do not touch each other and the pre-stressed tensioned members (usually cables or tendons) delineate the system spatially [1].Compressed elements can however be contiguous as long as they are only and always pin jointed and under compression; in this case, it could be considered that there are not several simple elements under compression, but just one complex component constituted by an assembly of elementary elements in compression [2]. When this happens the class of tensegrity (k), the maximum number of struts meeting at one node, is said to be greater than one, i.e. k>1. In this paper, the latter definition of tensegrity will be adopted, as well as the tensegrities of any class (k=1 and higher).

1.2. Double-Layer Tensegrity Grids (DLTGs)

Double-Layer Grids (DLGs) are spatial frames containing two parallel networks of members forming the top and bottom chords in the form of tessellations, the nodes of which are linked by vertical and/or inclined web members. The condition of parallelism is not essential, but commonly present. Double-Layer Tensegrity Grids (DLTGs) are a special type of DLGs; particularly, those that can be considered tensegrity structures. When the upper and lower nets are composed by members in tension and the whole structure is pre-stressed and participates of the tensegrity definition, it is accepted to consider it as a DLTG [3].The invention of tensegrity (late 1940s) is associated with Fuller, Emmerich and Snelson. These authors were also the first to propose different types of DLTGs, showing that this typology would be one of the most common and recurrent among the different types of tensegrity structures.

Since then, many configurations of tensegrity grids have been proposed. The first works by Motro and Hanaor were remarkable: Motro [4] used tensegrity pyramids for planar grids, by means of joining the ends of some struts (k=2). At the same time, Hanaor [5] experienced basically with the juxtaposition of tensegrity prisms and truncated pyramids, avoiding contacts between struts (k=1). Most of the existing DLTGs analyzed since then and until now have been slight variations of these kinds of grids proposed more than 25 years ago [6–9]. The third most studied DLTG is a structure composed by 'V22 expanders' (k=2), found by Raducanu [10] as a part of his PhD thesis. For an extensive literature review in relation to DLTGs, the reader can refer to Gomez-Jauregui et al. [11].

1.3. Deployable Double-Layer Tensegrity Grids (DDLTGs)

When a DLTG can be folded and unfolded, it can be termed a Deployable Double-Layer Tensegrity Grid (DDLTG). Unfortunately few examples of DDLTG have been reported, whereas there are many examples of deployable tensegrity towers, booms and antennas. There are some examples of 'demountable' DLTGs [7], which have the disadvantage that they have to be dismantled before being folded.The first proposal for a DDLTG was made by Hanaor [12], by means of elonging struts, shortening cables or a combination of both techniques. Hanaor experimented with compositions of 3 and 7 modules (the so-called Simplex, composed by 3 struts and 9 tendons) where there was no contact between struts (k=1); this fact made it easier to design the connections. Some years later, Bouderbala proved in his doctoral thesis, by means of models, the possibility of folding and unfolding a DDLTG composed of modules with 4 bars (half-cuboctahedron) or 6 bars (expanded octahedron) [13]. Smaili [14], in his doctoral thesis presented the most recent analysis of deployability in a DDLTG created using 'V22 expanders'. This study made use of numerical and physical models. Two folding methods were described: those relying on self-stress and those not relying on self-stress; the latter was also successfully applied to some other configurations.

1.4. Background, motivations, aims, limitations and organization of the paper

As discussed in previous sections, few examples of DLTGs can be found in the literature. Furthermore, analysis of their deployability has only been carried out for a limited number of these. The foldability of tensegrity structures is one of their most important characteristics. Being a type of pin-jointed structures, the elements under compression are, if not isolated (k=1), connected with ball joints that act as hinges, permitting the folding and the stowage in a compact volume. The kinematic indeterminacy of tensegrities is sometimes an advantage. In foldable systems, only a small quantity of energy is needed to change their configuration because the shape changes with the equilibrium of the structure. All these factors make DDLTGs optimal candidates to be incorporated into space applications or temporary shelter structures.

Therefore, the motivation of this paper is to explore new possibilities for deployable tensegrity grids and opening a new line of research for finding some other structures with similar characteristics.

The general aim of this project was to validate the feasibility to design, fabricate, build and fold a light and inexpensive DDLTG (made of Quastruts-S), which had already been conceived by this research team. Therefore, it was planned to do previously a study both numerically (dynamic simulation) and experimentally (small-scale physical model).

This project had some restrictions that made it an edifying challenge. The most important was the time: due to the agenda and schedule of the research team, the project had to be completed in two months. The structure also had to be built on a limited budget. Both of these factors help in a somewhat positive way to ensure an optimized design of both the grid and nodes.

