Perspectives in Science (2016) 8, 525—528

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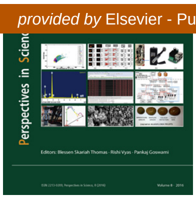

Development of a new connector for double layer space grids☆

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Received 20 February 2016; received in revised form 17 June 2016; accepted 17 June 2016
Available online 5 July 2016

KEYWORDS
THH connector;
Finite element analysis;
Double layer grid;
ANSYS

Summary Connection of the space grid elements by using connectors is one of the most common practices for construction of space structures. These connectors usually involve higher fabrication cost due to their complex geometry. To address this issue, in the present work, a new solid connector with simple geometry has been developed by truncating the corners of a cube, and is named as Truncated Hexahedron (THH). The experimental, theoretical and analytical studies have been carried out to obtain the stresses for THH connector. An instrumented axial loading test has been performed on actual THH connector, and the load-stress relationship has been obtained from load and strain measurement. A manual finite element analysis has also been carried out for theoretical computation of the stresses in the connector. Further, the THH connector has been modelled and analysed using ANSYS software and the obtained results have been compared with experimental and theoretically computed results. Subsequently, in order to assess the performance of THH connector in comparison to a standard connector (Spherical connector), a double layer grid has been analysed considering both Spherical and THH connectors at each joint of the grid separately, and it has been observed that the maximum principal stresses in both the connectors are mostly comparable. Hence, the newly developed THH connector can be considered to be as efficient as the Spherical connector. The study opens up a possibility of resorting to a new compatible connector for space grid structures, which can be easily manufactured due to its uncomplicated geometry, making it comparatively cheaper and quicker for fabrication.

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Introduction

Double layer grids form an important part of the space structures' family and are used to cover large open spaces with few or no internal supports. The connector is an extremely important part of a grid design (Koushky et al., 2007). Earlier research studies have attempted to understand the

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☆ This article belongs to the special issue on Engineering and Material Sciences.

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http://dx.doi.org/10.1016/j.pisc.2016.06.010

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behaviour of connectors. Researchers have proposed the classification of joint modules which permits the identification of basic components of the joint assembly processes and their corresponding classification and standardisation (Bazrov, 2010). The behaviour of ball joint or spherical connector has been studied under actual conditions in a double layer grid (Mostafavian et al., 2012) prior to utilising it for an actual double layer grid. Experimental studies on an original type of node joint for a steel space truss has been carried out and a connector which can be made in average technology conditions, has been developed and tested in ANSYS software for stresses upto elastic limit, and the results have been compared with the experimental values (Vacev et al., 2009). One of the popular connectors conventionally used for space grids is the spherical connector, however the complexity associated with fabrication of their curved surfaces, leads to higher cost for these connectors.

With 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 analysed using ANSYS software and experimental investigation has been conducted on the model connector to validate the ANSYS results. However, it should be noted that only surface stresses can be obtained by experimental investigation on a solid connector. Hence, an FEM based program has also been developed to validate the stresses within the connector obtained from ANSYS software. Further, in order to understand the behaviour of THH connector in comparison to the spherical connector at different locations of a space grid structure, a double layer grid has been studied for different magnitudes of vertical loading, considering the THH and Spherical connectors at the joints of the grid.

Analytical study of THH connector

A THH connector has been created by truncating a Regular Hexahedron (Cube). This can be achieved by truncating all corners of a cube with planes having three equal direction cosines $\pm 1/\sqrt{3}$, creating additional eight triangular faces and converting six square faces into octagonal faces. The THH connector can connect a maximum of 14 members at one joint. The selected direction cosines of triangular faces ensure that the line of action of forces of all the inclined as well as horizontal grid members at a connector remains concurrent.

For the experimental study, a model connector has been fabricated from mild steel solid cube of size 130 mm. All the corners of the cube have been trimmed by marking planes passing through three points at a distance of 38.076 mm in three orthogonal directions from each corner of a cube forming new eight equilateral triangular faces and six octagonal faces each having 53.8 mm edge length. The other connector material properties considered are, Modulus of elasticity $(E) = 2 \times 10^5\,\mathrm{N/mm^2}$, Poisson's ratio $(\nu) = 0.3$ and Yield strength (Fy) = $250\,\mathrm{N/mm^2}$. For the connection of members, the required faces have been threaded upto 30 mm depth. The threaded holes have been considered as 30 mm in diameter for octagonal faces and 28 mm in diameter for triangular faces with square threading of height 3 mm, pitch 6 mm and depth 2 mm. The THH connector considered for experimental study has also been modelled in ANSYS software. The uniaxial tensile force ranging from 4 to 20 kN have been applied on the connector in increment of 4 kN and the maximum principal stress developed at a point on the surface of the THH connector (at location coinciding with the point of observation for the experimental model) have been found using ANSYS software.

