

## Research Article

# Static Experiment and Finite Element Analysis of a Multitower Cable-Stayed Bridge with a New Stiffening System

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Received 4 September 2018; Accepted 28 November 2018; Published 13 January 2019

Academic Editor: Mario D'Aniello

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Based on the stiffness limitations of the midtower in multitower cable-stayed bridges, a new stiffening system (tie-down cables) is proposed in this paper. The sag effects and wind-induced responses can be reduced with the proposed system because tie-down cables are short and aesthetic compared with traditional stiffening cables. The results show that the stiffening effect of tie-down cables is better than that of traditional stiffening cables in controlling the displacement and internal force of the bridge based on a static experiment and finite element analysis. Therefore, the proposed system can greatly improve the overall stiffness of a bridge, and its stiffening effect is better than that of traditional stiffening cables in controlling the displacement and internal force. The results provide a reference for the application of such systems in practical engineering.

## 1. Introduction

Cable-stayed bridges are widely used because of their large spans, beautiful appearance, light weight, and good seismic performance. As bridge spans have increased, single- and twin-tower cable-stayed bridges have become increasingly unable to meet the associated demands, and multitower cable-stayed bridges have become more commonly constructed [1–4].

The mechanical behaviors of multitower cable-stayed bridges and single- or twin-tower cable-stayed bridge are considerably different. Because the sidespan cable is directly anchored to the abutment or side pier, the longitudinal stiffness and girder deflection of a single- or twin-tower cable-stayed can be effectively controlled when the deflection of the midspan is large.

The mechanical behaviors of multitower cable-stayed bridges are different. Because all the cables of the middle tower are anchored to the girder, the longitudinal stiffness of the midtower and girder deflection cannot be restricted. Thus, the midspan deflection and longitudinal displacement of the midtower are extremely large when the deflection of the midspan is large. Therefore, the overall stiffness of a multitower bridge is critical in design process.

Reasonable layouts of stiffening cables can improve the overall stiffness of a multitower cable-stayed bridge, and the main methods involving stiffening cables are as follows [5–7]:

- (1) Horizontal stiffening cables: it can effectively increase the overall stiffness of the bridge, but stiffening can be reduced by sag effects, which can also create aesthetic issues when the cables are too long.
- (2) Inclined stiffening cables: it can effectively increase the overall stiffness of the bridge, and such cables are aesthetically pleasing. However, stiffening can be reduced by sag effects, and wind-induced responses are considerable when the cables are too long.
- (3) Overlapped stiffening cables: overlapping cables provide a poor stiffening effect, and the associated construction is difficult.

The traditional methods of stiffening cables have many deficiencies in construction projects. Therefore, a new stiffening cable system (tie-down cables) is proposed in this paper (Figure 1).

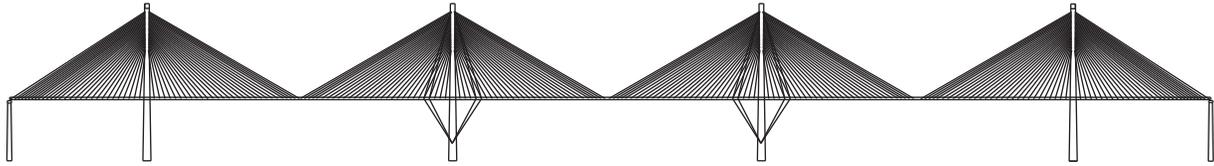


FIGURE 1: Multitower cable bridge with tie-down cables.

As shown in Figure 1, because one end of the tie-down cables is anchored to the tower and the other end is anchored to the girder, the tower and girder are connected to become a balanced system and increase the overall stiffness of the structure. Therefore, the tie-down cable system has the following advantages [8, 9]:

- (1) The overall stiffness of the structure is effectively increased by this system
- (2) The mechanical behaviors of the structure are improved by changing the anchor position on the girder, increasing the number of tie-down cables and increasing the axial force on the girder
- (3) Sag effects and wind-induced responses can be avoided because the tie-down cables are short
- (4) The appearance of the tie-down cable system is beautiful

A bridge model is established according to an actual bridge with a tower installed with two sets of tie-down cables [8]. In this paper, finite element software is used to simulate this new type of bridge, and the results are compared with those for several traditional cable-stayed bridges [10, 11]. The analysis results were then verified by a scaled static experiment.