The paper is organized as follows: Firstly, there is an introduction to the concept and background of tensegrity structures, DLTGs and DDLTGs, explaining the motivations, aims, scope and limitations of the study. Next section discerns the methodology used to deliver the project: overall design of the grid, particular design of the connections, fabrication of the preliminary prototypes, redesign, and purchasing of the commercial fasteners. Furthermore, the approach for assembling and erecting the DDLTG in such a way that it could be consequently loaded and tested is explained and a brief description of the folding process is given. The last part of this paper details the conclusions of the study.

2. Methodology

This experiment is the continuation or culmination of some investigations carried out previously [15]. This research team compared the behavior of a new family of Double-Layer Tensegrity Grids (DLTG) obtained by the juxtaposition of the Quastrut in some of its variations. The best behaviors corresponded to those of the original DLTGs obtained directly from a novel method for obtaining innovative tensegrity structures: the Rot-Umbela Manipulations [16]. Thus, the optimal grids were the so-called DLTG Quastrut-S1 and DLTG Quastrut-

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Z1. As a result, the main decision was to build a DLTG Quastrut-S1 composed by modules Quastrut-S in juxtaposition, with no rotations and no reflections (*Fig. 1*, Left).

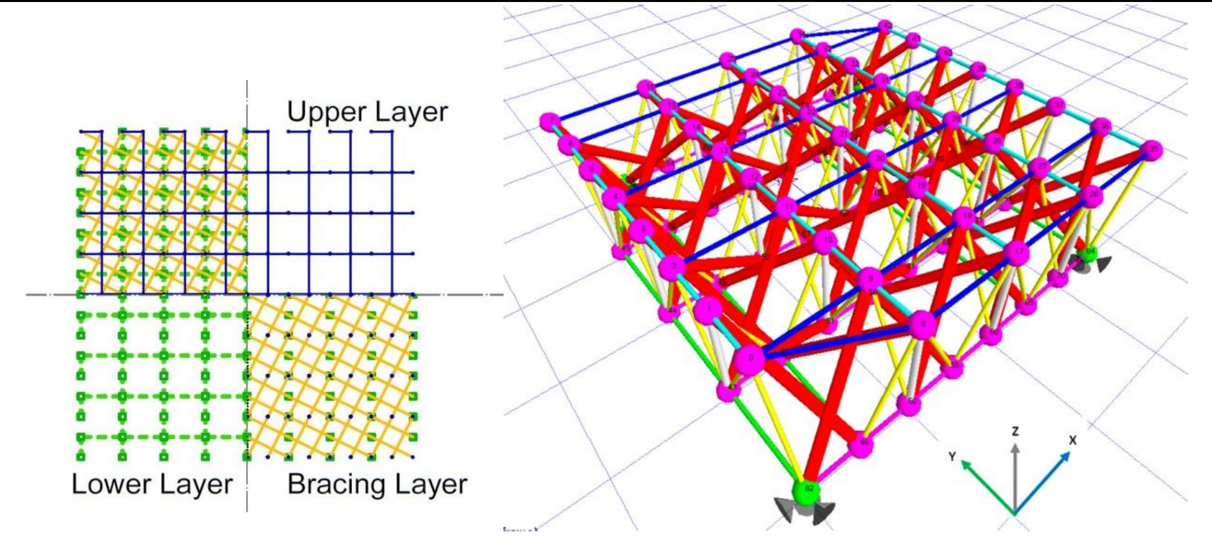

Fig. 1. **Left: DLTG Quastrut-S1 composed of modules Quastrut-S in juxtaposition, with no rotations and no reflections. Right: Completed design of the DDLTG after adding additional cables at the boundaries.**

2.1.Grid design

The typology of the DDLTG Quastrut-S1 had already been designed (*Fig. 1*, Right). However some important parameters till had to be decided upon. For the overall dimensions of the structure, it could not be larger than 5x5 m due to space restrictions in the laboratory where it was going to be assembled and tested. Therefore, the final dimensions of the DDLTG were 4x4 m, distributed in 16 equal modules of 1x1x1 m, 4 in each direction X and Y. The resultant grid had a total number of 86 nodes (Table 1) and 285 components: 64 struts and 221 cables (Table 2).

Under these conditions, the theoretical length of the struts would be 1,5 m, although some struts had to be slightly shorter depending on the typology of the node class at their ends (k2-k2, k1-k2 or k1-k1). The cables were contiguous in both directions of the horizontal straight alignments of upper and lower layers and therefore had a total length of 4 m each; the bracing cables were also contiguous, although in zig-zag in their plane, where each diagonal had a theoretical length of 1.118 m. The data relating to the cables and struts are gathered in Table 2.

