STUDY ON THE SEISMIC PERFORMANCE OF SPACE BEAM STRING STRUCTURE

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ABSTRACT :

The dynamic characteristic of space beam string structure is investigated in this paper. The modal analysis was firstly carried out for this structure and the upper single-layer shell without lower cable-strut system. Then time history analysis were performed to study the dynamic behavior of space beam string structure under earthquake action, including the effect of number of struts, sag-span ratio, stiffness of upper beams, prestress and area of cables. The results show that the lower cable-strut system does increase the stiffness of space beam string structure, and most vibration modes of the structure are vertical modes. The increase of numbers of struts, sag-span ratio and section of upper beams are conducive to increase of structural stiffness and resisting global deformation. But the effect of prestress and area of lower cables on the seismic performance of space beam string structure is slightly.

KEYWORDS: beam string structure, space structure, seismic analysis, modal analysis, cable

1. INTRODUCTION

In recent years, space structures have been developing rapidly all over the world. And string structure can be found in many large space structures (Hosozawa *et al.* 1999). The string structures are divided into two types: thoroughbred tension structures and hybrid tension structures. Hybrid tension structures can also be divided into the following categories: (1) structures using members, such as semi-rigid hanging members, which are made by changing the properties of tension members for the pure tension structures; (2) structures made by combining tension members with such rigid members as arches, beams and struts (Saitoh and Okada 1999).

Beam string structure is a typical type of hybrid tension structures, which is composed of upper beam, lower steel cables and struts. Applying pretension force to lower steel cables causes the structure to deform to an invert arch, which decreases the deflection of the structure greatly. Meanwhile, while the upper beam is an arch, horizontal thrust of the arch is offset by steel cables, consequently, the stress dominance of the arch-type structure and the high tensile performance of the cables are displayed sufficiently.

The beam string structure has been widely used, with Shanghai Pudong International Airport Terminal (Chen *et al.* 1999), Guangzhou International Convention and Exhibition Center (Sun *et al.* 2003), Harbin exhibition sports center (Li *et al.* 2003), National Gymnasium Roof Model (Fan *et al.* 2008) in China. There are also many research on the beam string structure, like static and parameter analysis (Bai *et al.* 2001, Sun *et al.* 2003), form-finding analysis (Yang *et al.* 2002, Zhou and Fang 2007, Zhang 2007), dynamic analysis (Ding *et al*. 2003, Jiang and Feng 2007, Wang *et al*. 2007), and model test (Chen *et al.* 1999, Zhao *et al.* 2007, Xue *et al*. 2008, and Zhao 2008).

This paper discusses a space beam string structures which is illustrated in Figure 1. It is composed of six single beam string structures, and divided into three groups. The angle between each group is 120 degree. The upper beam of the six single beam string structures are connected by some beam members, so the upper structure changed into a single layer latticed shell. The seismic behavior of this system was investigated in this study by modal analysis and time history analysis. Then, the effect of number of struts, sag-span ratio, stiffness of upper beam, prestress and area of cables on the seismic performance are considered. Finally, the analysis results are discussed in detail.

2. STRUCTURAL DESCRIPTION

The analysis model that is used in this study is shown in Figure 1. The structure is mainly consisted of outer ring truss, inner ring beam, upper beam, strut, and cable. A hexagon skylight roof is on the inner ring beam. The dome is divided into twelve planes, six isosceles triangles and six rectangles, by the upper beam of the six single beam string structures. Then the every side of isosceles triangle divides into eleven parts, and they are connected by steel rectangle pipes.

