Development and Testing of a Deployable Double Layer Tensegrity Grid

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ABSTRACT: Tensegrity is a structural principle based on the use of isolated or contiguous pin jointed components in compression inside a net of continuous tension. Although the concept has been studied for many decades, relatively few examples of tensegrity structures have been used for civil engineering purposes. This paper describes the development and testing of a 'Deployable Double Layer Tensegrity Grid' (DDLTG). This type of structure can be easily stored, transported, and erected within a short time frame, allowing for many uses such as temporary shelters, exhibition roof structures, etc. A large scale 4×4 m grid structure was designed and constructed using the 'Quastruts-S' tensegrity module. A series of novel functional nodes were developed to cater for the connection of multi-directional cables and struts, while allowing for member rotations to permit folding the structure. The overall behaviour of the DDLTG proved satisfactory, and the structure folded into a compact cluster 0.56 m in diameter. A comparison of preliminary experimental results with theoretical predictions is provided and discussed.

KEY WORDS: Tensegrity; Structure; Spatial Frame; Double-layer; Grid; Deployable; Testing

1 INTRODUCTION

The definition and characterisation of tensegrity structures is not uniform, with different authors expressing differing conceptions. Tensegrity systems are considered here as self-stressed and auto-stable structures composed of isolated components in compression inside a net of continuous tension, in such a way that the compressed members do not touch each other, and the pre-stressed tensioned members (usually cables or membranes) delineate the system spatially [1].

Although the concept has been studied for many decades, relatively few examples exist of tensegrity structures used for large scale civil engineering purposes. One of the most iconic however, is the Kurilpa Bridge in Brisbane, Australia, which exhibits certain tensegrity structural principles (Figure 1).

Figure 1. Kurilpa Bridge in Brisbane, Australia [2]

1.1 Grids Types

When defining spatial frames, a grid can be considered as a network of elongated members connected by nodes at their edges. When the grids are double layered (DLG), they create a more complex structure containing two parallel networks of members forming the upper and lower layers, which are connected by a third intermediate layer of inclined and/or vertical bars/struts.

A Double-Layer Tensegrity Grid (DLTG) is a special type of DLG. A grid is considered to be a DLTG when the upper and lower nets are composed of tensioned members, the structure is pre-stressed and the grid conforms to the tensegrity definition [3]. DLTGs were first proposed by Fuller, Emmerich and Snelson in the 1940s. Notable developments of the form have involved the use of tensegrity pyramids by means of joining the ends of some struts [4] and the juxtaposition of tensegrity prisms and truncated pyramids while avoiding contacts between struts [5] in the late 1980s. These structures have formed the basis for many of the DLTGs developed in the intervening period [6-8].

1.2 Deployable Double-Layer Tensegrity Grids (DDLTG)

When a DLTG structure has the capability of being folded and deployed due to its topology and geometry, it is termed a Deployable Double-Layer Tensegrity Grid (DDLTG). Although there are many examples of deployable tensegrity antennas, booms and towers, relatively few examples of DDLTG have been reported.

While some examples can be termed 'demountable' and require dismantling before being folded [8], the first proposal for a true DDLTG enabled deployment by means of elongating the struts, shortening the cables or a combination of both [9]. This structure trialed the so-called Simplex module, composed of three struts and nine tendons with was no contact between struts.

Later proposals investigated the possibility of deploying a DDLTG composed of modules with four or six struts using scale models [10]. The most recent example of a DDLTG made use of numerical and physical models to investigate a grid structure containing ‘V22 expanders’ [11]. Two folding methods were detailed, one relied on self-stress while the second did not. The latter method was also successfully applied to other grid configurations.

A potential advantage of tensegrity structures is their kinematic indeterminacy. When arranged as a foldable system, only a small quantity of energy is needed to change their configuration because the shape changes with the equilibrium of the structure. As a result, DDLTGs are potentially optimal systems to be incorporated into space applications or temporary shelter structures.

