

An Experimental and Analytical Investigation on a Newly Developed Truncated Hexahedron Connector

Vishal A. Arekar* , Yogesh D. Patil and Hemant S. Patil

Applied Mechanics Department, SVNIT, Surat – 395007, Gujarat, India; vishalarekar@yahoo.com, ydp@amd.svnit.ac.in, hsp@amd.svnit.ac.in

Abstract

Objective: The objective of this research work is to investigate the performance of a newly developed Truncated Hexahedron (THH) connector by analytical and experimental studies, and assess its suitability for space grid structures. **Method/Analysis:** The newly developed THH connector has been modeled in Finite Element Analysis Software - ANSYS and analyzed under uniaxial tension. Experimental studies on a real scale THH connector has been conducted with strain gauges attached on faces of the connector in form of three-element rectangular rosette. The maximum principal stresses on the surface of the connector obtained from ANSYS analysis have been compared with the experimentally obtained maximum principal stresses. **Findings:** The present study evaluates the principal stresses of the THH connector subjected to axial tensile loading by conducting analytical (ANSYS software) and experimental studies. Further, tolerable resemblance was observed in values of analytically and experimentally obtained maximum principal stresses on the surface of the connector. Hence, this validates the ANSYS model for the THH connector, which may be useful for evaluating the allowable load on the connector. The analytical studies conducted for different magnitude of vertical loading in double layer grid indicates linear variation of maximum principal stresses with the increase in the magnitude of loading. The newly developed THH connector has advantage of less length of web members in double layer or multilayer space grids as compared to MERO connectors, which will reduce the total weight of space grids. **Novelty/Improvement:** This study opens up possibility of resorting to a new compatible connector for space grid structures, which can easily be manufactured due to simple geometry, making it comparatively cheaper.

Keywords: ANSYS, MERO Connector, Space Grid Structures, THH Connector

1. Introduction

Double layer grids are considered as main group of space structures being light weight and having good aesthetic view, and are used to cover large open spaces with few or no internal supports. Because of simplicity in handling, manufacturing flexibility, quick on-site assembly and erection, the double layer grids are intended to be prefabricated. Hence, the different components of these space structures are usually produced in industrial units in large quantity with a higher degree of quality control. The members of double layer grids are inter-connected with various types of nodal connections and are usually assumed to carry axial loads only¹.

The joint, more specifically the connector, is a very important component of a space structure design. Primarily, the type of connector depends on the connecting

technique, whether it is welding, bolting or applying special mechanical connectors. It is also influenced by the shape of the members. Researchers² proposed classification of the joint modules which permits the identification of the basic components of joint assembly processes and their corresponding classification and standardization. A ball joint is considered as conventional joint usually used in double layer or multilayer grid structures. A number of studies have been conducted on ball joint and different types of joints. A ball joint behavior in a double layer grid under actual conditions was considered³ and then from the components utilized in practice and using ball joint system, a double layer grid was constructed. From experimental analysis of a steel space truss, an original type of connector has been developed which can be made using minimum technology, without special tools and requirements⁴. The connector was tested in ANSYS

* Author for correspondence

software for strain values till its elastic limit and compared with the experimental values. To find the mechanical properties of Ribbed Cast Steel Spherical Joint, the Finite Element Analysis (FEA) was carried out for the joint using SOLID95 elements, the three-dimensional solid elements, in ANSYS cell library⁵. Studies have been conducted by some researchers on Finite Element Modeling (FEM) of splice beam connections subjected to pure bending by modelling a three Dimensional (3D) finite element model of joint using the software package SUT-DAM, and have observed accurate correlation between FEM and experimental results⁶. Some researchers have examined behaviour of column base with box-shaped column under static loads by modelling a column connection with column base and showed the importance of base plate thickness of column⁷. These studies have indicated the importance of research studies on connection elements of the structures.