## 2. Finite Element Analysis

**2.1. The Main Parameters of the Bridge.** In this paper, finite element software MIDAS is used for finite element analysis. The bridge model adopts the parameters of Chongqing Zhongxian Yangtze River Bridge. The total length of the bridge is 1327.6 m. This bridge has three towers and four spans, with a midspan of 460 m, sidespan of 203.8 m, and tower height of 247.5 m. The concrete grade of the bridge tower is C45, and the main girder is a steel box girder.

**2.2. The Finite Element Model and Calculation Conditions.** The calculation models include cable-stayed bridges without stiffening cables and with horizontal stiffening cables, inclined stiffening cables, overlapped stiffening cables, and tie-down cables. The finite element model is shown in Figure 2.

In this study, two load cases were taken into account for each of the five model configurations with single-lane loading at sidespan and midspan, respectively. The load magnitudes of all girders were Chinese highway load I grade [12].

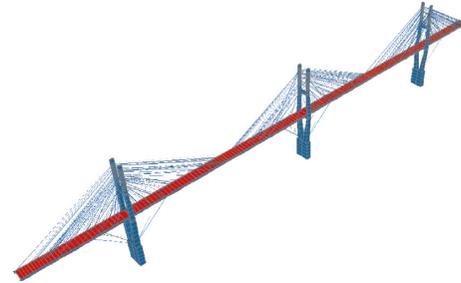


FIGURE 2: The model of the bridge.

## 3. Results and Discussion

**3.1. The Influence of the Stiffness of the Cable Bridge Based on Different Stiffening Cables.** The deflection curves of the girder loaded at the midspan and sidespan are shown in Figures 3 and 4. In Figures 3 and 4, model 1 is the cable bridge without stiffening cables, model 2 is the cable bridge with inclined stiffening cables, model 3 is the cable bridge with horizontal stiffening cables, model 4 is the cable bridge with overlapped stiffening cables, and model 5 is the cable bridge with tie-down cables.

As shown in Figures 3 and 4, the deflection of the girder can be effectively controlled with traditional stiffening cables, and the effect of the horizontal stiffening cables is best when loading occurs at the midspan. However, the girder deflection is not effectively controlled by traditional stiffening cables when loading occurs at the sidespan. The deflection of the girder is very effectively controlled by tie-down cables when loading occurs at the sidespan and midspan. Compared with the bridge without stiffening cables, the maximum deflection is reduced by 50% using tie-down cables. Tie-down cables are better than traditional cables for controlling girder deflection.

The displacement at important points on the girder and tower under the most unfavorable loads are shown in Tables 1 and 2.

As shown in Tables 1 and 2,

- (1) The stiffening effect of horizontal stiffening cables is best, and overlapped stiffening cables provide the worst stiffening effect among the traditional stiffening cables
- (2) The maximum deflection of the girder for midspan loading with tie-down cables decreases by 12.2% compared with that for horizontal stiffening cables, and the horizontal displacement of the midtower decreases by 21.7%

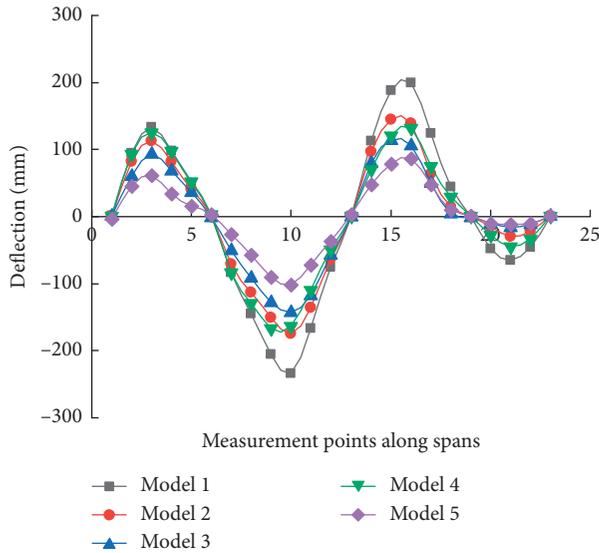


FIGURE 3: Deflection of the girder at midspan (mm).