Experimental and theoretical validation of developed ANSYS model

Experimental Validation

In order to understand the response of a THH connector under uniaxial loading, a real scale THH connector has been fabricated. The strain gauges, with gauge length of 5 mm, resistance of 350 Ω and accuracy of ±1 micro strain, have been attached on one face of the connector in the form of three-element rectangular rosette in such a way that the point of intersection of the lines through the strain gauges of the rosette (refer Fig. 1) intersects at the centroid of the octagonal face of the connector. This model has been mounted on the Universal Testing Machine the strain developed on the surface under observation has been measured using Digital Strain Gauge Indicator under tensile loading conditions.

The uniaxial tensile forces have been applied on the connector as described in ''Analytical Study of THH connector'' section, and the strain values have been recorded at each load increment. From the strain measurements, the maximum principal stress at a point under observation on the surface of THH connector have been calculated by considering the material as linear elastic and the stresses have been compared with ANSYS results, as presented in Table 1. It can be observed from the table that the surface stresses obtained from the ANSYS analysis and experimental study is comparable, which validates the analytical model of the connector developed in ANSYS.

Theoretical validation

In order to compute the internal stresses within the connector, a finite element analysis program has also been developed in Microsoft Excel for analysis of the THH connector. For discretisation of the connector, all the vertices have been considered as nodes. In addition each central point of the six octagonal faces and the centre of gravity of connector have also been considered as nodes. Hence, total 31 nodes have been considered for analysis of the connector as shown in Fig. 1.

The connector has been meshed into 56 elements by considering four noded tetrahedron elements such that each of the six octagonal faces are divided into eight equal triangular parts by considering the centre of the octagonal face as the common vertex of all eight triangles, two nodes of octanogal face as other two vertices and the fourth vertex being the centre of gravity of connector. This forms 48 tetrahedrons of equal dimensions. The remaining eight tetrahedrons are those formed from the cut triangular corner and the centre of gravity of the connector as their fourth

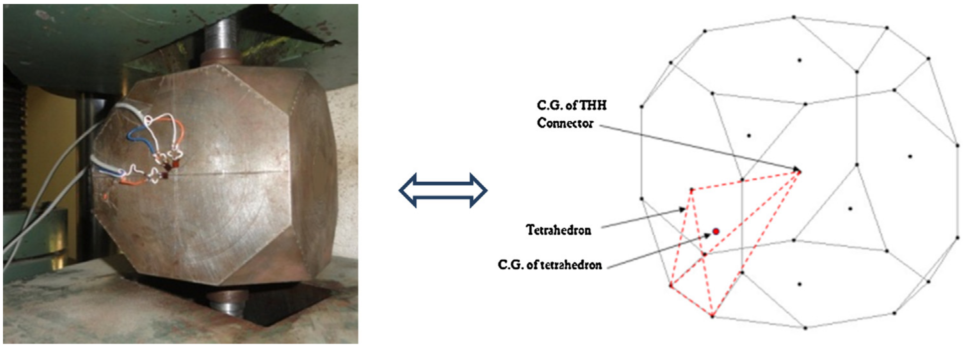

Figure 1 Experimental and theoretical model of THH connector.

Table 1 Comparison of maximum principal stresses for THH connector.

Load (kN)	Surface stresses Maximum principal stress (N/mm^2)		Internal stresses for a typical tetrahedron of the connector Maximum principal stress (N/mm^2)	
	ANSYS	Experiment	ANSYS	Theoretical
4	0.0916	0.1004	0.0608	0.0577
8	0.1832	0.1835	0.1216	0.1154
12	0.2748	0.3057	0.1824	0.1731
16	0.3664	0.4011	0.2432	0.2308
20	0.458	0.5505	0.304	0.2885

vertex. At each node three displacements in *x*, *y* and *z* directions have been considered and hence the size of the final stiffness matrix in the analysis is 93 × 93. The uniaxial tensile forces have been applied on the connector as described in ''Analytical Study of THH connector'' section. The maximum principal stress developed at the centroid of a typical tetrahedron element inside the THH connector (refer Fig. 1), have been calculated and compared with ANSYS results at same location, as presented in Table 1.

From Table 1, it can be observed that the maximum principal stress at a predefined point inside the connector computed from theoretical analysis are comparable to results obtained from ANSYS analysis. Hence, it can be concluded that the experimental and theoretical results for the THH connector validate the ANSYS results for the THH connector.

Analysis of THH connectors in double layer grid

Further, in order to understand the performance of the THH connector in comparison with the conventional Spherical connector, a double layer grid of size 12 m × 12 m having panel size 2.4 m × 2.4 m (5 panels) supported at four lower corners has been considered for analysis as shown in Fig. 2 (Gupta and Harde, 2011).

