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Influence of Removed Web Members in Shaping Formation for Hypar Space Truss

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ABSTRACT: *This paper discusses the behavior of post-tensioned and shaped hypar space truss, with consideration of the influence of removing some web members. Hypar space truss is post-tensioned at the bottom chords of one diagonal on the ground; the essential behavior characteristic of shape formation is discussed by using a small-scale test model. Results of experiments and nonlinear finite-element analysis indicate that a planar, rectangular- arranged structure can be deformed to a predicted hypar shape, by the proposed shape formation method. Also the feasibility of the proposed method for furnishing of a hypar shaped space truss has been presented, under the conditions of both non-removed and partially removed web members. It follows that a nonlinear finite element analysis method can be used in predicting the behavior of the space shape and the post-tensioning force in shaping of hypar space truss. Further, in comparison to the other cases, the results of test and analysis show that the active diagonal shaping in the non-removed web members and passive diagonal shaping of partially removed web members are in relatively good agreement.*

1. Introduction

Although the post-tensioning method has been primarily used in concrete structures, recently this method was applied to steel structures as well. For instance, it has been used to build arch and dome shaped or planar frame steel structures with a shape formation and self-erecting steel structures. A new type of post-tensioning technique has been studied and developed by some researchers; they have studied the barrel vaults, various typed domes, and frames by post-tensioning through theory and experiments. (Clark and Hancock, 1995; Hewen and Lewis 1997; Kim, 1998, 2000, 2001; Kim et al., 2002; Kim and Schmidt, 2000; Kim and Hao, 2001; Kim et al., 2001, 2005; Schmidt and Dehdashti, 1993; Schmidt and Li, 1995). The economic advantages for the post-tensioned and shaped space truss have been verified through laboratory structures and similar practical structures.(Clark and Hancock, 1995)

For space structures, some engineers consider that existing construction methods will remain the same as existing ones, without recognizing the changes in this practice. They can be altered, beneficially, due to new approaches for construction. Such approaches will be stimulated by the continual need for safer construction practices. The success of this alternative approach will depend upon the success of real world applications. Certainly, at the laboratory scale level, the approach is feasible and effective. Perhaps the approach may stimulate other ways of approaching the construction of space trusses; if so, then the work is worthwhile. Already, throughout the world, there are novel approaches being used, compared with the traditional procedure of using erection towers so that modules prepared at ground level are lifted by cranes to land on these towers where further connections are made in mid-air.

The main purpose of this study is to propose that a rectangular planar arranged structure can be formed into a hypar shaped space truss by post-tensioning; and the behavior characteristic of the shaping formation is examined through the role of web members. Attention is paid to the essential aspects that lead to shape formation and self-erection, including the initial planar layout and the space shape for hypar space trusses with non-removed or partially removed web members along the diagonal. A small-scale test model of such a post-tensioned and shaped hypar space truss is used to verify the role of some web members in shaping procedures, and the feasibility of the

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proposed shape formation method is demonstrated by the theory and experiment for a hypar space truss model.

2. Theoretical Background in Shape Formation for Hypar Space Truss

The basic structural type of the post-tensioned and shaped hypar space truss is a kind of single-chorded space truss (SCST). In the initial planar configuration, it is the SCST condition, so it has the mechanisms or near mechanisms; for these reasons, SCST can be shaped easily with relatively small post-tensioning forces. Because the SCST can resist with only its weight, the friction of its joints, and flexural stiffness of the top chords, it is a very weak structure. However, after post-tensioning and the self-locking process, the SCST can be a stable structure. Though the post-tensioning process may reduce the load capacity, due to the existence of compressive pre-stress forces in some critical members after shape formation, the reduction in ultimate load capacity of post-tensioned and shaped space trusses could be improved by stiffening only a few critical members. Also, the post-tensioned and shaped space trusses seem to have some evident advantages in economy, compared with the simplicity in construction, erection procedure, and the construction site conditions. Clarke and Hancock (1995) have concluded that stressed-arch (Strarch) frames exhibit greater stiffness and load capacity than conventional flexural structures.

The shape formation principle of post-tensioned and shaped hypar space truss, described in this paper, is based on the mechanism condition and geometric compatibility condition. A mechanism condition means that a mechanism or near mechanism condition (flexure only the top chords) must exist in its initial configuration, and that no mechanisms are allowed to exist in its final configuration. In three-dimensional space, the mechanism condition of a post-tensioned and shaped space truss can be expressed by a general Maxwell's criterion (Calladine, 1978)

The geometric compatibility condition between the initial and final configuration of a post-tensioned and shaped hypar space truss is that all the non-gap members remain the same length (only deflection without large strain) during the shape formation process. Also, distances between joints, in which the shorter bottom chords are placed to create gaps, must shorten to allow the post-tensioning operation; the gap sizes are determined with the shapes of structures. In general, the shape finding can be used in post-tensioned and shaped space truss; these shape-finding procedures are simulated through computer analysis, based on geometrically nonlinear analysis for a given arbitrary plan.

