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Mechanism and Behavior Characteristic of Space Truss Unit for Post-tensioning

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ABSTRACT : *This paper presents the results of a post-tensioning test and analysis of a pyramidal unit structure that is basic element for space structures. The behavior characteristics was analyzed and compared with the numerical analysis and the mechanism in test model was confirmed with geometrical analysis. The results of this paper show that the behaviors of space structures can be predicted in multi-directional Mero joint system. And the authors suggest the possibility of erection and shaping formation with comparatively small post-tensioning, and space structure with the mechanism should consider the nonlinear behavior due to large deformation.*

1. Introduction

Recently, space structures have been widely used. Due to space structures, the arrangement of their discrete members, and the applied external loads to connecting joints, the forces induced in space trusses under loads are mainly axial. This axial force leads to a more efficient use of materials, resulting in reliable, lightweight structures.

On the other hand, space trusses are not always as economical as a roof, because their final shape is usually constructed in situ, and assembling in the air is complicated and expensive. In the design of large-span and lightweight structures, the sequence of erection and method of construction become critical aspects of the design. Though the space trusses have become known for their pleasing appearance, decreased weight, easy fabrication, and rapid erection, the construction process may require many cranes, and scaffolding or an erection tower is complicated and expensive. The increasing popularity of the use of space trusses to span large column-free areas has focussed attention on the need for low-cost analysis of such structures. On some occasions, because the shaping and erection is a major portion of the cost for space trusses, the construction method itself would decide the type of structural system to be adopted.

It is proposed, herein, that the post-tensioning technique can be employed as a means of shaping and self-erecting steel structures.

In recent years, a new type of post-tensioning application has been studied and developed by researchers.

Post-tensioned, shaped barrel vaults, and various typed domes have been investigated through both theoretical and experimental means (Dehdashti and Schmidt, 1996; Hoe and Schmidt, 1986; Kim and Schmidt, 1998; Kim, 1998; Kim, 2000; Kim, 2001; Kim et al., 2002; Kim and Schmidt, 2000; Kim, et al., 2001; Schmidt and Li, 1995; Schmidt, Li and Chua, 1998; Schmidt and Selby, 1999). In these studies, the possibility of shape formation and non-linear behaviour characteristics for space truss units were shown through tests of the structural model. Further, shape formation of some dome-like space trusses has been studied using computer graphics according to post-tensioning in doubly-curved shape or form (Schmidt and Selby, 2001).

As mentioned in previous studies, constructing a space truss by means of post-tensioning is an innovative construction method. The distinguishing feature of this method is that a space truss is shaped and erected by a post-tensioning process, rather than by the traditional techniques, involving the substantial use of cranes and scaffolding. Thus, the shape formation procedure is integral to the erection process. In the proposed approach, a space truss with a defined and appropriate independent near-mechanism condition is initially assembled on the ground as a planar layout. The post-tensioning method is then applied to deform the space truss into a curved space shape. The space truss is erected into a space position and the structure is then transformed from a near-mechanism condition to a stable structure. In this paper, a space truss is defined to be in a near-mechanism condition.

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If a practical space truss is initially in a near-mechanism state, it can be deformed to the desired shape, using relatively small compressive or tensile forces. However, no practical space truss has been built at the present time to assess the system. It is therefore necessary to carry out full-scale tests on such a type of post-tensioned and shaped space truss to investigate the structural behavior, according to mechanism conditions during the shape formation process. The results of these studies could be used in analysis and design for space structures with Mero joint systems.

2. Space Truss Unit Model

2.1 Geometrical Analysis for Mechanism of Test Unit

All members in the experimental space truss unit have the properties shown in Table 1.

