

Article

Experimental Study on Small-Scale Shake Table Testing of Cable-Stiffened Single-Layer Spherical Latticed Shell

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Abstract: The cable-stiffened single-layer latticed shell is an innovative structural design that achieves a perfect balance between lightweight and stability by combining cables and a latticed shell. However, the study on dynamic response and failure mechanism of cable-stiffened single-layer latticed shell under seismic action is still lacking. Therefore, small-scale shaking table tests of two kinds of single-layer spherical latticed shells are carried out; the dynamic response and failure mode of the two shells under sine wave earthquake are investigated by using time history analysis. The conclusions show that the introduction of the prestressed cable plays an important role in improving the seismic performance of the single-layer latticed shell, and the cable-stiffened single-layer latticed shell has better load capacity and seismic performance under earthquake action than the ordinary single-layer latticed shell structure.

Keywords: cable-stiffened single-layer spherical latticed shell; shaking table test; earthquake action; dynamic stability



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1. Introduction

The cable-stiffened latticed shell structure represents an innovative latticed shell configuration. This design markedly enhances its load-carrying capacity and stability through the integration of prestressed cables among the joints of the latticed shell. Characterized by large spans, structural stability, cost-effective material use, and aesthetic qualities, this field has seen significant contributions from numerous researchers across various studies on latticed shell structures. Focusing on the issues of stability and collapse, several scholars have developed methodologies for calculating the distribution of internal forces and failure loads [1–6], along with collapse analysis techniques [7], by employing finite element analysis and considering both the unique properties of these structures and the nature of the applied loads. On this basis, Zhang et al. [8] proceeded to calculate the dynamic failure loads of latticed shell structures by adhering to relevant standards and employing fitted calculation formulas. Utilizing the energy principle, Xu and Sun [9] identified the precise moment at which a single-layer latticed shell structure becomes unstable under seismic influences by comparing the structural internal energy against the energy input from the exterior, thus accurately estimating the critical peak ground acceleration for the structure. Similarly, Zhu et al. [10] derived a method based on the energy principle for assessing the dynamic instability or collapse of latticed shell structures, with the accuracy of the method confirmed through vibration table experiments. In exploring the effects of varying component characteristics on latticed shell structures, Xiong et al. [11–13] focused their research on single-layer latticed shell structures incorporating semi-rigid aluminum alloy nodes. Through multi-parameter impact numerical simulation analysis, they formulated

equations for calculating the overall structural elasto-plastic buckling load. Further, Wu et al. [14] conducted vibration table experiments to examine the collapse phenomena and failure characteristics of aluminum alloy latticed shell structures, thereby demonstrating the remarkable seismic resilience of single-layer latticed shell structures and highlighting the risks of progressive collapse. Additionally, as a large-span spatial structure, environmental factors will have long-term impacts on the structures. Therefore, scholars have extensively studied the effects of environmental factors such as temperature, wind loads, geological conditions, and humidity on the durability and safety of structures during their long-term service life, with a focus on their influence on the dynamic characteristics of structures [15–17]. Building upon this foundation, relevant health monitoring technologies and algorithms have also provided practical support for the health monitoring and maintenance of latticed shell structures [18,19].

The cable-stiffened latticed shell structure, as a novel form of latticed shell structure, possesses numerous advantages and holds substantial potential for application and research. Consequently, in recent years, many experts and scholars have conducted comprehensive studies on cable-stiffened latticed shell structures. In terms of structural optimization, various optimization algorithms have been proposed by scholars. Wang and Wu [20] utilized shape optimization techniques aiming for the minimal strain energy of the cable-stiffened latticed shell structure, achieving local optimization result smoothing through the method of weights and ultimately obtaining a global optimization outcome. Zhao et al. [21] sought the optimal arrangement of initial prestress in cables using a hybrid optimization algorithm, effectively enhancing the load-carrying capacity of the cable-stiffened latticed shell and reducing the corresponding structure's peak bending moments. The team also used the AHP-TOPSIS decision-making method for further optimization of the structure, discovering that the complexity of the cable system is not directly proportional to the load-carrying capacity of structures [22]. Regarding the stability of cable-stiffened latticed shell structures and related influencing factors, numerous studies have been conducted. Feng et al. [23], employing continuum theory, proposed formulas for calculating the buckling load of single-layer cylindrical latticed shells with cable-stiffened thin plates, considering initial imperfections, and found that the shear stiffness of the grid is related to the axial stiffness of the cables. Yang et al. [24] examined hexagonal grid cable-stiffened latticed shell structures, concluding that the introduction of the cable system significantly improves the in-plane stiffness of structures. Li et al. [25–28] systematically investigated the effects of boundary conditions, cable configurations, and prestress on the stability of cable-stiffened latticed shell structures under seismic actions, noting that cable-stiffened latticed shell structures exhibit superior seismic performance compared to ordinary latticed shell structures. Wang et al. [29] integrated optimization algorithms into the overall stability study of cable-stiffened latticed shell structures, indicating that the buckling load decreases with the increase in amplitude of initial imperfections. In recent years, the rapid development of neural networks and deep learning algorithms has provided forward-looking insights for the optimization of reticulated shell structures. These algorithms offer a variety of approaches for multi-parameter and multi-angle optimization, serving as valuable references [30–34].

Synthesizing the results from the aforementioned studies reveals that the introduction of a cable-stiffened system has a significant impact on the structural stiffness. Therefore, under seismic influences, the mechanical performance of cable-stiffened latticed shell structures exhibits clear differences compared to ordinary latticed shell structures. While some scholars have begun to explore the changes in mechanical performance of cable-stiffened latticed shell structures under seismic actions, research on performance under such conditions remains relatively limited. Consequently, conducting related research on the dynamic response of cable-stiffened single-layer latticed shells under seismic actions using shake table tests is necessary. The spherical latticed shell (SLS) structure is renowned for its excellent stability, load-carrying capacity, and seismic performance. This paper focuses on conducting the small-scale shake table testing on cable-stiffened single-layer SLS models and compares them with ordinary single-layer SLS models of the same size. Additionally,

this paper analyzes the natural vibration characteristics, dynamic characteristics during the elastic stage, and plastic failure characteristics under strong earthquakes of the structures. This provides support for the study of the failure mechanisms of cable-stiffened SLS models through the data of the shake table testing and effectively promotes the application of cable-stiffened single-layer SLS structures in actual engineering projects.

2. Experimental Program

2.1. The Scaled Latticed Shell Model

To explore the dynamic response of cable-stiffened single-layer SLS structures under seismic conditions, this research conducted relevant small-scale shake table testing. The SLSs addressed in this study were all single-layer SLS configurations. Before the commencement of the testing, scale models necessary for the testing were designed, including both an ordinary SLS model without prestressed cables and a cable-stiffened SLS model, as displayed in Figure 1. The span and rise of models were designed to be 800 mm and 100 mm, respectively, yielding a rise-to-span ratio of 1/8. The shell models utilized circular steel tubes as members, with each model comprising 21 members, each tube having an outer diameter and wall thickness of 5 mm and 1 mm, respectively. Nine seamless steel tubes were selected from among these, and their cross-sectional dimensions were measured using a digital caliper: the average value of the measurements taken at both ends and the middle of the span was used for the outer diameter of the same seamless steel tube; the wall thickness was determined by averaging the measurements at two end cross-sections. The measurement results of the cross-sectional geometric dimensions of the seamless steel tubes are listed in Table 1. Therein, d_n and d_a respectively denote the nominal and actual values of the outer diameter of tubes, while t_n and t_a represent the nominal and actual values of the wall thickness. The findings revealed that the ratio of the actual to the nominal value of the outer diameter averaged to 1.00, with a coefficient of variation (CoV) of 0.008; the ratio of the actual to the nominal wall thickness averaged to 1.04, with a CoV of 0.019. This demonstrated that the seamless steel tubes used in this study exhibited minimal manufacturing errors, fulfilling the quality requirements specified in the standards [35], thus qualifying them for use as members in the subsequent small-scale shake table testing.