3. Layout of Experimental Model for Hypar Space Truss

As shown in Fig. 1, the planar layout for the hypar space truss is a rectangular SCST, consisting of 6×6 pyramidal units. In the planar layout sections, the loading diagonal (diagonal A-A in Fig. 1) is called a active diagonal, and the other diagonal (diagonal B-B in Fig. 1) is called a passive diagonal. To form a surface of negative Gaussian curvature by post-tensioning only the bottom chords of the active diagonal, the layout of the hypar space truss needs to be adjusted so that the edges are stiffened against flexure, so the edge bottom joints are connected with zero-gap bottom chords. In the case of a non-mechanism structure, it cannot be deformed to a true hypar surface with relatively small post-tensioning forces. To provide the appropriate mechanisms for shaping formation with relatively small post-tensioning forces, the most efficient way is to remove the inside web members of the pyramids along the active or passive diagonal (except the middle two, as shown in Fig.1 with dotted lines). When some web members in the diagonal are removed, the amount of the increase in the load capacity varies, with factors such as the distribution of member sizes, support conditions of structures (continuous, simply supported, with columns at the corners only or supported along the boundaries), loading patterns of external load (symmetrical or unsymmetrical), and geometry of the structure (square, rectangular, etc.). Because of the many possible combinations of these factors, simple rules to give typical patterns for the diagonals to be removed have not been determined. In this paper, planar arranged structures for a hypar space truss are three-typed rectangular SCST, as shown in Fig. 1, non-removed any web members along the diagonal (Case 1), removed four web members along the passive diagonal (Case 2), removed four web members along the active diagonal (Case 3) for the shaping formation test and analysis. All of these behavior characteristics will be compared with the results of the shaping formation test and theoretical analysis.

4. Finite Element Analysis and Experiment

The finite element method is used to predict the final space formation and post-tensioning forces of space truss and to investigate the feasibility of the proposed post-tensioning method. The shape formation process induces large deformations, and the analysis is performed with geometric nonlinear analysis by MSC/NASTRAN. In the finite element analysis herein, the closing of gaps for each bottom chord is simulated by the element shortening caused by a uniform negative temperature load, proportional to the values of gaps chosen to form a hypar shape. For the analysis by finite element method, the top chords are modeled with beam elements, while the other members are modeled with rod elements. Based on the results of the finite element analysis, the coordinate values of every joint in the hypar space shape can be obtained. When the final space shape is determined, the post-tensioning forces and induced stresses can be found from current results of the finite element analysis. These results can be used to form the desired space shape with the predicted post-tensioning forces.

The post-tensioning operation of a hypar space truss is achieved by tensioning a strand along the shorter bottom chords on the active diagonal of a planar layout. The bottom chords on the active diagonal are given some gaps,