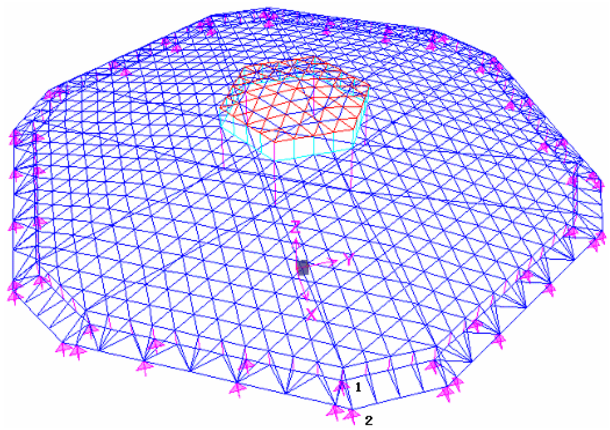

Figure 1 Structural model

The span of the dome structure is 66 m and the length of vertical strut is 6.5 m. The gradient of the upper beam is 8.75 degree. The member of the upper beam is the steel rectangle pipes with 500 mm height, 300 mm width and 14 mm thickness. And steel pipes of 300 mm in diameter and 8 mm in thickness are used as vertical strut. The pipes are made of steel with an elastic modulus of 210 GPa. The cross sectional area of the cable with an elastic modulus of 180 GPa is 2140 mm^2. A uniformly distributed load with a magnitude of 0.5 kN/m^2 is applied to the top surface of the dome in the vertically downward direction.

The Finite Element Analysis (FEA) software package ANSYS is employed in all structural analyses in this study with due consideration for the geometric nonlinearity effect. Tension-only elements are employed to model cables in the structure. Due to the cable pre-stress forces, all the cables are always in tension throughout all the analyses.

3. MODAL ANALYSIS

Free vibration frequency is one of the most important dynamic properties of reticulated shell structures, and it influences the dynamic response of structures under earthquake actions. The stiffness of a structure is one of the main factors that affect the vibration characteristic of a structure. The modal analysis of the reference model (Figure 1) and the upper single-layer lattice shell without the lower cable-strut system were carried out in this paper. Table 1 gives in tabular form the natural frequencies for the space beam string structure (SBSS) and the single-layer lattice shell without the lower cable-strut system (SLD). And the vibration modes of the reference model and single-layer lattice shell are shown in Figure 2 and Figure 3.

Table 1 Natural frequency distribution(Hz)

Mode	1	2	3	4	5	6	7	8	9	10
SBSS	3.035	3.037	3.239	3.364	3.368	3.701	3.972	4.427	4.428	5.295
SLD	2.940	2.940	3.101	3.152	3.152	3.363	3.829	4.310	4.311	5.225
Mode	11	12	13	14	15	16	17	18	19	20
SBSS	5.296	5.505	5.969	5.995	6.232	6.472	6.496	6.802	7.354	7.863
SLD	5.225	5.676	6.041	6.041	6.113	6.419	6.419	6.858	7.319	7.876