Table 1. Types and characteristics of the nodes of the DDLTG

Type of node	Quantity	Weight (kg)	Class (k)	Cross section
Corner nodes	8	0.175	1	RHS 40x80 (half) – 30 mm
Boundary nodes	12	0.168	1	RHS 40x80 (half) – 30 mm
Boundary nodes with vtcal. tensors	24	0.415	1	RHS 40x80 – 30 mm
Inner nodes	24	0.410	2	RHS 40x80 (half) – 85 mm
Inner nodes with vtcal. tensors	18	0.522	2	RHS 40x80 (half) – 85 mm
TOTAL	**86**			

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Table 2. Types and characteristics of the struts and cables of the DDLTG

	STRUTS			CABLES			
	K1-K1	**K1-K2**	**K2-K2**	**Diagonal**	**Horizontal [a]**	**Lower Boundary [b]**	**Vertical Tensors [c]**
Quantity	4	36	24	76	102	22	21
Material	Carbon steel S235JR			Galvanized high tensile steel wire rope			
Density (kg/m^3)	7850			7850			
Strength (MPa)	330 (yield point)			1770 (tensile strength)			
Cross section	Circular HSS 26.9x3			Strands of 7x19 wires			
Diameter (mm)	26.9			4.75		6.0	
Area (mm^2)	225.25			17.72		28.27	
Length (mm)	1500	1475	1450	1118	500 - 1000 -1118		1000
Weight (kg)	10.61	95.48	63.66	11.82	8.43	3.60	4.66

[a] Horizontal upper and lower layers

[b] Horizontal cables of the lower layer at the boundary

[c] Composed by turnbuckle + cable + eyebolt

The cross section of the struts was calculated by its buckling capacity, determined in accordance with Eurocode 3 (Design of Steel Structures) and the Spanish Standard DBE-SE-A. The resulting weight of the structure was 233 kg, covering 16 m2, that is 14.6 kg/m2, which for a space frame is considered a lightweight structure.

The number of states of self-stress (s) was 25 and the number of mechanisms (m) was 13. Static analyses of the structures were carried out using the software ToyGL [17], a real time implementation of a discrete element method (mass-spring systems).

2.2.Node design

The design of the different node types depends on their position and function. There are broadly two main types of connections: (i) an outer node (including boundaries and corners) of class k=1 (*Fig. 2*) and (ii) an inner node of class k=2 (*Fig. 3*). The design of the first type is not very complex because it only fixes one strut and several cables. However, the inner node needs a more specific design because there are several conditions that it has to fulfill:

- Foldability: the two struts connected at the node needs to rotate along the axis of the connection in order to permit folding the structure.
- Strength: the connection has to safely carry and transmit the tension and compression forces arriving to the node.
- Concurrency: In order to avoid eccentricities of the confluent forces, the cables have to run near the point of convergence of the struts. Otherwise, rotations in the nodes could occur due to the eccentricities.
- Standardization: normalizing the different kinds of nodes is important in order to minimize the variations and, thus, the different types of elements to be purchased, fabricated and assembled. If possible, the components of the node have to be off-the-shelf products to facilitate the short program, low budget and interchangeability of elements.
- Continuity: the solution has to enable the continuity of the cables passing through the node, in such a way that if the connection is released, the cables could run through it without being completely dismantled. This condition is essential to permit a fast assembly, effective application of pre-stress and easy foldability of the grid by releasing some selected cables only.
- Size: optimizing the size of the node is essential to make it small enough to avoid large eccentricities, high weight and cost, yet strong enough to carry all the forces transmitted by cables and struts.
- Multi-direction: the direction of the cables is different depending on the type of tendon: horizontal for upper and lower layers, diagonal for bracing layer and vertical for tensors. Therefore, the node has to be able to join different cables in different directions

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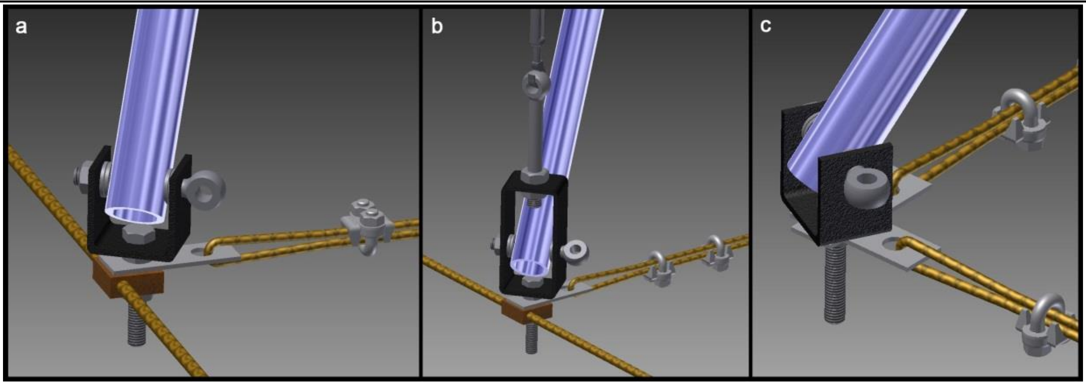