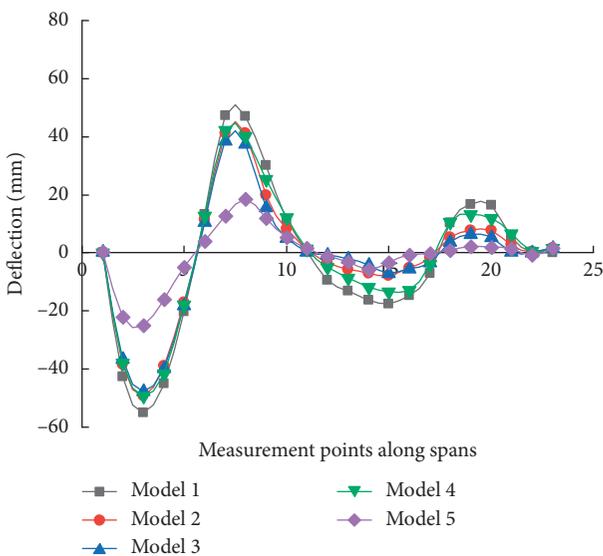


FIGURE 4: Deflection of the girder at sidespan (mm).

- (3) The maximum deflection of the girder for sidespan loading with tie-down cables decreases by 50.2% compared with that for horizontal stiffening cables, and the horizontal displacement of the midtower decreases by 87.1%
- (4) Tie-down cables are better than traditional stiffening cables in improving bridge stiffness

3.2. *The Influence of the Internal Force of a Cable Bridge Based on Different Stiffening Cables.* The maximum bending moment of the tower base and midspan of the girder for midspan and sidespan loading are shown in Tables 3 and 4. As shown in Tables 3 and 4,

- (1) The stiffening effect of the horizontal stiffening cables is the best, and that for overlapped stiffening

cables is the worst among the traditional stiffening cables in controlling the internal force

- (2) The maximum bending moment at the midtower based with tie-down cables decreases by 21.3% compared with that for horizontal stiffening cables for midspan loading, and the maximum bending moment of the midspan decreases by 34.1%
- (3) The maximum bending moment at the midtower base with tie-down cables decreases by 25.1% compared to that for horizontal stiffening cables for sidespan loading, and the maximum bending moment of the midspan decreases by 60.1%
- (4) Tie-down cables are better than traditional stiffening cables in controlling the internal force

In summary, tie-down cables are better than traditional stiffening cables in controlling displacement and the internal force of the girder and tower.

## 4. Static Experiment

4.1. *Model and Parameters.* A 1 : 200 reduced-scale model of a bridge was designed based on similarity criteria, with a 6.65 m total length, a 1.24 m tower height, and a span length of 1.025 m + 2.3 m + 2.3 m + 1.025 m = 6.65 m. The model is shown in Figure 5 [13, 14].

The experimental models with different stiffening cables are shown in Figure 6.

According to the above multitower cable-stayed bridge systems, two loading tests were conducted: a midspan load on one side of the bridge of 0.1 N/mm and a sidespan load on one side of the bridge of 0.1 N/mm (Figure 7).

Strain measurement points were arranged along the midspan of the main girder and bottom of the tower. Vertical displacement measurement points were arranged in the middle of each span and at the 1/4 span of the main girder span. The measurement point of horizontal displacement was located at the top of the main tower.

Polymethyl methacrylate (PMMA), with an elastic modulus of  $2.9 \times 10^3$  (MPa), was used to create the girders and towers in the model. High-strength steel wire with a diameter of 0.7 (mm) was used to make the cables, and a 0.12 (N/mm) counterweight was placed on the girder to tighten the cables.

According to the similarity criteria of the scale experiment, the section geometry characteristics of the structural components are shown in Table 5.

