NEW EXPERIMENTAL RESULTS OF THE RESEARCH ON REINFORCED NODE IN SPACE TRUSS

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ABSTRACT: In the first stage of this research the proposal of the reinforced node used in space truss was presented. Computer simulations and experimental lab tests were performed with small changes on the staking flattened-end connections, such as reinforcement and eccentricity correction. The results showed 68% increase in the truss load carrying capacity when the proposed changes were applied. However, small prototypes measuring 4 m^2 were used for laboratory testing. In this paper, for proposal validation, the same research was developed, this time in prototypes with 54 m^2. The outcome results of this research, confirmed a significant increase in the truss load carrying capacity. It is expected that factories can apply the reinforced node in space truss constructions to come.

Keywords: Space truss, steel connection, steel construction, steel roof

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1. INTRODUCTION

Truss structures constitute a special class of structures in which individual straight members are connected at joints. The members are assumed to be connected to the joints in a manner that permit rotation, and thereby it follows from equilibrium considerations, to be detailed in the following, that the individual structural members act as bars, i.e. structural members that can only carry an axial force in either tension or compression [1].

Three-dimensional structures made of steel bars, widely known as space trusses, are frequently use in construction of roofs. These structures consist of steel bars, connected by bolts at nodes. There are several types of connections to attach these members. The choice of a connection system depends on structural layout, types of sections and distribution of bars.

Many patented connection systems are available and new ones continue to be invented but the code of practice does not include specific design rules for these connections. MERO system or bolted jointing system (Figure 1) was the first patented system for space structures [2]. The buckling behavior was observed in Taniguchi's work [3]. Many other patented systems were also developed but designers have frequently used non-patented systems due to their lower cost compared to patented ones [4].

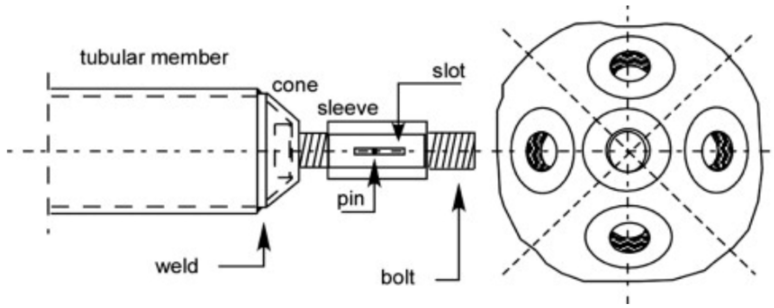

Figure 1. Mero Connection System [2]

One most used non-patented connection in China is the welded joint. It is possible to observe in reference [5] the design of welded tubular connections. Fatigue is an important issue in designing welded joints [6]. That paper presented a fracture mechanics approach to assess the fatigue life of CFCHS T-joints, which involves the determination of initial crack location and size, stress intensity factor and proper crack growth model (Figure 2). In [6], numerical and experimental analyses on welded joints were presented.

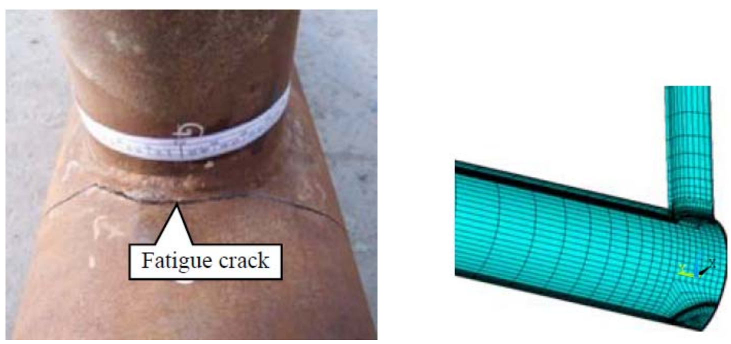

Figure 2. Fatigue Study in Welded Joints [6]

There are systems without a special nodal piece (Figure 3). In this case, the chord bars have flattened ends and can be continuous or not. Diagonal bars are flattened and bent at the ends. In Brazil, the most widely connection utilized in 3D trusses is the staking flattened-end connection (also known as typical connection, Figure 4) and the steel node (Figure 5).

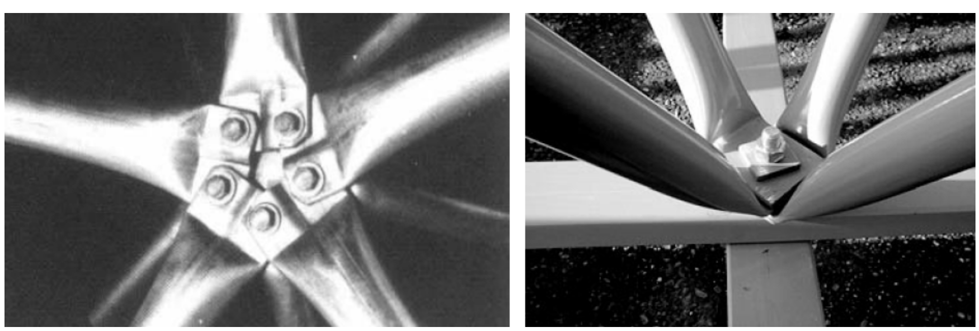

Figure 3. Systems Without a Special Nodal Piece [4]

Vacev's research [7] presented experimental analysis of the steel node. The joint was loaded by spatial set of forces that simulate real condition of the structure. Tested were made in real scale, according to the model originated after FE analysis. The results of a stress-strain FE analysis were presented and comparison of the two analyses was given for the most critical regions of the node.

