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THEORETICAL AND EXPERIMENTAL ANALYSIS OF STEEL SPACE-TRUSS WITH STAMPED CONNECTION

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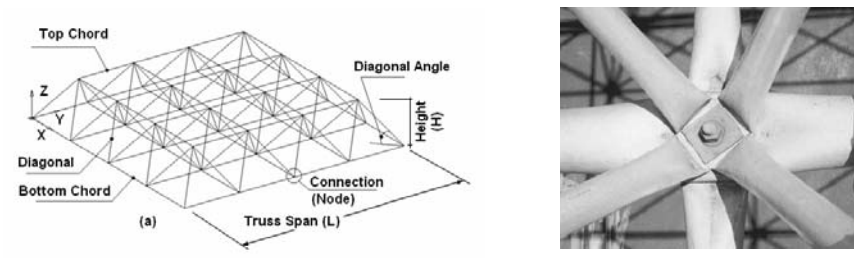
Abstract. *Tubular section members made of steel are common in space trusses. There are several types of connections to attach these members. The most popular is the staking end-flattened connection. The reduced cost and the fast assemblage of the truss are among the advantages of the staking end-flattened connection on 3D trusses. However, such connections present disadvantages like eccentricities and stiffness weakening of the tubular members. In this work, based on computer simulations and experimental lab tests on prototypes, small changes on the staking end-flattened connections such as reinforcement and eccentricity correction are evaluated. The results show an increase of 68% for local collapse and 17% for global collapse in the truss load carrying capacity when the suggested changes proposed in this article are used for the staking end-flattened connections.*

1 INTRODUCTION

Steel space trusses are frequently used as roof structures in industrial and residential buildings [7, 9] to cover large areas with no internal supports – Fig.1a. The complexity of the different types of connections is the main factor for the cost difference between the various truss systems. Bolted connections are preferred instead of welded connections due to easy transportation, fast assemblage, reduced cost, uncomplicated dismantling and expansion, availability of workforce, among other advantages. For many practitioner, manufacturing cost and fast assemblage are the main factors in the decision making process to choose the type of connection to use. For that reasons one of the most common connection used for steel space truss is the connection obtained by staking end-flattened tubes and joining them with a single bolt – Fig.1b. The staking end-flattened node is the simplest and therefore cheaper connection to manufacture for 3D trusses, but it has two main disadvantages [3,5]: the generated eccentricity bending moment and the reduction of stiffness in the tubes due to the end-flattening process.This article does not encourage the use of low quality connections, but it studies specifically the staking end-flattened connection which is very popular in many developing countries. This research attempts to improve such connection with simple and cheap changes. The investigations focus on modifications to the end-flattened node with the aim to improve the load carrying capacity of space trusses and, therefore, make it safer. The proposed modifications are simulated numerically and tested in Laboratory.

2 OBJECTIVE OF THIS RESEARCH

The stacked end-flattened connection behavior is very popular but its behavior is not yet fully understood. Such connection is of public domain and is the simplest and cheapest to manufacture. The two main disadvantages pointed out for the stacked end-flattened connection are: (a) nodal eccentricities E1 and E2 and (b) section flattening - see Fig.-2. Nodal eccentricity generates bending moments at the tube ends, and the end-flattening process reduces the stiffness of the bars. The main purpose of this research is to find an easy and cheap alternative to increase the load carrying capacity for three-dimensional trusses made of steel tubes jointed by stacked end-flattened tubes crossed by a single bolt as can be seen in Fig.-1b. The research is carried out in two fronts: (a) numerical modeling using finite elements in a chosen geometry, and (b) experimental investigation in 3D truss. The experimental tests will be performed in prototypes at the Structural Laboratory of the Department of Civil Engineering at the University of Brasilia (UnB) [5].