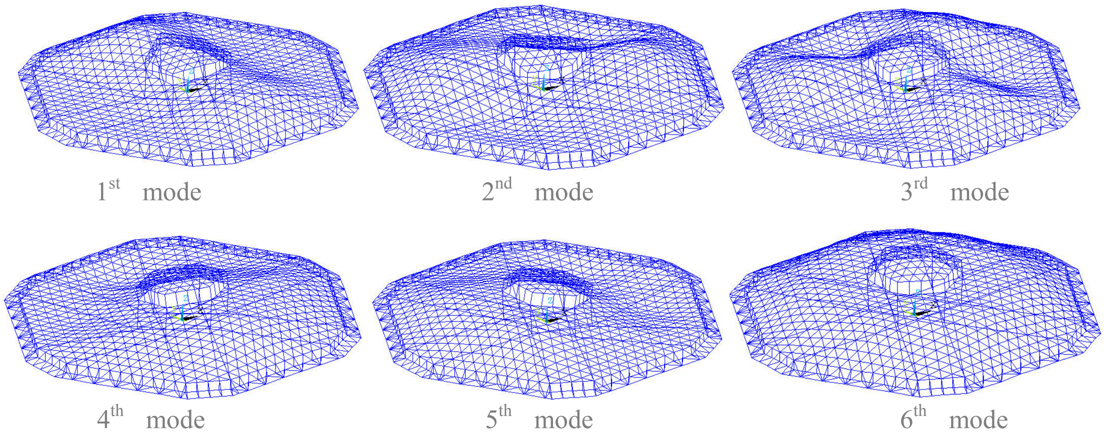

Figure 2 Vibration modes of space beam string structure

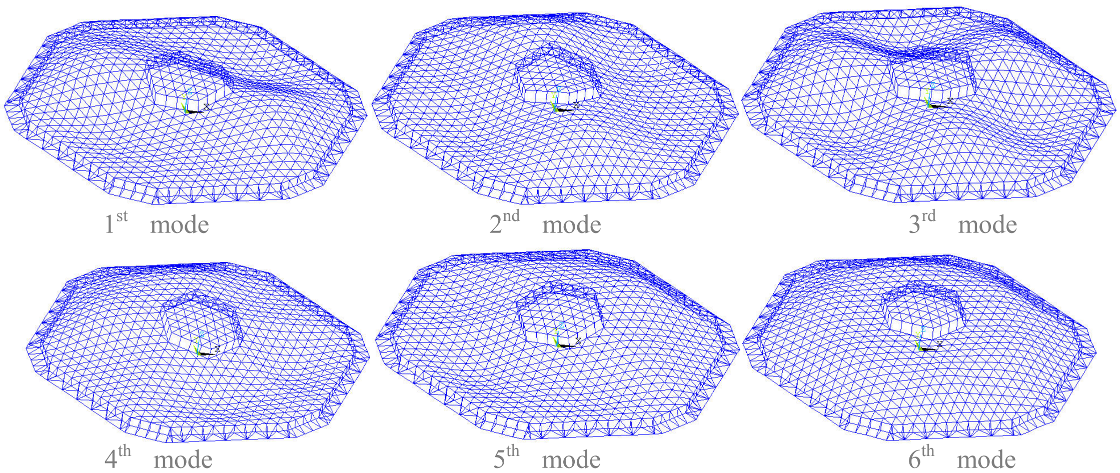

Figure 3 Vibration modes of upper single-layer lattice dome

From the above table and figures, it can be conclude that the space beam string structure with such beam section is stiff. The lower cable-strut system increases the natural frequencies of the structure, but it has minor effect on the increase of the natural frequencies. The fourth and fifth modes of the space beam string structure are horizontal vibration modes, the other lower modes of the structure are vertical vibration modes. There are many “mode twins”, like the first and second mode has the same mode shape and the natural frequencies of the two modes are close. This indicates the symmetry of the space beam string structure. The upper single-layer lattice dome has the same lower vibration modes with the space beam string structure; so the lower cable-strut has no effect on the lower vibration modes.

4. SEISMIC ANALYSIS

4.1. Analytical Method

The seismic response equilibrium equation of a lattice dome can be expressed as follows:

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=-[M]\{\ddot{u}_g\} \tag{4.1}$$

In which, [M], [C] and [K] is the mass matrix, the damping matrix and the stiffness matrix of a lattice dome respectively. $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ is the acceleration vector, velocity vector and displacement vector of lumped mass system respectively, $\{\ddot{u}_g\}$ is the acceleration vector of ground motions.

There are two methods that can be used for solving Eqn. 4.1. One is the imitative static method, such as vibration mode superposition method, and the other is the direct dynamic method, like time integration method. When the vibration mode superposition method is used to solve Eqn. 4.1, mode analysis is carried out at first for these structures. Because there are many similar frequencies for space beam string structures, it is difficult to estimate exactly the truncation frequency. Meanwhile there are many frequencies which require accurate calculation analysis. Indeed, the time integration method is usually used to study seismic properties of large structures if possible. This direct dynamic analysis method can be adopted to calculate seismic response of a structure to earthquake motion and obtain the displacement, velocity and acceleration of the node of the structure with a step-by-step integration.

4.2. Time History Analysis

An earthquake response analysis was performed using a three-dimensional finite element model to investigate the basic behavior of the space beam string structure under earthquake action. In this analysis the input earthquake motions were El Centro waves, which are generally thought of as typical earthquake motions. The input level was 220 gals for the X and Y direction input, and 110 gals for the Z direction input. The X direction, Y direction, Z direction and XYZ direction earthquake input are considered in this paper. Fig. 4 shows the typical elements and typical nodes of the space beam string structure (the elements and nodes of the black line). The serial numbers of the typical elements and nodes are from left to right.