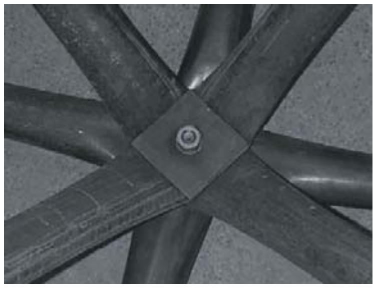

Figure 4. Flattened-end Connection [4]

Figure 5. Steel Node [7]

The advantages of the flattened-end connection (Figure 4) are price and installation time compared to the steel node (Figure 5). However, such connection (Typical Flattened-end) has disadvantages like eccentricities and stiffness weakening of the tubular members. Several accidents in space structures have also been reported in Brazil (Figure 6) [8].

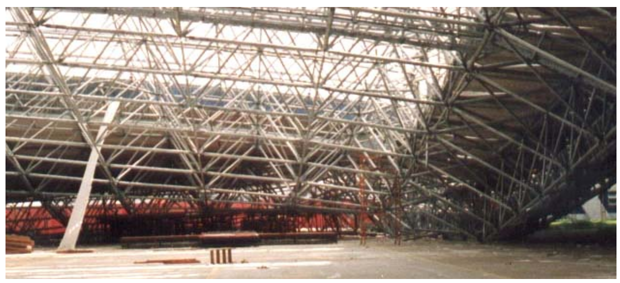

Figure 6. Convention center accident in Manaus [8]

Souza's research [9] presented the results of experimental analyses of space trusses using steel tubular bars with flattened-ends. The connections were formed by overlapped bars connected by single bolt (typical flattened-end). The behavior and collapse modes were determined by experimental analysis on six space trusses with 1.5 m height and spans of 7.5m x 7.5m and 7.5m x 15m (Figure 7). Structures with steel nodes (Figure 5) at the top corners and support points were also tested. The structural collapse was caused by either connection collapse or yielding at the bar ends. Traditional theoretical analysis models (linear truss model) are not suitable for these structures.

The connections failure was the predominant collapse pattern and was caused by plastic strains in the end bars, node rotations and slip among bars in the nodal region (Figure 8). These facts caused an increase in the displacements and the premature structural collapse.

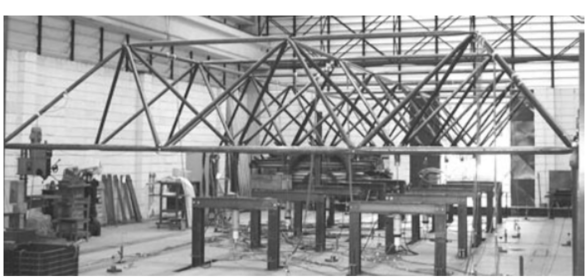

Figure 7. Experimental Tests [9]

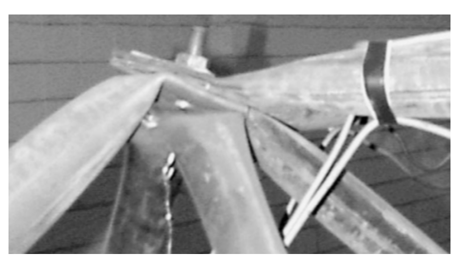

Figure 8. Collapse Mode [9]

Nodal eccentricities E_1 and E_2 (Figure 9) are present in the staking flattened-end connection. Nodal eccentricity generates bending moments on the tube ends, and the end-flattening process reduces the stiffness of the tubular sections. Initially on this research it was proposed the correction of the eccentricity E_2 by the application of a spacer between diagonals and parallel chords (Figure 10). The purpose of a spacer is to make the diagonal axis and chord axis meet in the same point (A=B). Equation 1 presents the formula for the calculation of the spacer size (*d*). Taking into account a pyramid unit with its base length (*l*) and height (*H*), the thickness (*t*) of the tube wall (flattened) and the eccentricities E_1 and E_2 [8].

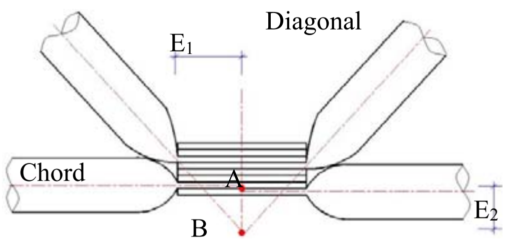

Figure 9. Eccentricities [8]

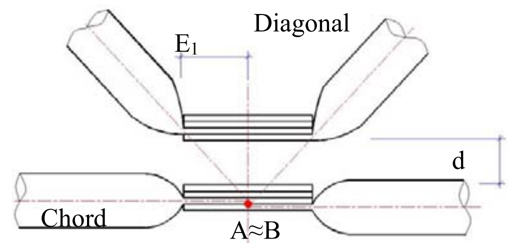

Figure 10. Correcting Eccentricity [8]

$$d = \frac{2HE_1}{l\sqrt{2} - 4E_1} - 8t \qquad (1)$$

1.1 Preliminary Steps on the Research

In recente years, the first step on this research were carried out by simple numerical finite element models and experimental investigation with small prototypes [8], [11] and [12]. The typical connection (Figure 11) and the suggested modifications (Figure 12) were compared. In order to do this, it was taken into consideration the prototype trusses (with $4m^2$) made of four pyramidal units connected at nodes (pyramid vertices). Each pyramid has a square base of *l*=1000 mm and height *H*=707 mm (Figure 13).