The MERO connection system is one of the most popular and widely used connectors for the double layer grids⁸. The standard MERO connector allows upto 18 tubular members to be connected at different angles. Researchers⁹ presented the relationship of force-displacement of MERO jointing system. The experiments showed the nonlinear behaviour of connector and the effect of degree of bolt tightness. The axial stiffness of the MERO connection was also evaluated¹⁰ considering 'hardening the screw' effect. The MERO connection system, the first commercially available, is still considered to be one of the most elegant solutions for the construction of space grid structures¹¹. In spite of gaining popularity, the MERO connector usually involve higher cost and time of fabrication due to the complex geometry with curved surfaces.

Keeping this in view, in the present study, a new solid connector with simple geometry and flat surfaces has been developed and named as Truncated Hexahedron (THH) connector. The connector has been modelled and analyzed using ANSYS finite element analysis software and the experimental investigations have also been conducted on the model connector to validate the ANSYS results. However it should be noted that only surface stresses can be measured and compared by experimental investigation.

2. Geometry of Connectors

2.1 MERO Connector

The MERO connector, introduced by Dr. Mengerhausen about 5 decades ago, has proved to be exceptionally

popular and used for various space structures⁸. The MERO connector consists of a node or joint which is of spherical shape and hot-pressed steel forging with flat facets and tapped holes. Generally, circular hollow (tubular) members are joined together by the connector and they are welded at the ends of these tubular members with cone-shaped steel forgings so as to accommodate connecting bolts⁸. Bolts are tightened with the use of a hexagonal sleeve and locked using dowel pin, resulting in a completed joint as shown in Figure 1. The MERO connector can assemble up to 18 tubular members without any eccentricity. The connectors of different sizes with diameters ranging from 46.5 to 350 mm can be produced, the corresponding bolts ranging from M12 to M64 with a maximum permissible force of 1413 kN¹². A typical space module of the MERO connection system is a square pyramid with both chord and diagonal members of the same length, 'a' with extended angles 90° or 60°. Thus, the height of the space module is $a/\sqrt{2}$, and the angle between inclined member and chord member is usually 54.7°.

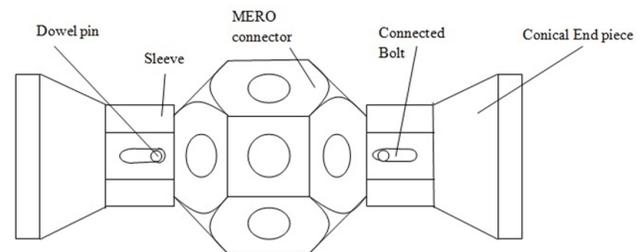


Figure 1. Typical schematic of a MERO connector.

2.2 Newly Developed THH Connector

Keeping in view the connection requirements of a double layer grid, a new (THH) connector has been created by truncating a cube or Regular Hexahedron (Cube). There are total six square faces and eight corners of any hexahedron. In the new THH connector (refer Figure 2.), all the corners of the hexahedron have been truncated with planes having three direction cosines $\pm 1/\sqrt{3}$ creating six regular octagonal faces and eight triangular faces. Out of the six octagonal faces, excluding top and bottom (C and D in Figure 2.) faces, the remaining four vertical (A, B, E and F in Figure 2.) faces can be used for the connection of horizontal planar grid members of either top or bottom layer of a double layer grid. The eight triangular faces can be used for the connection of inclined (web) members of a double or multilayer grid. The direction cosines of these triangular faces have been selected in such a way that line of action of the forces of all the web members as

well as horizontal grid members at a connector remain concurrent. The main advantage of these direction cosines is the height of a double layer or multilayer grid with THH connector will be less than that with MERO connector. Due to this, length of all the diagonal (web) members will reduce which will ultimately reduce the cost of whole double or multilayer grid.

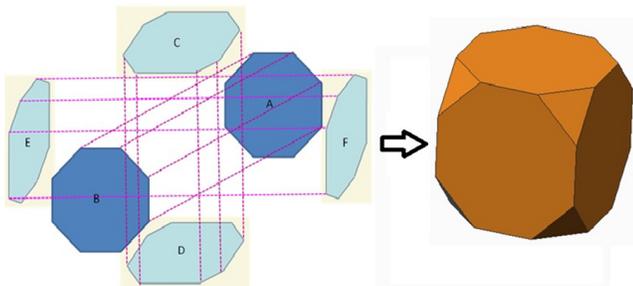


Figure 2. All octagonal faces and geometry of THH connector.