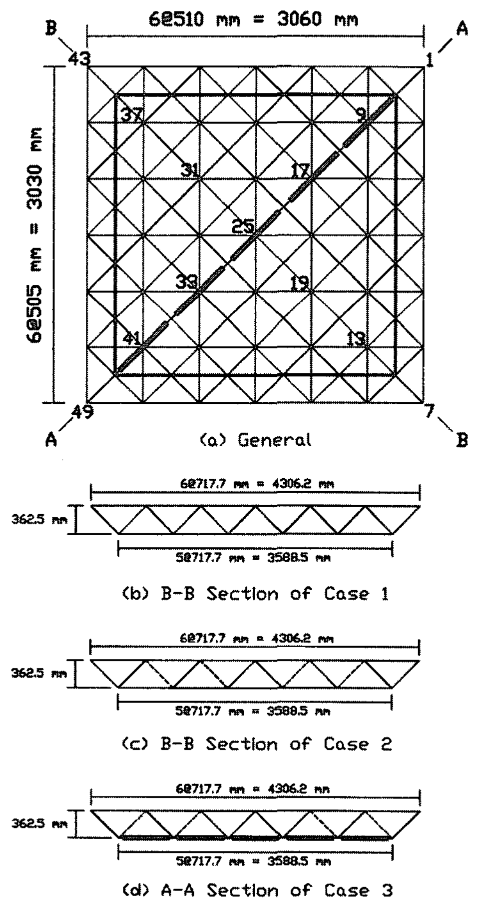


Fig. 1 Planar arranged structure (SCST) for hypar space truss

in proportion to the desired final shape of structure, according to the finite element analysis results. The gap chords comprise shorter tubes, and a strand passes through the tubes and the bottom joints. As the bottom chords shorten at the gap locations, the complete structure is shaped into a curved configuration and erected into its final position. All of the characteristics for the hypar space truss and the general features of the small-scale test model are outlined below. This test model consisted of 36 pyramids. The top chords were made of 13×13×1.8mm square hollow section (SHS) steel tubes; while the web members were made of 13×2.0mm circular hollow section (CHS) steel tubes; the edges bottom chords were made of 13×13×1.8mm square hollow section (SHS) steel tubes, the diagonal bottom chords were made of 27×8.75mm circular hollow section (CHS) steel tubes. The Young's modulus of the steel was 200GPa, and Poisson's ratio was 0.3. Both top chords and web members were of nominal strength Grade 350 (σy=350MPa) steel. Photo. 1 shows the planar layout of the experimental model that was made, based on the dimensions shown in Fig. 1. In this model test, when the post-tensioning forces are applied in the strand of active diagonal bottom chord, the gaps are closed tightly. After the post-tensioning, the hypar shaped space truss was seen as a smooth surface; it is shaped principally by the patterns of twisting deformation in the top chord plane and the flexural deformation of top chords at the joints. Although some top chords had significant flexural deformations at the joints, top chords remained straight. Photo. 2 is the final shape of hypar shaped space truss, by means of post-tensioning, the rectangular meshes of top chords deformed to rhombic forms.

5. Discussion

Figs. 2 and 3 show the space shape and the position of the hypar space truss surface, obtained from the finite element analysis and the experiment. Respectively, in the active diagonal direction, it was seen that the experimental shape of case 3 was most deep; case 1 and 2 were in good agreement for shaping. However, in the passive diagonal directed shaping formation, the experimental shape of case 2 was most deep, case 1 and case 3 are almost the same shape. In case 1, the surface height of the experimental hypar space truss was 375mm (after post-tensioning, the vertical difference between node 49 and 25 in Fig. 1), while the theoretical surface height was 405mm. So, the difference between the theory and experiment was 8% in the base of experimental value, and the difference in the vertical distance between node 7 and 25 was 5%. With the same

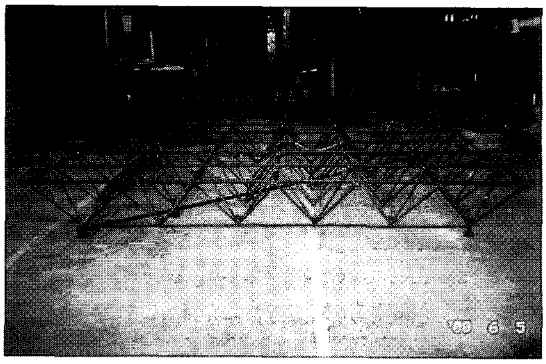


Photo 1 Experimental model before post-tensioning

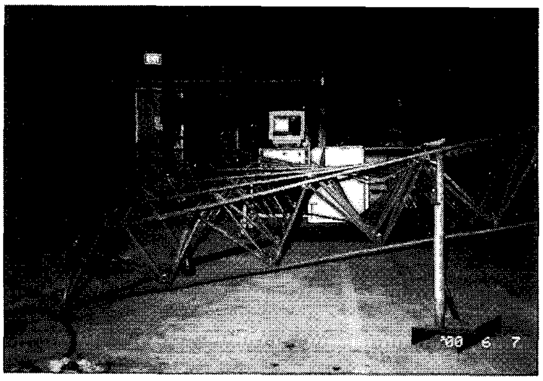
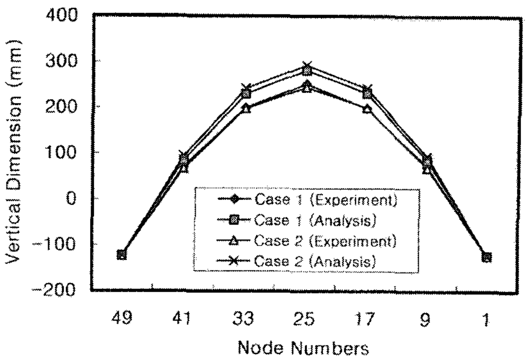
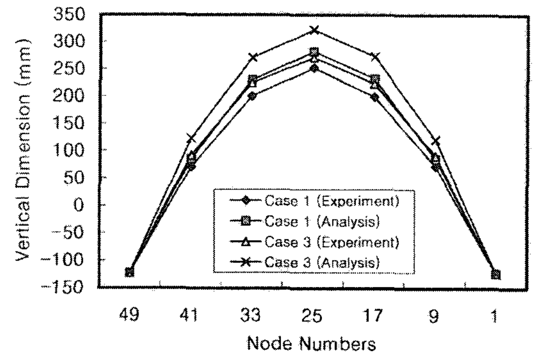