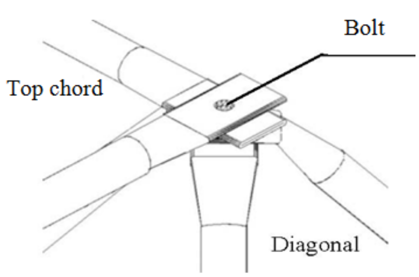

Figure 11. Typical Flattened-end

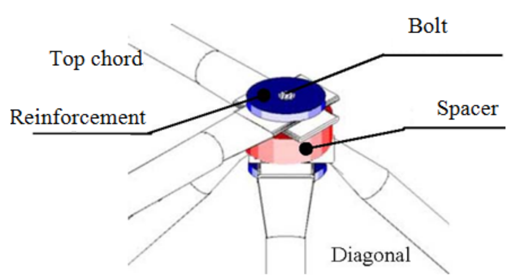

Figure 12. Modified Node

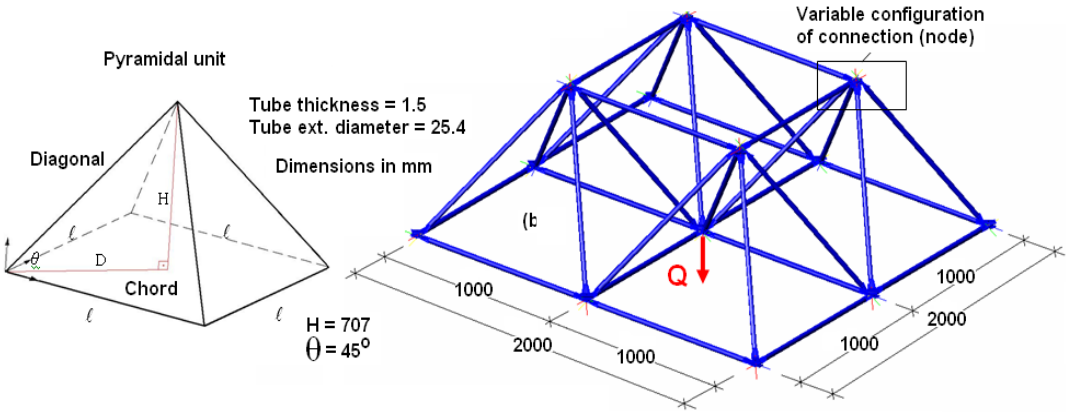

Figure 13. The Prototype Truss Geometry (mm)

1.2 First Numerical Results

The SAP2000 program [10] was used to discretize the 3D standard truss (Figure 14) and to carry only linear analyses. Prototypes were modeled with FRAME elements. The restrictions were applied to nodes 10, 11, 12 and 13. The imposed load of Q = 37 kN was applied to central node 9. The linear analyses showed that the presence of a spacer in the truss produces a significant fall in the bending moment and in the displacement present in the truss with staking flattened-end connections. The bending moment in the modified node model (Figure 16) had a reduction of at least 62% when compared to typical node (Figure 15).

The node displacement in the modified node model (Figure 18) dropped nearly 70% compared to typical node (Figure 17) [11]. Numerical linear analyses satisfactorily show that the spacer substantially reduces bending moments and displacements. It makes the truss stiffer and more resistant as can be seen by laboratory experiments reported in the next section.

