1. Introduction

‘Tensegrity’ is a developing concept using which amazing lightweight and adaptable structures can be created, giving the impression of a cluster of struts floating in the air. Tensegrity structures consist of compression and tension members, where in most cases the tension members may be cables and compression members bars where the cables surround the bars. Most of the cable–strut configurations are not in equilibrium, and when constructed may collapse to a different shape. Only the cable–strut configurations in a stable equilibrium can be classified as tensegrity structures. If well designed, the application of forces to a tensegrity structure will deform it into a slightly different shape in a way that supports the applied forces. A tensegrity structure’s struts cannot be attached to each other through joints that impart torques. The end of a strut can be attached to cables or ball jointed to other struts. Tensegrity structures can be defined as a pattern that results when the ‘push’ provided by struts and the pull provided by tendons achieve a win-win relationship with each other. Pull is continuous whereas push is discontinuous. The continuous pull is balanced by the discontinuous push, producing the integrity of tension and compression. A common example of a tensegrity is in a child’s balloon. When examined as a system, the rubber skin of the balloon can be seen as continuously pulling (against the air inside) while the individual molecules of air are discontinuously pushing against the inside of the balloon keeping it inflated. All external forces striking the external surface are immediately and continuously distributed over the entire system. Hence, the balloon is quite strong despite its thin material.

A large amount of literature on the geometry, art form and architectural appeal of the tensegrity structure exists, but there is little on the dynamics and mechanics of these structures. A study was conducted on the double layer tensegrity grids (DLTG) consisting of triangular prisms...
subjected to static loads using a first order linear analysis (small deflections) of prestressed pin-jointed networks based on the flexibility approach\(^7\). A generalised non-linear static analysis of ‘n–strut’ tensegrity systems and design equations for self-deployable tensegrity systems were derived\(^6\). Deployable structures were developed, based on the tensegrity concept, for applications in space. Various methods for form finding methods of tensegrity structures was proposed\(^7\). A detailed investigation into the origin and original patents of tensegrity structures was conducted\(^6\); general methods and the corresponding computer codes for creating tensegrity structures was proposed\(^6\); a new technique for developing tensegrity structures and their deployment in the field was developed. An experimental and analytical investigation was carried out on the prototype structures to study the behaviour of the structure under various parameters.

From the above literature the history and background of the tensegrity structures are studied to ensure the understanding of the fundamental concepts. The accepted definitions of tensegrity and a classification of these structures are given. Many case studies on towers and domical structures suggest the advantage of the tensegrity system in future engineering works. Most of the works are dedicated to conceptual design and simple models which will prove useful in the validation of the current work. The study of the tensegrity system applied to roofs would help us predict the efficiency of the chosen roof configuration for large span structures and also the advantage of these roofs for temporary structures in areas of calamities. In this paper, a finite model of a basic tensegrity module and a 2x2 tensegrity grid has been developed and analysed to study the mechanism of the structure under various prestressing forces. Later, based on the 2x2 grid the study was extended to 4x4 and 8x8 grid structures.

2. Material and Section Properties

In this study\(^10\), galvanized iron (GI) pipes of medium type, conforming to the Indian Standard\(^11\), were used as compression members. A 2.8 mm nominal diameter mild steel stranded wires of 6 x 19, confirming to Indian Standards\(^12\), were used as tensile members. The material properties and section properties of the members are as mentioned in Tables 1 and 2 respectively.

| Table 1. Material properties |
|-------------------------------|
| **Materials** | **Mass (kg/m)** | **Modulus of elasticity (N/mm²)** | **Yield stress (N/mm²)** | **Poisson’s ratio** |
|-------------------|----------------|-------------------------------|----------------------|-------------------|
| Galvanised Iron Pipes | 1.21 | 2.05 x 10⁵ | 240 | 0.25 |
| High Carbon Steel Wires | 6.09 | 0.954 x 10⁵ | 1421.335 | 0.25 |

| Table 2. Section properties |
|-------------------------------|
| **Section** | **Material** | **Diameter (mm)** | **Area (mm²)** |
|-------------------|----------------|------------------|----------------|
| Cables | High carbon steel wires | 2.8 | 6.53 |
| Struts | Galvanised iron pipes | Internal diameter 15.9 | External diameter 21.1 | 160.28 |

3. Analysis

A double layered plane tensegrity structure for roof systems has been developed and analysed using the finite element package. A basic tensegrity module and a 2x2 grid structure have been developed and analysed to study the mechanism under various prestressing forces. The study has also been extended to a 4x4 and 8x8 tensegrity grid structure to study the behaviour of large span tensegrity structures. The prototype configuration used in this project for the tensegrity grid structure is half cuboctahedron shown in Figure 1. It comprises of 12 cables (four top cables, four bottom cables and four side cables) and four struts in all. The development of the finite model and analysis of the work has been carried out using SAP2000.

![Figure 1. Half-cuboctahedron.](image-url)
3.1 Basic Tensegrity Module

A basic half-cuboctahedron tensegrity module is designed and the prestressing forces in the members are worked out using Stern’s design equations (1999). It comprises of 12 cables and 4 struts.

- All the cable elements are defined as cable sections of length 1m for bottom cables and 0.707m for top and side cables.
- All the strut members are defined as truss elements hence, no bending moments are developed in any of the members.
- At the bottom corner nodes, the degree of freedom is locked in all three translational directions and at the top nodes, all the degrees of freedom are released.