Fig. 2. **Designs for outer nodes (k=1): a) boundary node; b) boundary node with tensor; c) corner node.**

The design process of the nodes followed a classical route: it started with a conceptual design (freehand sketch) that was later converted into a 3D model with CAD software, then validated with Finite Element Analysis with a CAE tool and finally fabricated at full-scale in the laboratory (*Fig. 3*). On some occasions, the design process was augmented with 'additive manufacturing' - plastic prototypes were fabricated using 3D printers, to validate its interaction with other components, stability, functionality, etc.

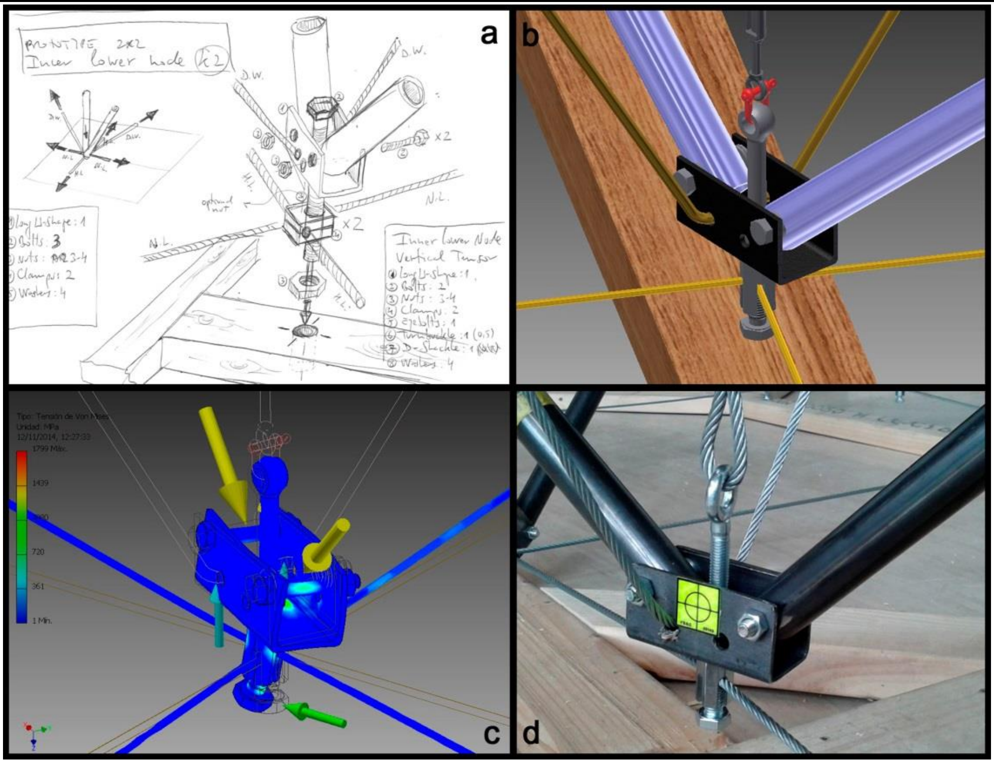

Fig. 3. **Process for the definition of the inner node (k=2): a) freehand sketch; b) 3D model with CAD; c) FEA with CAE; d) full-scale prototype.**

The resulting inner node has been granted with a patent [18]. In its most versatile version, it is composed by the following components:

1. A central U-shape core, composed of a standard rectangular hollow section (RHS 40x80) cut in half. It is drilled to incorporate the bolts/eyebolts and to let the diagonal cables to pass through.
2. Two circular hollow section struts (HSS 26,9x3) drilled to allow fixing to the central core with a bolt/eyebolt.
3. Two standard 8 mm dia. bolts (DIN 933 M8x50 or eyebolt DIN 444-C M8x60) with their respective washers to fix and constrain the struts. The use of eyebolts allows for the anchoring of additional cables.