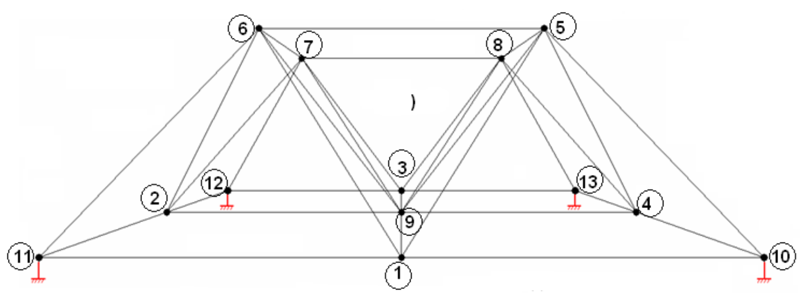

Figure 14. FE Prototype Models

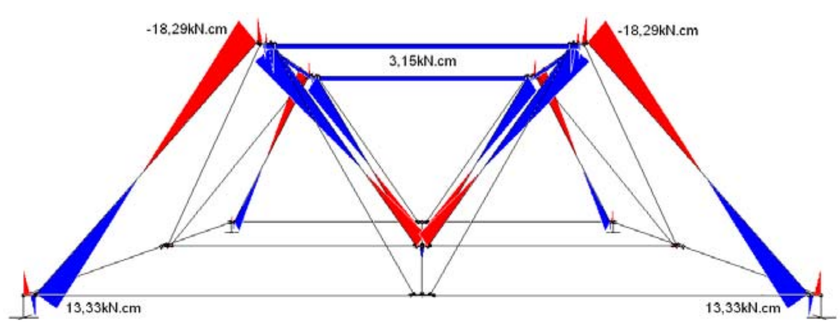

Figure 15. Bending Moment in the Typical Node

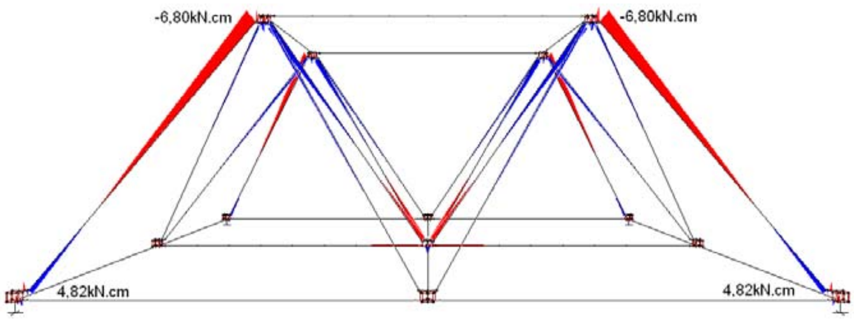

Figure 16. Bending Moment in the Modified Node

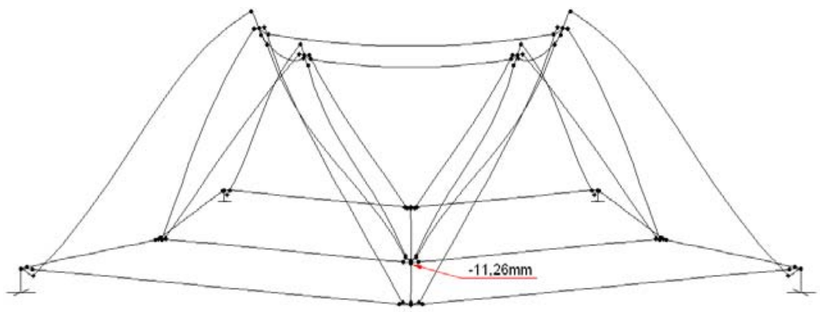

Figure 17. Displacement in the Typical Node

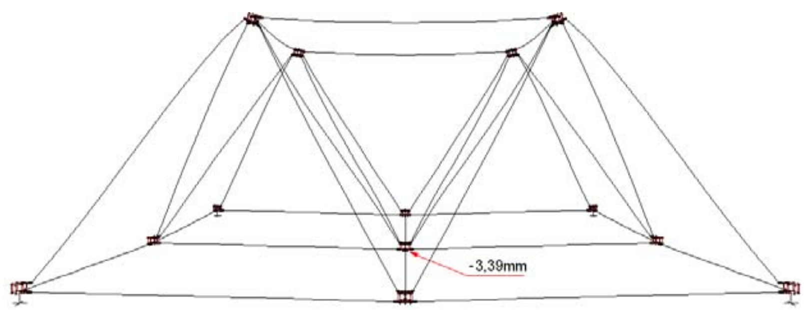

Figure 18. Displacement in the Modified Node

1.3 First Experimental Results

Six prototypes, as described in section 1.1, were tested in the Structural Laboratory at the Department of Civil Engineering in the University of Brasilia (UnB) [8]. Half of the prototypes were with typical flattened-end node and the other half with nodes with spacers and reinforcements (Figure 5 and 6). Spacers will correct eccentricity while reinforcements avoid early local instability in the region of the flattened ends of the tubes. The corners of the prototype trusses were fixed on a very stiff steel base available in the Laboratory. A downward vertical load was applied to the middle node 9 in load-steps of 1.0 kN (Figure 19).

Figure 19. FE Prototype Models

In Figure 20, the model with modified node (point 1 at 42 kN) had an increase of 68% on load capacity compared to typical node (point 2 at 25 kN). In the model with typical node the local collapse was basically characterized by an excessive wrinkling of a node or connection but not necessarily buckling of a member (Figure 21). For the modified model no excessive node deformation was observed when the structural collapse occurred (Figure 22) [12].

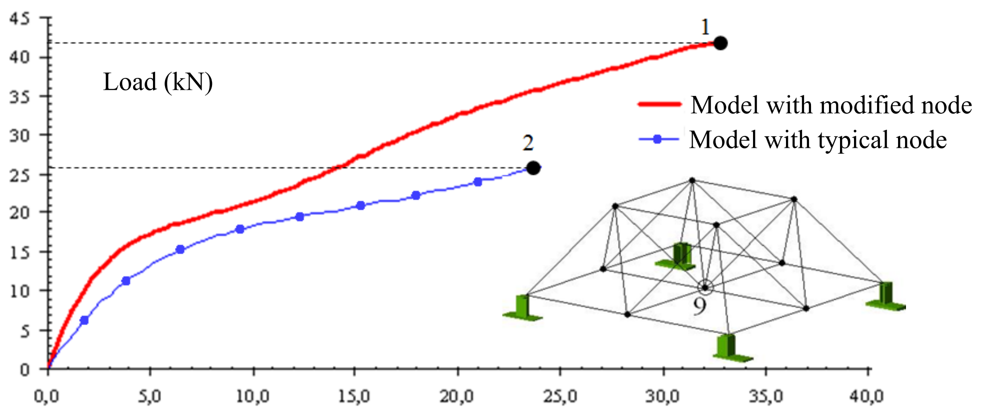

Figure 20. FE Prototype Models

Figure 21. Collapse of the Typical Model (P2 - 25kN)

Figure 22. Collapse of Modified Model (P1 - 42kN)

2. OBJECTIVE AND METHODOLOGY OF THIS RESEARCH

Despite the good results obtained in the preliminary studies [8], [11] and [12], further investigation is necessary before recommending factories to apply the reinforced node in future buildings. That is why the last study was carried out numerically and experimentally on prototypes with small dimensions. Therefore, the aim of the present research paper is to confirm the proposal of reinforcement using new experimental prototypes; but this time covering fifty four square meters. This study was carried out by numerical FE models and experimental investigation of 3D trusses. The performance of typical connection (Figure 11) and the suggested modifications (Figure 12) were again compared.

The prototype truss was made of pyramidal units connected at nodes corresponding to pyramid vertices. Each pyramid has a square base with length of l=1500 mm and height of H=1061 mm (Figure 24). The diagonal inclination angles are, therefore, 45º in respect to the base plane of the pyramid. The truss steel tubes have 38 mm (1½ in) of external diameter and 1.20 mm (0.047 in) of thickness. The tubes are made of Brazilian steel known in industry as MR250 [13] which is equivalent to the ASTM A36 [14]. Standard Samples were tested in lab (accord to Figure 23) and the following properties were observed: Yielding Stress adopted to be 250 MPa (value between 250 and 290 MPa); Modulus of Elasticity, 205000 MPa (value between 200000 and 210000 MPa) and Poisson's ratio 0.3. Taking into account the truss dimensions and tube thickness, the spacer is found to be 21.50 mm (7/8 in) thick. The adopted diameter of the spacer was 76.2 mm (3 in). Reinforcement plates of 4.76 mm (0.18 in) thickness reinforced the node – plates just need to be thicker than the tube thickness. The spacer was made of steel, but in recent study we are trying cheaper material [15].