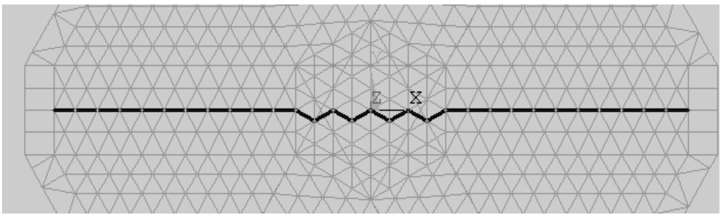

Figure 4 Typical elements and typical nodes

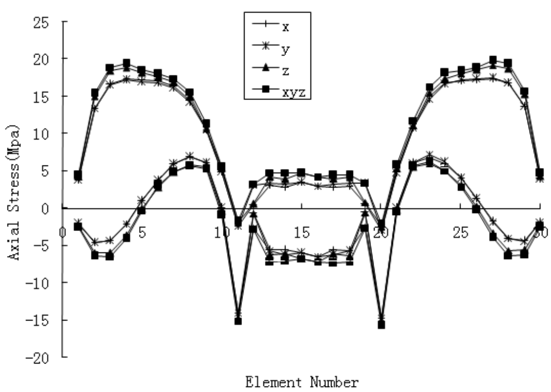

Figure 5 Axial stress

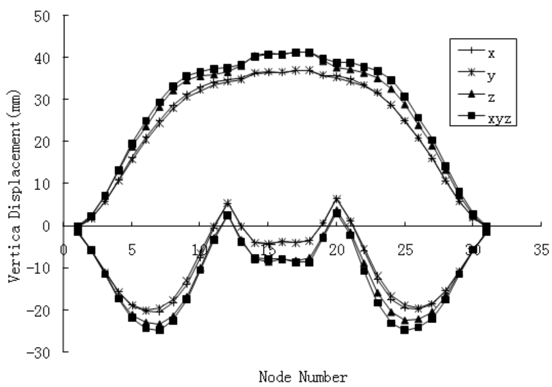

Figure 6 Vertical displacement

The maximal and minimal axial stresses of the typical elements are illustrated in Figure 5, and the maximal and minimal vertical displacements of the typical nodes are shown in Figure 6. It can be seen from these figures that the axial stresses and vertical displacement under three direction earthquake input are larger than any single direction earthquake input. So the three direction earthquake input must be considered in the space beam string structures. And in the following parameter study, the three direction earthquake input will be used.

4.3. Comparison between Space Beam String Structure and Upper Single-layer Lattice dome

Figure 7 are the comparison of axial stresses and vertical displacements between space beam string structure (SBSS) and upper single-layer lattice shell without lower cable-strut system (SLD). The axial stress and vertical displacement in this figure is including the axial stress and vertical displacement caused by cable prestress. The prestress in cables leads that the upward vertical displacements of SBSS are larger than the SLD. But the variable extents of the axial stress and vertical displacement of SBSS are smaller than SLD. So the lower cable-strut system improves the seismic performance of space beam string structures.

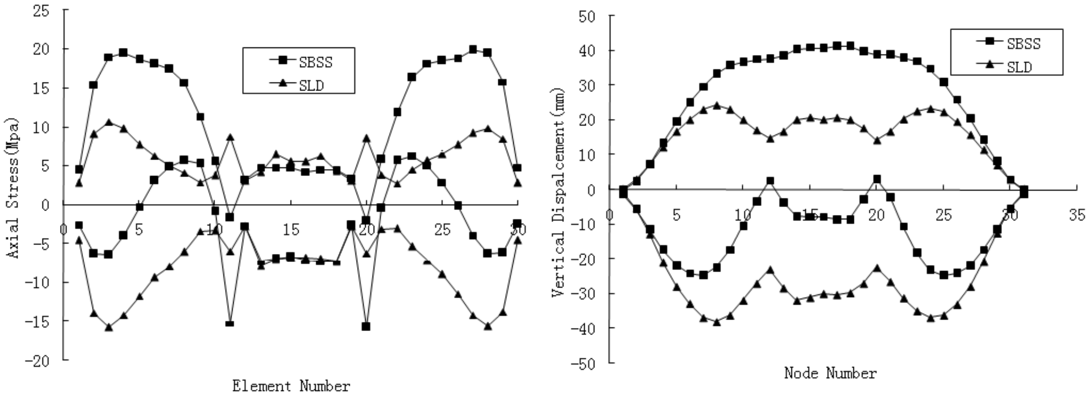

Figure 7 The axial stress and vertical displacement

5. INFLUENCE OF VARIOUS FACTORS

5.1. The Number of Struts

Struts are the elastic supports to the upper beam in the space beam string structure. The struts' improvement to the seismic performance of the structure is studies, and models composed of 2, 4 and 6 struts are adopted. Other calculated parameters of these three models are identical. It suggests that the fluctuant extent of the vertical displacement decreases according with the increase in the number of struts in Figure 8. So it can be deemed that the struts do improve the performance of the structure under earthquake action.