(b)

Fig.-1: (a) Truss elements: square on square, (b) End-flattened node system

To gain loading capacity in the truss, this research studies correction to the eccentricity and additional reinforcements to the bar ends. These two initiatives should reduce, at least in part, the disadvantages outlined above and, consequently, increase the truss load carrying capacity. Cuenca reported [6] using nuts, bolts and washers to reduce eccentricities - Fig.-2. No research was found dealing with the determination of the nut size and on how much more load a truss with such node corrections can get. In this article such studies will be carried out numerically and experimentally. To correct the eccentricity (Fig.-2b), a steel washer serving as a spacer was placed in-between the diagonal bars and the chord (inferior and superior chords) –Fig.-2c. Such washer, made of steel, is hereon called spacers. To overcome the reduction of the bar stiffness, a reinforcement plate is placed over the ends of the diagonal, but opposite to the chords reaching a node. Fig.-3 outlines the traditional and the suggested modifications in the stacked end-flattened node generating four types of nodes that will be examined in this article. The four types corresponds to: (a) Ideal Link (IL), (b) Typical Link (TL) or the staking end-flattened node, (c) Typical Traditional Link with Spacer (TLS), and (d) Typical Traditional Link with Spacer and a reinforcement plate (TLSR) – see Fig.4 - The spacers and the reinforcement plates may be circular or squared.

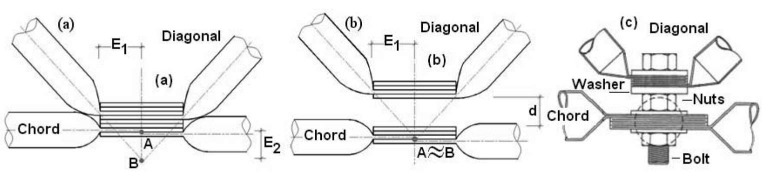


Fig.-2: (a) Eccentricities and flattened ends. (b) Correcting eccentricity. (c) Cuencas' node with nuts and washers – (ref. [6] - modified)

3 THE PROTOTYPES

To compare how the load carrying capacity of 3D space trusses increase, according to modifications at the end-flattened joints suggested (see Fig.-4), the truss prototype geometry is chosen as shown in Fig.-5. Numerical models, using Finite Elements, of this prototype truss are also assembled. The numerical models and protopytes differ only in the configuration of the connections. It is noted that the prototype truss is made of pyramidal units (Fig.-5a) connected at nodes (pyramid vertices). Each pyramid has a square base with *l*=1000 mm and height H=707 mm (Fig.5b).

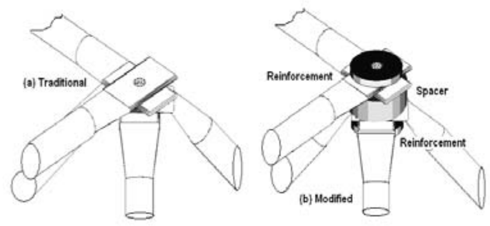


Fig.-3: (a) Typical end-flattened node. (b) modified.

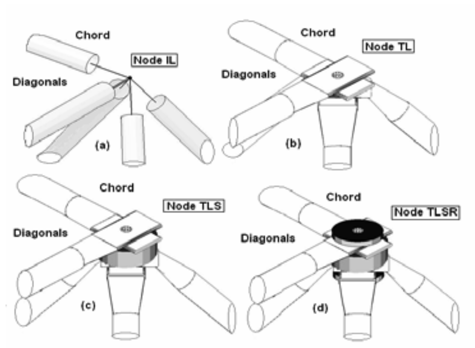


Fig.-4: (a) IL, (b) TL, (c) TLS, and (d) TLSR.

The diagonal inclination angles are, therefore, 45^o with respect to the base plane of the pyramid. The steel tubes of the truss have 25.4 mm (1") as external diameter and 1.59 mm (5/8") of thickness. Details of the dimensions of the truss chords and diagonals may be seen in Figs.-6. Due to the flattening process of the diagonal tube ends, the inclination angle 47.5^o corresponds to 45^o in the ideal truss case in which the diagonal is defined by the line AB in Fig.-6c. The tubes are made of Brazilian steel known in industry as MR250 [1] which is equivalent to the A36 [2] with the following engineering properties: yielding stress, 250MPa; ultimate stress, 400MPa; Modulus of Elasticity, 205000MPa and Poisson's ratio, 0.3.

