Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia
Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures
28 September – 2 October 2009, Universidad Politecnica de Valencia, Spain
Alberto DOMINGO and Carlos LAZARO (eds.)

Analysis and experiments for form finding of the SCST structures

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Abstract

This paper is focused on the form finding of three kinds of SCST structures that are constructed with bolt type joint by gusset plate, bolt type joint, and ball type(Mero type) joint by means of cable-tensioning. The cable-tensioning method for SCST structure is a innovative, fast, and economical construction method in the special construction site or field condition, the cable-tensioning is performed with the strand in the bottom chords of space structures. In this paper, the unit shape of test models consist of uniform pyramids, from the planar structures on the ground, the space structures are shaped and erected into its final curved space structures by cable-tensioning. The cable-tensioning is applied along the diagonal direction, the circumference line direction, or the middle line direction of the each SCST structures. The feasibility of the proposed cable-tensioning technique and the reliability of the established geometric model were confirmed with finite element analysis and experiments for a small-scale test models. Through the experiments in the three types of SCST structures, within the yield limit of the members, a planar layout can be deformed to desired space shape by means of cable-tensioning. As a results, the proposed cable-tensioning technique could be applied the form finding of the various SCST structures, so we can know the behaviour characteristic of the joint for each types in form finding for practical design purposes. For a special site condition of construction field, this cable-tensioning technique should be an economic and reasonable construction method compare to conventional construction method including the heavy crane and scaffold.

Keywords: ball type joint, bolt type joint, cable-tensioning, form finding, nonlinear finite element, SCST, space structure, temperature load.

1. Introduction

Since the beginning of the commercial use with space structure type, these structure types have now become widely used as a many structure types in the world. They are usually used to provide long span roof coverings for buildings such as stadiums, public halls, exhibition centers, aeroplane hangers, offshore drilling platform, power transmission towers and many other structures, where there is a need to avoid columns. Because the space structure consists of tension and compression member that can be maximized the capacity of load resistance, the space structure is an efficient and light structure type compare to conventional beam-column typed structures. Space structures are relatively lightweight, aesthetic, easy to fabricate and transport, flexible in workability, and require short period for construction work. In general, because a space structure consists of many joints that are sensitive to stress and strain, and the characteristic of this joint effect to total behaviour of structure, it is necessary to handle carefully in design and construction. In order to develope a more innovative construction techniques, extensive research has been carried out on the behaviour characteristic of form finding for space structures by means of cable-tensioning method. Although the cable-tensioning method has been used principally in concrete structures, its application to steel structures has gained acceptance over recent in decades. Therefore, by means of cable-tensioning, to improve the construction method and propose an alternative solution, shape formation test and theoretical analysis for the space structure was conducted with the small scaled test models that were consisted of only bolt type joint, bolt type joint with gusset plate, and ball type joint and steel pipe. These structures were investigated by the theoretical analysis and experiments in laboratory for the cable-tensioned and shaped space structures. The main advantage of cable-tensioned and shaped space structures is their fast and economical construction and fabrication in special construction site. And because the shape formation procedures are integral with the erection process, this method can save the construction costs by eliminating or minimizing the need for scaffolding and heavy cranes. Because the planar layouts are assembled at ground level with a single-layer of top chords and pyramid units of web members, work efficiency and safety are increased. A new types of cable-tensioned and shaped space structure has been studied for domes, arch, hypar shaped space structures(Kim et al [4]-[16]). In this study, specially for the three kinds of joint types in space structure, the experiments for the form finding have been performed with applying the cable-tensioning to the strand located in the bottom chords of space structures, these results are compared with the results of nonlinear analysis with MSC/NASTRAN or MIDAS, and the characteristics of the behaviour for each models are analysed. As a result, the authors can suggest the possibility and feasibility of form finding, and the behaviour characteristic of joint for each space structures.

2. Principles of forming finding for space structure

For the form finding of space structures, the principle of cable-tensioned and shaped space structure, space shape, and principle are analyzed in following section.

2.1 Form finding principle

The shape formation principle of cable-tensioned and shaped space structures described in this paper is based on the mechanism condition and geometric compatibility condition. A mechanism condition means that a mechanism or near mechanism conditions (flexure only the top chords) must exist in its initial configuration, and that no mechanisms are allowed to exist in its final configuration. The mechanism condition of a cable-tensioned and shaped space structure in three-dimensional structure can be expressed by a general Maxwell's criterion (Calladine [1]).

