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Aerodynamic stability of cable-stayed-suspension hybrid bridges*

ZHANG Xin-jun (张新军)[†1], SUN Bing-nan (孙炳楠)[2]

([1]School of Civil Engineering and Architecture, Zhejiang University of Technology, Hangzhou 310014, China)
([2]School of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310027, China)
[†]E-mail: xjzhang@zjut.edu.cn

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Abstract: Three-dimensional nonlinear aerodynamic stability analysis was applied to study the aerodynamic stability of a cable-stayed-suspension (CSS) hybrid bridge with main span of 1400 meters, and the effects of some design parameters (such as the cable sag, length of suspension portion, cable plane arrangement, subsidiary piers in side spans, the deck form, etc.) on the aerodynamic stability of the bridge are analytically investigated. The key design parameters, which significantly influence the aerodynamic stability of CSS hybrid bridges, are pointed out, and based on the wind stability the favorable structural system of CSS hybrid bridges is discussed.

Key words: Cable-stayed-suspension (CSS) hybrid bridge, Aerodynamic stability, Parametric analysis
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INTRODUCTION

The cable-stayed-suspension (CSS) hybrid bridge is developed from the traditional cable-stayed bridge and suspension bridge, and has some advantages of the two bridge types described as follows:

1. As compared with the suspension bridge of the same span length, the suspension portion is greatly shortened, so the tensional forces in the main cables are greatly decreased, which helps to decrease the construction costs of the main cables and the massive anchors, and the difficulty of constructing them in water, and therefore makes it possible to build CSS hybrid bridge on soft soil foundation. In addition, different structural materials can be used in the suspension and cable-stayed portions. For example, the prestressed concrete girder in the cable-stayed portion and the light steel box girder in the suspension portion, and the materials in the deck can be also saved.

2. As compared with the cable-stayed bridges of the same span length, the cable-stayed portion is greatly shortened, the height of towers can be significantly decreased, and the axial compressive forces in the deck are also greatly reduced. The cantilevers in erection are also greatly shortened, and the wind stability of the bridge under erection is therefore improved.

Therefore, it can make up the deficiencies in the structural behavior, construction, economy and the wind stability of the traditional suspension bridge and cable-stayed bridge, and becomes an attractive alternative in the design of long and super long-span bridges.

The idea of using cables and stay cables to support bridge spans was conceived by Gimsing (1997), although few CSS hybrid bridges were built before 1920's. But after that, this bridge system was used in the rehabilitations of some existing suspension bridges such as the Brooklyn Bridge in America, the Tancarville Bridge in France, the Salazar Bridge in Portugal, etc., and also was proposed in the design of many strait-crossing bridges such as the Great Belt East Bridge, the Gibraltar Bridge, the Messina Strait Bridge, the Izmit Bridge in Turkey, the Tagus River Bridge in Portugal and some strait-crossing bridges in

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Japan. In 1997, the first modern CSS hybrid bridge in the world was built in China with main span of 288 meters (Meng *et al*., 1999). In the 21st century, many long and particularly super long-span bridges were planned in crossing straits and islands engineering projects. Many of them were built under the natural conditions unfavorable for building cable-stayed bridge or suspension bridge, such as soft soil foundation, violent typhoon, and the deep-water foundation. However, due to its advantages mentioned above, the CSS hybrid bridge is a competitive alternative for designing of these bridges.

The design of CSS hybrid bridges involves problems of static and dynamic behavior, construction, economy, wind stability, etc., which need to be fully investigated. In previous studies, more attentions were paid to the static and dynamic behaviors under dead and service loads, the economics, etc. (Meng *et al*., 1999; Xiao and Xiang, 1999; Xiao, 2000), but few investigations were done on the aerodynamic stability of CSS hybrid bridges. Just like the suspension and cable-stayed bridges, the CSS hybrid bridge is also a structural system of great flexibility, and very susceptible to wind action. The wind stability is a governing factor for the design of this bridge system, and should be fully investigated.

In this paper, based on the method of 3D nonlinear aerodynamic stability analysis developed by Zhang *et al*.(2002), in which the geometric nonlinearity of bridge structures and the effects of nonlinear wind-structure interaction are considered, parametric analyses on the aerodynamic stability of a CSS hybrid bridge with main span of 1400 meters were conducted, some design parameters that significantly influence the aerodynamic stability are pointed out, and the favorable structural system of the bridge is also discussed based on the wind stability.