2 STRUCTURE DETAILS

2.1 Grid Design

The DDLTG constructed for this work is termed a ‘Quastruct-S1’ (Figure 2), the detailed development of which was undertaken previously [3]. This grid type is composed of modules of four struts, with nets of cables resembling an s-shape on the upper and lower layers. It is a novel form developed by applying a rot-umbela manipulation to the patented 4^4-Be1-Te1 DLTG [12, 13]. The Quastruct-S1 is a Class 2 tensegrity structure, with the classification number defining the number of struts meeting at the same joint.

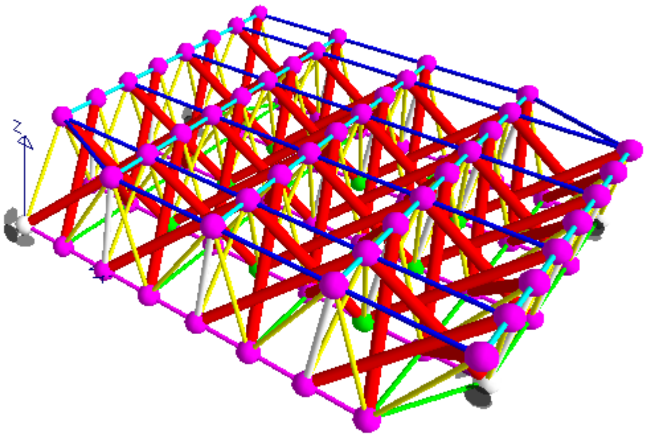

Figure 2. Structural analysis model of Quastruct-S1 DDLTG

A 4×4 m grid was designed, containing 16 equal 1 m^3 modules. The grid contained 86 nodes, 64 struts and 221 cable segments (Figure 2). The grid was analysed using the ToyGL graphical simulation program that implements the discrete element method in real time [14]. The program provides a versatile method for the design and static analysis of tensegrity systems, permitting direct feedback on structure behaviour to real time changes (Figure 3).

Member elements were designed in accordance with Eurocode 3 Design of Steel Structures. HSS 26.9×3.0 circular hollow sections and 4.75 diameter galvanised high tensile steel wire rope were used throughout. The total mass of the structure was 233 kg, equivalent to 14.6 kg/m^2 which is considered light for a space frame structure.

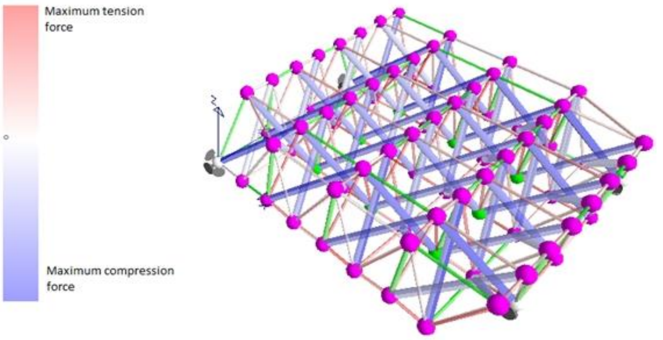

Figure 3. Visualisation of member axial forces under loading

2.2 Node Design

A key component of the design process of the grid was the design of the nodes, in particular the inner node (Figure 4). A number of design options were developed using hand sketches, 3D computer models and full scale prototypes.

The design criteria were numerous: the node had to adequately transmit forces of up to 9 converging members whilst facilitating folding of the structure. A compact design was important to minimise member eccentricities. Standard off the shelf elements were to used where possible to minimise cost and fabrication time.