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4. Two standard 8 mm dia. nuts (DIN 934 M8 or lifting eye nuts DIN 582 M8). The choice of lifting eye nuts allows for the anchoring of additional cables.
5. One standard 10 mm dia. eyebolt (DIN 444-C M10x90) for anchoring the turnbuckle that tensions the vertical tensor and for fixing the bidirectional cable clamp.
6. Bidirectional cable clamp, fabricated from a standard threaded connector (DIN 555-5 M10) modified by milling process to create the slotted grooves for accommodating the horizontal cables (8) and fixing the vertical eyebolt.
7. A short hexagonal 10 mm dia. bolt (DIN 933 M10x20) fixed to the threaded connector thus clamping the horizontal wires and restricting their relative displacement.

This inner node can be easily fabricated and assembled at a very low cost. The cost of materials for this connection is approximately €5, including as choices the bolts DIN 933 and the nuts DIN 934, as well as the corresponding “half” turnbuckle (one for each vertical tensor joining two nodes). The overall cost of the connection has also to allow for the machining and fabrication of certain elements as detailed below.

2.3. Purchasing of standardized elements

All the components of the nodes are easily obtained at a hardware or DIY store. Similarly other elements of the main structure, including the struts, thin plates, wire rope clips, turnbuckles, etc., are standard off-the-shelf items.

It became clear during the construction of a preliminary 2x2 m prototype DDLTG that the using of standard cable grips was very time consuming. Therefore the final structure made use of a commercially available system from Gripple, offering a variety of end connections for cable structures. The system used for the DDLTG consists of a 4.75 mm dia. wire rope with a crimped loop at one edge and a special Gripple clip at the other. This made the cable adjustment much easier and allowed the horizontal and diagonal cables to be tensed with little effort.

2.4. Assembly and erection

The structure was assembled over a timber frame that served as a datum to level the different layers and to precisely locate the node positions. The location of each node point was marked on the timber base and a hole drilled to receive a bolt from the node. This ensured that the node was kept in the correct position during assembly.

The three chords of the grid were assembled separately and then joined together. Firstly, the cable net of the upper layer (without the nodes) was set out, tensed to a minimum level and then removed. Secondly, the cable net of the lower layer was set-out and kept in place. Then the struts, with all the nodes attached to their end, were placed and joined to the lower cable net. Previous to this operation, the struts were assembled together as different subassemblies: four simple, four double, four triple and ten quadruple ‘zig-zag’ contiguous chains of struts.

The most efficient assembly sequence began with the quadruple chains of struts because they were in the center of the grid and they were relatively stable thereby requiring minimal temporary support. Once these were in position, the triple, double and simple subassemblies were placed consecutively.

The next step was to place the upper cable net onto the upper nodes of the struts: the bidirectional cable clamps fixed the locations were two horizontal cables had to meet and the single cable clamps fixed the ends of the wires to the boundary nodes. After this operation, the overall DDLTG was stable, although not rigid.

The bracing chord of diagonal cables was assembled in the structure, in such a way that these elements were contiguous and ran through holes within the nodes. The ends were clamped with the Gripple system in such a way that they could be released without being dismantled from the holes that they ran through.

Fig. 4. **Perspective of the DDLTG with the lower, bracing and upper layers. Yellow markers for surveying the nodes.**

Finally, the 21 vertical tensors, each composed of a 6 mm dia. cable and a turnbuckle, were attached via eyebolts (*Fig. 4*) to the upper and lower nodes. These elements were the active cables, providing the state of self-stress to the DDLTG by reducing the distance between the upper and lower layers via tensioning with the turnbuckle. It can be understood intuitively that as the distance between the upper and lower layers reduces, the structure tends to expand like a 'scissors framework'. As a result the horizontal cables stretch and go in tension. At the same time, the struts go into compression as they are confined and have no space for stretching because they are attached to the cables at the boundaries.

2.5. Loading and measurement

The first load step was the implementation of the state of self-stress. Its determination is very important and difficult: some methods are based on direct measurements of the forces in the elements [19], while some others use indirect measurement techniques [20]. In this experiment, the authors opted for the direct method, therefore three force transducers (500kg load cells) were installed on the cables connecting at one of the corner nodes to measure forces in the bracing cable (diagonal) and X, Y directions of lower layer cables.

There are several options for applying the pre-stress to the DDLTG: enlargement of the struts and/or shortening of the cables (vertical tensors, diagonal cables and/or horizontal cables). For this project, it was calculated that the target state of self-stress would be achieved by shortening the vertical tensors by 5 cm. However, the implementation of this operation was not fully successful, and it was detected that a small number of the cables were not pre-stressed as predicted. Nevertheless, the equilibrium and rigidity of the DDLTG was successful.