DESCRIPTION OF THE EXAMPLE BRIDGE

The example CSS hybrid bridge consists of a main span of 1400 m and two side spans of 319 m as shown in Fig.1, which was proposed for construction in the east channel of Lingding Strait in China (Xiao, 2000). The central span consists of the cable-stayed portion of 788 m and the suspension portion of 612 m. The spacing of two main cables is 34 m, the cable sag to span ratio is 1/7.6, and the spacing of hangers is 18 m. The stay cables are anchored to the girder at 18 m intervals in the central span and 14 m in the side spans. The deck is a steel streamlined box steel girder of 36.8 m wide and 3.8 m high. The towers are the door-shaped frames with 3 transverse beams. The cross section and material properties of the bridge are given in Table 1.

A 3D finite element model (FEM) of the bridge was established for the aerodynamic stability analysis, in which the girder and towers were modeled by 3D beam elements, the hangers, main cables and stay ca-

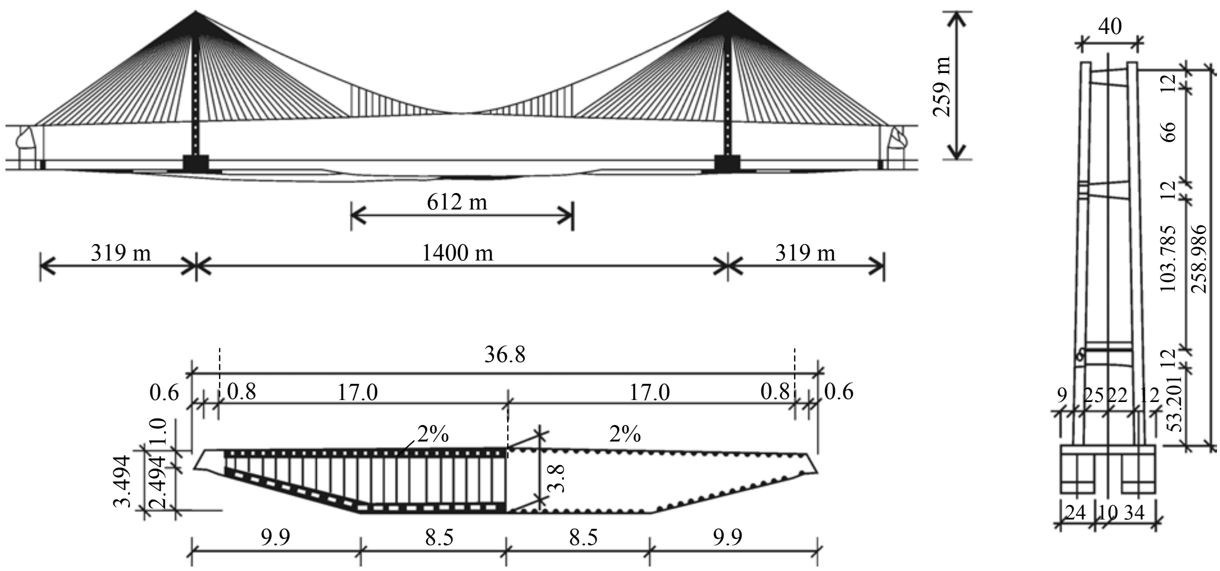

Fig.1 General configuration of the cable-stayed-suspension hybrid bridge

Table 1 The cross section and material properties of the bridge

Members	E (MPa)	A (m^2)	J_d (m^4)	Iz (m^4)	Iy (m^4)	M (kg/m^3)	Jm (kg·m^2/m)
Girder	2.1×10^5	1.2481	5.034	1.9842	137.754	14732.0	1.852×10^6
Main cable CS	2.0×10^5	0.3167	0.0	0.0	0.0	8400.0	0.0
Main cable SS	2.0×10^5	0.3547	0.0	0.0	0.0	8400.0	0.0
Hanger	2.0×10^5	0.0064	0.0	0.0	0.0	7850.0	0.0
Stay cable	2.0×10^5	0.008	0.0	0.0	0.0	7850.0	0.0
Towers C	3.3×10^4	30.0	350.0	320.0	220.0	2600.0	5.7×10^5
Towers TB	3.3×10^4	10.0	150.0	70.0	70.0	2600.0	4.7×10^5