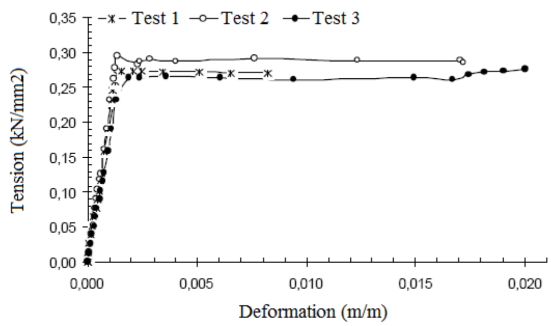

Figure 23. Characterization of Material in Lab

Restrictions for displacement and rotations are applied to nodes on the supports of the truss located on the corners representing the support conditions which are replicated in the experimental tests. See in Figure 25 the nodes where the loads "Q" were concentrated.

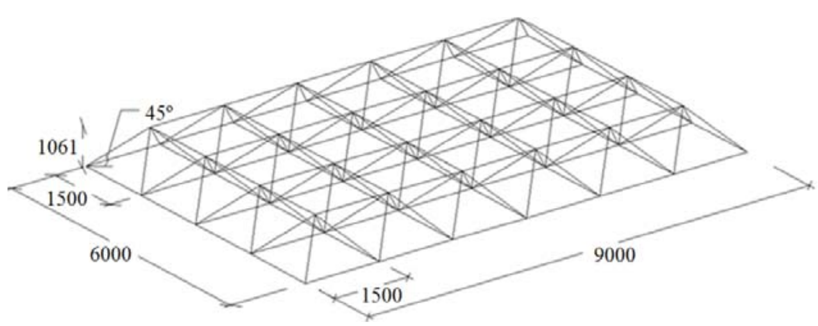

Figure 24. The Current Prototype Truss Geometry (Units in Millimeter)

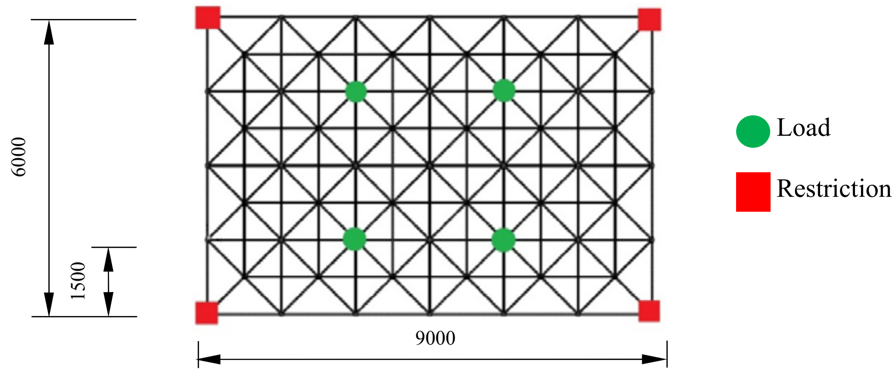

Figure 25. Plan View of the Prototype (Units in Millimeter)

3. NUMERICAL STUDY

3.1 Finite Element Model

SAP2000 [11] is here used to discretize the 3D standard truss. From the 3D view of FE prototype model in Figure 26, it is possible to observe the element members. Restrictions for displacement and rotations are applied to corners. The support conditions were replicated in the experimental tests. Point loads were applied at four nodes, beginning at 10.0 kN and adding up to 40.0 kN. Two types of FE, from the SAP element library, were used for the numerical modeling. The SHELL elements were used to discretize the spacer. The FRAME elements were used to discretize the bars. Two models are discretized: The typical connection (Figure 27) and the suggested modifications (Figure 28). Nodes 1 to 5, at the line in the middle of the truss (Figure 26), were used to compare the vertical displacements of the two models.