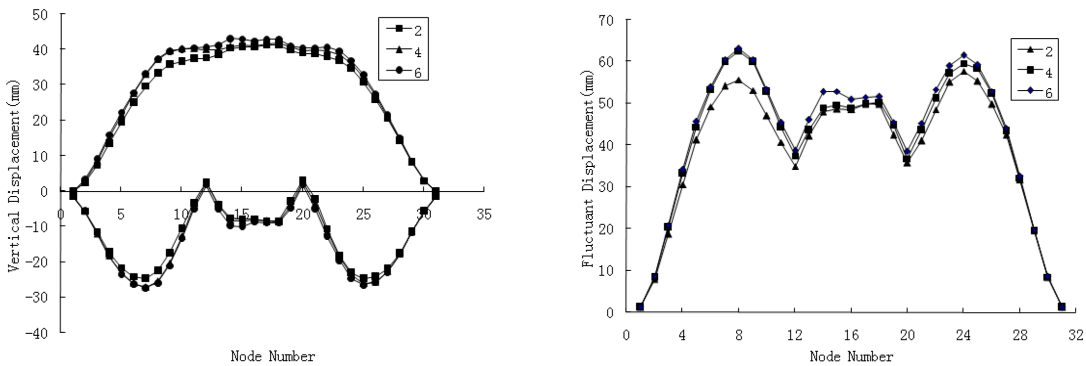

Figure 8 The vertical displacement and fluctuant extent of displacement with different number of struts

5.2. The Ratio of Sag-span

Three models with different sag-span are analyzed to investigate the seismic performance of space beam string structure. Two struts are also adopted. Besides the sag-span ratio, other parameters in the three models are identical. From a qualitative point of view, on the premise of fixed other conditions, increasing the sag will generate enhancement of performance of the struts. Figure 9 is the maximal and minimal vertical displacements of typical nodes under earthquake action and the fluctuant extent of the vertical displacements of these nodes. In this case, it illustrates that the increase of sag-span ratio is conducive to strengthen structural stiffness.

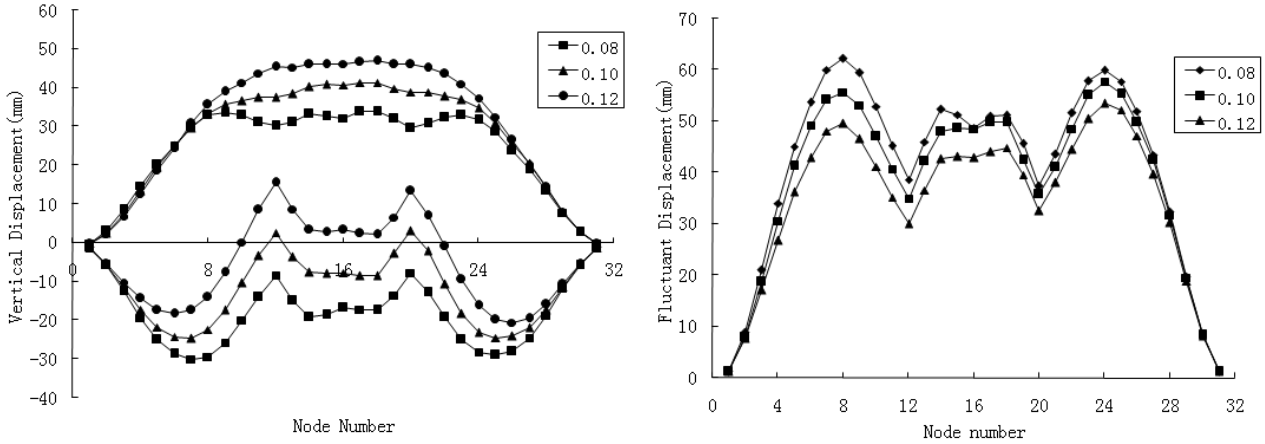

Figure 9 The vertical displacement and fluctuant extent of displacement with different sag-span ratio