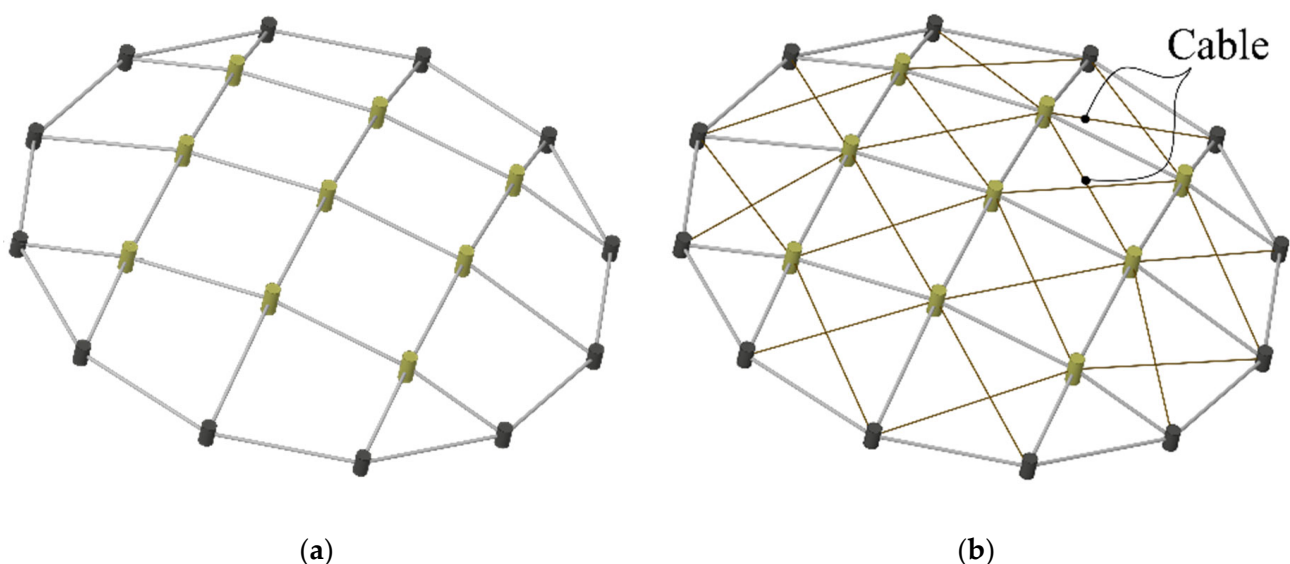
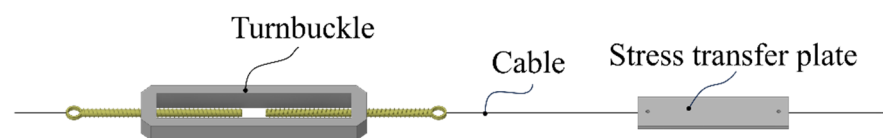


Figure 1. The scaled latticed shell model. (a) Ordinary SLS. (b) Cable-stiffened SLS.

Table 1. Nominal and actual values of geometric dimensions.

Member	Outside Diameter			Wall Thickness		
	d_n (mm)	d_a (mm)	d_a/d_n	t_n (mm)	t_a (mm)	t_a/t_n
No. 1	5.0	5.02	1.00	1.0	1.09	1.09
No. 2		5.05	1.01		1.05	1.05
No. 3		4.99	1.00		1.03	1.03
No. 4		4.97	0.99		1.05	1.05
No. 5		5.04	1.01		1.04	1.04
No. 6		5.03	1.01		1.04	1.04
No. 7		5.01	1.00		1.03	1.03
No. 8		5.04	1.01		1.02	1.02
No. 9		4.97	0.99		1.04	1.04
Mean			1.00			1.04
CoV			0.008			0.019

The joints of the SLS model were divided into mid-joint and edge-joint, corresponding to the yellow and black joints displayed in Figure 1, respectively. Both mid-joint and edge-joint were designed as cylindrical joints with a diameter of 20 mm, and their design heights were 40 mm and 30 mm, respectively. The connections between the members and joints of the SLS model were achieved through welding. Building on the ordinary SLS model, as shown in Figure 1a, the cable-stiffened SLS model, as shown in Figure 1b, integrated prestressed cables arranged along the grid diagonals, creating a structure with in-plane arranged cables. To effectively apply and accurately measure the prestress in the cables, a prestressed cable system was introduced, as displayed in Figure 2. The system was composed of three parts: stress transmission plates, cables, and turnbuckles. The rectangular stress transmission plates measured 15 mm in length and 2 mm in width; the cables had a diameter of 1.2 mm; the turnbuckles had a minimum length of 50 mm. By incorporating this prestressed cable system into the cable-stiffened SLS model, the magnitude of the prestress applied to the cables could be determined from the stress values obtained through the stress transmission plates, and the magnitude of the prestress could be adjusted by turning the turnbuckles. In the designed cable-stiffened SLS model presented in this paper, the initial prestress magnitude for all cables was set to 100 MPa.

**Figure 2.** Prestressed cable system schematic diagram.

2.2. Material Tests

Before conducting the small-scale shake table testing, the material tests were conducted on the seamless steel tubes and cables used in the SLS models to obtain their accurate material properties. The material tests for the seamless steel tubes were conducted on an electronic universal testing machine, as shown in Figure 3a. Five seamless steel tubes from the same production batch as those used in the SLS model were selected for material tests, and the stress-versus-strain curves for these tubes were obtained, as displayed in Figure 3b. The material properties of these five seamless steel tubes, such as the elastic modulus E , yield strength f_y , and ultimate strength f_u , can be derived from their stress–strain curves, as listed in Table 2. It could be found that the elastic modulus, yield strength, and ultimate strength of the seamless steel tubes averaged 201.3 GPa, 303.1 MPa, and 405.3 MPa, respectively, with corresponding CoVs of 0.011, 0.008, and 0.011. This indicated that the material properties of the seamless steel tubes selected for this study were quite stable.

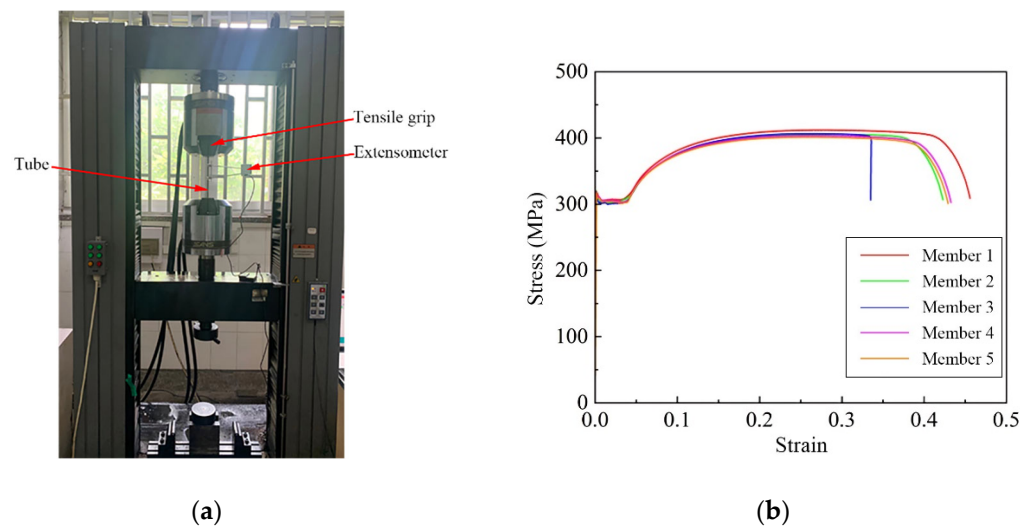


Figure 3. Material tests of steel tubes. (a) Electronic universal testing machines. (b) Stress-versus-strain curves.

Table 2. Material properties of steel tubes.

Member	1	2	3	4	5	Mean	CoV
E (GPa)	200.3	201.8	204.7	200.8	199.1	201.3	0.011
f_y (MPa)	306.7	302.3	301.5	303.4	301.6	303.1	0.008
f_u (MPa)	412.0	406.2	405.8	402.1	400.4	405.3	0.011

To address the challenge of measuring the elastic modulus of cables, a setup that could be used to measure the elastic modulus of cables was designed, as displayed in Figure 4a. In this setup, turnbuckles were used to tension the cables to be measured, prestress transmission plates were employed to measure the stress in the cables during tensioning, and a displacement gauge was used to measure the axial displacement of the cables during tensioning. Utilizing this measuring setup, the material tensile tests on five cables from the same production batch as those used in the shell model were conducted, and the stress-versus-strain curves for these cables were obtained, as displayed in Figure 4b. The elastic modulus corresponding to these cables could be derived from their stress-versus-strain curves, as listed in Table 3. It was found that the average elastic modulus of these five cables and the CoV were 59.8 GPa and 0.049, respectively, meeting the requirements for the elastic modulus of cables specified in the standard [36].