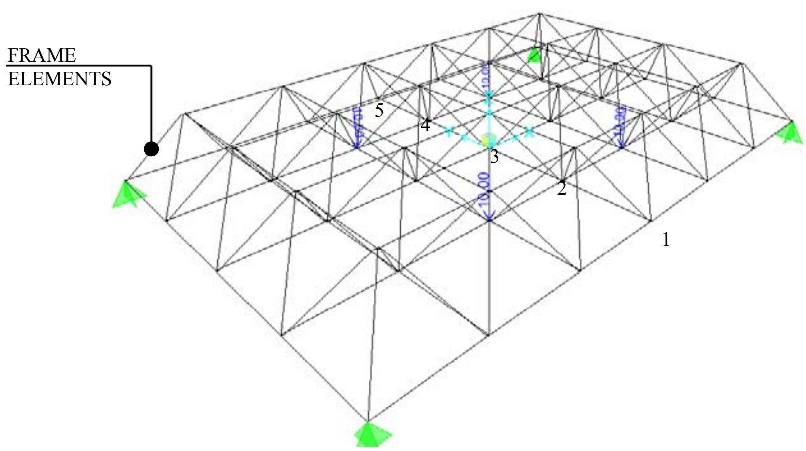

Figure 26. FE Prototype Models

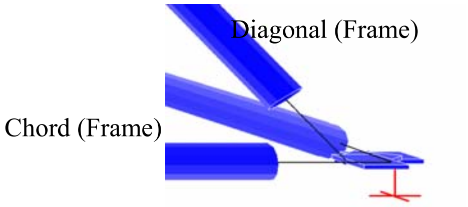

Figure 27. Typical Flattened-end

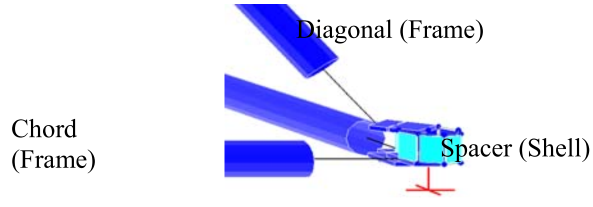

Figure 28. Modified Node

The prototype geometry has symmetry in both axis X and Y. For this reason, the elements stresses were symmetrically distributed. Despite the model was made with all the members, results were analyzed only in a quarter of the model. In Figure 29 it is possible to observe the selected elements that were used for the analyses of the axial forces and bending moments.

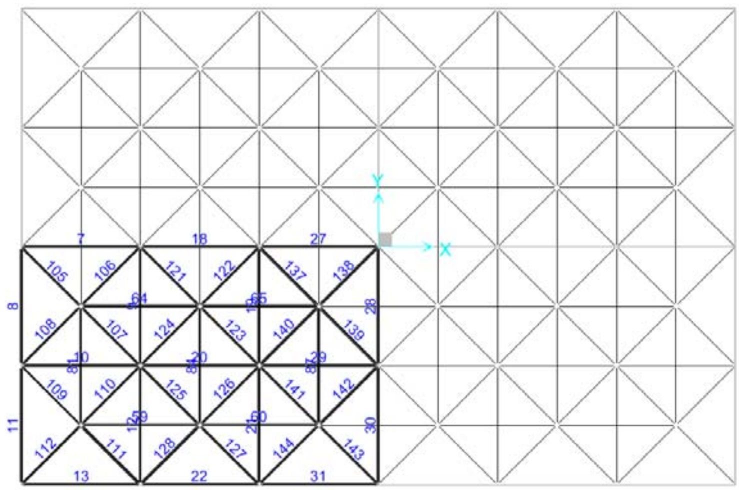

Figure 29. Plan View of FE Prototype Model

3.2 Axial Force

Figure 30 shows the graphs of the axial forces in the element members with modified nodes and typical nodes. With this graph it is possible to observe that the axial forces are almost the same. The numbers of truss elements were also depicted in Figure 29.

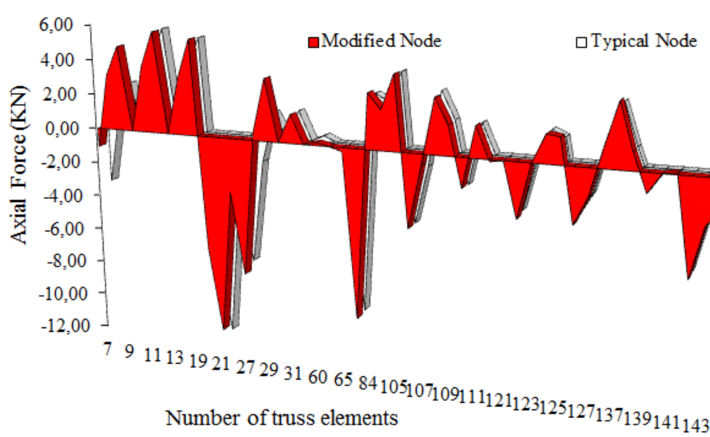

Figure 30. Axial Force Results of the Truss Elements

3.3 Bending Moment

Figure 31 shows the graphs of the bending moments in the element members with modified nodes and typical nodes. The presence of spacers in the modified truss produces a significant fall in the bending moment. The reduction was nearly 52% in all members.

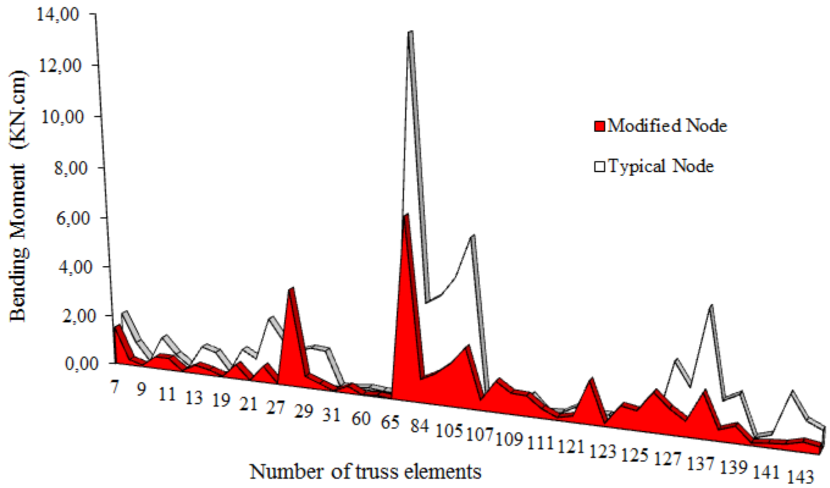

Figure 31. Bending Moment Results of the Truss Elements

3.4 Displacement

Figure 32 shows the graphs of the displacements of the middle nodes (in Figure 26) for trusses with modified nodes and typical nodes. Again, the presence of spacers in the modified truss produces a reduction in the displacement values. The reduction was about 16%.