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

where, $R = b - (3j - r),$ in which, R = degree of statical indeterminacy; S = number of independent prestress states that exist; M = number of independent mechanisms; b = total number of members; j = total number of joints; and r = number of restraints on the structure. Using this criterion, a mechanism condition of a cable-tensioned and shaped space 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.

2.2 SCST structure system

The suitable basic structural type of the cable-tensioned and shaped space structure is single-chorded space truss, it is called SCST structure. In the initial planar configuration for cable-tensioning, it is the SCST condition, so it has the mechanisms or near mechanisms, for these reasons, SCST can be shaped easily with relatively small cable-tensioning forces. Because the SCST structure is very weak structure, it can resist for deformation with only its weight, the friction of its joints, and flexural stiffness of the top chords. But after the cable-tensioning and the self-locking process, the SCST can be a stable structure. Though the cable-tensioning process may reduce the load resisting capacity, due to the existence of compressive pre-stress forces in some critical members after shape formation, the reduction in ultimate load capacity of cable-tensioned and shaped space structure could be improved by stiffening only a few critical members decided in analysis. And although the top chords are flexed during the cable-tensioning, this bending is not serious for the safety of the structural behaviour(Dehdashti [2], [3]). In general, numerical analysis technique using computer has been applied to form a shape of space structure, and general study has been performed to predict the structural shape under a certain geometric and material conditions such as length, height of structure, applied load, and required stress condition. Generally form finding of space structure by cable-tensioning shows a difference according to the type of plan layout and gap size of the chord. These test models satisfy with the mechanism condition and geometric compatibility condition, which were required in form finding by cable-tensioning.

3. Planar layouts of experimental models

General features of the small scaled test models for this study are as following; for the test model (A) as shown in Figure 1, the model shape is the circular type (diameter: 2,488.25*mm)*, it is consisted of top chords of square hollow section(SHS) 13×13×1.5*mm*, web members of circular hollow section(CHS) 13×2.5*mm*, bottom chords of CHS 13×2.5*mm*. And the Poisson's ratio is 0.3, yield stresses(σ_y) are 450 *Mpa* for top chord, 440 *Mpa* for web chord, 440 *Mpa* for bottom chord, and Young's modulus(E) is 200 *Gpa.* The top chords and webs are connected with the bolt type joint by gusset plate, the bottom of web members are welded joint as shown in Figure 2. And the cable-tensioning is applied to the direction of circumference for finding the dome shaped test model. For the model (B) as shown in Figure 3, the test model is rectangular type, the top chords were made of *SHS* 13×13×1.8*mm* steel tubes, while the web members were made of CHS 13×2.0*mm* steel tubes, the bottom chords were made of CHS 27×8.75*mm* steel tubes. The Young's modulus of the steel was 200*GPa*, and Poisson's ratio was 0.3. The top chords and web members were of nominal yield strength Grade 350 (σ_y=350*MPa*) steel. In the test model (B), the connections of the top chords and web members are made of bolt type joint without gusset plate as shown in Figure 4. And the cable-tensioning is applied to the direction of diagonal for finging the hypar shaped test model. For the test models (C, D) as shown in Figures 5 to 7, the test models are consisted with CHS 40×4*mm*. The Young's modulus is taken as 136 *GPa*, Poisson's ratio is 0.3 and yield strength is 334 *MPa.* In the test models (C, D), the joints of all of the members are connected with the ball type joint as shown in Figure 4. And the cable-tensioning is then applied to the direction of middle line to obtain the arch shaped test model.