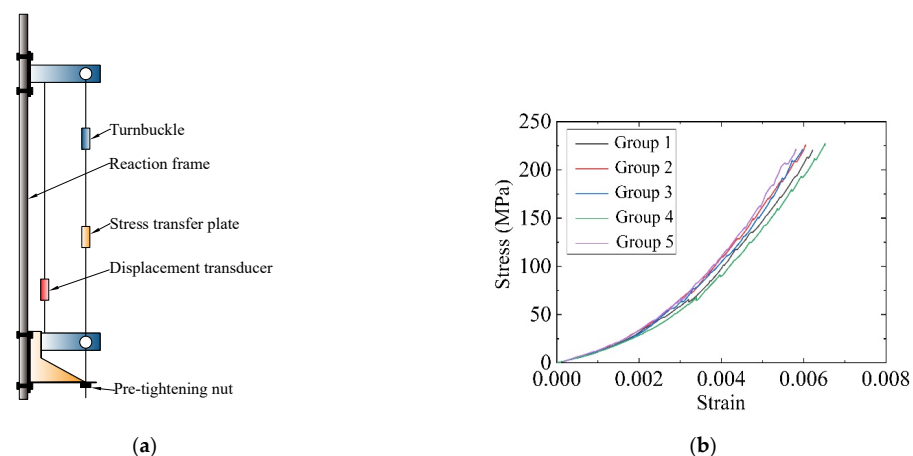


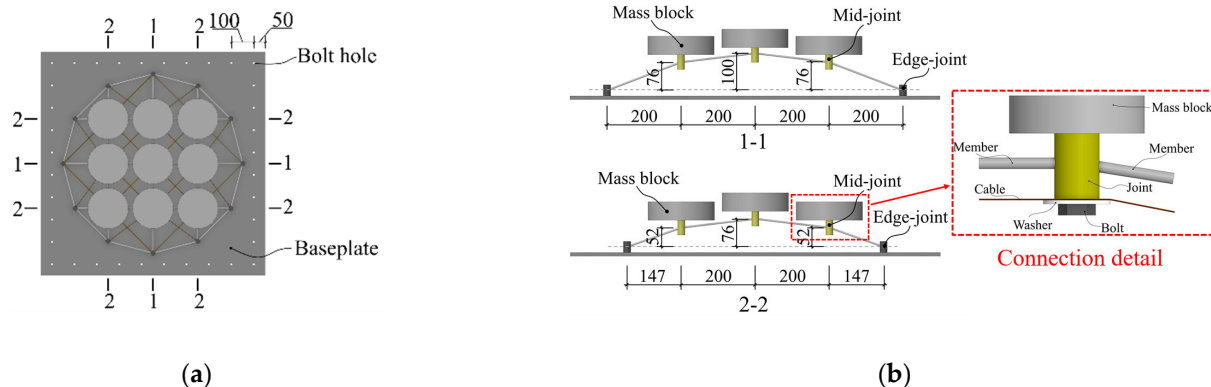
Figure 4. Material tests of cables. (a) Test setup. (b) Stress-versus-strain curves.

Table 3. Elastic modulus of cables.

Member	1	2	3	4	5	Mean	CoV
E (GPa)	55.4	60.7	60.8	63.2	58.8	59.8	0.049

2.3. Model Assembling

To ensure a stable connection between the SLS model and the shake table, a connecting steel plate was installed at the bottom of the SLS model to guarantee that seismic loads could be steadily transferred to the model, as displayed in Figure 5a. The connecting steel plate had dimensions of 1000 mm in length and width, with a thickness of 10 mm; bolt holes were pre-drilled on the plate with a spacing of 100 mm and a distance of 50 mm from the edges of the connecting plate. M10 bolts were used to connect and secure the connecting steel plate to the surface of the shake table, and the SLS model was fixed onto the connecting plates by welding the edge-joints of the model to the connecting plate. When arranging the prestressed cables, both ends of these cables were connected to the edge-joints via hooks, and the cables were fixed through the mid-joints using bolts and washers. To accurately simulate the effect of the self-weight of the roof panels on the shell structure, the nodal loads were applied to the SLS model by installing mass blocks at the mid-joints, as displayed in Figure 5b. These mass blocks had identical geometric dimensions and material properties, with a diameter of 180 mm, a height of 50 mm, and a mass of 10 kg. Figure 5b shows the details of installing the mass blocks and securing the prestressed cables at the mid-joints: the bolts beneath the mid-joints were tightened, passing through the joints and connecting to the mass blocks above the mid-joints, thus completing the installation and securing of the mass blocks. Simultaneously tightening the bolts also secured the prestressed cables under the effect of the washers beneath the mid-joints, thereby achieving a cross-arrangement of each cable within the grid.

**Figure 5.** Model assembling. (a) Vertical view. (b) Side view.

This study conducted dynamic response tests on an ordinary SLS model and a cable-stiffened SLS model using a small-scale shake table. The objective was to compare and investigate the impact of prestressed cables on the seismic performance of the SLS models. The experimental content included testing the natural vibration and dynamic characteristics of the SLS models. Therefore, during the testing process, it was necessary to monitor and record response parameters of the SLS models, including structural displacement and acceleration responses, as well as member deformation and plastic development. The arrangement of measurement points and devices for this study is shown in Figure 6. Two mid-joints, A1 and A2, of the SLS model were selected as displacement measurement points. Before conducting the shake table testing, two displacement transducers were placed in both horizontal and vertical directions at mid-joints A1 and A2, respectively, to measure and record the horizontal and vertical displacements occurring at these joints during the tests, totaling four displacement transducers. Additionally, one accelerometer was

placed horizontally at mid-joint A2 and at the shake table surface to record the horizontal acceleration magnitude of the latticed shell model at these points during the tests, totaling two accelerometers. The strain gauges were also installed on eight members of the SLS model to measure their strain variations during loading. The identification numbers and locations of these eight members are displayed in Figure 6. For the cable-stiffened SLS model, the stress in the prestressed cables was measured by corresponding stress transmission plates, with the arrangement method and locations of these plates displayed in Figures 2 and 6b. Taking the cable-stiffened SLS model as an example, the actual setup of the SLS model and measurement devices is displayed in Figure 7. Before starting the small-scale shake table testing, the sampling frequency for all sensors was set to 100 Hz.

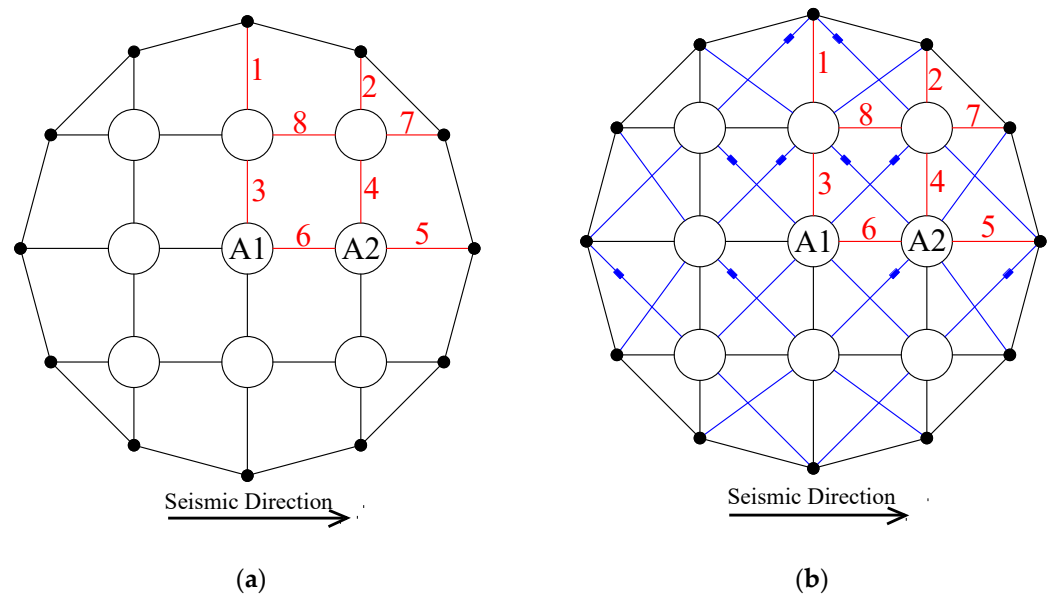


Figure 6. Test point layout schematic diagram. (a) Simple SLS. (b) Cable-stiffened SLS.