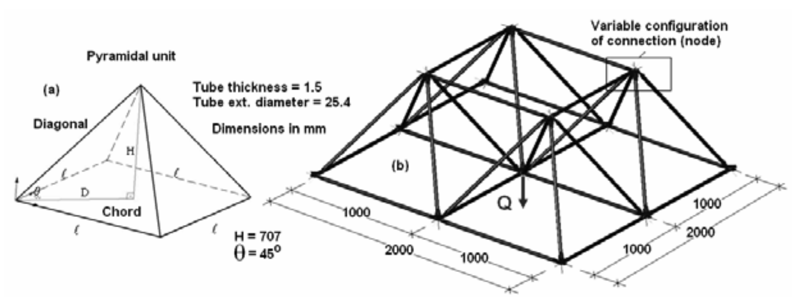


Fig.-5: (a) Pyramid units. (b) The prototype truss

The thickness of the spacer (d) (see Fig.-2) is a geometry problem. Taking into account a pyramid unit (Fig.-5) with its base length (ℓ) and height (H), the thickness (t) of the tube wall (flattened) and the eccentricities E1 and E2 (see Fig.-2). Eq.(1) presents the formula for the calculation of the spacer size (d). Taking into account the truss dimensions and tube thickness, the spacer is found to be 20 mm thick. The adopted diameter of the spacer was 50 mm (2"). Plates of 1.91 mm (3/4") thickness reinforced the node. For more details see reference [4,5].

$$d = 2HE_1 \Big/ \left(\ell\sqrt{2} - 4E_1 \right) - 8t \qquad (1)$$

The maximum compressive load at those bars can be determined from the Standards [1, 2]. The critical compressive bar strength is Nc= 13kN, which corresponds to an approximate load Q$\approx$37 kN applied at the middle node as illustrated in Fig.-5b.

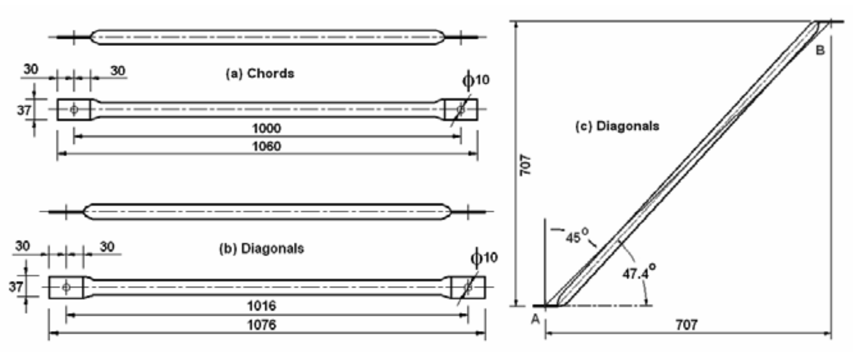


Fig.-6: Dimensions of (a) chords, (b) diagonals, (c) angles.

4 NUMERICAL MODELS AND PRELIMINARY RESULTS

Let's investigate the stress distribution at the truss under the load Q = 37 kN and considering the modifications suggested to the end-flattened connections. The corresponding Finite Element Model is shown in Fig.-7a. The load Q is applyied at node 9 (Fig.-7b). SAP2000 (Structural Analysis Program) [8] is here used to discretize the 3D standard truss with its different node/connection configurations – (see Fig.-4). Two types of finite elements from the SAP element library are used for the numerical modeling: the FRAME element and the SHELL element. The SHELL elements were used to discretize the connections. From the section before, the engineering properties (Modulus of Elasticity and Poisson's ratio) of steel and the geometry of the tubes (diameters, thicknesses and lengths) were specified in the SAP input files.

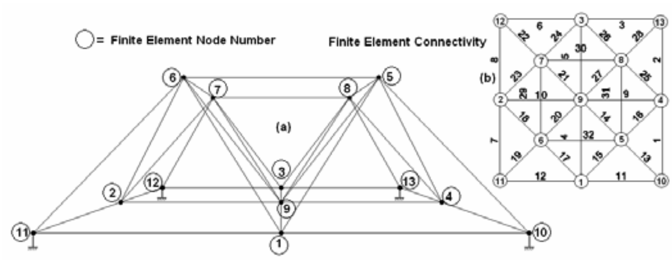


Fig.-7: (a) Finite element node numbers. (b) Finite element connectivities.