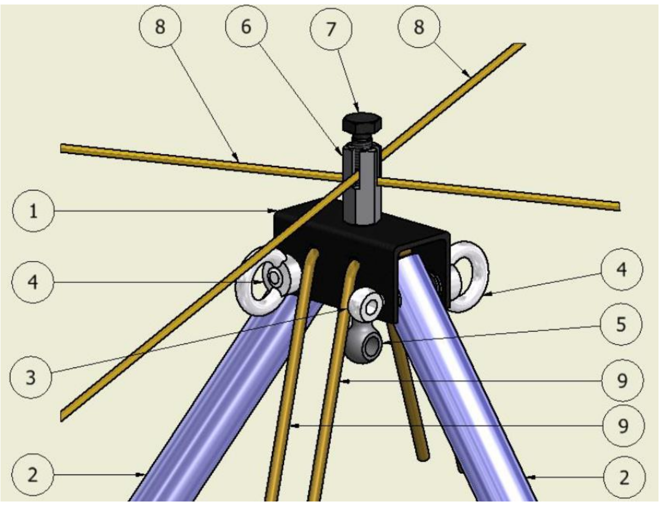

Figure 4. Detail of inner node [15]

Table 1. Components of inner node

ID	Component Detail
1	Central U-shape core
2	Circular hollow section struts
3	Bolts to constrain struts / eyebolt to anchor cables
4	Standard nut / lifting eye nut to connect to 3
5	Eyebolt to anchor turnbuckle for tensioning vertical cable
6	Bi-directional clamp for horizontal cables
7	Bolt to fix horizontal cables in clamp
8	Horizontal cables
9	Diagonal cables
10	Fixing plate (shown in Figure 5)

The component details of the final design, for which a patent was granted [15], are given in Table 1. Folding is achieved by allowing the compression struts to rotate along their axis of connection and allowing the diagonal cables to pass freely through when their ends are released.

Figure 5. Inner node fixing plate (highlighted in red)

2.3 *Assembly of Grid*

A full scale timber template was used to facilitate accurate positioning of the nodes (Figure 6a). A detailed fabrication sequence was developed which included the preassembly of certain component groups to streamline the process [16]. The broad sequence involved the placing of lower cable net, followed by the strut subassemblies and then the upper cable net. At this stage the grid was stable but not rigid. The diagonal cables are then placed and the grid completed by the addition of the vertical tensors and the closing of the inner node fixing plates.

The vertical tensors are the 'active elements' of the structure. Through shortening of their length using a turnbuckle, the grid is forced to expand like a 'scissors framework' and a state of self-stress is introduced into the grid. It was determined that a shortening of the tensors by 50 mm would achieve the targeted self-stress and provide a stable and rigid DDLTG which could then be lifted into position. The grid was supported on 4 No. 1.2 m high fabricated steel posts to allow load application and structural testing.

2.4 *Folding and Deployment of Grid*

The patented node design allows for a fast and efficient folding of the structure. Once the vertical tensors, diagonal cables and inner node fixing plates are released, the structure can be folded progressively by folding the struts inward. The structure folds along two axes and transforms from a 4×4 m grid to a cluster of cables and struts of diameter 0.56 m and approximate height 1.6 m (Figure 6b). The reduction in area from 16 to 0.25 m^2 equates to a 'coefficient of deployability' (16/0.25) of 64. As the nodes have not been dismantled in the folding process, re-deployment of the grid can be completed quickly and efficiently as a reversal of the folding process described above.