A THH connector has been prepared from a mild steel cube having dimensions of all sides 150 mm for the experimental studies. All the corners have been trimmed using plane passing through three points each at a distance of 43.934 mm in three directions from corner of a cube shown in Figure 3 so as to convert six square faces of the cube into regular octagonal faces. There are total 6 octagonal faces and 8 triangular faces of the THH connector. The mass of THH connector is 25.3 kg. The other properties under consideration are modulus of elasticity (E) = 2×10^5 N/mm², Poisson’s ratio (ν) = 0.3 and yield strength (FY) = 250 N/mm². For the connection of members, the required faces have been threaded as shown in Figure 3. The threaded holes considered are 30 mm indiameter and 30 mm in depth, while the threads are square threading with height 3mm, pitch 6 mm and depth 2 mm.

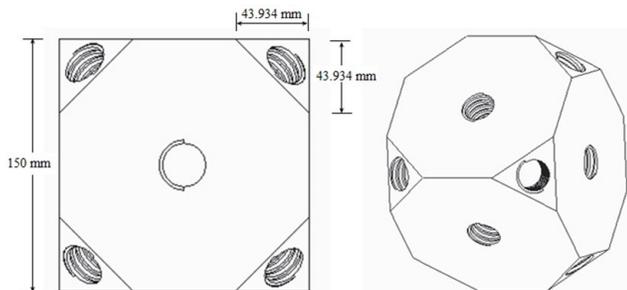


Figure 3. Plan and isometric view of the THH connector.

3. Study Of THH Connector

3.1 Analysis in ANSYS 14.5 Software

When the joints of the double or multi layer grids are subjected to static loads, provided that all the member forces are concurrent at joints, the axial force governs and non-axial effects become secondary significance in the member design³. Hence, if the behavior of joints is the focus of study then their axial behaviour only is to be considered for analysis³. Therefore, the newly developed THH connector has been analysed for uniaxial tensile loading condition in finite element analysis software - ANSYS (Figure 4). The uniaxial tensile load P has been applied ranging from 0 to 30 KN in increments of 2 KN. The maximum principal stresses at a particular location on the surface of the connector (at 37.5 mm distance from one of the octagonal face of the connector) for all the values of P have been found, and the variation of maximum principal stress with respect to uniaxial tensile load is shown in Figure 5. It should be noted that the location at which stresses have been obtained from ANSYS analysis is same as the point of intersection of the lines through the three strain gauges of the rosette from experimental studies. The properties of connector viz., Young’s modulus of elasticity, poisson’s ratio and yield strength have been considered as described in Section 2.2.

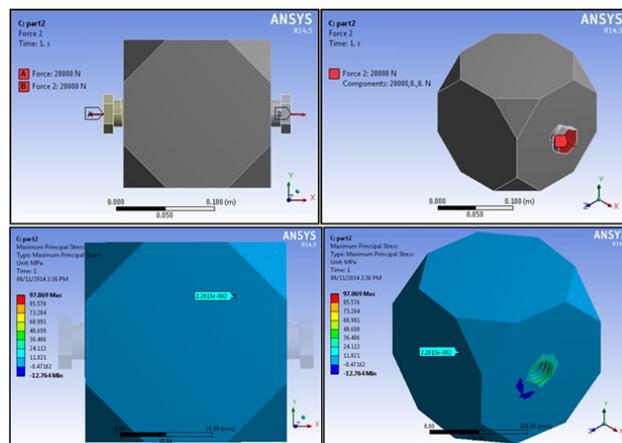


Figure 4. Model of THH connector and typical maximum principal stress value obtained from ANSYS.