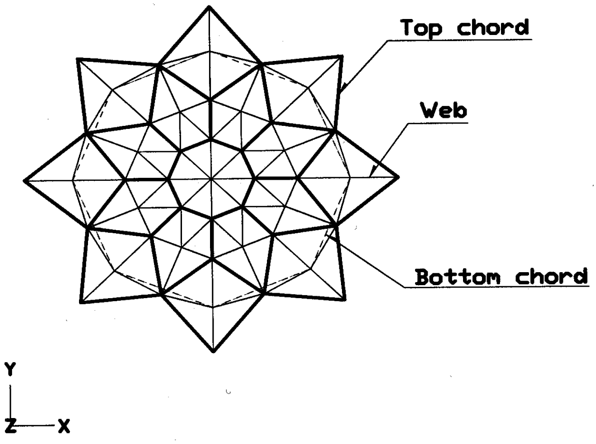
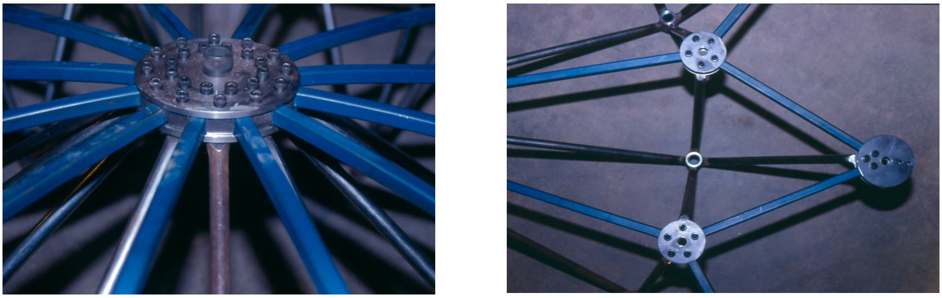


Figure 1 Layout of experimental model (A)



(a) (b)

Figure 2 Connection types by bolt with gusset plate in test model (A)

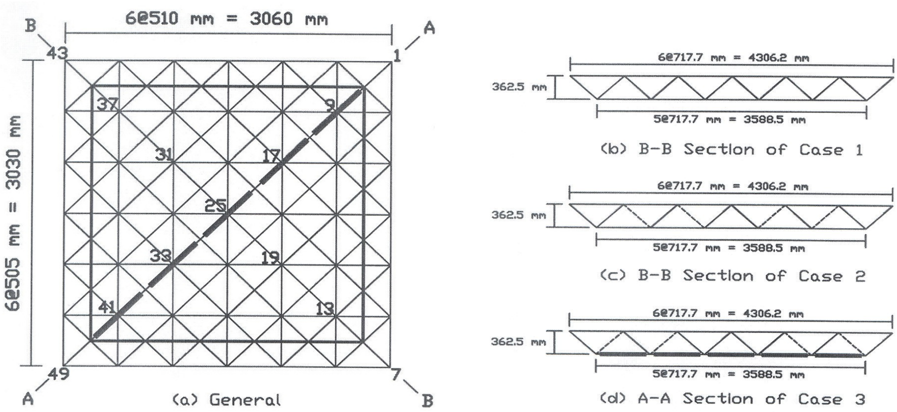


Figure 3 Layouts of test model (B)

(a) Bolt type joint (b) Ball type joint

Figure 4 Connection types of only bolt and ball type joint

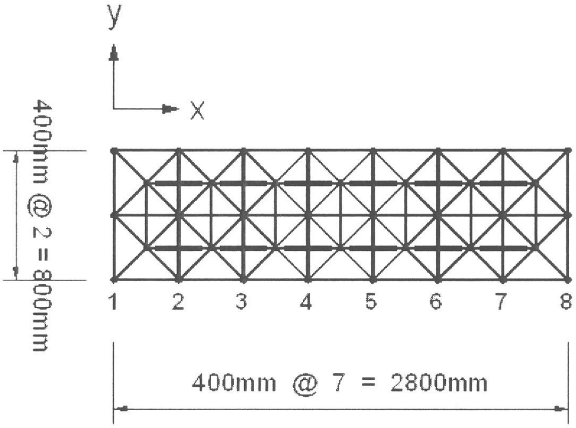


Figure 5 Layout of Test Model(C)

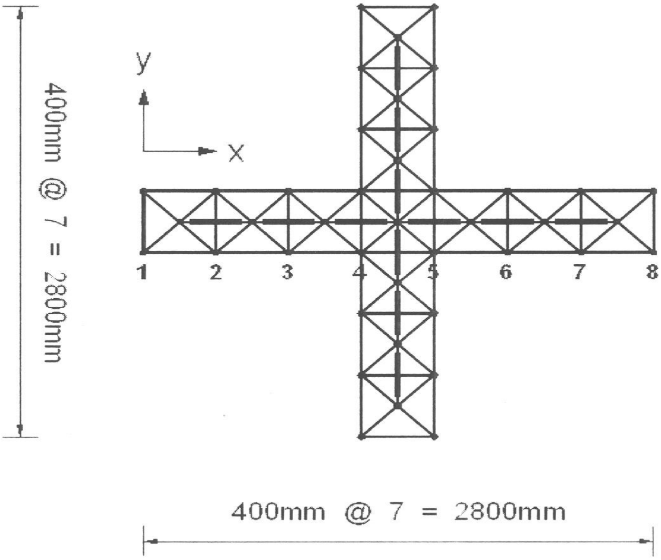


Figure 6 Layout of Test Model(D)