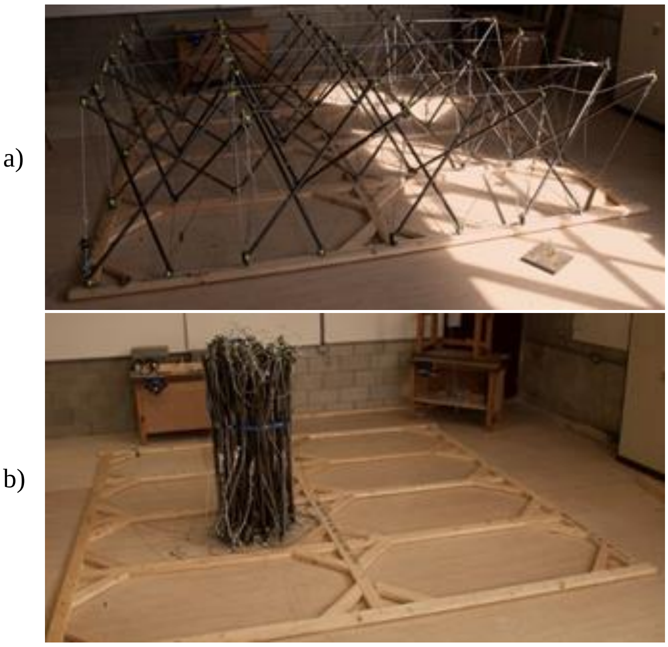

Figure 6. View of the DDLTG in its a) unfolded and b) folded configurations

3 GRID TESTING

3.1 *Instrumentation*

In order to monitor the behaviour of the grid under loading, 5 compression struts and 3 tension cables were instrumented (Figure 7).

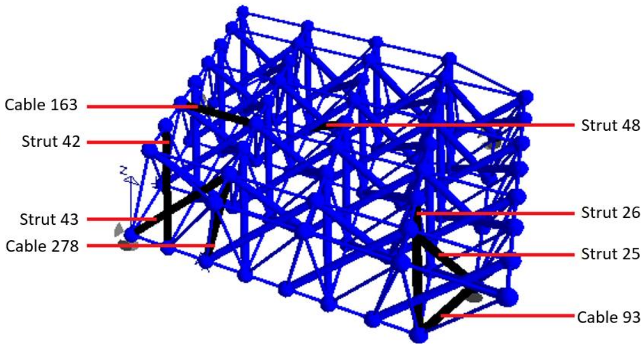

Figure 7. Instrumented grid members

The struts were chosen so as to provide data on 2 heavily loaded members (struts 25 & 43), 2 moderately loaded members (struts 26 & 48) and 1 lightly loaded member (strut 42). Each strut was instrumented with a pair of biaxial strain gauges set up in half bridge format. The gauges had a 3 mm gauge length and a nominal resistance of 350 Ω (Omega SGD-3/350-RYB21). The instrumented areas were surrounded with a protective covering to avoid damage during the assembly and testing of the grid (Figure 8). A DataTaker DT85 Series 2 data logger was initially used, however the electrical noise was found to be high. An Omega DP25B controller was used in its place and, in half bridge format, the system was able to provide a resolution of 1.5 με.

Figure 8. Instrumented compression struts with projective coverings over strain gauges

A cable member was chosen in each of the upper, lower and diagonal layers (cables 163, 93 & 278). The cables were instrumented with 5 kN load cells (Control Transducers P5-500). The load cells and gauges were calibrated using a Zwick Roell 500 kN servo hydraulic testing machine.

Displacement of the grid was monitored using a Leica TC407 total station, with reflective targets attached to each node on the upper layer. Measurements were taken after each load increment.

3.2 *Loading*

Due to the scale of the structure, load was applied in the form of small precast concrete slabs to 8 nodes on the lower grid. The nodes were selected to ensure an even distribution of load, while allowing for their safe application from outside the structure boundary. Two sizes of slab were used, of mass 14.4 and 24.4 kg, and they were attached to the structure via specially fabricated steel hangers (Figure 9).

Figure 9. Grid test layout with structure partially loaded (increment 4 of 6)

There were 6 increments of live load applied, beginning with the steel hangers alone and finishing with the hangers and 5 concrete slabs. The maximum total load applied to the grid was 8.54 kN, which equates to 0.53 kN/m^2. This value is comparable to the characteristic load value of 0.4 kN/m^2 which is defined in Eurocode 1 Actions on Structures for Category H roofs, i.e. those which are only accessible for normal maintenance and repair.

4 RESULTS

4.1 *Deflection*

After the application of the structure self-weight, a mean vertical deflection of 201 mm of the upper nodes was recorded. Figure 10 illustrates the live load deflection curves for 6 sample upper layer nodes. It is evident that the structure behaves in a generally linear manner, with a mean maximum live load deflection of 59.1 mm recorded.