From Figure 5 it can be observed that with increase in tensile load, the maximum principal stress increases linearly. This indicates that the stresses on the surface of

the connector, for the range of loading considered, are within the elastic limit. Further, efforts have been made to compare the stresses on the surface of the THH connector obtained analytically with the experimentally obtained stresses as discussed in Section 3.2.

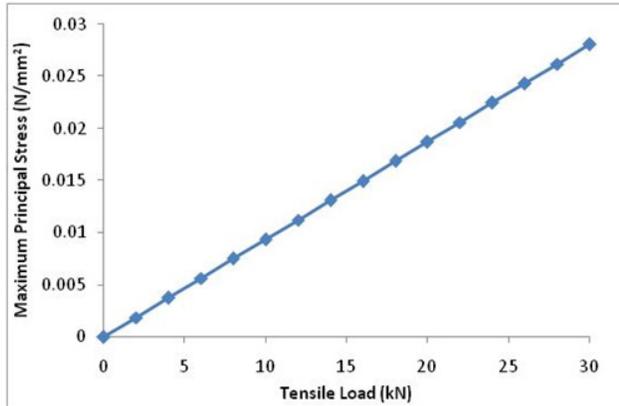


Figure 5. Variation of maximum principal stress with tensile load from ANSYS analysis.

3.2 Experimental Studies

3.2.1 Model Preparation and Testing

In order to understand the actual response of a THH connector under uniaxial loading, the real scale Truncated Hexahedron (THH) connector has been fabricated. A Mild Steel cube having 150 mm dimension on all sides, has been procured as shown in Figure 6(a). Now for cutting the corners, the distance of 43.934 mm has been marked on each of the three edges making a corner, and a cut was made in such a way that the resulting (cutting) plane would pass through all the three marked points, as shown in Figure 6(b). The process has been repeated for all the seven corners. Finally, threaded holes have been made on two vertical but opposite faces of the cube where the diameter and depth of the hole have been kept 30 mm each and the dimensions of the threading have been considered as 3 mm height, 6 mm pitch and 2 mm depth. Bolts with the same dimensions have also been made so as to match the actual field conditions of transferring of forces on the connector (Figure 6(c)). The strain gauges have been attached on faces of the connector in the form of three-element rectangular rosette. Wires have been attached to both the terminals of the strain gauges through light soldering as shown in Figure 6(d). The distance of the point of intersection of the lines through the strain gauges of the rosette (refer Figure 7) is 37.5mm from one of the octagonal faces of the connector. Then this model has

been put onto the Universal Testing Machine for applying tensile force and measuring the strains developed on the surface under observation. The other ends of the wires have been connected to the Digital Strain Gauge Indicator.

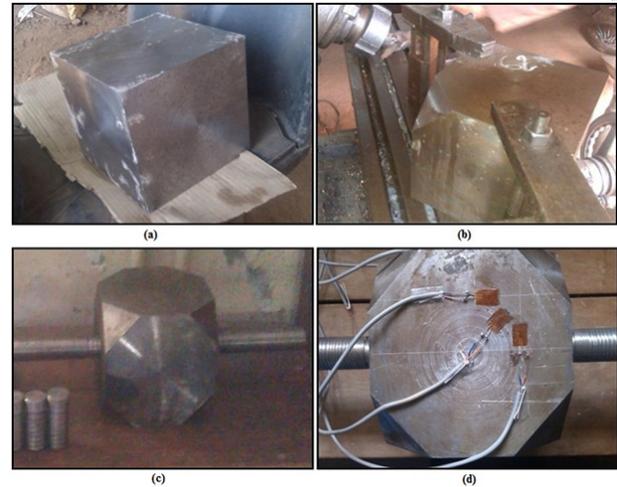


Figure 6. Real Scale connector model preparation.(a) Mild steel cube having 150 mm x 150 mm x 150 mm size.(b)Corner trimming of the cube.(c) Model of THH connector with inserted threaded bolts.(d) Connection of strain gauges to THH connector.