The structure has been analysed for different prestressing forces.

- Case 1: Assuming a prestressing force of 1.25 kN on the top cables and the corresponding forces for all other members are worked out using Stern’s equations (1999).

The relationship between the internal forces is stated as,

\[
\frac{F_t}{L_t} = \frac{F_s}{L_s}
\]

\[
a F_s = b F_b
\]

\[
F_t = 2 \left( \frac{L_t}{b} \right) F_s \sin \left( \frac{\pi}{n} \right)
\]

\[
F_s = 2 \left( \frac{L_s}{a} \right) F_a \sin \left( \frac{\pi}{n} \right)
\]

where, \(F_t\) is the force in the top cable, \(F_b\) in the bottom cable, \(F_a\) in the leg ties, \(F_s\) in the strut. \(a\) is the length of top cable, \(b\) the bottom cable, \(I_t\) the leg tie and \(I_s\) the strut. Using above equations, the relationships for the half cuboctahedron configuration can be found considering \(a=0.707m\), \(b=1.0 m\), \(L_t=0.707m\) and \(L_s=1.224m\). Hence, all forces can be derived in terms of strut force as,

\[
F_a = 0.578 F_s
\]

\[
F_b = 0.707 F_s
\]

\[
F_s = F_b
\]

- Case 2: Assuming a prestressing force of 1.5kn on the top cables and the corresponding internal member forces are worked out as above.

For the above cases, the structure is analysed for various static loads. The 3D view of the structure modelled in SAP2000 is shown in Figure 2.

3.2 Analysis of the Tensegrity Grid

A finite model of 2x2 grid tensegrity structure has been developed by agglomeration of 4 basic half-cuboctahedron modules and analysed under static loads for prestressing forces of 1.25kN and 1.5kN on top cables. A 3D view of the structure is shown in the Figure 3. For the central bottom node, all the three degrees of translations and rotations are locked.

For the above cases, the structure is analysed for various static loads. The 3D view of the structure modelled in SAP2000 is shown in Figure 2.

Based on the 2x2 grid structure, the study has been further extended to large span tensegrity structures of 4m x4m and 8m x8m grids and the same has been developed.
and analysed. The 3D view of the 4x4 and 8x8 grid structures are shown in Figures 4 and 5 respectively.

Figure 4. 3D view of 4x4 grid in SAP 2000.

Figure 5. 3D view of the 8x8 grid in SAP 2000.

4. Results and Discussion

The finite model of the single module and grid structures of the 2x2 grid, 4x4 grid and 8x8 grid structures are well analysed under different static loads to understand the behavior of the structures.

4.1 Single Module Tensegrity Grid

The analysis of the single module tensegrity structure under various static loads shows a better result in Case2 though much variation is not observed. The maximum nodal displacements observed on the top nodes for both the cases under various loads are shown Figure 6.

Figure 6. Maximum nodal displacements of 1x1 module.

The member forces are also well analysed. The maximum force is observed in the top cables. Figures 7 and 8 show the forces developed in the struts and the top cables respectively for both the cases.

Figure 7. Strut forces of 1x1 module.

Figure 8. Cable forces of 1x1 module.

4.2 Behaviour of Tensegrity Grids

On the analysis of the finite model of 2x2 grid tensegrity
structure under various loads, the maximum nodal displacement is observed in the top centre nodes. Figure 9 shows the maximum nodal displacements of the 2x2 grid structure.

The permissible nodal displacement of L/250 as per research value\(^\text{10}\), which is 8mm for 2m x 2m structure is attained at a uniform nodal load of 750N. Figures 10 and 11 shows the strut forces and maximum cable forces developed in the bottom centre cable in the structure for both the cases respectively.

From the above data, it can be seen that the cable forces and the strut forces developed in the 2x2 grid for both cases are similar.

### 4.3 Behaviour of Large Span Tensegrity Grids

Based on the 2x2 grid structure the 4x4 and 8x8 structures have been modelled and analysed. The Figure 12 and Figure 13 show the maximum nodal displacements observed in the case of 4x4 and 8x8 grids respectively.

From Figure 12, it can be observed that the permissible displacement of 16mm (i.e. L/250) for 4x4 grid is obtained at a nodal load of 1125N.

From Figure 13, it can be observed that the permissible displacement of 32mm (i.e. L/250) for 8x8 grid is obtained at a nodal load of 2000N.

In this paper, the feasibility of a temporary roof shelter for large span structure has been explored. The large span grids
made of the cluster of struts floating in the air consists of very thin cable elements that make the system attractive. The portability and stowage in compact volume are the added benefits of the deployable grid structure that make the structure feasible for temporary shelters. Initially, a 1x1 single module is developed, analysed and extended to a 2x2 grid by agglomeration. The 2x2 grid is developed as a single unit as it connects to the common bottom cables in the centre. Based on the 2x2 grid the 4x4 and 8x8 grids have also been developed and analysed. From the results, one can infer that the larger span tensegrity grid structures are more feasible. However, studies on different configurations of tensegrity modules and grids can help us arrive at the right choice for a given scenario. Further studies aim at the development of hexagonal configuration module grid system and its feasibility for roof systems compared to the half-cuboctahedron module.

6. References

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