5.3. Stiffness of Upper Beam

Three models with different upper beam section are analyzed to study the seismic performance of space beam string structure. Besides the upper beam section, other parameters in the three models are identical. Steel rectangle pipes with 650 mm height, 390 mm width and 18 mm thickness are used as principal members of the model B. The reference model (Figure 1) are model A, and model C is with the steel rectangle pipes with 350 mm height, 210 mm width and 10 mm thickness. Figure 10 shows the maximal and minimal vertical displacements of typical nodes and the fluctuant extent of the vertical displacements of these nodes decreases apparently with the increase of stiffness of upper beams. It clarifies that the stiffness of upper beams is crucial to space beam string structure.

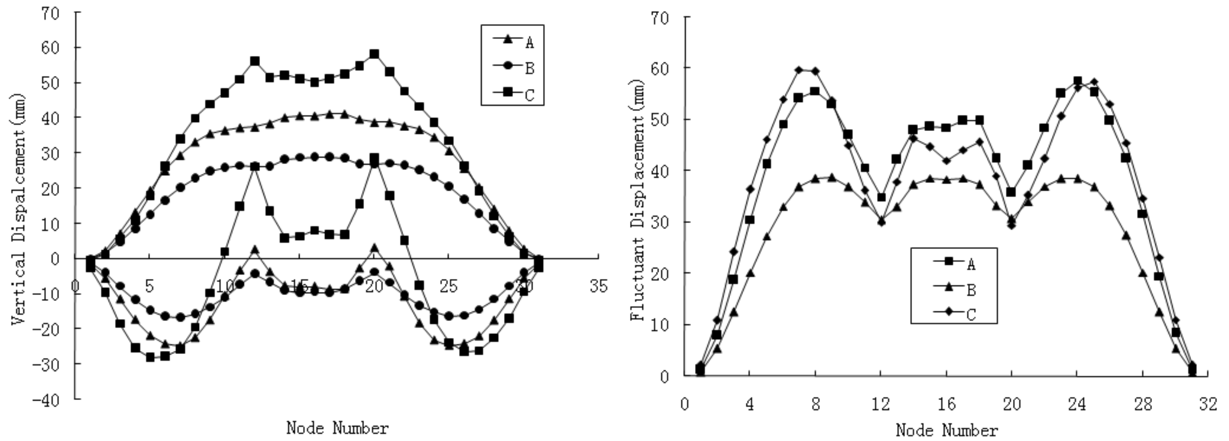

Figure 10 The vertical displacement and fluctuant extent of displacement with different beam section

5.4. Prestress of Lower Cables

Three models with different prestress of lower cables are analyzed to discuss the seismic performance of space beam string structure. Besides the prestress of lower cables, other parameters in the three models are identical. From figure 11, there is a little rise in the fluctuant extent of vertical displacement with the decrease of prestress of lower cables. It indicates the effect of prestress of lower cables on the seismic performance of space beam string structure is slight.