### 4.2. Analysis of Experimental Results

4.2.1. *The Influence of the Stiffness of Cable Bridge with Different Stiffening Cables.* The deflection curves of the girder by loading on midspan and sidespan are shown in Figures 8 and 9. In the Figures 8 and 9, model 1 is the cable bridge without stiffening cables, model 2 is the cable bridge with inclined stiffening cables, model 3 is the cable bridge with horizontal stiffening cables, model 4 is the cable bridge

TABLE 1: The displacement at important points for midspan loading (mm).

Model	Maximum deflection of midspans		Maximum deflection of sidespans		Horizontal displacement of the midtower top	Horizontal displacement of the side tower top	
	Left midspan	Right midspan	Left sidespan	Right sidespan		Left tower	Right tower
1	-233.3	203.82	131.2	-48.36	-113.99	73.04	37.20
2	-174.6	148.36	109.6	-29.68	-51.66	64.64	28.06
3	-140.2	117.67	91.5	-13.28	-39.22	53.23	23.62
4	-168.9	129.37	124.9	-46.57	-104.55	62.07	32.05
5	-123.2	87.83	58.5	-14.47	-30.68	36.39	12.35

TABLE 2: The displacement at important points for sidespan loading (mm).

Model	Maximum deflection of the midspan		Maximum deflection of the sidespan		Horizontal displacement of the midtower top	Horizontal displacement of the side tower top	
	Left midspan	Right midspan	Left sidespan	Right sidespan		Left tower	Right tower
1	96.79	-37.12	-110.2	36.58	123.96	77.87	94.82
2	84.22	-15.92	-97.80	15.67	80.16	49.07	63.32
3	80.60	-13.64	-94.49	13.83	78.19	57.13	68.86
4	85.19	-40.20	-99.61	39.35	121.22	77.36	83.90
5	36.11	-7.54	-47.05	4.31	10.04	25.15	7.60

Note. The upward displacement of the midspan is positive and the downward displacement of the midspan is negative. Additionally, the left horizontal displacement of the tower top is positive and the right horizontal displacement of the tower top is negative.

TABLE 3: The maximum bending moment at important points for midspan loading (kN · m).

Mode	Middle of the midspan	Middle of the sidespan	Midtower root	Side tower root
1	10805.36	-16386.50	-330204.8	292478.56
2	9352.90	-13571.68	-309350.4	288344.90
3	6916.48	-10020.06	-301217.1	282902.44
4	9932.80	-14447.20	-301407.2	242140.06
5	4561.46	-8891.52	-237170.3	159448.66

TABLE 4: The maximum bending moment at important points for sidespan loading (kN · m).

Mode	Middle of the midspan	Middle of the sidespan	Midtower root	Side tower root
1	-10528.42	9545.42	139434.24	-121417.9
2	-10280.90	8728.70	101917.82	-133426.0
3	-9743.78	7806.66	100138.48	-131929.3
4	-6839.16	8141.60	139430.16	-116011.2
5	-6085.10	6253.04	80013.00	-39926.60

with overlapped stiffening cables, and model 5 is the cable bridge with tie-down cables.

As shown in Figures 8 and 9, deflection of girder can be controlled very effectively by traditional stiffening cables and the effect of horizontal stiffening cables was best. But tie-down cables are better than traditional stiffening cables on controlling deflection of girder. The experimental results are well consistent with that of computer simulation.

The important points of displacement of girder and tower top are shown in Tables 6 and 7.

As shown in Tables 6 and 7,

- (1) Stiffening effect of horizontal stiffening cables is best and that of overlapped stiffening cables is worst among traditional stiffening cables.

- (2) Maximum deflection of girder of loading span with tie-down cables decreases by 20.1%, and horizontal displacement of midtower with tie-down cables decreases by 30.4% by loading on midspan compared with horizontal stiffening cables.
- (3) Maximum deflection of girder of loading span with tie-down cables decreases by 49.2%, and horizontal displacement of midtower with tie-down cables decreases by 91.1% by loading on sidespan compared with horizontal stiffening cables.
- (4) Tie-down cables are better than traditional stiffening cables in improving stiffness of the bridge. The experimental results are well consistent with that of computer simulation.



FIGURE 5: Experimental model of the bridge.