For a post-tensioned and shaped space truss, a mechanism condition (flexure only the top chords) must exist in its initial configuration, but no mechanisms should exist in its final configuration. This requirement is necessary because the final configuration of the structure must be kinematically indeterminate in order to allow the final shape to be achieved with relatively small post-tensioning forces. In its final shape, the structure must be at least statically determinate, if not statically indeterminate, so that it is stable and can carry external loads. The mechanism condition of a post-tensioned and shaped space truss in X, Y, Z space can be expressed by the following relationship (Calladine, 1978):

$$R - S + M = 0 \tag{1}$$

where R = b - (3j - r), the degree of statical indeterminacy; S = number of independent pre-stress states; M = number of independent mechanisms; b = total number of members; j = total number of joints; and r = number of restraints on the structures. Using this criterion, a mechanism condition of a post-tensioned and shaped structure can be expressed as: $M > 0$ ($R < 0$, $S = 0$) in its initial planar layout, and $M = 0$ ($R \geq 0$, $S \geq 0$) in its final space shape. According to a general Maxwell criterion, if it were pin-jointed, the number of mechanisms existing in this space truss unit is one.

To verify the number of mechanisms of this test model, the geometrical relationship is shown in Fig. 1.

The elongation of the passive diagonal length, B, and the vertical displacement of the in-plane free joint C in Fig.1, can be expressed as follows:

$$\Delta H = L1\,Sin\beta \tag{2}$$

$$\Delta B = \frac{Sin\beta}{Sin\alpha}L1 - D \tag{3}$$

Table 1 Member Properties

Member Size	CHS 76×5.5 *mm*
Member Length	2,250 *mm*
Young's Modulus (E)	200 *Gpa*
Poisson's Ratio (ν)	0.3
Yield Strength (σ_y)	350 *Mpa*

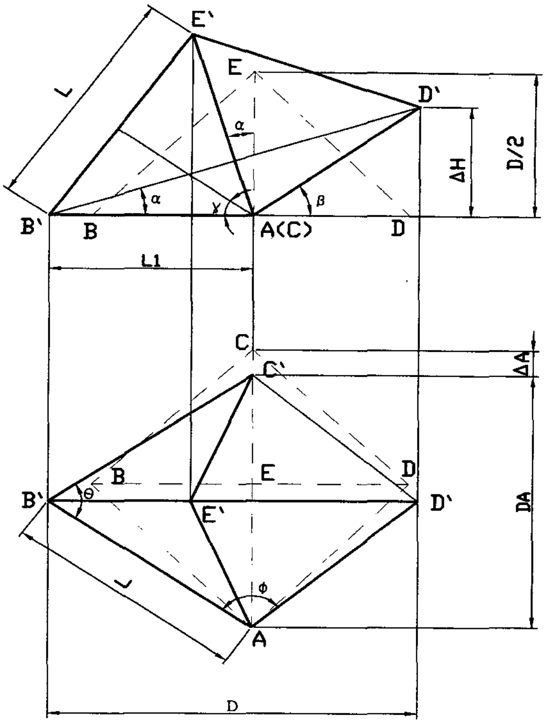

Fig. 1 Relationship of geometrical layout for space truss unit

$$\gamma = arcSin\left(\frac{L}{2L1}\right) \tag{4}$$

$$D = \sqrt{2}\,L \tag{5}$$

$$L1 = \sqrt{\left(0.5L^2 + \frac{L\Delta A}{\sqrt{2}} - 0.25\Delta A^2\right)} \tag{6}$$

In plane deformations of the test unit, of the angles between members (Fig.1) can be expressed as follows:

$$\theta = 2arcSin\left(\frac{DA}{2L}\right) \tag{7}$$

$$DA = D - \Delta A \tag{8}$$

The change of the in-plane angles can be expressed as

$$\Delta\phi = -\Delta\theta = 90° - \theta \tag{9}$$

In the above equations, there are only two independent variables, L and ΔA. Before and after the test, L is constant (neglecting the axial deformation).

Therefore, ΔA (the shorting of the active diagonal length) is the only independent variable. This is in agreement with the number of independent mechanisms existing in the test unit.