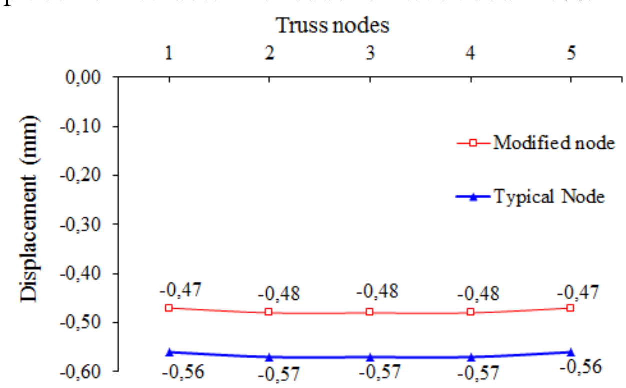

Figure 32. Displacement Results of the Truss Elements

4. EXPERIMENTAL STUDY

4.1 Experimental Program

The experimental program seeks simple quantitative and qualitative information on space trusses, taking into account two different nodal types (Figure 33 and 34). Static tests were carried out on truss prototypes under an increasing vertical load applied to four nodes (Figure 25). Four hydraulic jacks and one hydraulic pump were used (Figure 35).

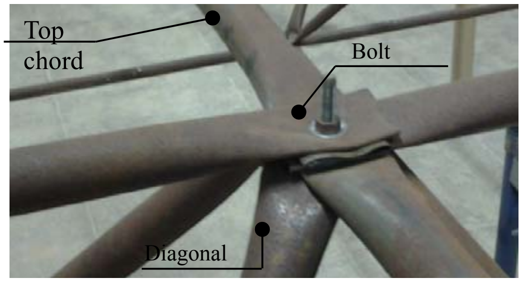

Figure 33. Typical Flattened-end

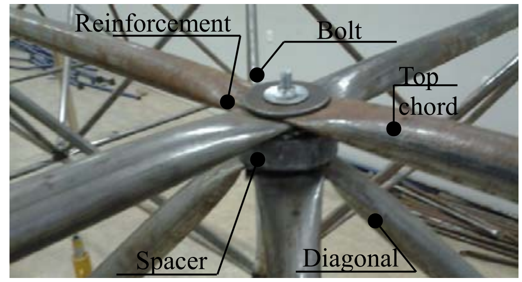

Figure 34. Modified node

Figure 36 shows the hydraulic pump control and their components, such as electric engine, oil compartment box and manual valve control. The measuring system of the displacement and the load were composed by Dial Test Indicator (DTI), DTI Support, Load cell and Reading panel, shown in Figure 37. The load is gradually applied up to the moment truss collapse is reached. For each specific connection system, i.e. nodal types, one experimental truss prototype was built and tested. The prototypes were tested in the Structural Laboratory at the Department of Civil Engineering in the Federal University of Cariri. The corners of the prototype trusses were fixed on a very stiff steel column available in laboratory. Downward vertical loads are applied to the nodes. Figure 38 shows the complete assembly for the lab tests.

