Control Of Mechanisms In Post-Tensioned And Shaped Space-Truss Domes

L. C. Schmidt, H. Li
Dept. of Civil, Mining and Environmental Engg.,
Univ. of Wollongong, NSW 2522, Australia

Tel: 02-42213138
Fax: 02-42213238
Email: lewis_schmidt@uow.edu.au

ABSTRACT: This paper concerns the shape formation tests of post-tensioned and shaped steel domes. The test domes, assembled initially at ground level in an essentially flat condition, are shaped to a curved space form and erected into the final position by means of a post-tensioning technique. Based on previous studies on this shape formation principle, two post-tensioned and shaped steel domes have been constructed. The results of the shape formation tests are reported in this paper.

1 INTRODUCTION

Post-tensioned and shaped space trusses are a type of recently developed steel structure which is capable of being shaped to a curved space shape and erected into the final position from a planar layout by means of post-tensioning. The basic structural module of the post-tensioned and shaped space truss is the so-called Single-Chorded Space Truss (SCST), a truss with a single-layer of chords, together with out-of-plane web members. In the initial planar configuration, the SCST provides near mechanisms that can be readily shaped with relatively small post-tensioning forces, as flexure occurs only in the top chords. By means of post-tensioning, the SCST can be deformed to the desired space shape. After a self-locking process for certain members that are inserted too short initially, the SCST becomes a stable structure and can carry significant loads (Schmidt 1989).

The post-tensioned and shaped steel domes studied in this paper belong to the Space-Shape-Based type (Li and Schmidt 1997), i.e., the planar layout of the dome is determined by its desired space shape. Previous studies have verified the possibility of shaping a Space-Shape-Based dome from a planar layout by post-tensioning (Schmidt and Li 1995a, b). In this paper attention is paid to the construction of the test domes. The studies in this paper include two Space-Shape-Based post-tensioned and shaped domes, which are referred to as SSBD 1 (Space-Shape-Based Dome 1) and SSBD 2, respectively.

The principal objective of the studies on SSBD 1 is to form a true part-spherical dome from a flat condition, and the principal objective of the studies on SSBD 2 is to investigate its maximum deformation extent without excessive distortion due to inelastic member behaviour. The shape formation tests of SSBDs 1 and 2 are based on previous studies on this shape formation principle, the space and planar geometric models established by means oyan optimization method (Schmidt and Li l995a), and the shape formation analysis by means of the finite element method (Schmidt and Li 1995b).

2 SHAPE FORMATION TEST OF SSBD

The planar layout for SSBD 1 is shown in Figure 1. In the initial planar layout, the total number of top chords and web members b is 156; the total number of joints j is 61 (37 surface joints and 24 web joints). Assuming a pinjointed truss and that the number of overall restraints r is 7 (the minimum number to prevent a structure from rigid body movement is 6), and substituting them into the Maxwell criterion $R = b - (3j - r)$, and $R - S + M = 0$ (Calladine 1978), it is found that the structure includes 20 independent mechanisms (M = 20, R = -20) before the post-tensioning operation (as the number of prestress states S = 0). This means that 20 members or additional restraints need to be added to the planar layout in order to form a stable structure (M = 0) that is just statically determinate.