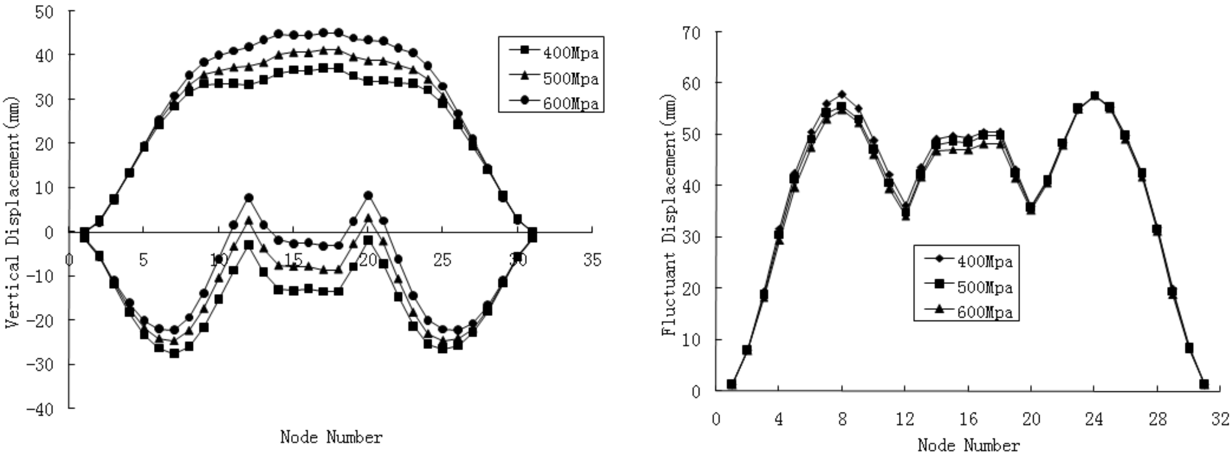

Figure 11 The vertical displacement and fluctuant extent of displacement with different cable prestress

5.5. Area of Lower Cables

Three models with different area of lower cables are analyzed to investigate the seismic performance of space beam string structure. Besides the area of lower cables, other parameters in the three models are identical. It is shown that the fluctuant extent of vertical displacement increased slightly as the area of lower cables reduced in Figure 12. The cutline of this figure is the equivalent diameter of cables. It illustrates that the seismic performance of space beam string structure has small relationship with the area of lower cables.

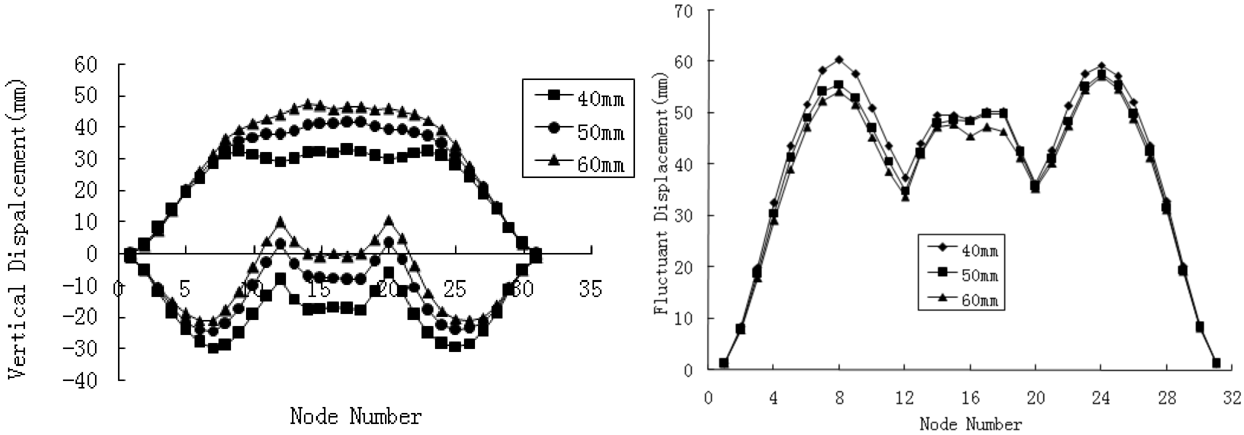

Figure 12 The vertical displacement and fluctuant extent of displacement with different cable area

6. CONCLUSION

This paper discusses seismic performance of a new type hybrid structure-space beam string structure. Comprehensive modal and seismic analyses are carried out on this structure. By comparing the results of analysis, conclusions can be drawn as follows:

1. The lower cable-strut system increases the natural frequency of space beam string structure.
2. Most of low-order modes of the structure are vertical vibration modes. There are many "mode twins", like

the first and second mode has the same mode shape and the natural frequencies of the two modes are close. This indicates the symmetry of the space beam string structure.

3. The upper beam axial stresses and node vertical displacement under three direction earthquake input are larger than any single direction earthquake input. So the three direction earthquake input must be considered in the space beam string structures.
4. The increase of numbers of struts, sag-span ratio and section of upper beam are conducive to increase of structural stiffness and resisting global deformation.
5. The effect of prestress and area of lower cables on the seismic performance of space beam string structure is slightly.

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