E–elastic modulus; A–area, J_d–orsional moment of inertia; Iz–vertical bending moment of inertia; Iy–lateral bending moment of inertia; M–mass density; Jm–mass moment of inertia per unit length; CS–center span; SS–side span; C–tower's column; TB–tower's transverse beam

bles were modeled by 3D bar elements. The connections between bridge components and the supports of the bridge were properly modeled. Since the girder of the bridge was very similar to that of the Runyang Bridge being constructed in Jiangshu Province of China, the aerostatic and aerodynamic coefficients of the Runyang Bridge were used in the aerodynamic stability analysis of the bridge (Chen and Song, 2000). The damping ratio was taken as 0.5%. It is to be noted that the following aerodynamic stability analyses were all under wind attack angle of 0°.

COMPARISON OF THE AERODYNAMIC STABILITY

Currently, the main span of cable-stayed bridge has not yet exceeded 1000 m, whereas that of most of the suspension bridges is beyond 1000 m. To compare the aerodynamic stability of the CSS hybrid bridge with the suspension bridge with the same span length, an example suspension bridge is assumed herein. The girder and towers are the same for the two bridges. The cross section areas of main cables are determined by the tensile forces under dead and service loading with a safety factor of 2.5. The sag to span ratio is taken as 1/10.5, and the spacing of hangers is 18 m.

Table 2 shows the calculated frequencies of main modes participating in flutter. The critical wind speeds of aerodynamic stability of CSS hybrid bridge is 77.9 m/s, and that of suspension bridge is 71.3 m/s.

As can be seen in Table 2, the modal frequencies of the CSS hybrid bridge are all higher than those of the suspension bridge, particularly the torsional frequency. The critical wind speed of the CSS hybrid bridge is also higher than that of the suspension bridge. It is because that, as compared with the suspension bridge, the cable-stayed portion helps a great deal to improve the vertical and particularly the torsional stiffness of the bridge, higher torsional frequency and greater aerodynamic stability are consequently achieved for the CSS hybrid bridge. Therefore, viewed from the aspect of aerodynamic stability, the CSS hybrid bridge is superior to the suspension bridge with the same span length.

Table 2 The frequencies of main modes participating in flutter

Bridge type	Modal frequencies (Hz)			
	1-S-V	2-S-V	3-S-V	1-S-T
CSS hybrid bridge	0.1360	0.2032	0.2712	0.3051
Suspension bridge	0.1349	0.1880	0.2610	0.2598

PARAMETRIC ANALYSIS

Investigations by Xiao and Xiang (1999), Xiao (2000), Meng *et al.*(1999) showed that the static and dynamic characteristics of the cable-stayed-suspension hybrid bridges are greatly affected by some design parameters such as the cable sag, the suspension portion length, the arrangement of the stay cable planes, the subsidiary piers in side spans, the deck form, etc. In the following sections, parametric analysis is conducted to investigate how these design parameters affect the aerodynamic stability of the CSS hybrid bridge.

Cable sag

The cable sag, being an important design parameter for the CSS hybrid bridge, has important influence on the height of towers and the inclination angles of the stay cables, and are closely related to the tensile forces in the main cables and stay cables and ultimately the stiffness and dynamic characteristics of the bridge.

To gain understanding of how the cable sag affects the aerodynamic stability of the bridge, aerodynamic stability analyses of the bridge with different cable sags were conducted. Table 3 gives the frequencies of main modes participating in flutter and the critical wind speeds when the sag to span ratios are assumed as 1/7.6, 1/10 and 1/12 respectively. The critical wind speed decreases with decrease of cable sag. The tower's height and the inclination angles of stay cables are both decreased with the reduction of cable sag. The supporting efficiency of the stay cables and also the stiffness of the bridge are therefore reduced, which leads to the reduction of modal frequencies, particularly the torsional frequencies. From the viewpoint of aerodynamic stability, the cable sag should not be too small for the bridge.