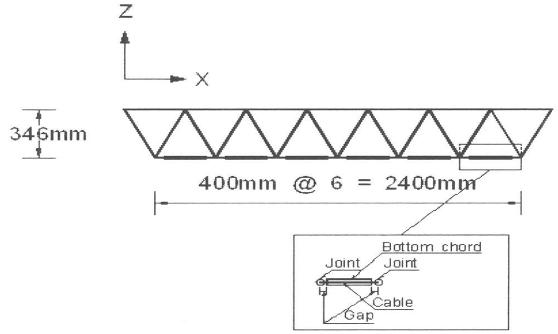


Figure 7 Layout of test models (C, D) and detail of bottom chord
for test models (A, B, C, D)

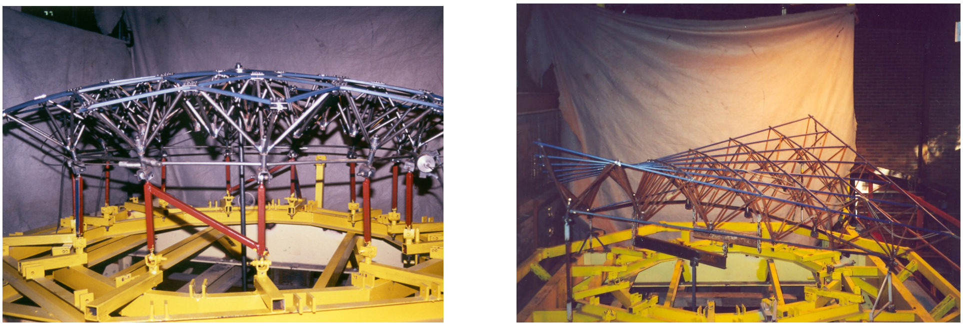
4. Analysis and experiments for form finding

4.1 Nonlinear analysis

A finite element simulation for the form finding must exactly represent the practical procedure of shaping. In such an analysis, the important point is how to model the mechanism for the closing of the gaps in the bottom chords. In reality, the bottom chords are composed of separate bottom chords and a continuous strand for cable-tensioning, the strand is located in the inside of the bottom chord tubes and passed through the joints. In the finite element analysis herein, the closing of the gaps in the bottom chord gaps were simulated by the element shortening caused by a negative temperature loads, in these researches, negative temperature loads were applied on bottom chords of test models for form finding of space structures, and nonlinear finite element analysis has been performed with to analyze the behaviour of test models. The MSC/NASTRAN and DIDAS is used to consider the nonlinesrity of the structure behaviour. To consider the large displacement effects, an approximate updated Lagrangian method is employed in NASTRAN, and the Newton Rapson Method is used in MIDAS.