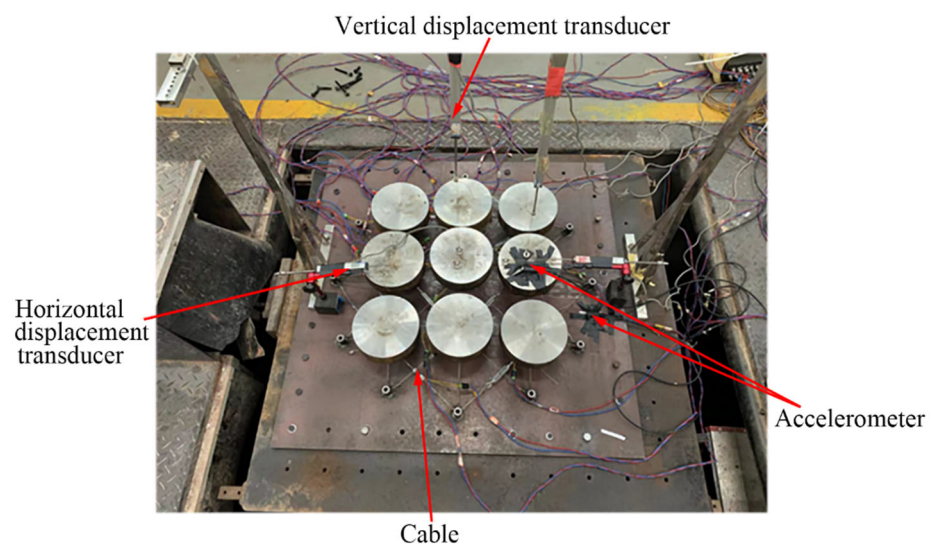


Figure 7. Cable-stiffened SLS model and measurement setup.

2.4. Loading Protocol

For this study, an electro-hydraulic servo-controlled shaking table was employed, with a table surface measuring 1.2 m long and 1.2 m wide. The maximum payload capacity of the shaking table is 1000 kg. In the horizontal direction, the shaking table can achieve a maximum acceleration of 2.0 g, a maximum velocity of 0.5 m/s, and a maximum

displacement of 100 mm. Within the operational limits of the shaking table, the small-scale shake table testing conducted in this study consisted of two parts: tests of natural vibration characteristics and dynamic characteristics, with the loading scheme listed in Table 4, where work condition 1 corresponded to the test of natural vibration characteristics, while the remaining conditions corresponded to the test of dynamic characteristics. During the natural vibration characteristics test, a 0.1 g white noise excitation was input into the SLS model, as displayed in Figure 8. Using the dynamic data acquisition system to collect the time history curve of the SLS model, the time domain signal output from the time history curve could be converted into a frequency domain signal through Fast Fourier Transform (FFT). The natural frequencies of the SLS model could then be determined by the peak frequencies corresponding to the power spectral density curve which was obtained by FFT. For the dynamic characteristics test, a 6 Hz sinusoidal wave was input into the SLS model instead of an actual recorded seismic wave. An acceleration amplitude of 1 g for the 6 Hz sinusoidal wave is shown in Figure 9. Different acceleration amplitudes were selected for the dynamic characteristics test under different work conditions. Work conditions 2 to 5 used acceleration amplitudes of 0.2 g, 0.4 g, 0.8 g, and 1 g, respectively, aiming to obtain the dynamic responses of both the ordinary SLS model and the cable-stiffened SLS model during the elastic stage; work condition 6 used an acceleration amplitude of 1.8 g to observe the dynamic responses and failure modes of the two types of SLS models during the plastic stage.

Table 4. Loading scheme.

Condition	1	2	3	4	5	6
Type	White noise	Sine wave	Sine wave	Sine wave	Sine wave	Sine wave
Amplitude	0.1 g	0.2 g	0.4 g	0.8 g	1 g	1.8 g

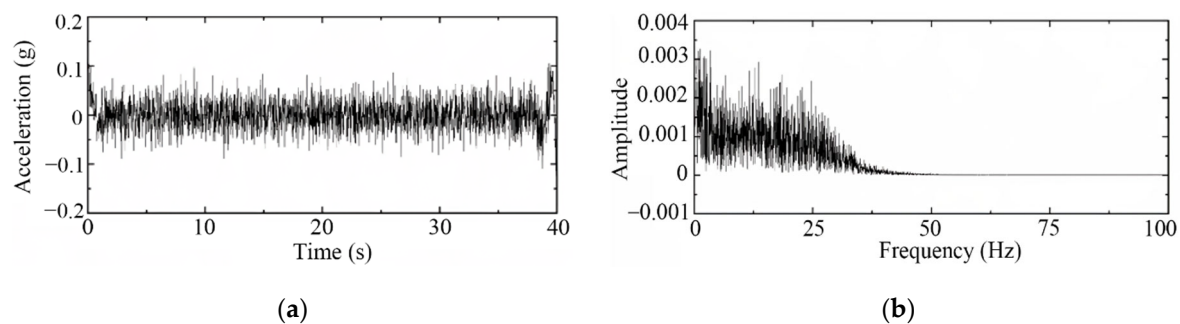


Figure 8. Natural vibration test. (a) Acceleration–time history curve. (b) power spectral density curve.

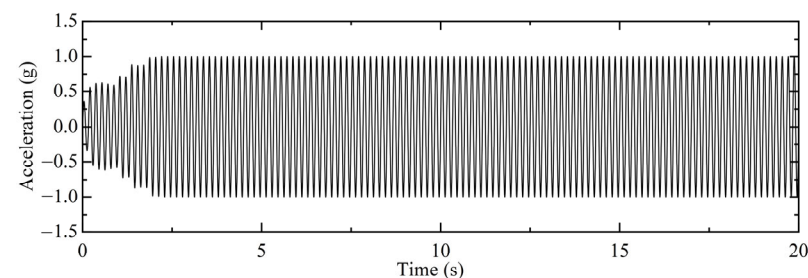


Figure 9. Dynamic characteristics test.

3. Natural Vibration Characteristics

The test of natural vibration characteristics was initially conducted on the SLS models. By inputting a white noise excitation with an acceleration amplitude of 0.1 g into the SLS

model, the acceleration–time history curve at joint A2 was obtained using the accelerometer installed at joint A2. Subsequently, the obtained acceleration–time history curve of the SLS model was subjected to FFT to acquire its power spectral density curve and determine the corresponding natural frequencies. The tests of natural vibration characteristics of both the ordinary SLS model and the cable-stiffened SLS model were carried out using a small-scale shake table. During the test on the ordinary SLS model, an unexpected failure occurred in the connection between the monitoring instruments and the model, preventing the acquisition of a valid acceleration–time history curve. As a result, the power spectral density curve for the ordinary SLS model through the small-scale shake table testing could not be obtained, nor could the corresponding natural frequencies be determined. To address this issue, by referring to the finite element modeling method in the ref. [37], the finite element analysis software ABAQUS (2021 version) was utilized to create a high-precision finite element model consistent with the SLS model involved in the test. Through numerical simulation, the first two natural frequencies of this model were obtained, which were 8.75 Hz and 9.72 Hz, respectively, and the first-order natural vibration mode is shown in Figure 10a.