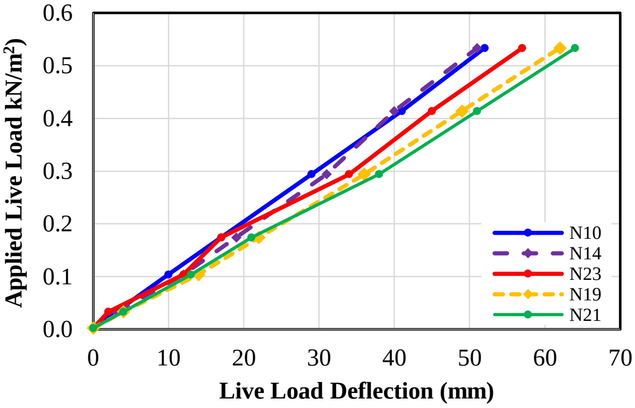

Figure 10. Load deflection curves for 6 sample upper layer nodes

The recorded experimental deflections were significantly greater than those predicted by the analysis model. The ToyGL model predicted a mean vertical deflection of 6.5 mm under self-weight and a mean live load deflection of 23.9 mm.

4.2 *Strut Forces*

Figure 11 illustrates the compression forces in the instrumented struts under loading. The response to load is generally linear, with a maximum force of 3.32 kN recorded in strut 25.

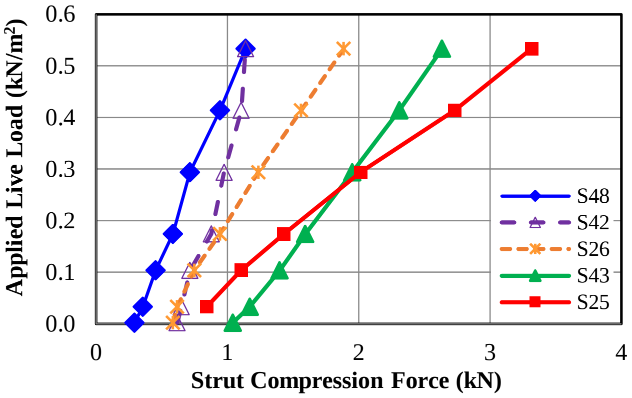

Figure 11. Measured strut forces

The ratios of theoretical to experimental compression forces for 3 struts are illustrated in Figure 12 for each increment of live load. While there is broad agreement of the forces under self-weight, it is evident that the theoretical and experimental values diverge in a linear manner as load increases with the experimentally recorded values less that those predicted.

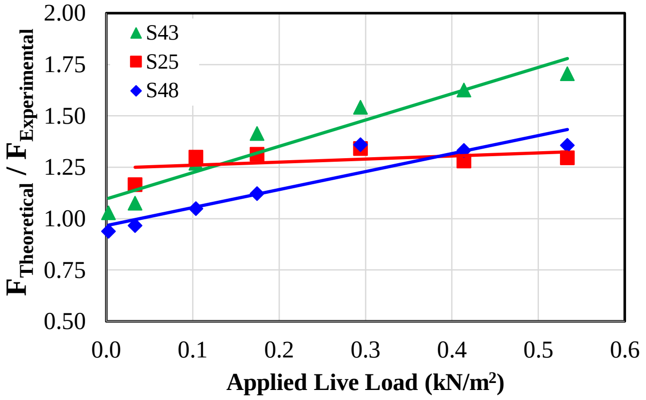

Figure 12. Comparison of theoretical and experimental strut forces

4.3 *Cable Forces*

Figure 13 illustrates the tension forces in the instrumented cables under loading. The response for cables 93 (lower layer) and 278 (diagonal layer) to load are generally linear, however cable 163 (upper layer) clearly goes slack upon loading. A maximum force of 1.19 kN is recorded in cable 93.