To investigate the distribution of normal forces (tractions and compressions) and bending moments along the bars of the space trusses, three 3D finite element models were built corresponding to trusses with connections IL, TL and TLS. No FE model is necessary for the truss with TLSR connection, since there is no significant change in the force & moment distribution with respect to the truss with TLS node. For the TLS connection model, all the FE nodes were completely coupled between chords and diagonals, making TLS connection rigid. The truss with IL nodes (Ideal Link nodes), is simple to represent in a FE model just using FRAME elements. In this case, the bars show no eccentricity and, therefore, the ends of the bras match perfectly at a nodal point. The TL (Typical Link or staking end-flattened node) is modeled with FRAME elements, but the flattened tube ends are modeled with SHELL (plate) elements. The ends are bent to make the diagonals math with the chords. The TLS node has a washer serving as a spacer to correct the TL eccentricity. The FE modeling is straightforward employing again FRAME and SHELL elements - placing a thick (20 mm) plate elements in-between the diagonals and chords. In the FE models, nodes are numbered from 1 to 13, and elements from 1 to 32 – see Fig.-7b. Restrictions for displacement and rotations are applied to nodes at the supports of the truss located at the corner – representing the support conditions to be replicated in the experimental tests. Node 9 in Fig.-7 is the middle node where the concentrated load "Q" is applied. The elastic linear distributions of the normal forces and bending moments, along the bars, are represented in Figs.-8, 9, 10. The normal force distribution shows minor changes among trusses with IL, TL, and TLS connections, but the bending moment distribution variations among the numerical models are more significant. Fig.11 reviews the bending moment distributions so that changes among the trusses with different connections are noticed. The presence of a spacer in the truss with TLS produces a significant fall in the bending moment values present in the truss with TL – the staking end-flattened connections. Actually, the moment distributions of the trusses with TLS connections move toward the ideal truss with IL.