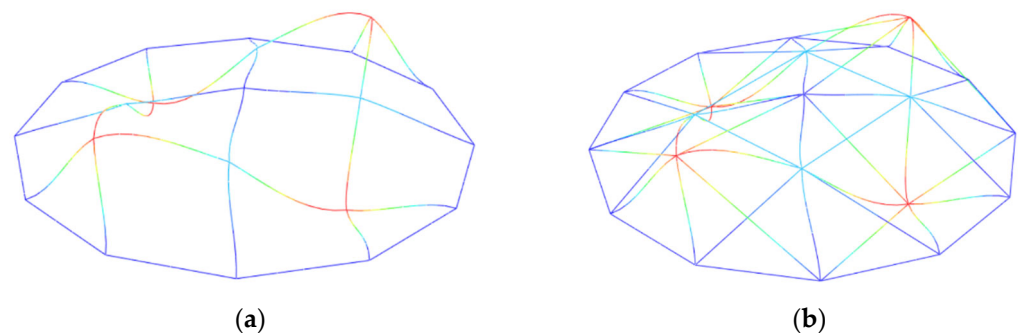


Figure 10. The first-order natural vibration mode. (a) Ordinary SLS. (b) Cable-stiffened SLS.

During the test of natural vibration characteristics of the cable-stiffened SLS model, improvements were made to the fixation and connection methods between the model and the monitoring instruments to avoid recurrence of similar issues. After ensuring that the connections were effective and the monitoring instruments could accurately capture the corresponding acceleration values, the cable-stiffened SLS model was subjected to white noise sweep and subsequent tasks. During the 0.1 g white noise sweep, the model exhibited almost no oscillation. The acceleration–time history curve at joint A2 was measured using the accelerometer mounted at that point, as displayed in Figure 11a. Further, this acceleration–time history curve was subjected to FFT to obtain the corresponding power spectral density curve, as displayed in Figure 11b. It was observed that the first few natural frequencies of the cable-stiffened SLS model were concentrated between 13 Hz and 17 Hz, indicating a dense modal pattern. Specifically, the first and second natural frequencies of the cable-stiffened SLS model were identified as 13.24 Hz and 13.71 Hz, respectively. Comparing the ordinary SLS model with the cable-stiffened SLS model, the distribution of the first two natural frequencies of the latter was more concentrated. Moreover, compared to the ordinary SLS model, the first and second natural frequencies of the cable-stiffened SLS model increased by 51.31% and 41.05%, respectively. This suggested that the introduction of prestressed cables could effectively enhance the stiffness of the SLS structures, thereby improving its stability and seismic resistance. Additionally, following the same method used to establish the finite element model for the ordinary SLS, a high-precision finite element model for the cable-stiffened SLS was created. The first-order natural vibration mode obtained from the analysis is shown in Figure 10b. The calculated first-order natural frequency is 15.26 Hz. Compared to the test results, there is a difference of 2.02 Hz in the natural frequency between the finite element analysis and the test. This discrepancy is due to the finite element model aligning the mass block directly with the joints in the latticed shell, whereas in the test model, the mass block was fixed above the joint with

a bolt, resulting in a positional difference of the mass block. Despite this, the natural frequency from finite element analysis still falls within the concentration range of the first few natural frequencies of the test model (previously mentioned as 13–17 Hz). Therefore, it can be considered that the established finite element model is relatively accurate, which also indicates that the natural frequencies of the ordinary SLS obtained using finite element analysis are reliable.

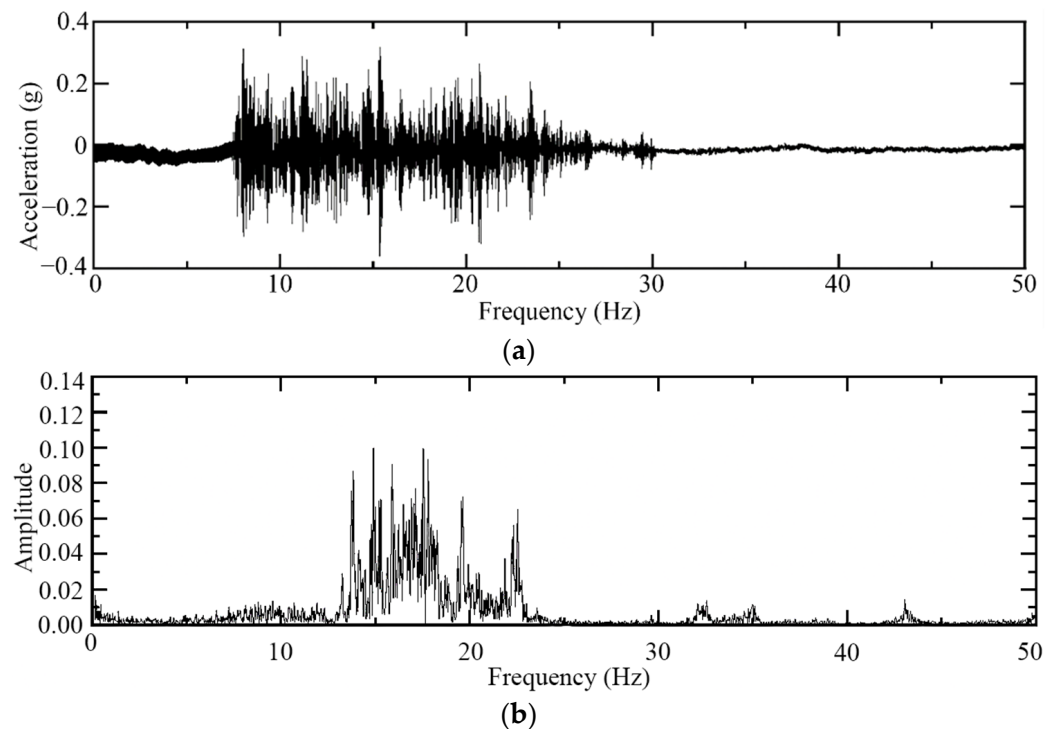


Figure 11. Cable-stiffened SLS natural vibration analysis. (a) Acceleration–time history curve. (b) Power spectral density curve.

4. Dynamical Properties

Following the completion of the natural vibration characteristics tests, this section conducted dynamic characteristics tests on the two SLS models during both the elastic and plastic stages. The tests applied horizontal loads using 6 Hz sine waves of varying amplitudes, with the acceleration–time history curve of the load displayed in Figure 9, lasting for 20 s, and the direction of load application as illustrated in Figure 6. In the elastic stage, work conditions 2 to 4 were sequentially selected for input loading; in the plastic stage, work condition 5 was chosen for input loading. During the tests, by comparing the displacements measured at mid-joints A1 and A2, it was found that the displacements measured at joint A2 were larger than those at A1 for both models. Therefore, to analyze the dynamic response of the SLS models under load, this section focused on the displacement data measured at mid-joints A2 as the target for analysis.

4.1. Elastic Stage

The SLS models were subjected to loads according to work conditions 2 to 4, with acceleration amplitudes of 0.2 g, 0.4 g, 0.8 g, and 1.0g, respectively. To determine whether the SLS model had entered the plastic stage, the yield strain for the members was calculated using the yield strength and elastic modulus obtained from material tests, resulting in a yield strain of 0.001506 ($\mu\epsilon = 1506$). By measuring the strain on critical members (marked in red in Figure 6) under different work conditions, it was found that after the application of a 1.0 g sine wave, none of the members in the cable-stiffened SLS model exceeded the yield strain. In the ordinary SLS model, only one member reached a maximum strain of 0.001673 ($\mu\epsilon = 1673$), surpassing the yield strain. Therefore, it could be considered that

under the four work conditions with acceleration amplitudes less than 1.0 g, both ordinary and cable-stiffened SLS models remained in the elastic stage.