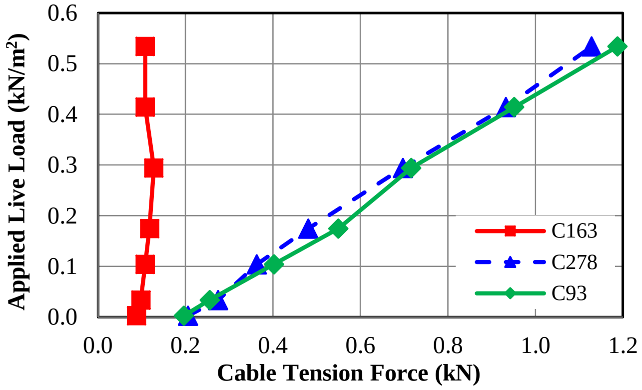

Figure 13. Measured cable forces

The ratios of theoretical to experimental tension forces for cables 93 and 278 are illustrated in Figure 14 for each increment of live load. The theoretical model significantly overestimates the tension forces in the cables.

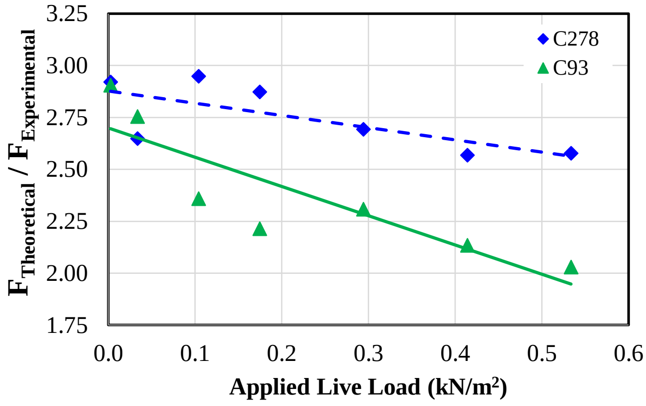

Figure 14. Comparison of theoretical and experimental cable forces

5 DISCUSSION

During testing of the DDLTG, a number of observations were made regarding the performance of certain details. It was noted that the top of the steel supports rotated inwards under loading. Rotation of the other nodes was also observed due to the high level of eccentricity between converging members (up to 80 mm). These resulted in the slacking of several of the upper cables, reducing the grid's stiffness and increasing its deflection. Improvements to the support arrangement and node design are suggested for future works.

The addition of the inner node fixing plate (Figure 5) reduced the tendency of the node to rotate under imbalanced loading. It is possible however that its behaviour is then closer to a fixed node than a true pin. This could introduce bending moments in the members with a resultant change in the distribution of forces within the structure and is an area that requires further investigation.

The method of applying self-stress to the structure is a very important area which can have a significant impact on the member forces. In this work the vertical tensors are shortened to introduce the self-stress, however there is no control on the tension in the remaining cables. If the initial tension level in these cables is not set correctly, either too low or too high, the tensions induced by the self-stressing will be imbalanced, affecting the overall stiffness of the structure and the distribution of forces within it.

In contrast to the above, the ToyGL analysis model considers perfect pin-joint nodes, with no eccentricity, no rotation, no bending moments, no friction, etc., and as such differences to the measured values are not unexpected.

6 CONCLUSIONS

This paper describes the development and testing of a novel 'Deployable Double Layer Tensegrity Grid' (DDLTG). A large scale 4×4 m grid structure was designed using the 'Quastruts-S1' tensegrity module. Nodes were developed to cater for the connection of multi-directional cables and struts, while allowing for member rotations to permit folding of the structure.

The grid was constructed, instrumented and load tested to determine its functionality and structural performance. The overall behaviour of the grid proved satisfactory, and the structure folded into a compact cluster 0.56 m in diameter.

The structure was loaded to an equivalent live load of 0.54 kN/m^2. While the overall structural behaviour was as expected, recorded deflections were greater and measured member forces were less than those predicted by the analysis model. Potential reasons for the differences are discussed.

It is concluded that the developed DDLTG offers many advantages as it can be easily stored, transported, and erected within a short time frame, allowing for uses such as temporary shelters, exhibition roof structures, etc. Further work is required to improve the modelling of the structure to better predict its structural performance, as well as improving the node design and the method of applying self-stress.

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