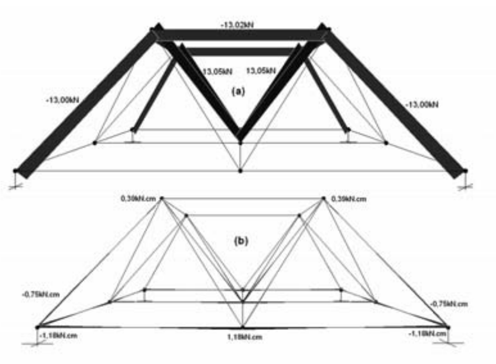


Fig.-8: For IL: (a) Axial force. (b) Bending

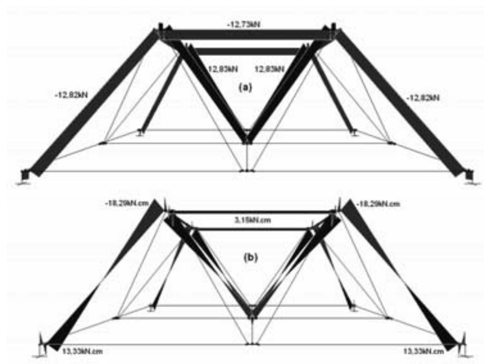


Fig.-9: For TL: (a) Axial force. (b) Bending

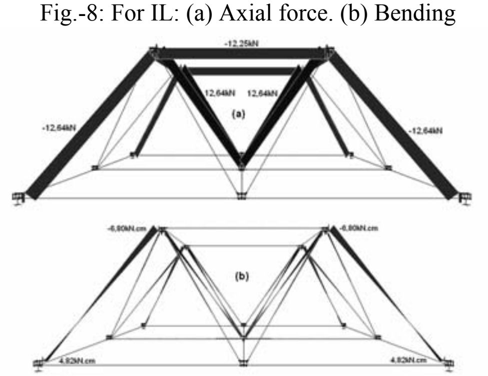


Fig.-10: For TLS: (a) Axial force and (b) Bending

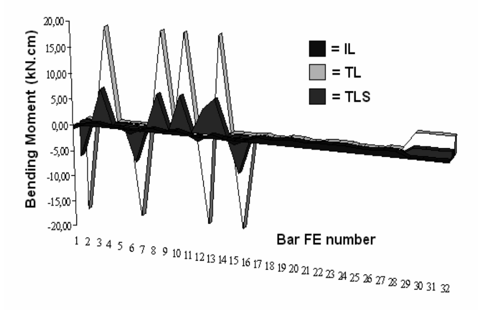


Fig.-11: Bending distribution for IL, TL, TLS

5 EXPERIMENTAL RESULTS

This section investigates by means of experimental tests the distribution of normal forces and bending moments along the bars of the trusses with links TL, TLS and TLSR. This experimental program seeks to collect simple quantitative and qualitative information on the standard space truss taking into account different nodal types. To achieve this goal, static tests are carried out on truss prototypes under an increasing vertical load applied at the middle node (node-9 in Figs.-5 and 7). The load is gradually applied until truss collapse is reached. For each specific connection system, three experimental truss prototypes were constructed. Prototypes with IL nodes (Ideal Link) were not built since the goal is to observe how much load capacity can be gained with simple modifications on trusses with the common TL nodes (the staking end-flattened nodes). Therefore, considering the three links under analyses (TL, TLS and TLSR) a total of nine prototypes were manufactured. A system of identification for the prototypes is in Table-1.

Table-1: Identifier nomenclature for the nine truss prototypes

Lab Test Identifiers	Summary
TLE1, TLE2, TLE3	Truss with TL nodes for 3 lab tests with static load
TLSE1, TLSE2, TLSE3	Truss with TLS nodes for 3 lab tests with static load
TLSRE1, TLSRE1, TLSRE1	Truss with TLSR nodes for 3 lab tests with static load

Truss Node	Meaning
TL =	Nodes with Typical Link or staking end-flattened node
TLS =	Nodes with a Spacer correcting the TL eccentricity
TLSR =	Nodes with a Spacer and a reinforcement plate applied to TLS nodes
and En =	E = Experimental, n = Test number

The 9 prototypes (TLEn, TLSEn, and TLSREn, n = 1, 2, 3) were tested in the Structural Laboratory at the Department of Civil Engineering in the University of Brasilia (UnB). The corners of the prototype trusses were fixed on a very stiff steel base available in Laboratory. A downward and vertical load is applied at the middle node (node 9). Fig. ure 20 shows the complete assembly for the lab tests. Each prototype measures in cm 200x200 in base and 70.7 in height; and has the geometry as outlined in Fig.-5. Tube dimensions and material properties were specified before in section 4 of this article. At the middle node, the pulling load is supplied by the cable which is attached to a hydraulic jack. Load values are controlled with the load cell. The hydraulic jack has 300 kN load capacity and the load cell reads up to 500 kN with 0.1 kN precision.

At node 9, the cable pulls the prototype downward in load-steps of 1.0 kN and after every given load-step readings of the total load, displacements, and strains were taken. For the data acquisition from the strain gages, the system Spyder-8 connected to computer and controlled by the Catman-4.5 software was used. For node 9, Fig.-13 shows the loads-displacement curves for the 9 prototypes tested. These curves generate polynomial curves which are also plotted in Fig.-13 as average curve. The plots are up to the points where global collapse is achieved - points 1, 2 and 3 in Fig.-13.

Global collapse is here understood as the instant where any small load increment is no more bearable to the prototypes. Global collapse is also characterized by the buckle of critical members under combined compression and bending. For the same load level, it was also observed that trusses with TL nodes (staking end-flattened nodes) showed greater displacement than the other prototypes tested. Actually, in Fig.-13, point 1 corresponds to coordinates (36kN; 46mm), point 2 (38kN; 36mm) and point 3 (42kN;

33mm). However, the global truss collapse does not reflect the excessive deformation (or local collapse) observed at the prototype connections.