In work conditions 2 to 4, the time history curves of the vertical directional displacement at joint A2 for both the ordinary SLS model and the cable-stiffened SLS model are shown in Figure 12. It was observed that, during the elastic stage under different work conditions, the maximum displacements measured at joint A2 for the cable-stiffened SLS model were consistently smaller than those for the ordinary SLS model. This suggested that the dynamic response of the cable-stiffened SLS structure in the vertical direction during the elastic stage was weaker than that of the ordinary SLS structure, indicating better seismic performance. Further comparison of the time history curves of vertical displacement at joint A2 for the two SLS models under different work conditions revealed that when the acceleration amplitude was 0.2 g, the dynamic response of the cable-stiffened SLS model in the vertical direction was significantly weaker than that of the ordinary SLS model. However, as the acceleration amplitude increased to 0.4 g, the difference in dynamic response in the vertical direction between the two decreased, and the degree of overlap of the time history curves increased. With further increases in acceleration amplitude to 0.8 g and 1.0 g, the differences between the two models became more pronounced, even more so than at 0.2 g. The reason for this phenomenon may be that, in work conditions 2, 4, and 5, the prestressed cables effectively improved the seismic performance of the SLS structure under loads of 0.2 g, 0.8 g, and 1.0 g; while in work condition 3, the effectiveness of the prestressed cables in enhancing the seismic performance of the SLS structure was reduced under a load of 0.4 g. Figure 13 displays the time history curves of the horizontal directional displacement at joint A2 for the two SLS models under different work conditions. It can be observed that when the acceleration amplitude was low, the horizontal displacement of the ordinary SLS model was greater than that of the cable-stiffened SLS model. However, as the amplitude increased, the difference gradually narrowed. When the acceleration amplitude increased to 1.0 g, the horizontal displacement of the cable-stiffened SLS model surpassed that of the ordinary SLS model. However, compared to the vertical displacement, the horizontal displacement of the SLS models was much smaller.

To more accurately assess the seismic performance differences between the two types of SLS structures, the root-mean-square (RMS) displacement and maximum displacement for each set of displacement–time history curves were calculated, as shown in Figure 14. In these figures, black dashed lines represent the ordinary SLS model, while red solid lines represent the cable-stiffened SLS model; solid data points indicate vertical displacement at joint A2, while hollow data points represent horizontal displacement. It was observed that, during the elastic stage, the trends of RMS displacement and maximum displacement for both SLS models were very similar. Whether using the RMS displacement or the maximum displacement as the evaluation criterion, the horizontal displacement of both types of SLS models was significantly less than their vertical displacement. The influence of acceleration amplitude on the dynamic response of the SLS models in the horizontal direction was relatively limited. However, the acceleration amplitude had a significant impact on the dynamic response in the vertical direction, with the vertical displacement of the cable-stiffened SLS model always being notably less than that of the ordinary SLS model. Furthermore, comparing the trends of vertical displacement changes between the two types of models, a phenomenon of the gap decreasing and then increasing was observed in both displacement indicators, consistent with the phenomenon discovered through time history curves previously. Specifically, when the acceleration amplitude was at 0.4 g, the vertical and horizontal displacements of both types of SLS models were closest, suggesting that, at this point, the seismic performance of them was similar. This might be because the contribution of prestressed cables to improving the seismic performance of the SLS structure was relatively limited under a 0.4 g load. When the acceleration amplitude reaches 1.0 g, both types of latticed shells exhibit a significant increase in vertical displacement. In contrast, the increase in horizontal displacement is relatively small. Notably, the horizontal displacement of the cable-stiffened SLS exceeds that of the ordinary

SLS. This phenomenon can be attributed to the greater stiffness of the cable-stiffened SLS. When subjected to large shaking amplitudes from the shake table, the higher stiffness of the cable-stiffened SLS results in greater horizontal displacement. In summary, during the elastic stage of SLS structures, vertical dynamic responses played a dominant role compared to horizontal dynamic responses, and this dominance was more pronounced at higher acceleration amplitudes. Compared to ordinary SLS structures, the introduction of prestressed cables enhanced the seismic performance of the cable-stiffened SLS structure during the elastic stage: with similar horizontal dynamic responses, the vertical dynamic response of the cable-stiffened SLS structure was significantly weaker than that of the ordinary SLS structure, demonstrating superior stiffness and stability.

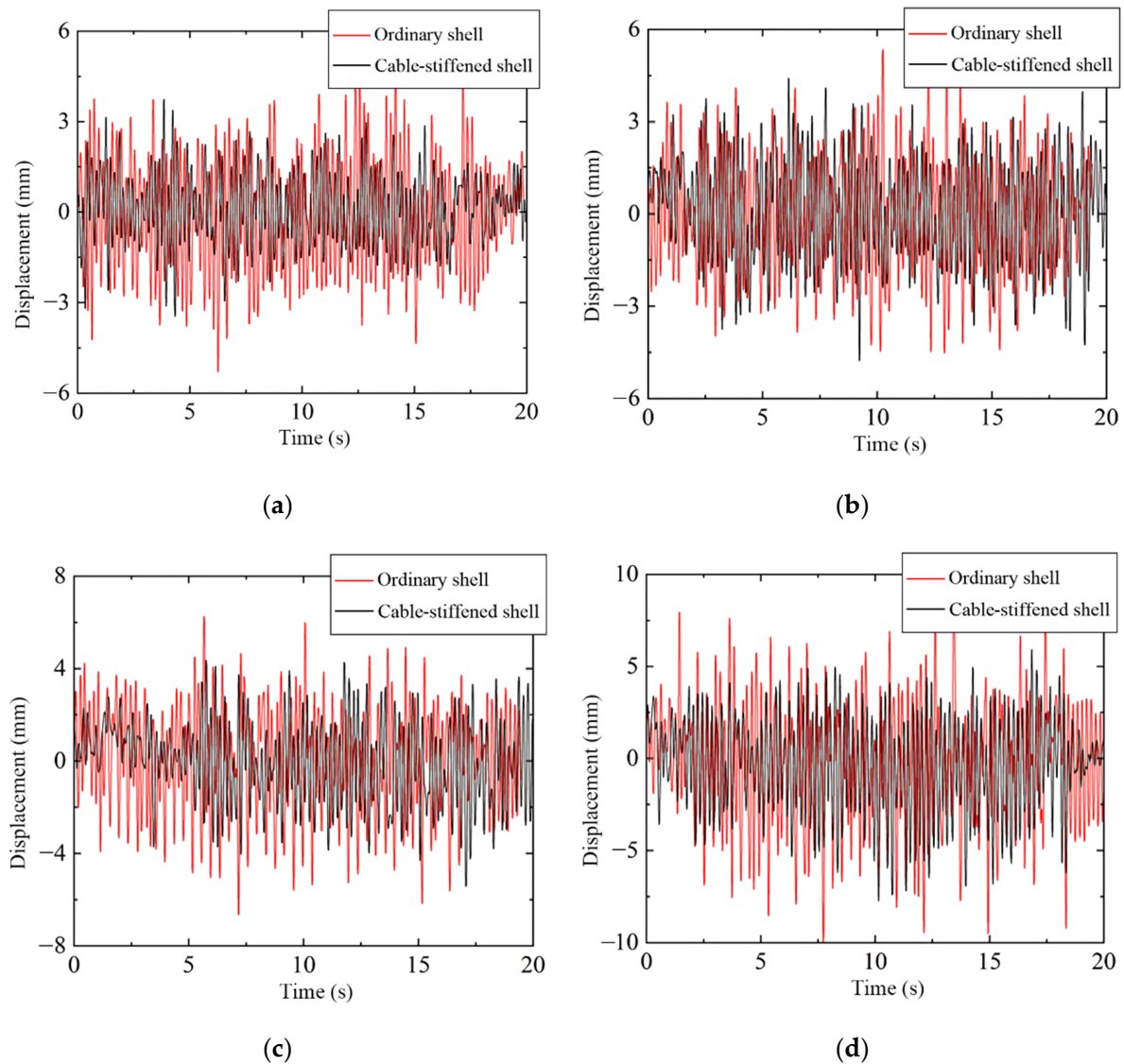


Figure 12. Vertical displacement response with amplitude varying. (a) 0.2 g. (b) 0.4 g. (c) 0.8 g. (d) 1.0 g.