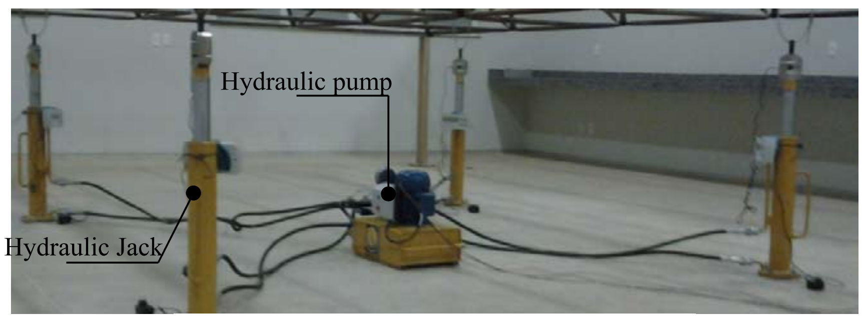

Figure 35. Load System Applied in the Lab

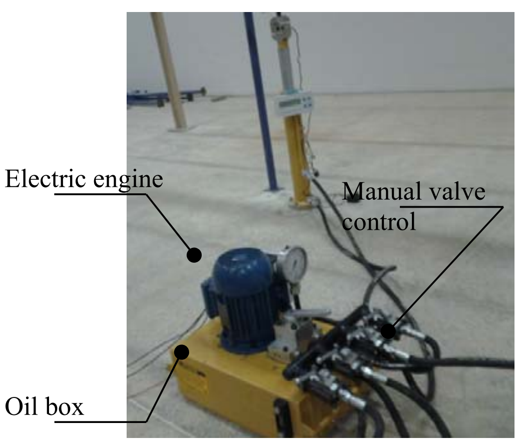

Figure 36. Hydraulic Pump Control

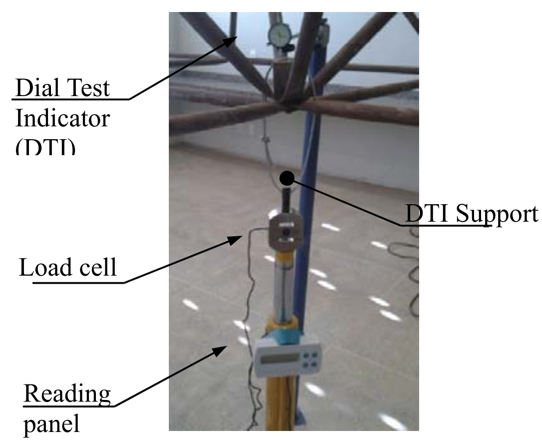

Figure 37. Measuring System

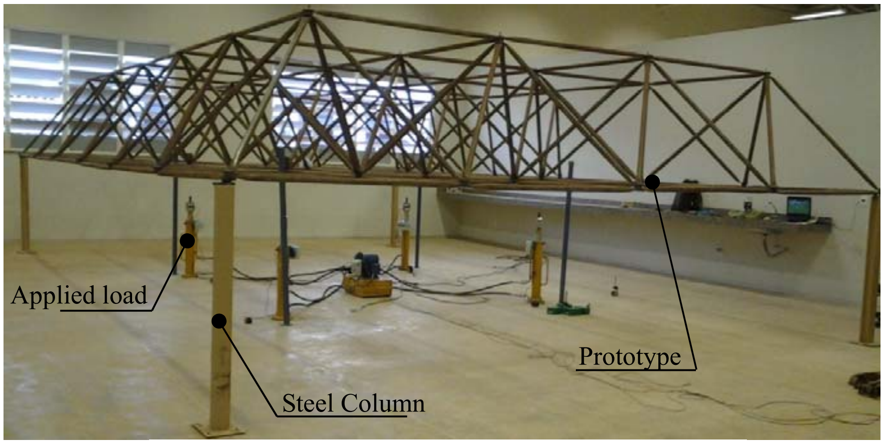

Figure 38. Prototypes in the Laboratory at UFCa

Each prototype has a rectangular base of 6m x 9m wide (54 m^2) and 0.94 m high, with geometry as outlined in Figure 24. Tube dimensions and material properties were specified previously. At the four nodes, (see Figure 25), the pulling load Q is produced by four cables which are attached to hydraulic jacks. Load values are controlled with the load cells. The hydraulic jacks have 160 kN on load capacity and the load cells read up to 100 kN with 0.1 kN precision. The cables pull the prototype downwards in load-steps of 1.0 kN. After every given load step, readings of the total load and displacement were measured at the node where loads were applied.

4.2 Experimental Results

In this research, global collapse is the instant when any small load increment is no longer taken by the probed prototypes. Global collapse is also characterized by the buckling of critical members under compression and bending combined. In Figure 39, the experimental results were plotted with results stating typical prototypes collapse at point 2 where Q = 24 kN and node with reinforcement at point1 where Q =35.1 kN (4x8.78 kN), representing an increase of 46.2% in the collapse load. For the same load level, it was also observed that trusses with typical nodes (staking flattened-end nodes) presented greater displacements than the prototypes with spacers and reinforcements.

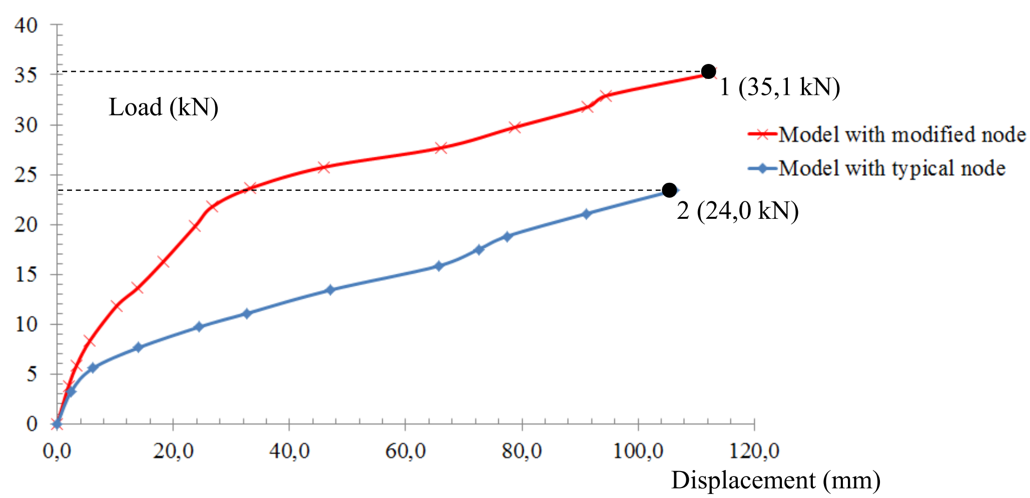

Figure 39. Experimental Results

Figure 40. Collapse in Typical Model (24kN)

Figure 41. Collapse in Modified Model (35.1kN)

In fact, as shown in Figure 40, the corresponding prototypes with typical node showed excessive wrinkling and displacement of about 106 mm with the load of 24kN. For prototypes with spacers and reinforcements no excessive deformation was observed when the applied load Q reached 25 kN with displacement of about 45mm (Figure 41). Therefore, for the same load (24kN) the typical prototypes (with staking flattened-end connections) presented local collapse whereas no local collapse was observed in the modified prototypes.

5. CONCLUSION

The goal of this research was to validate the proposal of correcting staking flattened-end nodes to improve the load carrying capacity of space trusses. Such trusses are commonly used with staking flattened-end nodes, also known as typical nodes. They are cheap and fast to assemble. The flattened-end node shows eccentricities and the flattening process reduce the moment of inertia of the tubes. The eccentricities at the nodes produce bending moments. To increase the load carrying capacity of this type of 3D truss, spacers and reinforcement plates were proposed. Linear numerical analyses satisfactorily show that spacers correct eccentricities and significantly reduce the bending moment at the nodes.

Experimental and numerical studies were realized, with outcome results proving that correcting the connection eccentricities with spacers and reinforcement plates significantly increases the load capacity of 3D trusses. The experimental tests showed that the implementation of spacers and reinforcements increased in 46% the prototypes strength to withstand local collapse. These alternatives can be easily implemented to new truss design or in the upgrade of existing trusses. The next step of this research will be a study considering second-order FE analyses of the space truss members, as done by [16]. Thereby, it will be possible to simulate the displacements of the truss members and compare them to experimental results.

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