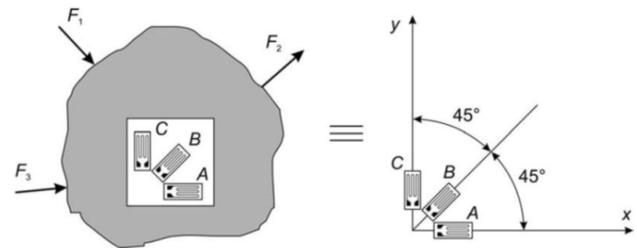


Figure 7. Three-element rectangular rosette.

3.2.2 Strain and Principal Stress Measurement

The electrical strain gauges have been used in the experiment having gauge length 5 mm, resistance 350 Ω and accuracy of $\pm 1\mu\epsilon$ (i.e., 10^{-6} strain). The three-element rectangular rosette employs gauges have been placed at 0° , 45° and 90° positions, as indicated in Figure 7.

Referring to Figure 7, the strain transformation relation equations are:

$$e_A = e_x \cos^2 a_A + e_y \sin^2 a_A + g_{xy} \cos a_A \sin a_A \quad (1)$$

$$e_B = e_x \cos^2 a_B + e_y \sin^2 a_B + g_{xy} \cos a_B \sin a_B \quad (2)$$

$$e_C = e_x \cos^2 a_C + e_y \sin^2 a_C + g_{xy} \cos a_C \sin a_C \quad (3)$$

Here, ϵ_A , ϵ_B and ϵ_C are the strains measured in strain gauges A, B and C respectively; ϵ_x and ϵ_y are the required linear strains in X and Y direction respectively; γ_{xy} is the required shear strain; α_A , α_B and α_C are the angles of strain gauges A, B and C respectively with positive X direction measured in anticlockwise direction.

Therefore, for three-element rectangular rosette, considering $\alpha_A = 0^\circ$, $\alpha_B = 45^\circ$ and $\alpha_C = 90^\circ$, the above equations can be rewritten as,

$$e_A = e_x, e_B = \frac{1}{2}(e_x + e_y + g_{xy}), e_C = e_y \tag{4}$$

From above equations, the required strains can be calculated as,

$$e_x = e_A, e_y = e_C, g_{xy} = 2e_B - e_A - e_C, \tag{5}$$

Thus, by measuring the strains experimentally, the Cartesian components of strains can be determined by using Equation (5). Next, by utilizing the following Equations (6) and (7), the principal strains ϵ_1 and ϵ_2 can be calculated.

$$e_1 = \frac{1}{2}(e_x + e_y) + \frac{1}{2}\sqrt{(e_x - e_y)^2 + (g_{xy})^2} \tag{6}$$

$$e_2 = \frac{1}{2}(e_x + e_y) - \frac{1}{2}\sqrt{(e_x - e_y)^2 + (g_{xy})^2} \tag{7}$$

Finally, the maximum principal stress can be found by the following Equation (8):

$$s_1 = \frac{E}{1 - \nu^2}(e_1 + \nu e_2) \tag{8}$$

3.2.3 Experimental Results

The uniaxial tensile force has been applied on the connector from 0 to 30 kN in increments of 2 kN (same as considered in ANSYS analysis) and the strain values have been recorded at each load increment. It should be noted that the strains on the surface of the connector were too less for the tensile force up to 26 kN and hence could not be measured. Therefore, only the strain readings for 28 kN and 30 kN could be measured and are tabulated in the Table 1.

Table 1. Experimental Measurement of Strains

Load (kN)	Strain Readings (10^{-6})		
	ϵ_A	ϵ_B	ϵ_C
0 to 26	-	-	-
28	-4	0	1
30	-13	0	3

The maximum principal stresses at a point under observation on the surface of the THH connector have been calculated based on Equation (8) and the results have been compared with ANSYS results as shown in Table 2.