Table 3 The modal frequencies and critical wind speeds for different cable sags

The sag to span ratios	Frequencies (Hz)			Critical wind speed (m/s)
	1-S-V	2-S-V	1-S-T	
1/7.6	0.1426	0.2224	0.3152	77.9
1/10	0.1345	0.2105	0.2775	71.0
1/12	0.1268	0.2020	0.2537	65.6

Suspension portion length

Increasing or shortening the suspension portion enables the CSS hybrid bridge to behave like the suspension bridge or the cable-stayed bridge. To investigate the effect of the suspension portion length on the aerodynamic stability of the bridge, cases of the bridge with different suspension portion lengths were analyzed. The critical wind speeds are given in Table 4.

Table 4 shows that the critical wind speed decreases with increasing the suspension portion length. As the suspension portion length increases, the bridge behaves gradually as a suspension bridge; the stiffness and modal frequencies of the bridge are all reduced. Therefore, shorter suspension portion is aerodynamically favorable for the bridge, but the favorable ratio of suspension portion to span should be further investigated in connection with other factors such as the static behavior, economics, etc. of the bridge.

Table 4 The critical wind speeds for different suspension portion to span ratios

The suspension portion to span ratio	Critical wind speed (m/s)
0.4	87.1
0.5	82.4
0.6	78.2

Arrangement of the stay cable planes

Like the cable-stayed bridges, the stay cable planes of the CSS hybrid bridge can be made to be vertical or inclined, which mainly depends on the lateral configuration of the towers. For the example bridge, the cable planes are inclined inward as in Case A shown in Fig.2. To investigate the effect of the arrangement of stay cable planes on the aerodynamic stability, two cases are assumed: One is that the cable planes are vertical as in Case B in Fig.2, and another is that the cable planes are inclined outward as in Case C in Fig.2. Except for the arrangement of cable planes, the other design parameters remain the same for all the cases. The vertical cable planes are achieved by making the anchor sections in the columns of towers vertical. In order to get the inclined outward cable planes, an inverse Y-shaped construction is installed in the central position between the two columns of towers. Table 5 gives the calculated critical wind speeds under three cases.

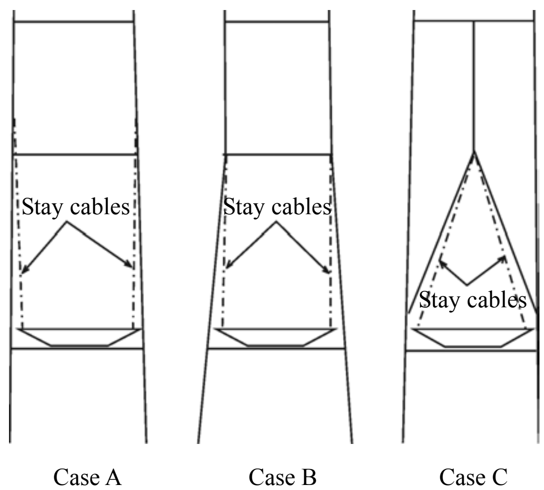

Fig.2 Different arrangement of the stay cable planes

Table 5 The critical wind speed for different stay cable planes

Cases	Critical wind speed (m/s)
A	77.9
B	82.4
C	89.8

Compared with Case A, the critical wind speed is increased by 12 m/s for Case C, and 4.5 m/s for Case B. This increase in critical wind speed is very similar to that of the cable-stayed bridges (Zhang and Sun, 2003). It is well known that Case C is normal practice to improve the aerodynamic stability of cable-stayed bridges. Therefore, for the CSS hybrid bridge, making the stay cable planes inclined outward or vertical is confirmed analytically to be aerodynamically favorable.

Deck form

As mentioned above, different materials can be used in the CSS hybrid bridge deck called composite deck here. To investigate the effect of different deck form on the aerodynamic stability, the bridge with a composite deck is assumed, in which the prestressed concrete and steel box girders are used in the cable-stayed portion and the suspension portion respectively, whereas the cross section configurations are identical as shown in Fig.3. Table 6 gives the calculated critical wind speeds under different deck forms.