2.2 Post-stressing Test of Space Truss Unit

The space truss unit is connected with the Mero joint system as shown in Fig. 2. In this study, general geometry and support for the test model of the space truss unit is shown in Fig. 3. To suggest the information for theoretical analyses, these experiments were performed with the load controlled and displacement controlled test. The post-stressing and displacement test were carried out on a strong floor at the University of Wollongong, Australia. The space truss unit was post-stressed by the hand-operated hydraulic jack in Joint C, toward the fixed joint (Joint A), and along direction C-A in Fig. 3. A hand-operated hydraulic jack was connected in a series with a load cell to the loading joint (Joint C in Fig. 3). In the following sections, the loading diagonal (diagonal C-A in Fig. 3) is called the active diagonal, and the other diagonal (diagonal B-D in Fig. 3) is called the passive diagonal. When Joint C was jacked toward the fixed joint (Joint A), along the active diagonal C-A in Fig. 3, the length of the active diagonal was shortened, and the length of the passive diagonal was lengthened. When the jack loads reached 5.6kN, the test was terminated, and the test unit was unloaded, as the maximum stroke of the hydraulic jack had been reached. The test results for relative joint displacements are shown in Fig. 4. In Fig. 4, each point plotted corresponds to an increment jack load of approximately 1kN. The shortening of the active diagonal length is equal to the horizontal displacement of the loaded joint. The lengthening of the passive diagonal is measured in terms of the relative displacement of Joint B. The vertical displacement of the in-plane free joint (Joint D) is measured relative to its original position.

A different loading procedure was adopted to allow greater shortening of the active diagonal. A chain block was connected to the loading joints in a series with a load cell (Joint A and Joint C in Fig. 3).

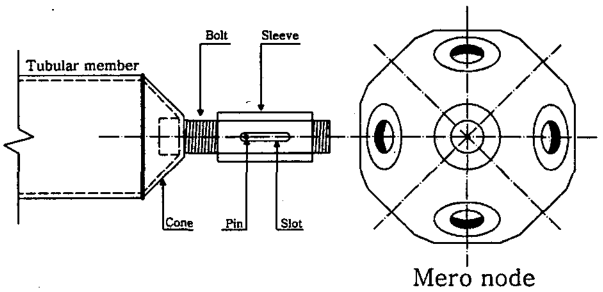

Fig. 2 Mero node system

The test unit was post-tensioned by pulling Joint C toward the fixed Joint A along direction C-A in Fig. 3. The post-tensioning process was commenced from the unloaded position reached in the previous load controlled test. The length of the active diagonal was shortened, and large deflections in three dimensions occurred in the space truss unit. The test was terminated when Joint C could no longer be moved, owing to limitation of the equipment. The maximum force between Joint C and Joint A was 5.6kN.

The vertical displacement of Joint D, relative to its original position, was 937m; unloading then took place. The second set of test results is given in Figs. 5 and 6, where each point plotted corresponds to an increment of pulley force of approximately 0.5kN.

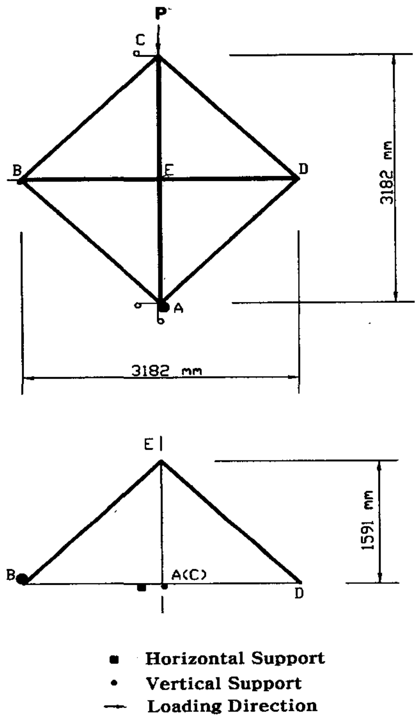

Fig. 3 Geometry and support condition of test model.