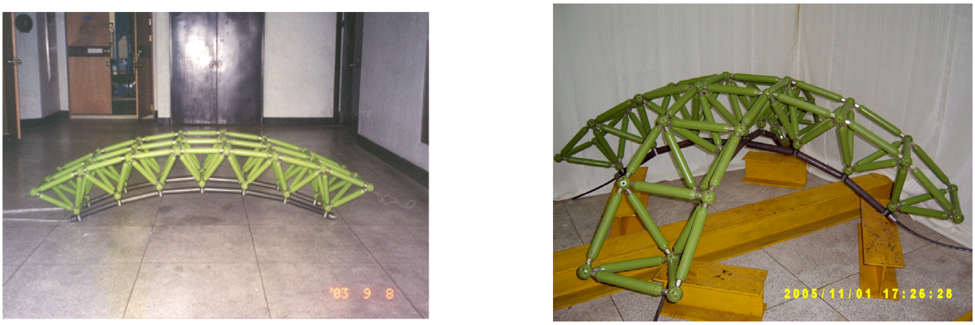
4.2 Experiments

The planar layouts were assembled on the floor by connecting the prefabricated pyramidal units. The size of gap in bottom chord is closely related to desired shape of space structure. By cable-tensioning of the test model, when the gaps of bottom chords were closed, space structure was formed into its required shape. Consequently when the gaps were completely closed between the each joint of the bottom chord, i.e. there were no gaps in bottom chords, the cable-tensioning process was completed. The final space structures are shown in Figures 8, 9. As shown in Figures 10 to 12, the form finding of space structure, the values by nonlinear finite element analysis are showing closer to experimental values. Therefore, nonlinear analysis should be performed with estimating the final shape of space structure and cable-tensioning load required to form the space structure. The vertical displacement of the top joint is plotted in Figures 10 to 13. As shown in Figure 10, for the test model (A), the difference between the theory and experiment was 7% ~ 60%. The good agreement between the finite element results and experimental results was obtained from the central part of the test model, but the edge part is big difference comparatively compare with the central. As shown in Figures 11, 12, for the test model (B), in the case of A-A section, the difference of form finding between the theory and experiment was 12% ~ 15%, and in the case of B-B section, the difference of form finding between the theory and experiment was 12% ~ 17%. compare with other test models, this test model had comparative big discrepancies with numerical and experimental results. It is an important reason that the joint is simple joint type, and the pyramidal unit of the edge line has the lower chord, and the top chords are continuous at all test model, it is different type compared with the other test models (A, C, D). As shown in Figure 13, for the test models (C & D), the behaviour is almost similar with the each model, the difference between the theory and experiment was 3% ~ 9%. It is a almost good agreement between theory and experiment, In this model, the reason are assumed that all joints are ball type(Mero type), ideally all the member are acted as a axial members. In this research, the behaviour characteristic of test models is similar to the result of author's previous researches for many SCST structure, Through the experiments in the three types of SCST structures, within the yield limit of the members, a planar layout can be deformed to desired space shape by means of cable-tensioning. we can guess the some difference for each test models is owing to type of joints. Thus, the behaviour characteristic of joint in space structure is more significant than that of any other member element. Generally in form finding, some discrepancies between theory and experiment exist due to the geometric imperfections of test models, the rotations and slippage of joints, and the weakness of top chords stiffness at joint in the test model. But nevertheless these imperfections affect the structural behaviour of the form finding; most of these factors are not considered in detail for the finite-element modelling. Consequently for improvement of the efficiency of the finite element method for simulating the structural behaviour of form finding of space structure involving mechanism or near-mechanism, further research is necessary.



(a) Model (A) (b) Model (B)

Figure 8 Cable-tensioned space shape for test models (A, B)



(a) Model (C) (b) Model (D)

Figure 9. Cable-tensioned space shape for test models (C, D)

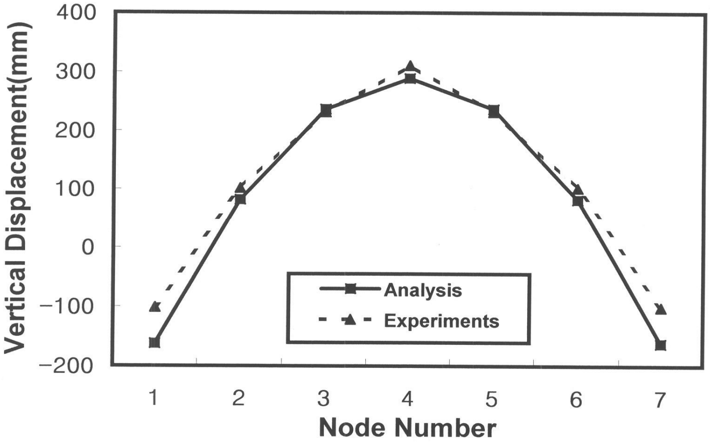


Figure 10 Vertical displacement of top joints in model (A)