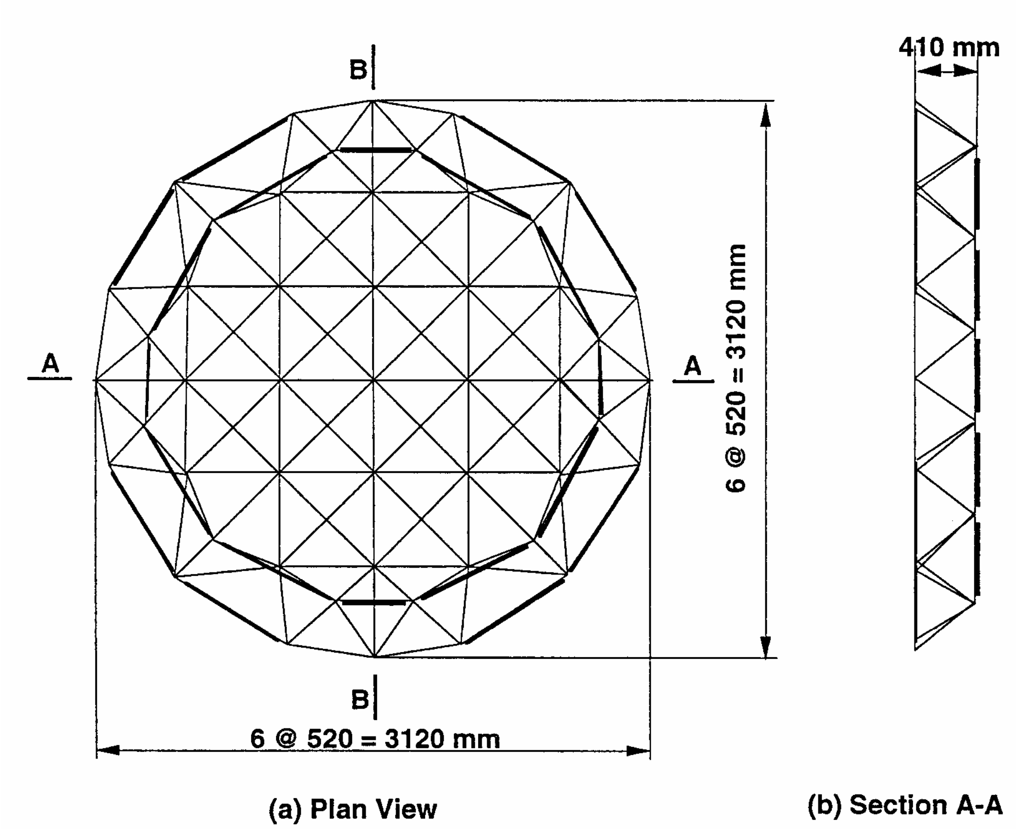

Figure 1 Planar layout (planar geometrical model) of SSBD 1

There are alternative changes possible in the choice of members to be shortened in the planar layout to form the curved space shape. When shortened these members will suppress mechanisms, according to the Maxwell criterion (Calladine 1978). The principal objective of the post-tensioning method is to select the M independent mechanisms that follow from the many possible distance changes. Several potential post-tensioning layouts exist in the given planar arrangement of members, and the selection of the most convenient post-tensioning method, both from a practical and from a structural point of view, is still an open question (Li and Schmidt 1997).

Based on the number of mechanisms (M = 20), a post-tensioning method, as shown in

Figure 1, is proposed for SSBD 1. Eight peripheral gap top chords and twelve short bottom chords are added to the planar layout as indicated with thick lines in Figure 1. If all the gaps close after the post-tensioning operation, the total number of members b will become 176, while the total number of joints j remains 61. In this case, $M = 0$ and $R = 0$, i.e., the dome has no mechanism left after post-tensioning. The above results show that the proposed post-tensioning method satisfies the mechanism condition (Schmidt and Li 1995b).

The experimental planar layout of SSBD 1, as shown in Figure 2, is a modified Single Chorded Space Truss (SCST). The two top chords and four web members in the non-regular pyramidal units are adjusted to suit the circular boundary of SSBD 1. The planar layout was assembled on the floor from a single-layer mesh grid of top chords and pyramidal units of web members. All of the non-gap top chords of the dome were continuous. One series of continuous chords was placed over the other continuous series, and bolted together with 6 mm high tensile cap screws. The ends of the continuous top chords were bent in the horizontal plane in order to form the quadrilateral meshes. Four web members were welded to a bottom joint to form a pyramidal unit. The pyramidal unit was also bolted to the top chords with 6 mm high tensile cap screws.

The top and bottom chords were made of 13 x 13 x 1.8 mm square hollow steel (SHS) tubes, while the web members were made of 13.5 x 2.3 mm circular hollow steel (CHS) tubes. The properties of the steel were as follows: Young's modulus E = 200 GPa, Poisson's ratio n = 0.3; the experimental yield stress was 450 MPa for the top chords, and 440 MPa for the web members.