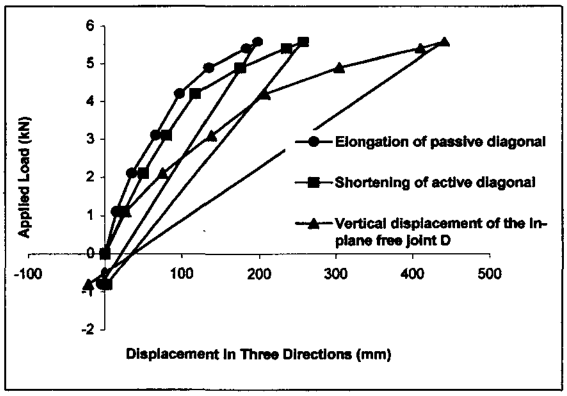

Fig. 4 Post-stressing force and displacement in load controlled test.

3. Discussion

In this space truss unit, a Mero joint system was used in connecting the space truss; the connector is a multi-directional joint system, allowing up to tubular members to be connected together at various angles. The main advantage of this system is its particular joint connection, which allows the elimination of moments at the joints, and ensures that they are acted upon only by actual forces. In previous studies, the joints of the space trusses are considered neither pin nor rigid connections, and are called semi-rigid connections. In this study, however, the characteristic of semi-rigid connection is not considered. Fig. 4 shows the results of the load controlled test. It can be seen from these figures that in the initial stage (while the jack force is less than 5.6kN), the elongation of the passive diagonal is almost equal to the shortening of the active diagonal, and the relationships between the jack force and the displacements are nonlinear.

After unloading, the test space truss unit had negligible residual deformations. In Fig. 4, the elongation of the passive diagonal and the vertical displacement of the in-plane free joint are plotted against the applied jack load. The vertical displacement of the free joint (Joint D) was 441mm, when the force was near to 5.6kN. The fact that the 5.6kN force can make such a unit produce such large displacements clearly shows that the space truss unit includes a mechanism.

Fig. 5 and Fig. 6 show the results of the displacement-controlled test. As can be seen from Fig. 5 and Fig. 6, in general the relationships between the load and displacements in the three directions are similar to those of load-controlled tests, except that they had larger displacements in the initial stage. In the initial stage of Fig. 5 and Fig 6, the slope of the curve did not change, but the change in slope shows that initial slipping-sliding took place in the joint. In addition, after the pulley load reached about 5.6kN, the increase of shortening in the active diagonal was more rapid than the elongation of the passive diagonal. The elongation of the passive diagonal reached 442mm, whereas the shortening of the active diagonal reached 780mm, and vertical displacement at Joint D reached 973mm, However, the force between Joint C and Joint A was only about 5.6kN.

After unloading, the residual deformations were bigger than the result of the load-controlled test, but no obviously significant deformations were found in the joint bolts and hubs when the space truss test unit was disassembled. Because all the members have a greater stiffness than the bolted-joint connection, the joint displacements were due to the rotations at the joints, instead of the axial and flexural deflections. This led to the large deformations of the test unit, as the test unit involved a mechanism condition.

After unloading, and from the disassembly of the test unit, it was seen that members and joint elements of the test unit underwent no permanent deformation. The joints are close to, a pin-joint connection, but they are not ideal.

The exact relationship between force and deformation of the members should be determined by experiment. The restraints existing in the joints are so small that they can be ignored for practical trusses. But these restraints are large enough for space trusses in which some mechanism condition is included, so that the restraints cannot be ignored.