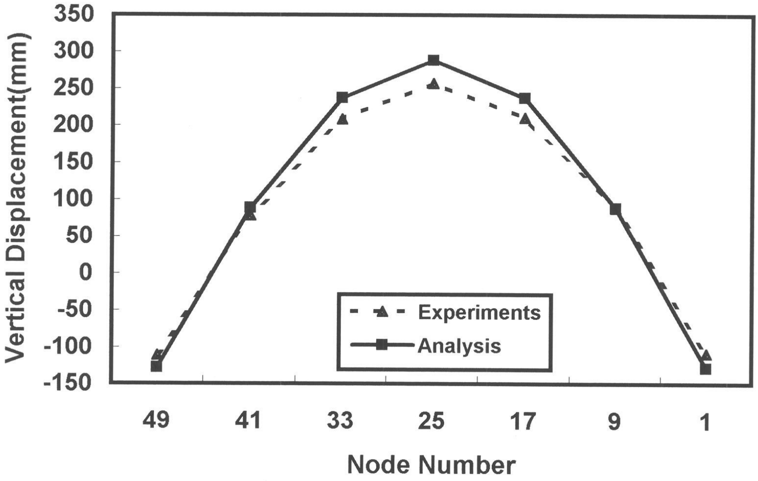


Figure 11 Vertical displacement of A-A section for top joints in model (B)

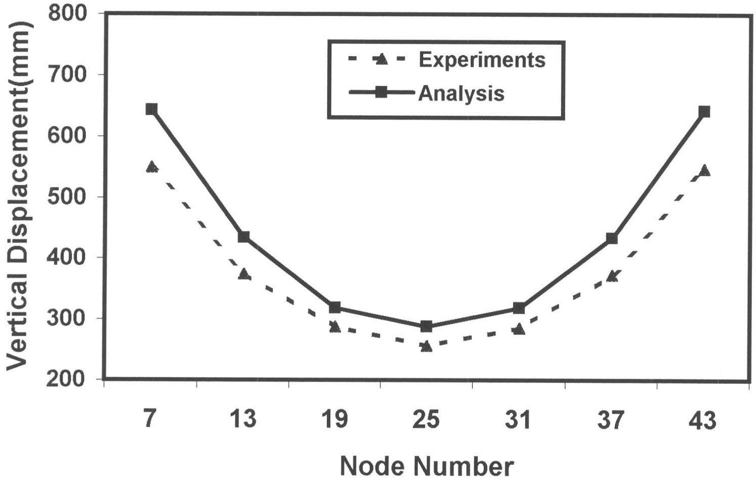


Figure 12 Vertical displacement of B-B section for top joints in model (B)

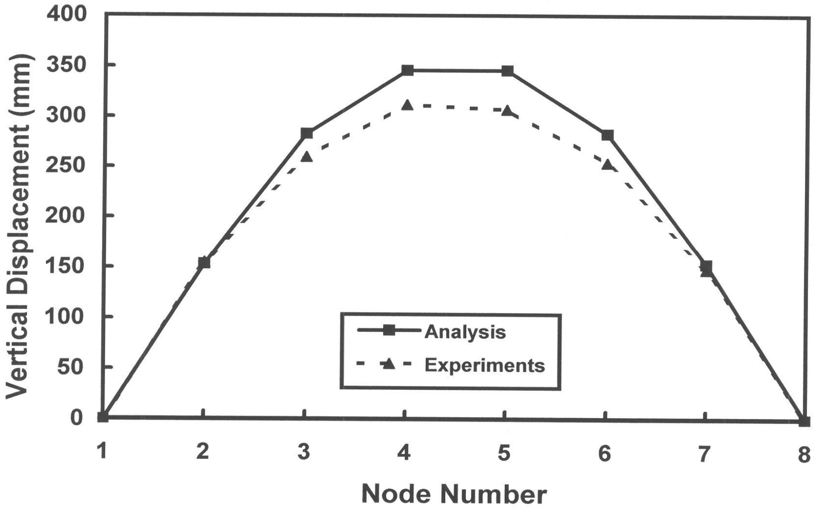


Figure 13 Vertical displacement for top joints of models (C, D)

5. Conclusions

Through the experiments and nonlinear finite element analysis for the form finding of three types of jointed space structures, the following conclusions can be drawn:

1)The shaping formation for space structure with three types of joint is possible by cable-tensioning, and in special site condition, the form finding of space structure by cable-tensioning can be considered as a economic and time saved construction technique compared with the conventional techniques using a big crane or scaffold for erection.

2)A nonlinear finite element analysis method can be used for predicting the space shape and the cable-tensioning forces in a form finding for each joint type of space structure.

3)In form finding of SCST structures, the behaviour of structures is concerned with the connection type of joint.

4)There are some discrepancies due to joint types, differences between the test model and theoretical model, so the behaviour for the form finding needs further study.

6. References

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