The double layer grid is subjected to concentrated load P, applied vertically downward to each node of the top layer. The analysis of the grid has been carried out for different values of P ranging from 2 kN to 10 kN in increment of 2 kN. The forces in the members of the grid at various joints (marked in red colour in Fig. 2) obtained from this analysis have been transferred to separate ANSYS models of Spherical and THH connectors. The connectors have been modelled with holes having threads (as described in ''Analytical Study of THH connector'' section) for connection of the members.

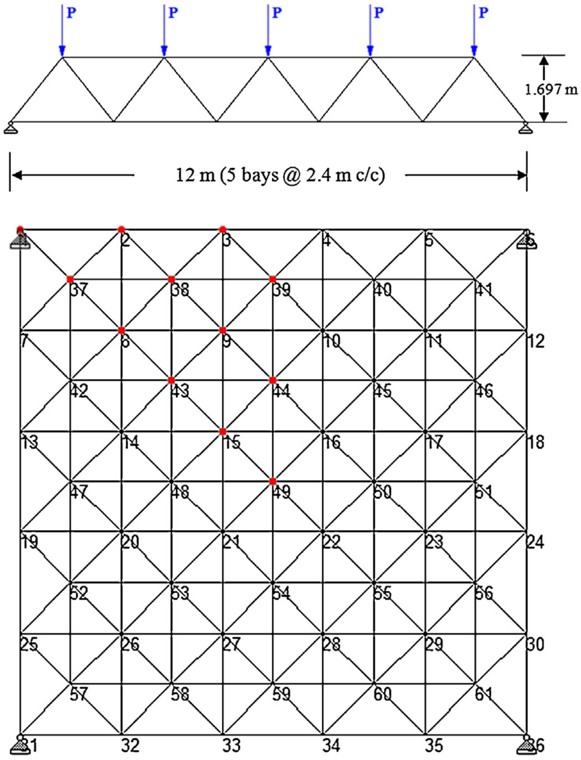

Figure 2 Plan and elevation of the double layer grid.

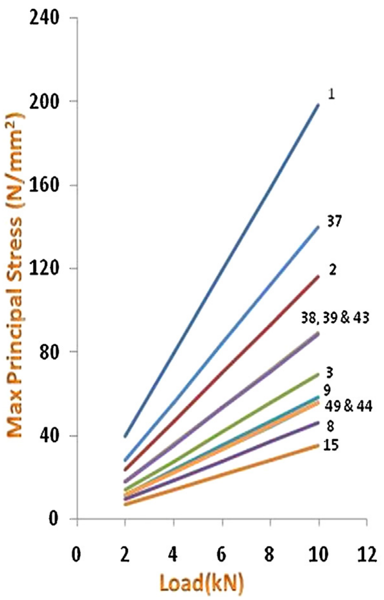

Figure 3 Maximum principal stress at different joints (Spherical connector) of the double layer grid.

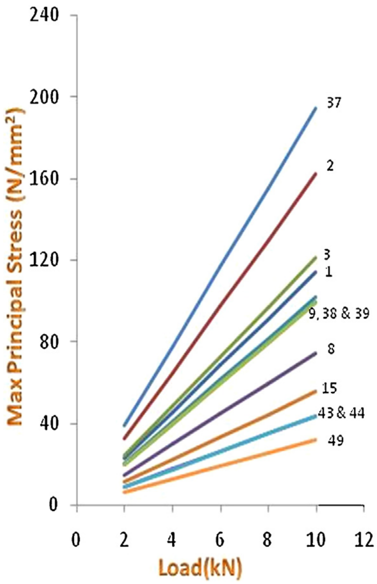

Figure 4 Maximum principal stress at different joints (THH connector) of the double layer grid.

The applied loads have been plotted with respect to the maximum principal stresses developed at the thread location of the Spherical and THH connectors as depicted in Figs. 3 and 4 respectively.

It can be observed from the figures that the maximum principal stresses near the top and bottom corner locations (node 1 and 37) are higher than other joints of the double layer grid as expected and hence, the stress at these locations is expected to govern the design of connectors for the double layer grid. Further, using extrapolation, it can be shown that the maximum principal stresses at these locations exceed the permissible stress for the connector for vertical loading of approximately 12.5 kN on this double layer grid. From the figures, it can also be noted that the maximum principal stresses for spherical and THH connectors are comparable.

The analysis of THH connector at various joint locations of a double layer grid suggests the feasibility of this connector for multi-layer space grid structures. The proposed THH connector in this study, due to its non-complex geometry and ease of fabrication, promises to be an alternative solution for connection of members of double or multi-layer grids.

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