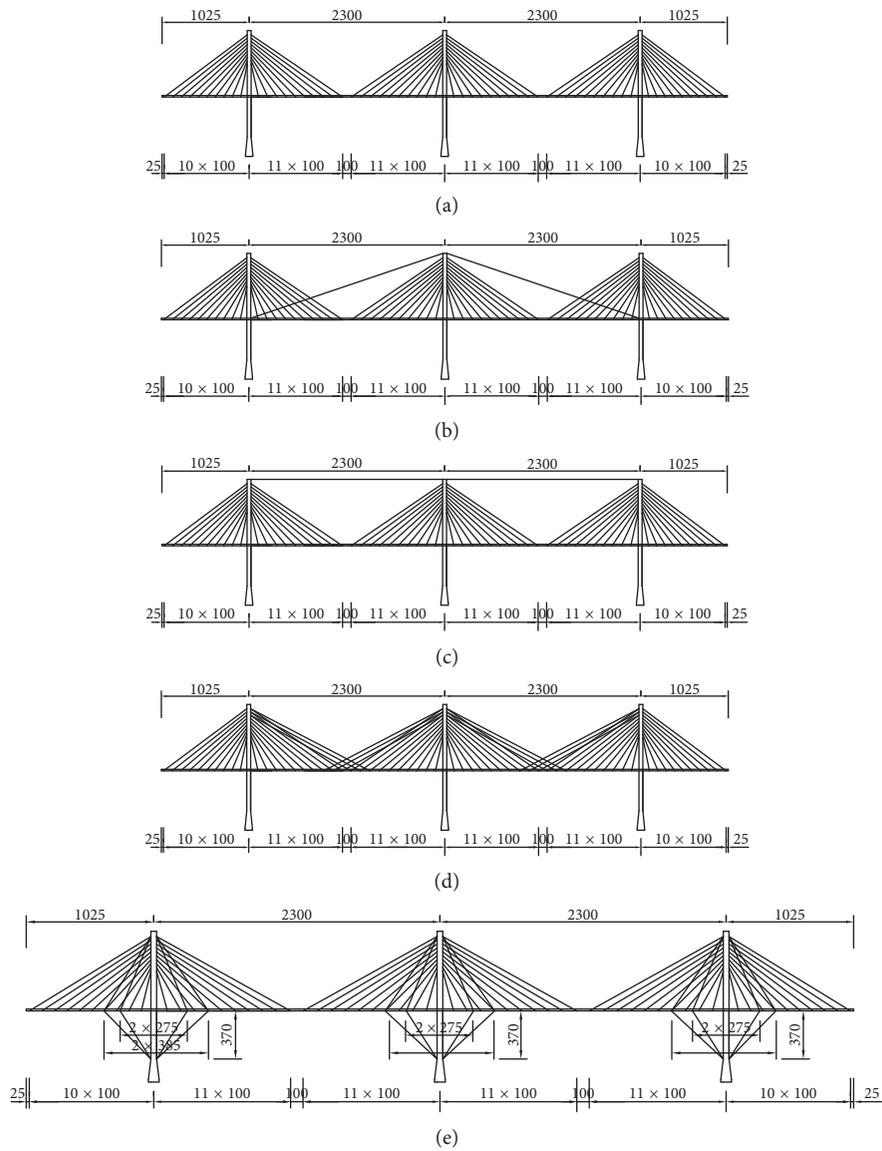


FIGURE 6: The experimental models. (a) Multitower cable bridge model without stiffening cables (mm). (b) Multitower cable bridge model with inclined stiffening cables (mm). (c) Multitower cable bridge model with horizontal stiffening cables (mm). (d) Multitower cable bridge model with overlapped stiffening cables (mm). (e) Multitower cable bridge model with tie-down cables (mm).

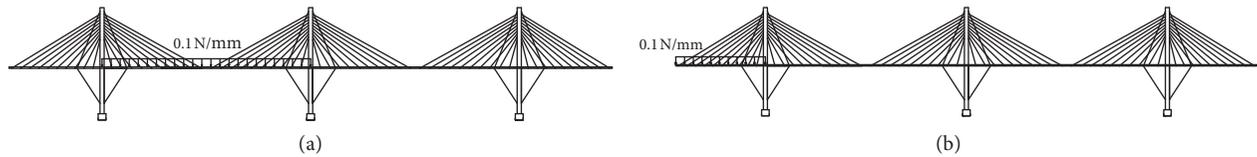


FIGURE 7: The experimental model. (a) Midspan loading of the multitower cable bridge. (b) Sidespan loading of the multitower cable bridge.