Photo 2 Final shape of hypar shaped space truss by post-tensioning



(a) Shaping formation of case 1&2

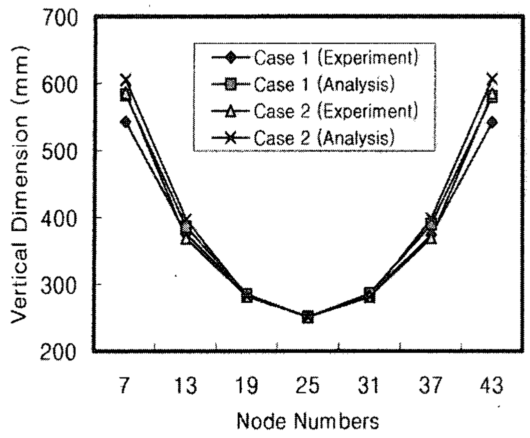


(b) Shaping formation of case 1&3

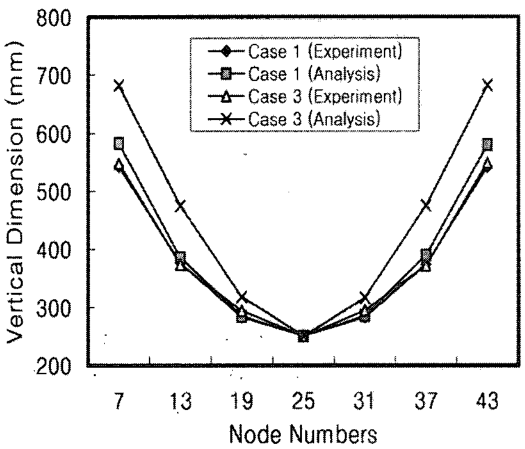
Fig. 2 Vertical dimension for A-A section for the removed web cases of hypar space truss

The passive diagonal directed shaping formation accuracy shows the small difference, compared to active diagonal directed shaping formation in case 1 and 2, but case 3 is contrary and a big difference. In spite of a comparatively big post-tensioning load, for the active diagonal shaping formation, case 1 was in relative agreement between the finite element analysis and experiment, compared to case 2 and 3. The experimental value of case 1 is bigger than that of case 2, and the experimental value of case 3 is bigger than that of case 1. For the passive diagonal shaping formation, case 2 was in relative agreement between the finite element analysis and experiment, compared to case 1 and 3. The experimental value of case 2 is bigger than that of case 1, and the experimental value of case 3 is bigger than that of case 1. In the case of hypar space truss with non-removed web, for the active diagonal shaping formation, though the post-tensioning force is comparatively large, the shaping formation accuracy is relatively high, compared to the space structures of the partially removed web members. But for the passive diagonal shaping formation, the accuracy is relatively high in the case of partially removed web members along the passive diagonal. As a result, though gap sizes of the diagonal bottom chords are the same in all cases, the characteristics of shaping formations are different, according to the non-removed or partially removed direction of web members.

These results should be assumed to be the characteristics in the geometry of structure and the direction of removed web members, so it is very important to decide the direction of removal and geometry of structure (Hewen and Lewis 1997). Generally, in shaping formation of the same condition, some discrepancies between the theory and experiment are owed to the geometric imperfections of the members and assembly and the rotations and slippage of joints in the test model. Nevertheless, these imperfections affect the structural behavior of the shaping formation; most of these factors are not considered in detail for the finite-element modeling. Though the post-tensioned and shaped hypar space truss has the characteristics of a mechanism and a structure, a finite-element method only considers the structural characteristics without considering the mechanism. As a result, it will have low efficiency in treating such problems involving near-mechanisms, like this experimental model. Consequently, for improvement of the



(a) Shaping formation of case 1&2



(b) Shaping formation of case 1&3

Fig. 3 Vertical dimension for B-B section for the removed web cases of hypar space truss

efficiency in the finite-element method for simulating the structural behavior of post-tensioned and shaped space trusses, further research is necessary.

6. Conclusions

For the hypar shaped space truss, discussed in this paper, the following conclusions can be drawn.

(1) The shape formation process is integral to the erection process, and the feasibility of the proposed method for a hypar shaped space truss has been presented. Such a post-tensioned and shaped hypar has evident advantages in simplifying fabrication and erection processes.

(2) A nonlinear finite element analysis method can be used for predicting the space shape in the shaping formation of hypar shaped space truss.

(3) Shaping of hypar space truss is in relative agreement between the experiments and theoretical analysis in active diagonal shaping formation of non-removed members and in passive diagonal shaping formation of partially removed web members along the passive diagonal, compared to the other cases.

(4) Specially, there is some discrepancy in the results between theory and experiment for the shaping formation in the non-removed or partially removed web members along the diagonal. This is due to the differences between the test model and theoretical model, and the direction of member removal and geometry of the structure; further investigation is recommended.

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