To form a part-spherical surface, the tubular bottom chords were cut shorter according to the space and planar geometrical model faces (Schmidt and Li 1995a). The tubular bottom chords were assembled to the planar layout by high tensile steel strands. For simplicity, only four strands were used to assemble the 12 shorter tubular bottom chords to the planar layout. Each strand passed through four edge bottom joints and through three shorter tubes.

The gap top chords were made of two different size SHS steel tubes as shown in Figure 2. The smaller tube could slide freely in the larger one. During the shape fornnation test, the gap top chords were not tensioned. It was expected that the overall length of such combined gap top chords could close to the desired value as the gaps in the bottom chords were closed (although they should also be post-tensioned).

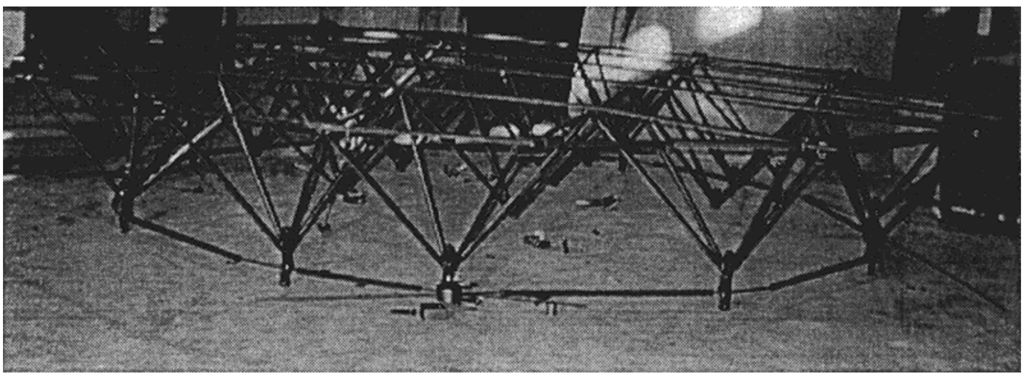

Figure 2 Planar layout of test SSBD 1

The post-tensioning procedure began with the planar layout in its initial position, i.e., all the top chords were flat. A hydraulic jack was used to apply an axial force to the individual strands that passed through each set of three tubular bottom chords. During the post-tensioning procedure, the supports of the dome were the peripheral bottom joints, which were free to slide horizontally and to rotate. The post-tensioning force that closed the gaps in each set of three bottom chords was 2.1 kN.

The test SSBD 1 is shown in Figure 3. It was found that the test dome did not have a true part-spherical surface. The curvatures along the two directions A and B in Figure 1 were not the same. Both the periphery of the top surface and the periphery formed by the bottom chords was not a circle but an ellipse in plan. The test SSBD 1 was symmetrical along the two centerlines A-A and B-B in Figure 1. The surface spans along the two directions A and B in Figure 1 were 3110 mm and 3063 mm, respectively. The overall height of the experimental dome was 568 mm.