The second load step was the application of the self-weight, supporting the structure at the four corner pin-nodes of the lower layer (worst scenario). As DDLTG behaved as expected: there was notable deflection (36.8 cm at the lower center node); some tensioned elements slacked (2 of lower layer, 32 of upper layer, all of the boundary diagonal cables and 10 vertical tensors); and some other cables experienced a significant increase in tensile force.

There were also some nodes that, due to an imbalance of load, rotated through 90º. Even though these nodes could adequately support the applied loads, this instability is not acceptable. Further iterations of the node design have aimed to ensure that this issue does not arise in current DDLTGs.

The locations of the nodes were surveyed by means of a Leica TC407 total station, with targets placed on each node (*Fig. 4*). The tensile forces recorded in the three monitored cables were 69, 353 and 745 N for the diagonal, Y and X cables respectively.

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For the last load step, in order to obtain a measurable deformation of the grid, the authors opted for a distributed application of 2, 5 and 10 kg calibration weights. The 10 kg weights were applied to the nine central nodes of the lower layer; the 2 kg weights were applied to the 14 boundary nodes; a 5 kg weight was finally added to the lower middle node. This distribution achieved a total applied mass of 123 kg. The DDLTG was clearly capable of supporting these loads without difficulty, in fact the deflection increased by only 5 cm (at the lower middle span point). The load cells in the three monitored cables showed values: 118, 598 and 1206 N for the diagonal, Y and X cables respectively. The detailed analysis of the behavior of the DDLTG has been deferred for future publications.

2.6. Folding of the structure

The method to create the mechanisms in the grid, such that it is possible to fold it, is based on untying one end of the contiguous cable that forms each diagonal (10 in total) and untying each vertical tensor (21 in total). This task can be undertaken quickly due to the practical design of the connections, i.e. it only requires the release of Gripple clips and turnbuckle hooks.