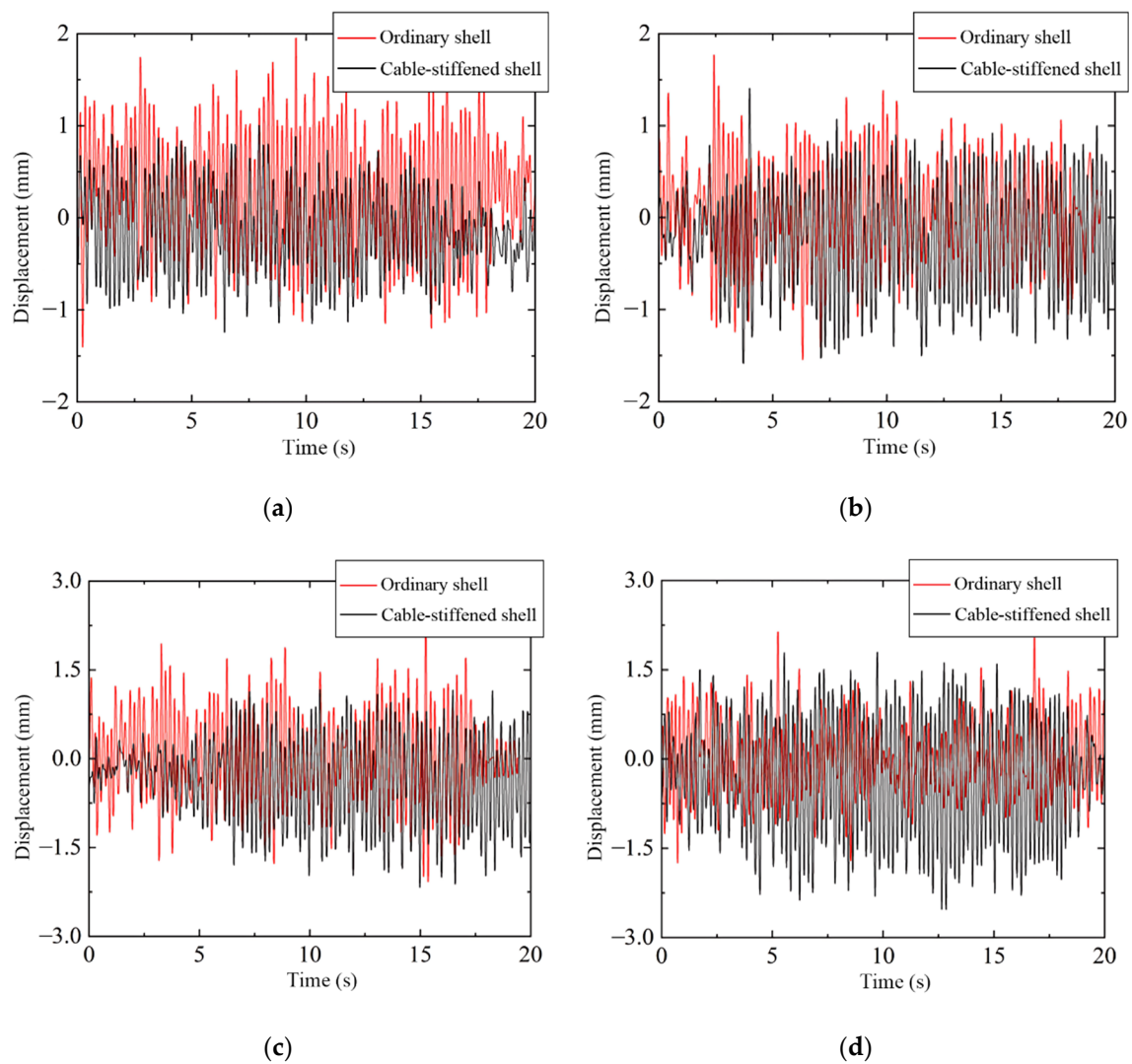


Figure 13. Horizontal displacement response with amplitude varying. (a) 0.2 g. (b) 0.4 g. (c) 0.8 g. (d) 1.0 g.

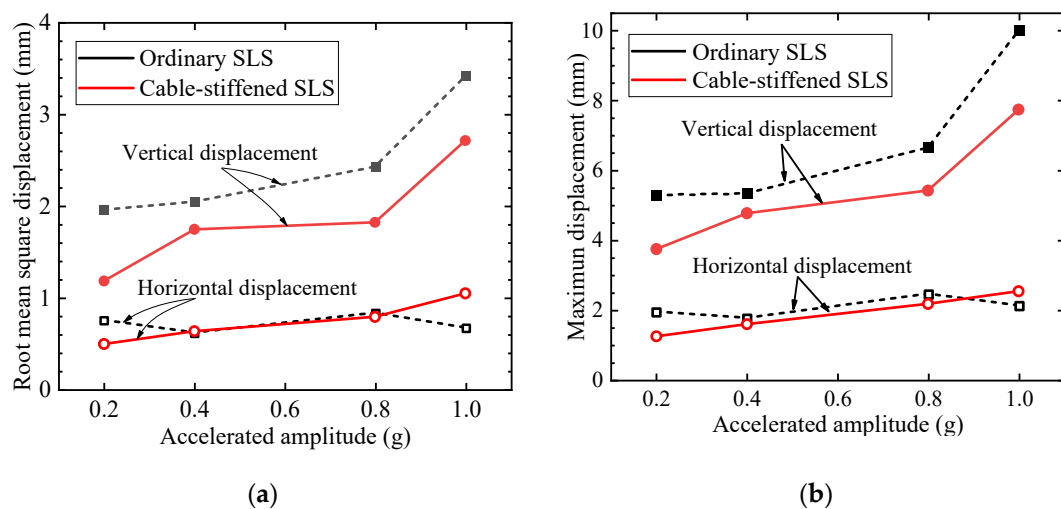


Figure 14. RMS and maximum displacement of A2 joint. (a) RMS displacement. (b) Maximum displacement.

4.2. Plastic Stage

In work condition 6, with an acceleration amplitude of 1.8 g, both SLS models experienced significant vibrations and deformations during the loading process, as displayed in Figure 15. The ordinary SLS model exhibited particularly intense vibrations and substantial overall deformation: most members showed severe bending deformation, and several central joints were in a tilted state with horizontal positions shifted. In contrast, the cable-stiffened SLS model also exhibited noticeable shaking, but its overall deformation was significantly less than that of the ordinary SLS model, and the structure largely maintained its original form: most members did not bend, only a few members showed deformation, and the joints did not exhibit significant tilting or shifting. This comparison highlights the enhanced seismic performance of the cable-stiffened SLS model under high acceleration loads.

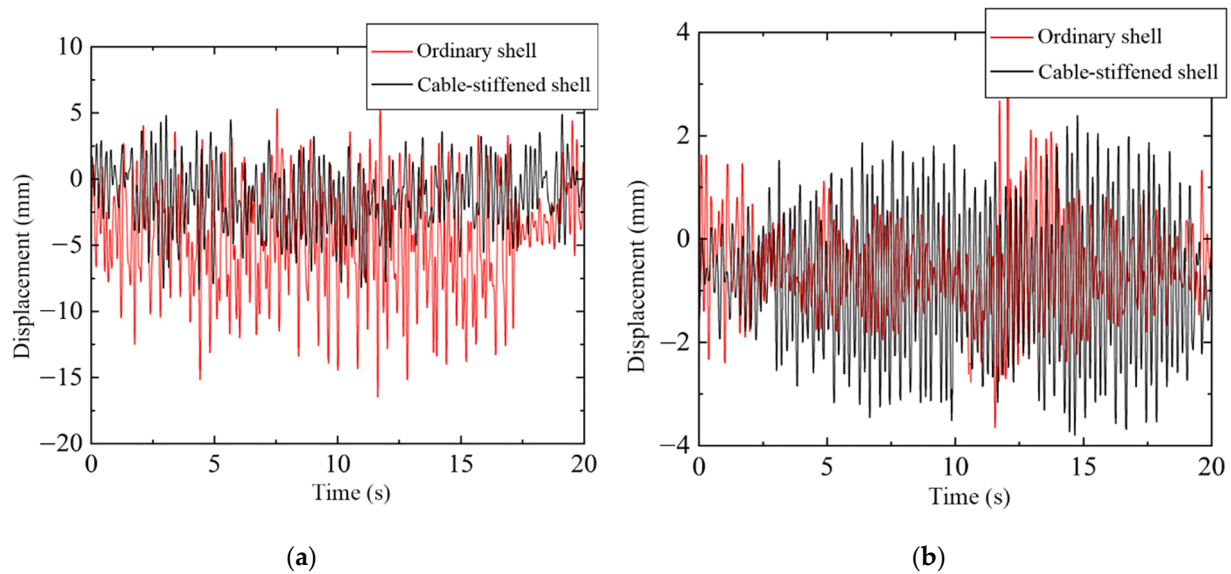
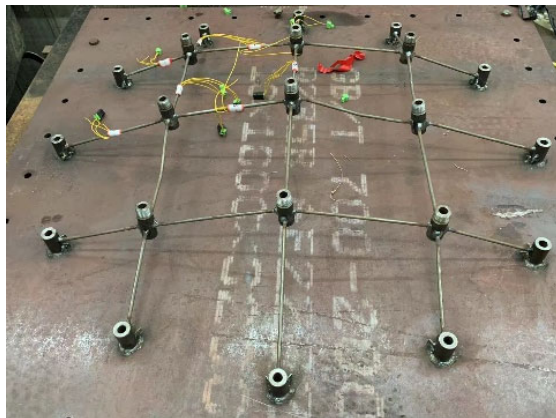
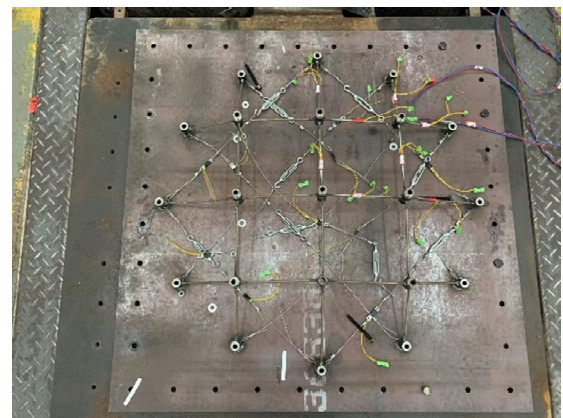