TABLE 5: Model parameters of the concrete members.

Model	$E$ (MPa)	$A$ (mm <sup>2</sup> )	$I$ (mm <sup>4</sup> )
Girder	$2.9 \times 10^3$	$9.1 \times 10^{-4}$	$1.97 \times 10^{-8}$
Top of tower	$2.9 \times 10^3$	$5.5 \times 10^{-4}$	$7.76 \times 10^{-8}$
Middle of tower	$2.9 \times 10^3$	$6.5 \times 10^{-4}$	$15.76 \times 10^{-8}$
Bottom of tower	$2.9 \times 10^3$	$21.25 \times 10^{-4}$	$76.11 \times 10^{-8}$
Pier	$2.9 \times 10^3$	$21.67 \times 10^{-4}$	$164.35 \times 10^{-8}$

Note.  $E$ , the elastic modulus;  $A$ , the elastic modulus cross-sectional area;  $I$ , the moment of inertia.

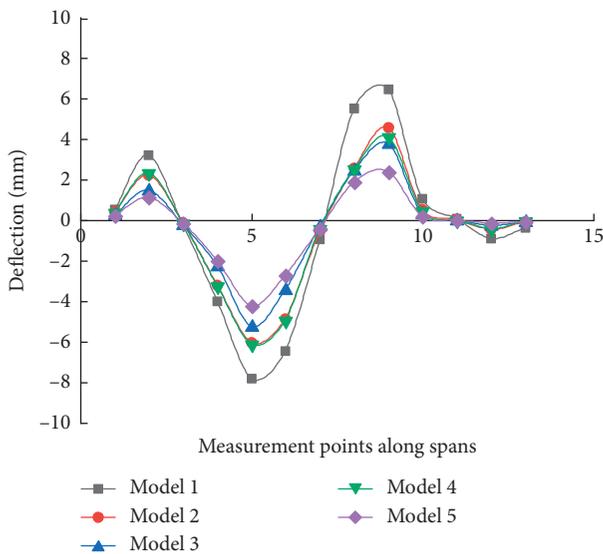


FIGURE 8: Twisted curve of main beam by loading on midspan (mm).

The influence of internal force of cable bridge with different stiffening cables.

The maximum bending moment of tower root and midspan of girder by loading on midspan and sidespan are shown in Tables 8 and 9.

As shown in Tables 8 and 9,

- (1) Stiffening effect of horizontal stiffening cables is best and that of overlapped stiffening cables is worst among traditional stiffening cables in controlling internal force
- (2) Maximum bending moment of midtower root of loading span with tie-down cables decreases by 57.2%, and maximum bending moment of midspan of loading span with tie-down cables decreases by 24.5% by loading on midspan compared with horizontal stiffening cables
- (3) Maximum bending moment of midtower root with tie-down cables decreases by 63.6%, and

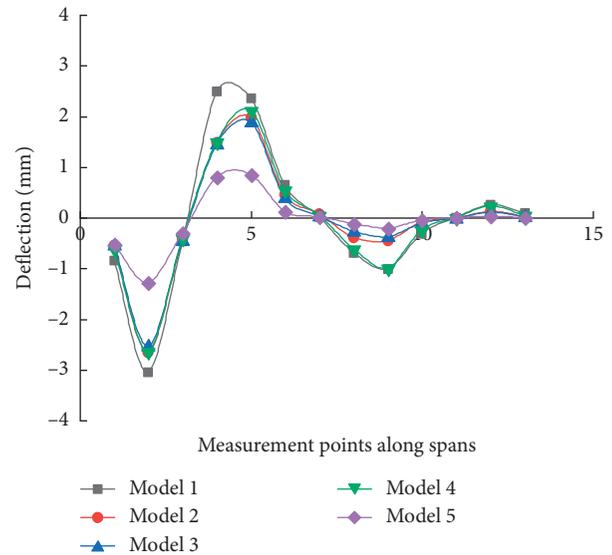


FIGURE 9: Twisted curve of main beam by loading on sidespan (mm).

maximum bending moment of midspan of loading span with tie-down cables decreases by 3.1% by loading on sidespan compared with horizontal stiffening cables

- (4) Tie-down cables are better than traditional stiffening cables in controlling internal force

In summary, experimental results are well consistent with that of computer simulation, and tie-down cables were better than traditional stiffening cables in controlling displacement and internal force of girder and tower.