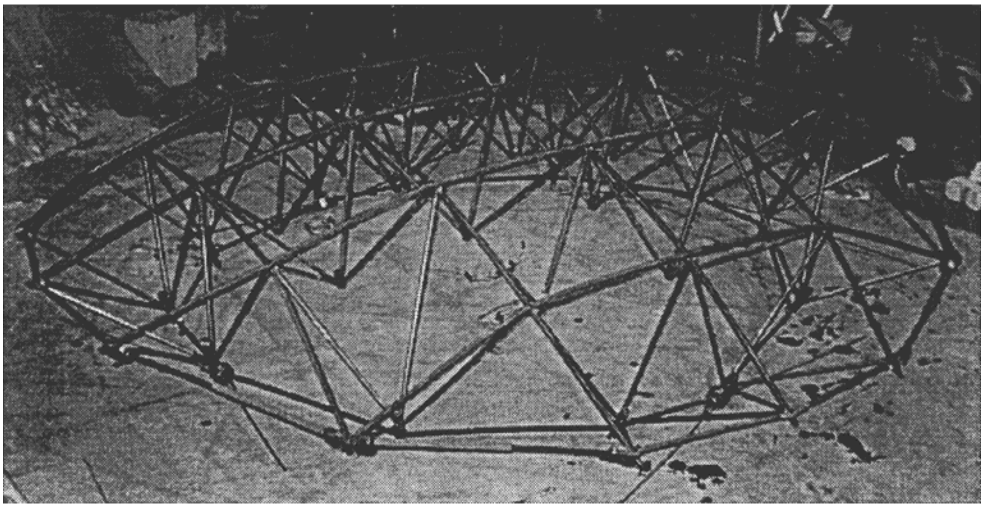

Figure 3 Space Shape of Test SSBD 1

The difference between the two curvatures along the directions A and B in Figure 1 can be attributed to the existence of more mechanisms in SSBD 1 than the mechanisms practically controlled by the post-tensioning operation, and the slight position difference in the levels of the top chords in the two directions. Because the top chords had bolt holes at joint positions, the top joints were weaker than the members, and the structural behavior of SSBD 1 was more like that of a pinjointed structure. The gap top chords, which were expected to slide to the desired length when the gaps in the bottom chords closed, had different lengths at the end of the post-tensioning operation. This meant that the movements of the eight mechanisms in the gap top chords had not been efficiently controlled. Because the top chords were continuous and one series of continuous chords was placed over the other continuous series, the bending moments in the upper layer of top chords were larger than those in the lower one. In a structure in which eight independent mechanisms exist, such a structural difference is enough to induce a significant difference in deformations. As a result, the curvatures along the two directions A and B were not the same.

The space shape of SSBD 1 was achieved principally by the in-plane rotation and the out-of-plane flexural deformation of top chords at the top joints. The segments of the top chords between panels remained straight axially, although square meshes of top chords deformed to rhombic forms as can be seen in Figure 3. All the deformations in test SSBD 1 were within the yield limit of the materials, because the release of the posttensioning force caused the dome to flatten to a planar layout again.

3 SHAPE FORMATION TEST OF SSBD 2

The planar layout of SSBD 2 is the same as that of SSBD 1, except the eight gap top chords are removed. The principal objective of the studies on SSBD 2 is to investigate its maximum elastic deformation extent. The gaps in the lower chords were increased over those for SSBD1.

The post-tensioning method for SSBD 2 was the same as that for SSBD 1. However, at the end of the test, two continuous upper top chords yielded and subsequently fractured at four joints. Such a failure is due to the severely reduced cross section at the joint due to the bolt hole, and the limited strain hardening capacity of the higher tensile steel used for the chords. This meant that SSBD 2 reached its maximum deformation due to fracture of the top chords at the joints. The final space shape of SSBD 2 is shown in Figure 4, and the detail of a fractured top chord at the top joint is shown in Figure 5. The post-tensioning force that closed the gaps in each set of three bottom chords was 14 kN.