Figure 15. Deformation of members under 1.8 g accelerated magnitude. (a) Ordinary SLS. (b) Cable-stiffened SLS.

Table 5 lists the maximum micro-strain of eight characteristic members of the two SLS models under an earthquake time history with an acceleration amplitude of 1.8 g. For the ordinary SLS model, the maximum micro-strain of five members exceeded the yield strain, resulting in a plastic member ratio of 62.5%, whereas the cable-stiffened SLS model had a plastic member ratio of only 25%. Compared to the ordinary SLS model, the plastic member ratio of the cable-stiffened SLS model under the extremely high load of 1.8 g acceleration amplitude decreased by 60%, consistent with the member deformation scenarios displayed in Figure 15. Figure 16 shows the displacement–time history curves at joint A2 for the two SLS models under work condition 6. With an acceleration amplitude of 1.8 g, the vertical and horizontal displacements at joint A2 of the two SLS models showed significant differences. The maximum horizontal displacement for both SLS models did not exceed 4 mm. In contrast, the maximum vertical displacement for the cable-stiffened SLS model was 8.3 mm, while that for the ordinary SLS model reached 16.5 mm. This indicates that under the load of 1.8 g acceleration amplitude in work condition 6, the vertical dynamic response of the two SLS models still played a dominant role compared to the horizontal dynamic response, consistent with the phenomenon observed in work conditions 2 to 5. Moreover, comparing the maximum vertical displacement of the two SLS models revealed that the maximum displacement of the cable-stiffened SLS model was significantly reduced by about 50% compared to the ordinary SLS model, aligning with the overall deformation scenarios displayed in Figure 17. It can be concluded that introducing prestressed cables into SLS structures can effectively enhance the stiffness, stability, damping capacity, and seismic resistance of the structure, significantly reducing overall deformation and ensuring the integrity and safety of the SLS structure under extreme conditions.

Table 5. Maximum micro-strain of measured member.

Member	1	2	3	4	5	6	7	8
Ordinary SLS ($\mu\epsilon$)	2660	1943	1441	2474	3004	1285	1457	2159
Cable-stiffened SLS ($\mu\epsilon$)	1849	1222	1247	1468	2058	837	993	1182

**Figure 16.** Displacement response under 1.8 g accelerated amplitude. (a) Vertical displacement response. (b) Horizontal displacement response.**(a)****(b)****Figure 17.** Deformation of SLS models under 1.8 g accelerated magnitude. (a) Ordinary SLS. (b) Cable-stiffened SLS.

Summarizing the results from all work conditions for elastic and plastic stage, Table 6 lists the maximum displacements within the time range at joint A2 in both vertical and horizontal directions. It was observed that, across all work conditions, the maximum vertical displacement of the SLS models was significantly greater than their maximum horizontal displacement. This suggested that the controlling deformation for both types of SLS structures was primarily vertical deformation. Thus, comparing the maximum vertical displacements at joint A2 for the two SLS models revealed that the maximum vertical displacements increased with the increase in acceleration amplitude. The introduction of prestressed cables resulted in the cable-stiffened SLS model exhibiting smaller maximum

vertical displacements under the same acceleration amplitudes compared to the ordinary SLS model. From the content of this section, it could be concluded that the cable-stiffened SLS structure, with the introduction of prestressed cables, possessed higher stiffness and stability, along with better damping and seismic performance compared to the ordinary SLS structure in both elastic and plastic stage. Under dynamic loads with various acceleration amplitudes, the deformation of the cable-stiffened SLS structure was significantly reduced compared to the ordinary SLS structure, and the extent of damage to components was also significantly lower.

Table 6. Maximum vertical and horizontal displacement of A2 joints (mm).

Work Condition	Amplitude	Ordinary SLS		Cable-Stiffened SLS	
		Vertical	Horizontal	Vertical	Horizontal
2	0.2 g	5.30	1.95	3.74	1.24
3	0.4 g	5.34	1.77	4.77	1.59
4	0.8 g	6.65	2.46	5.42	2.17
5	1 g	9.96	2.13	7.74	2.53
6	1.8 g	16.48	3.65	8.34	3.80

5. Conclusions

This paper conducts small-scale shake table testing on both ordinary single-layer spherical latticed shell (ordinary SLS) and cable-stiffened single-layer spherical latticed shell (cable-stiffened SLS), comparing their dynamic responses and examining the impact of prestressed cables on the performance of the latticed shells during both the elastic and plastic stages. The conclusions are as follows:

1. By conducting white noise sweep tests, the natural frequencies of the SLS models were analyzed. With consistent member geometrical dimensions and material properties, the cable-stiffened SLS exhibited higher first two natural frequencies compared to the ordinary SLS, indicating that the arrangement of cables could enhance the overall stiffness of the structure.
2. Under the same acceleration amplitude, the maximum vertical displacement of characteristic joint of the cable-stiffened SLS was less than that of the ordinary SLS. As the amplitude increased to higher levels, the difference between the two became more pronounced, demonstrating that the arrangement of cables could mitigate the vibration of the SLS, especially under more severe earthquake conditions where the impact of prestressed cables on the seismic performance of the SLS was more evident.
3. With increasing acceleration amplitude, the vertical vibration of the ordinary SLS was significantly greater than that of the cable-stiffened SLS, but the horizontal vibration of the ordinary SLS was slightly less than that of the cable-stiffened SLS. This was because the introduction of prestressed cables led to a more uniform distribution of internal forces in the cable-stiffened SLS under strong seismic actions, improving the overall stress condition of the structure and thus reducing vertical vibrations. This indicated that the arrangement of cables could still reduce the overall vibration of the SLS.
4. In the work condition of the plastic stage, where the acceleration amplitude of the load reached 1.8 g, the ordinary SLS exhibited a plastic member ratio of 62.5%, with significant member deformation and joint displacement occurring extensively. In contrast, the cable-stiffened SLS had a plastic member ratio of only 25%, with only some members experiencing bending and smaller joint displacements. This demonstrates that the introduction of prestressed cables can effectively improve the overall stress condition of the structure, delay the development of plasticity in members, and enhance the seismic load-carrying capacity of the structure.

The results of this paper underscored the effectiveness of prestressed cables in enhancing the seismic resilience of SLS structures, providing a valuable design principle for engineering applications aiming for improved seismic performance. Building on the

research in this paper, the cable-stiffened SLS warrants further in-depth study. Based on the test results, a finite element model can be established to conduct parametric analysis, determining the impact of the various factors such as geometric dimensions and cable prestress values on the dynamic performance of the latticed shell. Additionally, a detailed investigation into the plastic development process and failure modes of the cable-stiffened SLS can more accurately predict potential structural failures under destructive earthquakes. With the rapid development of various optimization algorithms, multi-angle structural optimization of the cable-stiffened SLS can also broaden its future applications.

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