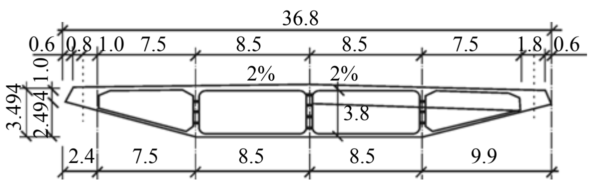

Fig.3 The concrete deck in the cable-stayed portion

Table 6 The critical wind speeds for different deck forms

Deck forms	Critical wind speed (m/s)
Single steel box girder	77.9
Composite deck	94.1

As compared with the case of single steel box girder, the critical wind speed is increased by 16.2 m/s when the composite deck is used (Table 6). The remarkable increase of the critical wind speed is largely due to the greater gravity stiffness of the heavier prestressed concrete box girder being used instead of the light steel box girder used in the cable-stayed portion so that the vertical bending and torsional frequencies are both increased. Thus from the viewpoint of aerodynamic stability, it is suggested that the composite deck should be used for the CSS hybrid bridge.

Subsidiary piers in side spans

Commonly, a few subsidiary piers are used in the side spans to improve the vertical bending stiffness of cable-stayed bridges (Zhang and Sun, 2003). To investigate the effect of the subsidiary piers in side spans on the aerodynamic stability, cases as shown in Tables 7 and 8 are analyzed.

Table 7 The critical wind speeds for different number of subsidiary piers in side spans

Number of the subsidiary piers	Critical wind speed (m/s)
0	77.9
1	82.9
2	84.1

Table 8 The critical wind speeds for different location of single subsidiary pier in each side span

Locations	Critical wind speed (m/s)
1/4*Ls*	82.9
1/3*Ls*	83.1
1/2*Ls*	83.5

Note: *Ls* is the length of side span

Table 7 shows that the subsidiary piers help to improve the aerodynamic stability of the bridge. When subsidiary piers are used in side spans, the vertical bending frequencies are greatly increased, although little torsional frequency change occurs. In addition, both the vertical bending and torsional mode shapes are changed greatly and become more complicated. Therefore, the subsidiary piers in side spans are proved analytically to be both statically and aerodynamically favorable for the bridge. However, as seen in Table 8, the critical wind speed is almost not affected by the location of the subsidiary pier in side spans.

CONCLUSION

In this paper, the effects of some design parameters on the aerodynamic stability of a CSS hybrid bridge are fully investigated, and the following conclusions are drawn:

1. The CSS hybrid bridge is confirmed analytically to be aerodynamically superior to the suspension bridge with the same span length.

2. Increasing the cable sag is helpful for improving the aerodynamic stability of the CSS hybrid bridge.

3. The short suspension portion is aerodynamically favorable for the CSS hybrid bridge.

4. The aerodynamic stability of CSS hybrid bridges can be greatly improved by using outward inclined cable planes.

5. The composite deck is confirmed to be an effective measure to improve the aerodynamic stability of the CSS hybrid bridge, and therefore should be used in the CSS hybrid bridge.

6. The subsidiary piers in side spans are analytically proved to be aerodynamically favorable for the CSS hybrid bridge.

References

Chen, A.R., Song, J.Z., 2000. Wind-resistant Research on the Runyang Bridge. Research Report, Tongji University (in Chinese).

Gimsing, N.J., 1997. Cable-supported Bridges–Concept & Design. John Wiley & Sons Ltd., England.

Meng, Y., Liu, D., Sun, S.H., 1999. Study on the design of long-span cable-stayed-suspension hybrid bridges. *Journal of Chongqing Jiaotong Institute*, **18**(4):8-12 (in Chinese).

Xiao, R.C., 2000. Research on the design of cable-stayed-suspension hybrid bridges. *China Civil Engineering Journal*, **33**(5):46-51 (in Chinese).

Xiao, R.C., Xiang, H.F., 1999. Mechanics characteristics and economic performances study for cable-stayed-suspension hybrid bridges. *China Journal of Highway and Transportation*, **12**(3):43-48 (in Chinese).

Zhang, X.J., Sun, B.N., 2003. Study of design parameters on flutter stability of cable-stayed bridges. *Wind and Structures*, **6**(4):279-290.

Zhang, X.J., Sun, B.N., Xiang, H.F., 2002. Nonlinear aerostatic and aerodynamic analysis of long-span suspension bridges considering wind-structure interactions. *J. Wind Engrg. Indust. Aerodyn*, **90**(9):1065-1080.