DEVELOPMENT AND ANALYSIS OF A PENTAGONAL PRISM TENSEGRITY SYSTEM IN ROOF STRUCTURE

Rohith S
P G Student, Department of Civil Engineering, SRM University, Kattankulathur, Tamil Nadu, India.

R. Ramasubramani
Assistant Professor, Department of Civil Engineering, SRM University, Kattankulathur, Tamil Nadu, India.

ABSTRACT
The deployable tensegrity structures were developed to meet the fast growing demand for temporary structural systems, that requires a compact storage space. Though the concept of tensegrity can be dated to the late 1960’s, only very few applications exist. This paper focuses on the experimental and analytical study on a pentagonal configuration tensegrity module. The study in this paper confines to a single pentagonal module. The behavior of the structure is observed during the experimental and analytical study based on the nodal displacements and member forces. The analytical study has been conducted using a FEM package and the results are well compared.

Key words: Deployable, Tensegrity, Pentagonal Module, Grid Structure.


1. INTRODUCTION
Structures capable of large configuration changes from the compact-packed state to a large-deployed state is known as deployable structures. Obvious advantage of these structures is the ease in storage and transportation. Hence, they serve great as temporary structures.

Tensegrity structures are comparatively new and developing structural systems, say about 60 years old[1]. Though a lot of study has been conducted in this field, very few practical applications exist. This concept has also received attentions from mathematicians, architects and biologists etc. A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in
space [2]. Deployable tensegrity structures have an added advantage since the compressive elements in the tensegrity systems are disjointed. Hence, this makes it possible to fold the tensile members and hence the structure can be stored in compact volume and transported easily after use.

However, the most challenging step is the design of the tensegrity structure, which is generally known as the form finding process. Though several form finding methods are available for the design of a tensegrity structure, no single method can be concluded for the design of tensegrity structures in general. The pentagonal module in this paper has been designed using the equilibrium equations developed by Ian Stern in 1999[3]. The cables and the struts have been designed accordingly. This paper reviews the behaviour of the pentagonal tensegrity module, under the application of various loads. The mechanism of the structures is studied based on the nodal displacements and member forces, obtained from the experimental and analytical data.

2. FABRICATION AND TESTING OF MATERIALS

A deployable tensegrity module, of a pentagonal prism configuration has been fabricated in the structural engineering laboratory, SRM University, Chennai. The structure has been fabricated, based on cable mode deployability concept [4], [5],[6]. The Mild Steel pipe has been used for the struts and the MS stranded wires of 6 x 19 strands has been used for the cables. The cables and pipes were tested in the UTM of 1000 ton capacity as shown in Figure 1 and Figure 2. The key material and section properties are as given in table 1 and table 2.

![Figure 1 Testing of MS pipes in UTM](image)
Eye bolts of size M12 are used to connect the cables to the pipes. All measurements has been taken from centre to centre of the eye bolts.

2.1. FABRICATION AND TESTING OF THE SINGLE TENSEGRITY MODULE

The structure has been designed as per Sterns equilibrium equations [3], the length of bottom cables, tie cables and the top cables are 1m, 0.95m and 0.59m respectively. The cables were connected to the joints using aluminium ferrules by means of hydraulic press to ensure strong joints with no slip. At first a reticulated cable network was fabricated by connecting cables to the eye bolts. One turn buckle of size 200mm was connected in one of the tie cables to provide deployability to the structure. MS pipes of lengths 1.38m were then placed in the required positions loosening the turn buckle to 15 cm length. In order to perform FEM analysis, it is essential to determine pre stress levels in the structure at the self-equilibrium configuration. In order to determine the pre-stress values, 3 strain gauges of 2mm, 120Ω were
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connected to one top, one bottom and one tie cable respectively. One 5mm, 120 Ω strain
gauge was connected to one of the struts as well. Once all the strain gauges are then
c弄ected to data logger, the turn buckle is then tightened and the tie cable attains a length of
0.95m. The pre-stress values at this self-equilibrium position were recorded. The structure is
then tested for different loads as shown in Figure 3 for nodal displacement and member
forces.

![Figure 3 Testing of the single Tensegrity Module under the application loads](image)

3. FEM ANALYSIS
The prototype of the pentagonal tensegrity module as described in the previous section has
been modeled using the FEM package, SAP 2000 v.18. All the cable elements were defined
as cable sections, and the strut members were defined as truss elements. Hence no bending
moments are developed in any of the members. The material was assumed as linearly elastic
and isotropic. All the bottom nodes are restrained against translation in the vertical direction.
The values of the Young’s modulus of the strut and the cable elements obtained experimentally has been used. The FEM model of the single pentagonal tensegrity module is shown in Figure 4.

![Figure 4 3D view of single module in SAP 2000](image)
The pre-stress forces in the cables were assigned as target forces based on the experimental analysis performed. Since, initial pre-stress forces were not available for all the members they were worked out from the equations developed by Stern (1999). For a pentagonal prism tensegrity module, the member forces are as follows,

\[ F_s = \frac{\sqrt{2(5 - \sqrt{5})L_s}}{2a} F_b \]

\[ F_t = \frac{\sqrt{2(5 - \sqrt{5})L_t}}{2a} F_b \]

\[ F_a = \frac{b}{a} F_b \]

Where, \( F_s, F_a, F_b \) and \( F_t \) are the force in strut, top cable, bottom cable and tie cable respectively. \( a, b, L_t, L_s \) are the length of top cable, bottom cable, tie cable and strut.

Nodal displacement and member forces of the structure have been analyzed for various loads acting uniformly on each node.

### 4. RESULTS AND DISCUSSIONS

The comparison of the nodal displacements obtained from the experimental and analytical studies are shown in Figure 5. Both the deflection curves shows a non-linear variation and the stiffness of the structure have been observed to increase with loading. The steep increase in deflection is observed at smaller loads and on further application of loads only small variations are observed. Despite a variation of 20%, the trend remains same in both the cases.

![Figure 5 Comparison of the nodal displacements](image_url)

Figure 6 represents the comparison of strut forces obtained from the experimental and analytical study. The experimental values show a non-linear steep variation compared to analytical result. The experimental value is observed to be lower than analytical value up to 1200 N and on further increase in loading the experimental value shows a slightly higher deflection than the analytical values.
Comparison of the cable forces in the experimental and analytical study are shown in Figure 7. The top cable shows a higher value than the bottom and tie cables. The plot shows higher variations (-22% and +32%) between experimental and analytical results. At initial loads, up to 750 N, the experimental value is observed to be higher than the analytical value. On further loading, the numerical value is observed to be higher and has a steeper slope.

5. CONCLUSION
This paper covers a method of fabrication, instrumentation and testing of a pentagonal prism tensegrity module. The testing of pentagonal prism module was continuously monitored using strain gauges and dial gauges. FEM model of tensegrity system was modeled in SAP 2000 and analyzed. Later, the model has been updated based on the experimental findings. The structural response of FEM model well matched with the experimental model both in terms of member forces and nodal displacements. Only a variation of 20% has been observed in the values. Further, studies aim at developing and analyzing tensegrity grids by joining single pentagonal prisms for roofing purposes. The deployability of the tensegrity structure would make it suitable for the temporary shelters.
REFERENCES

[1] Valentin Gomez Jannegui, Tensegrity Structures and Their Applications to Architecture, Queen’s University, Belfast, 2007.