## 5. Conclusions

The following conclusions could be achieved through finite element calculation results and static experiment:

- (1) The sag effects and wind-induced response could be avoided because the tie-down cables are short and appearance of tie-down cables system is more beautiful compared with traditional stiffening cables
- (2) Stiffening effect of horizontal stiffening cables is best and overlapped stiffening cables is worst among traditional stiffening cables in controlling displacement and internal force
- (3) Stiffening effect of tie-down cables is better than traditional stiffening cables in controlling displacement and internal force

TABLE 6: The displacement at the important points by loading on midspan (mm).

Model	Maximum deflection of midspan		Maximum deflection of sidespan		Horizontal displacement of midtower top	Horizontal displacement of side tower top	
	Left midspan	Right midspan	Left sidespan	Right sidespan		Left tower	Right tower
1	-7.82	6.44	3.22	-0.89	-4.49	2.72	1.08
2	-6.04	4.56	2.83	-0.51	-3.17	2.65	1.06
3	-5.23	3.78	2.11	-0.23	-2.86	1.76	0.59
4	-6.12	4.12	3.15	-0.82	-4.21	2.20	0.84
5	-4.18	2.24	1.12	-0.16	-1.99	1.48	0.46

TABLE 7: The displacement at the important points by loading on sidespan (mm).

Model	Maximum deflection of midspan		Maximum deflection of sidespan		Horizontal displacement of midtower top	Horizontal displacement of side tower top	
	Left midspan	Right midspan	Left sidespan	Right sidespan		Left tower	Right tower
1	2.35	-1.01	-3.04	0.26	1.01	1.21	1.13
2	1.97	-0.45	-2.66	0.12	0.87	0.91	0.83
3	1.88	-0.38	-2.54	0.10	0.79	0.98	0.89
4	2.11	-0.99	-2.64	0.23	0.97	1.13	1.02
5	0.85	-0.21	-1.29	0.04	0.07	0.89	0.77

Note. Upward displacement of midspan is positive and downward displacement of midspan is negative. Left horizontal displacement of tower top is positive and right horizontal displacement of tower top is negative.

TABLE 8: The maximum bending moment at the important points by loading on midspan (N · m).

Mode	Middle of the midspan	Middle of the sidespan	Midtower root	Side tower root
1	563.60	-645.00	-13033.80	12680.70
2	481.70	-543.40	-10032.10	9861.40
3	421.60	-490.40	-9343.30	8712.50
4	510.50	-588.30	-10121.70	10327.20
5	318.10	-432.50	-4002.40	6336.90

TABLE 9: The maximum bending moment at the important points by loading on sidespan (N · m).

Mode	Middle of the midspan	Middle of the sidespan	Midtower root	Side tower root
1	-138.10	668.10	1388.70	-3969.90
2	-134.20	627.30	1400.20	-3215.70
3	-126.50	615.50	1367.40	-3045.80
4	-127.30	631.60	1380.50	-3899.40
5	-122.60	616.60	1376.80	-1108.80

- (4) Experimental results are well consistent with finite element calculation results

In addition, seismic, wind-resistant, fatigue effect, and detail structure of tie-down cable system still need to be further researched to make tie-down cable system be applied to the actual project [15–19]. Further studies are needed to solve this problem.

## Data Availability

The experimental raw data used to support the findings of this study are included within the article and have been deposited at [http://doi.org/repository\\_10.4121/uuid:15a7323f-4738-4b53-b349-3ed00ebb9957](http://doi.org/repository_10.4121/uuid:15a7323f-4738-4b53-b349-3ed00ebb9957).

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Supplementary Materials

The supplementary materials are related photos of the experiment. (*Supplementary Materials*)

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