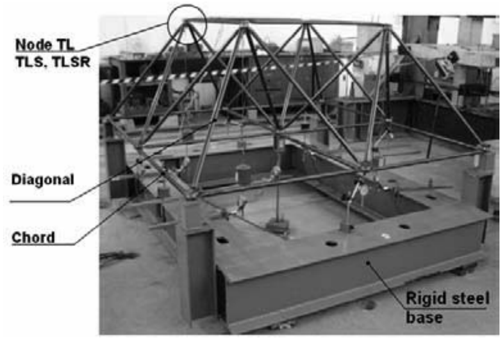


Fig.-12: Assembly of the truss prototypes for tests

Local collapse is basically characterized by an excessive wrinkling of a node or connection but not necessarily buckling of a member. Actually, in the last Fig-13, at point 4 (25kN), the corresponding prototypes (TLE1, TLE2 and TLE3) show excessive wrinkling of few connections. For prototypes TLSEn and TLSREn no excessive deformation is observed for the same 25 kN load. Therefore, for 25 kN, TLEn prototypes (with staking end-flattened connections) show local collapse and quite the opposite were observed in the others prototypes (TLSEn and TLSREn).

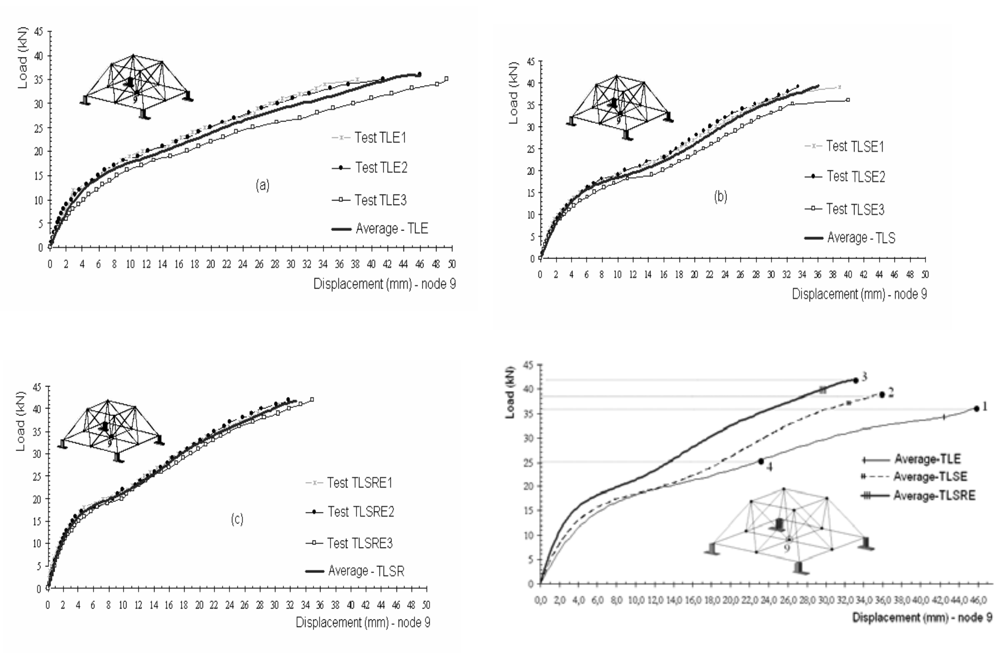


Fig.-13: Load-displacement averaged curves for TLEn, TLSEn and TLSREn prototypes.

Therefore, in average, and considering only the local collapse, TLEn prototypes collapse at 25 kN, TLSEn at 38,5 kN (53% more) and TLSREn at 42 kN (68% more). For global collapse, compared to TLEn prototypes, TLESn increased 2.5 kN (7% more) while TLSREn increased 6 kN (17% more).

6 CONCLUSION

The goal of this research was to improve the load carrying capacity of space trusses that uses staking end-flattened connections. The use of spacers and reinforcement plates were suggested to increase the load carrying capacity of this type of truss. This article also presented an equation to calculate the size of the spacers. In this research, to test the effectiveness of using spacers and reinforcement plates, 9 finite element models and 9 prototypes made of steel tubes, under a central point load were considered. Different types of connections on prototypes were analyzed with numerical simulations and experimental tests. The analyses showed that correcting the eccentricities with spacers and using reinforcement plates on the connections increase substantially the strength of the prototypes. Using spacers, the experimental tests showed that the local collapse strength of the prototypes increased in 53%, and using spacers and reinforcement plates the increase was 68%. For global collapse, just using spacers the increase in strength was 7% and when spacers and reinforcement plates are utilized, the increase in strength was 17%. This alternative can be easily applied to new truss design or in recovery of trusses in use.

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