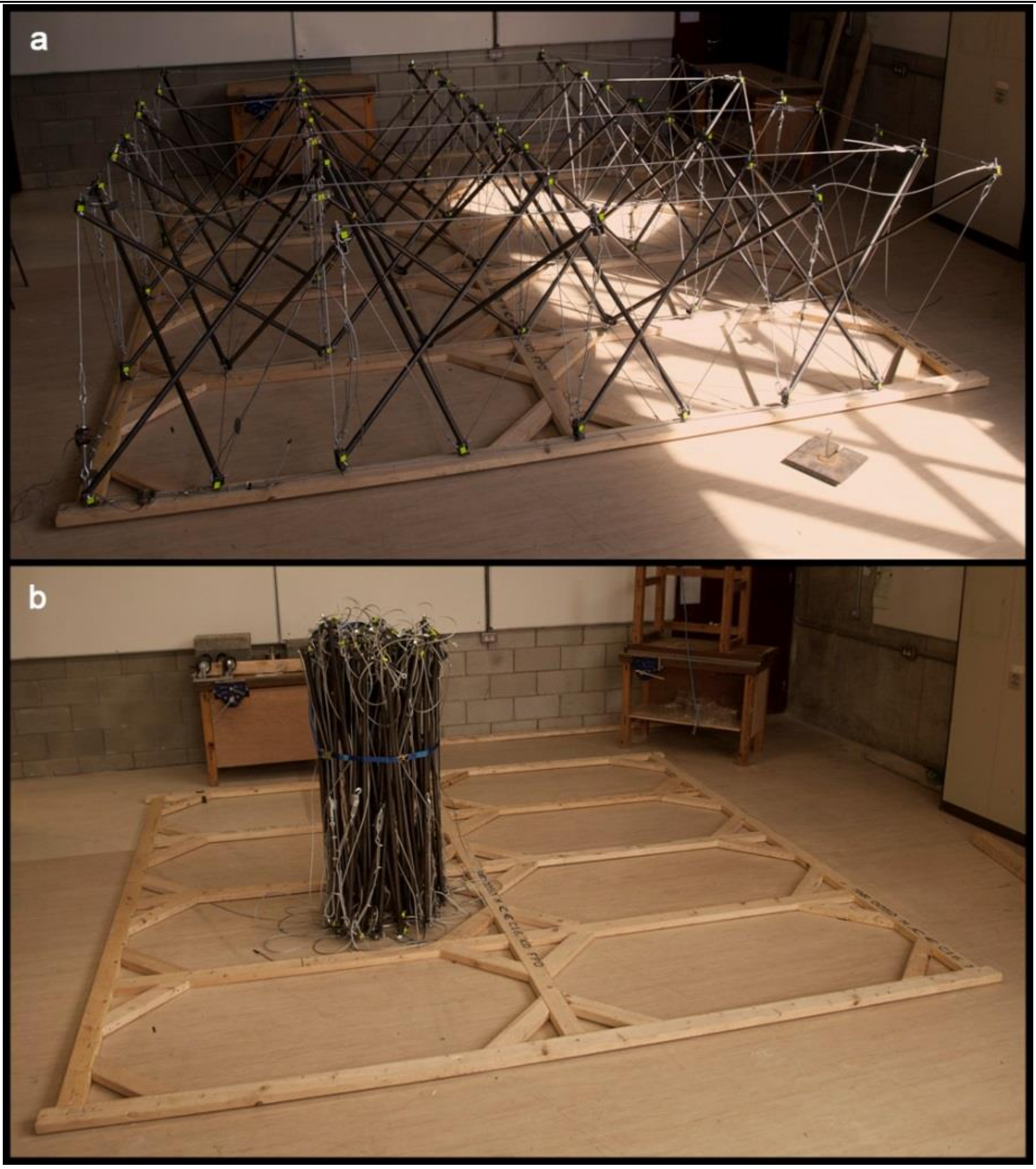

Fig. 5. DDLTG 4x4 in its unfolded (a) and folded (b) configurations.

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Then, the grid can be folded progressively by folding the struts inwards. There is no need of tools or additional help because the application of a small force to one end of the strut results in an immediate rotation due to the high moment produced. This phase proved to be quite easy and fast, taking approximately 30 minutes to fold and tie the structure completely. The DDLTG described here proposes folding along two axes (e.g., axes X and Y) which actually converts the grid from a 3D form to a "thick" 1D form (e.g. in axis Z). The grid, in its folded and unfolded configuration, can be seen in *Fig. 5*. At the end of the process, the result is a cluster of struts and cables, with a height slightly longer than that of the struts (1,5 m) and a perimeter of 178 cm. This equates to a radius of 28 cm and an approximate area of 0.25 m2. Thus, what the authors have termed, the 'coefficient of deployability' (16 m2 / 0.25 m2) is 64. Thanks to the design of the nodes and grid, redeployment of the grid is also very easy because there is no need of re-assembling the connections again due to the fact they have not been dismantled.

3 Conclusions

A procedure to design, fabricate, build and fold a novel DDLTG has been planned, executed and analyzed. The completion of the validation has been successful since the main objectives have been achieved: the design is simple and effective; the fabrication easy and inexpensive; the assembly safe and fast; and the folding converts the grid into a very compact cluster, even more so than some other existing DDLTGs referenced in the introduction to this paper.

The design of the nodes is robust, suitable for connecting two struts and several cables coming from different directions (horizontal, vertical and/or diagonal). However, when the forces are not fully balanced, some nodes tend to rotate. The connections permit the deployment of the struts around the nodes; therefore, it is possible to correctly fold the chains of struts and, consequently, the whole grid.

Some difficulties arose during the implementation of the state of self-stress and these issues remain to be resolved. Moreover, it was difficult to validate the exact value of stress in the different elements. A further investigation must be undertaken on this issue.

In conclusion, a first prototype of a light and inexpensive DDLTG has been created that can be easily fabricated and assembled. The design permits it to be folded for storage or transportation and assembly within a short timeframe. Therefore, it can be employed as a temporary shelter in disaster relief areas, a roof structure for fairs or expositions, etc.

1.1.Further development

There are some outstanding items relating to the DDLTG requiring further study, e.g. deflections, displacement of nodes and forces in cables as well as the comparison of theoretical and experimental results. These items will be detailed in later works which will also include a study on the ability of structural analysis tools in accurately predicting the behavior of the DDLTG.

The analysis of the process for folding and unfolding deployable tensegrities by means of CAD/CAE methods is not straightforward, and it is a challenge that has been rarely undertaken previously. Future works will include in-depth research into the feasibility of active controlled deployment for all actuated cables.

Furthermore, it would be desirable to define a systematic, ordered and properly sequenced protocol to fold the DDLTG. If such a study is successful, it will be possible to predict the feasibility of deployment of some other DLTGs; it will also permit minimizing the number of cables to release and the number of movements to apply to the struts in order to fold the structure to a maximum compactness.

Acknowledgements

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References

[1] Gomez-Jauregui, V. (2010) *Tensegrity structures and their application to architecture.* Servicio de Publicaciones de la Universidad de Cantabria. Santander (Spain)

[2] Motro, R. (2003) *Tensegrity : Structural systems for the future*. Kogan Page Science. London (UK).