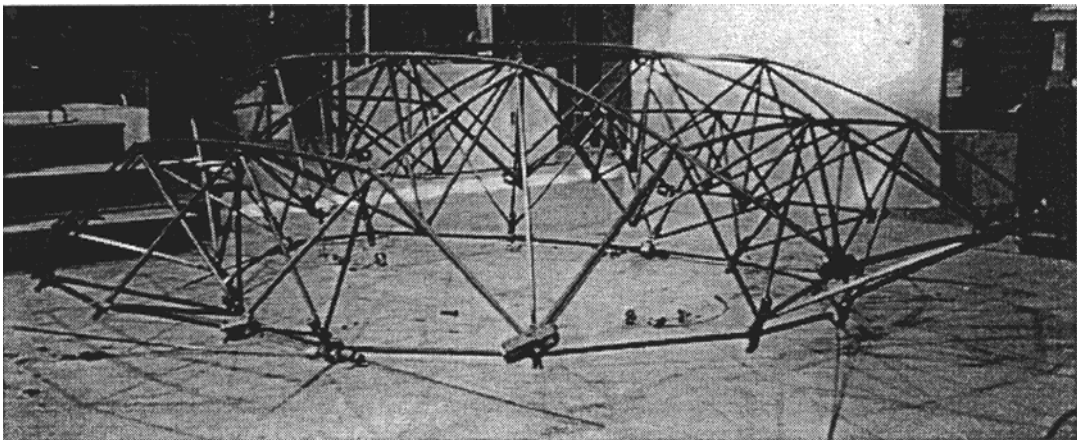

Figure 4 Space shape of test SSBD 2

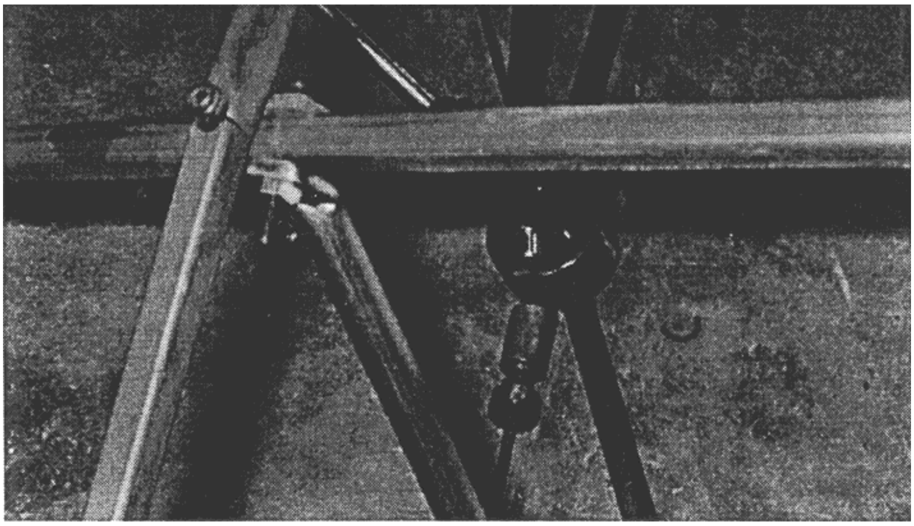

Figure 5 Fractured top chord at a joint of test SSBD 2

It was found that the test dome did not have a true part-spherical surface. The central area of SSBD 2 was almost flat, and the curvatures along the two directions A and B in Figure 1 were not the sarne and were not smooth. In plan, the periphery of the top surface and the periphery formed by the bottom chords were ellipses. The surface spans along the two directions A and B in Figure 1 were 2360 mm and 2285 mm, respectively. The overall height of the experimental dome was 682 mm.

While the difference between the two curvatures along the two directions A and B can be attributed to the existence of the eight uncontrolled mechanisms, and the slight position difference in the top chords along the two directions, the flat central area of SSBD 2 was due to yielding of the top chords at joints. Because two top chords yielded at the four joints near to the edge, the post-tensioned forces applied to the bottom chords could not be transferred to the central part, and the deformations of the edge pyramids were large. As a result, the central area was relatively flat and the edge area approached slope of 45°.

The test SSBD 2 reached its maximum elastic deformation extent due to two top chords yielding followed by fracturing at four joints. This failure demonstrated that the maximum elastic deformation extent of such a post-tensioned and shaped dome depended on the strength of the top chords. Because the top chords were weakened by the bolt holes at the joints, they failed at joint positions.

4 CONCLUSIONS

It is possible to shape a planar layout into a desired space shape from a planar layout by means of a post-tensioning method. The two test domes described herein, however, did not achieve the part-spherical shape, due to the lack of control of some mechanisms. This demonstrates that when the top joints are not stiff enough, the behaviour of the truss is closer to that of a pin-connected structure. Therefore, a necessary condition to form a desired space shape from a planar layout with low joint stiffness is that the movements of all the existing mechanisms must be effectively controlled.

The space shape of a post-tensioned and shaped space truss is principally determined by the post-tensioning method (i.e., positions and values of the gaps). The maximum elastic deformation extent of a post-tensioned and shaped space truss dome is determined by the strength and stiffness of the top chords and their joints.

ACKNOWLEDGMENTS

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