Table 2. Comparison between ANSYS and Experimental Results

Load (kN)	Maximum Principal Stress (N/mm ²)	
	ANSYS	Experimental
28	0.0262	0.0199
30	0.0281	0.0228

4. Discussion

From Table 2 it can be observed that the maximum principal stress at surface of the connector obtained from analytical and experimental results are comparable within tolerable limits, which validates the ANSYS model for the THH connector. The slight difference in the values of maximum principal stress at the surface from ANSYS analysis and experimental studies could be attributed to the following two factors: 1. In the experimental study, the stress is computed from principal strains, which are obtained from the actual measured strains in the three strain gauges of the rosette. However, the ANSYS model employs finite element analysis to compute the stresses at the point of interest (in this case at the location of point of intersection of the lines through the three strain gauges of the rosette as shown in Figure 7). This may create some difference in the stresses obtained from ANSYS and experimental results; and 2. Possible experimental error due to sensitivity of the strain gauges.

Further it should be noted that maximum stress in the connector will occur at the bolt location where the load is being applied on the connector, and this stress would govern for the design of the connector. However, experimental measurement of the stresses at this location is not feasible due to difficulty with placement of strain gauges. Hence, the present study compares the experimentally and analytically obtained maximum principal stresses on the surface of the connector. The ANSYS analysis for the connector can be utilized to obtain stresses within the connector at different locations including the governing stress for design at the bolt location. This suggests that the ANSYS model for the connector is quite useful for estimating the stresses in the connector due to forces from multiple members joining at the connector in a real space grid structure.

5. Conclusion

The new solid THH connector having simple geometry has been developed by truncating the corners of a cube. The present study evaluates the principal stresses of the THH connector analytically (ANSYS software) and experimentally. Due to actual/larger size of the connector, strains induced on the surface are very less and hence, experimental results for few load values within elastic limit of the connector could be obtained. Tolerable resemblance was observed in values of analytically and experimentally obtained maximum principal stresses on the surface of the connector. Hence, this validates the ANSYS model for the THH connector, which may be useful for evaluating the allowable load on the connector. The newly developed THH connector has advantage of less length of web members in double layer or multilayer space grids as compared to MERO connectors, which will reduce the total weight of space grids. Hence, this study has opened up the possibility of availability of a new competent connector which can be easily fabricated in average technology conditions making it comparatively cheaper.

6. References

1. Koushky AL, Dehdashti G, Fiouz A. Nonlinear analysis of double-layer grids with composite nodes under symmetric and unsymmetrical gravity loads. *International Journal of Space Structures*. 2007; 22(2):133–40.
2. Bazrov BM. Classification of joints. *Russian Engineering Research*. 2010; 30(4):399–403.
3. Mostafavian SA, Davoodi MR, Amiri JV. Ball joint behavior in a double layer grid by dynamic model updating. *Journal of Constructional Steel Research*. 2012; 76:28–38.
4. Vacev T, Kisin S, Rankovic S. Experimental analysis of an original type of steel space truss node joint. *Architecture and Civil Engineering*. 2009; 7(1):43–55.
5. Zhang Y, Chen Z, Liu Y, Wei X, Bu Y. Study on mechanical properties of ribbed cast steel spherical joint in complex stress state. *Advanced Materials Research*. 2011; 284–286:1120–5.
6. Mohamadi-Shoore MR, Ghafari H, Amankhani M. Finite element modeling of RHS splice beam bolted connections. *Indian Journal of Science and Technology*. 2013; 6(3):4193–8.
7. Kiani A, Izadinia M. An overview on effects of geometric parameters in column connection behavior via finite element method. *Indian Journal of Science and Technology*. 2015; 8(28):1–7.
8. Subramanian N. *Principles of space structures*. Berlin:-Wheeler Publishing; 1981.
9. Ghasemi M, Davoodi MR, Mostafavian SA. Tensile stiffness of MERO-type connector regarding bolt tightness. *Journal of Applied Sciences*. 2010; 10(9):724–30.
10. Ebadi M, Davoodi M. Evaluate axial stiffness of the MERO connection under the effect of hardening the screw. *International Journal of Science and Emerging Technologies*. 2012; 4(1):116–22.
11. Chilton J. *Space grid structures*. Oxford: Architectural Press; 2000.
12. *Handbook of structural engineering*. CRC Press; 2005.