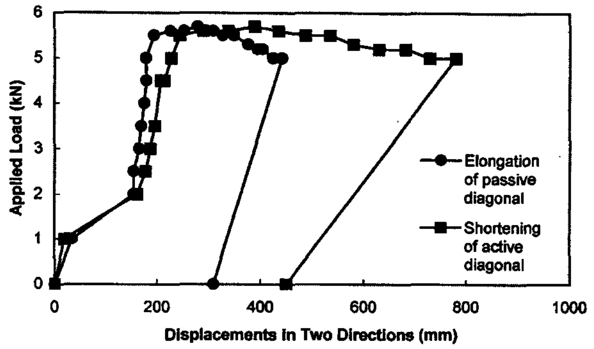

Fig. 5 Post-tensioning force and displacement in displacement controlled test

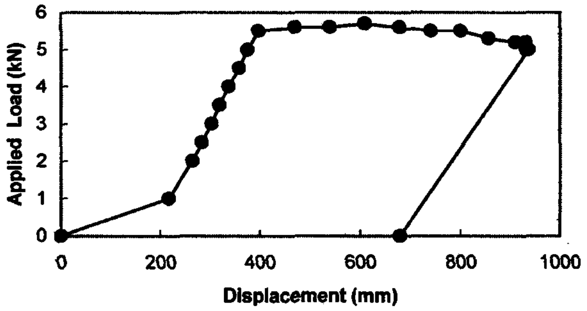

Fig. 6 Post-tensioning force and displacement of joint D in displacement controlled test.

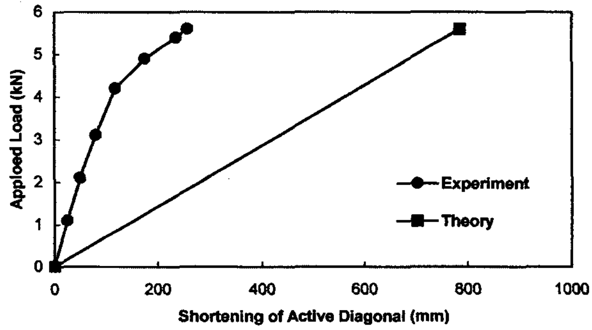

Fig. 7 Relationship between force and displacement of space truss unit

Otherwise, incorrect results for forces will be obtained. Therefore, understanding of the restraint behaviour in joints is important in the analysis of space trusses in which some near-mechanisms are considered.

For comparison of the experimental results with the theoretical analysis results, the test unit was analyzed by a commercial program(MSC/NASTRAN), which is based in finite element theory.

All elements were modelled as a beam element. The relationship between force and displacement of space truss unit was shown in Fig. 7. The big discrepancy, the divergence between experiment and theory with finite element method, is obvious.

In this paper, the divergence is due to determining that the properties of the semi-rigid joint and nonlinear characteristics are similar to previous studies.

Though the result of this analysis is linear, the result of the experiment is nonlinear. This is concerned with the result of modeling for joint. In addition, due to the test unit being near to a mechanism, the test unit is sensitive to the constraints of the joint, in which a small change of the joint constraint stiffness will cause some larger response in the space truss unit.

4. Conclusions

Based on the results of test and analyses of a space truss unit that is suitable for a practical post-tensioned and shaped space truss using the Mero joint system, the following conclusions can be drawn.

1) A mechanism condition and a geometrical compatibility condition were satisfied, in order to allow a practical post-tensioned and shaped space truss module to be formed. Geometrical analysis was shown to verify the number of mechanisms in space truss.
2) The tests have shown that there is sufficient joint rotation capacity to enable a space truss unit, constructed from a commercial joint system, to allow shaping without causing material yield in the joints.
3) Consequently, it can be expected that planar space trusses can be formed into a curved space shape, and erected to the desired position by suitable post-tensioning of a commercial system.
4) The post-tensioning force needed to deform a structure, significantly, is relatively small, but the deformation is large when the space truss involves some mechanisms or near-mechanisms.
5) The test of the space truss unit shows nonlinear behavior, thus, the characteristic of nonlinear should be considered in practice.

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