[3] Gomez-Jauregui, V., Otero, C., Arias, R., Manchado, C. (2012) “Innovative Families of Double-Layer Tensegrity Grids: Quastruts and Sixstruts,” *Journal of Structural Engineering ASCE*, Vol. 139, no. 9, pp. 1618–1636, DOI: 10.1061/(ASCE)ST.1943-541X.0000739.

[4] Motro, R. (1987) “Tensegrity systems for double layer space structures,” *in Proceedings of International Conference on the Design and Construction of Non-conventional Structures,* no. 2, (pp. 43–51). , Edinburgh, Scotland: Civil- Comp Press.

[5] Hanaor, A. (1987) “Preliminary investigation of double-layer tensegrities,” *in Proceedings of International Conference on the Design and Construction of Non-conventional Structures,* no. 2, Edinburgh, Scotland: Civil- Comp Press.

[6] Liapi, K.A. (2002) “A Novel Portable And Collapsible Tensegrity Unit For The Rapid Assembly Of Tensegrity Networks,” in *Space Structures* 5, 12, Guildford, UK: Thomas Telford, pp. 39–46.

[7] Panigrahi, R., Gupta, A., Bhalla, S. (2009) “Dismountable steel tensegrity grids as alternate roof structures,” *Steel and Composite Structures*, Vol. 9, no. 3, pp. 239–253.

[8] Quirant, J., Motro, R., Kazi-Aoual, M. (2003) “Designing tensegrity systems: the case of a double layer grid,” *Engineering Structures*, Vol. 25, no. 9, pp. 1121–1130, DOI: 10.1016/S0141-0296(03)00021-X.

[9] Tran, H.C., Lee, J. (2010) “Initial self-stress design of tensegrity grid structures,” *Computers and Structures*, Vol. 88, no. 9-10, pp. 558–566.

[10] Raducanu, V. (2001) “Architecture et système constructif: Case de systémes de tenségrité,” PhD Thesis, Université de Montpellier II.

[11] Gomez-Jauregui, V., Otero, C., Arias, R., Manchado, C. (2011) “New configurations for double-layer tensegrity grids,” *in Structural Engineers World Congress 2011*, pp. 67, Como (Italy)

[12] Hanaor, A. (1993) “Double-layer tensegrity grids as deployable structures,” *International Journal of Space Structures*, Vo. 8, no. 1-2, pp. 135–143.

[13] Bouderbala, M., Motro, R. (2000) “Folding Tensegrity Systems,” in *IUTAM-IASS Symposium on Deployable Structures: Theory and Applications*, Vol. 80, S. Pellegrino and S. D. Guest, Eds. Dordrecht: Springer Netherlands, pp. 27–36.

[14] Smaili, A. (2004) “Systemes legers pliables/depliables: cas des systemes de tensegrite,” PhD Thesis, Université de Montpellier II.

[15] Gomez-Jauregui, V., Manchado, C., Otero, C. (2013) “Comparison between new families of Double-Layer Tensegrity Grids,” *in Proceedings of the First Conference Transformables 2013. In the Honor of Emilio Perez Piñero*, pp. 201–206, Seville, Spain: EDITORIAL STARBOOKS. Felix Escrig and Jose Sanchez (eds.).

[16] Gomez-Jauregui, V., Arias, R., Otero, C., Manchado, C. (2012) “Novel Technique for Obtaining Double-Layer Tensegrity Grids,” *International Journal of Space Structures*, Vol. 27, no. 2-3, pp. 155–166, DOI: 10.1260/0266-3511.27.2-3.155.

[17] Averseng, J., Quirant, J., Dubé, J.-F. (2012) “Interactive design and dynamic analysis of tensegrity systems,” *International Journal of Space Structures*, Vol. 27, no. 2-3.

[18] Gomez-Jauregui, V., Manchado, C., Otero, C., Iglesias, A., Galvez, A., Quilligan, M. and Casey, T. “Nudo de conexión para estructuras desplegables”. Patent ES 2555635 (B2). Granted 2016/05/03.

[19] Averseng, J., Crosnier, B. (2004) “Prestressing tensegrity systems - Application to multiple selfstress state structures,” *International Journal of Structural Stability and Dynamics*, Vol. 4, no. 4, pp. 543–557

[20] Angellier, N., Dubé, J.F., Quirant, J., Crosnier, B. (2013) “Behavior of a Double-Layer Tensegrity Grid under Static Loading: Identification of Self-Stress Level,” *Journal of Structural Engineering*, Vol. 139, no. 6, pp. 1075–1081, DOI: 10.1061/(ASCE)ST.1943-541X.0000710.