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Investigation on mechanics performance of cable-stayed-suspension hybrid bridges

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Abstract. The cable-stayed-suspension hybrid bridge is a cooperative system of the cable-stayed bridge and suspension bridge, and takes some advantages and also makes up some deficiencies of both the two bridge systems, and therefore becomes strong in spanning. By taking the cable-stayed-suspension hybrid bridge, suspension bridge and cable-stayed bridge with main span of 1400 m as examples, the mechanics performance including the static and dynamic characteristics, the aerostatic and aerodynamic stability etc is investigated by 3D nonlinear analysis. The results show that as compared to the suspension bridge and cable-stayed bridge, the cable-stayed-suspension hybrid bridge has greater structural stiffness, less internal forces and better wind stability, and is favorable to be used in super long-span bridges.

Keywords: cable-stayed-suspension hybrid bridge; suspension bridge; cable-stayed bridge; mechanics performance.

1. Introduction

The cable-stayed-suspension hybrid bridge is a new cable-supported bridge developed from the traditional cable-stayed bridge and suspension bridge, and takes some following advantages: (1) As compared to the suspension bridge with 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 also the difficulty of constructing them in water, and therefore makes it possible to build in the soft soil foundation; (2) As compared to the cable-stayed bridges with the same span length, the cable-stayed portion is also greatly shortened, the height of towers, the length of stay cables, and the axial forces in the deck are consequently reduced. In addition, the cantilevers during erection are also greatly shortened, and the wind stability of the bridge under construction is therefore improved; (3) 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. As a result, 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 therefore becomes an attractive alternative in the design of long and

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particularly super long-span bridges.

The idea of using cables and stay cables to support bridge spans was conceived by Roebling (Balsamo and Drewery 1989), Dischinger (Narasimha 1991), Steinmann (Finzi and Castllani 1992) and Gimsing (Gimsing 1992, 1997) etc, but few cable-stayed-suspension hybrid bridges were built before 1920s. After that, this concept 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 frequently proposed in the design alternatives of many strait-crossing bridges such as the Great Belt East Bridge in Denmark (Gimsing 1992), the Gibraltar Bridge in Italy (Lin and Chow 1991), the Messina Strait Bridge in Italy (Finzi and Castllani 1992), the Izmit bridge in Turkey (Gimsing 1997), the Tagus River Bridge in Portugal, the Bali Strait Bridge in Java, the and some strait-crossing bridges in Japan (Hu 2000, Wang *et al.* 2001). Due to the limitation of computational technique and lack of the corresponding analytical theory, this bridge system was not realized until 1997. In 1997, the first modern cable-stayed-suspension hybrid bridge in the world was built in China with a main span of 288 meters (Meng, *et al.* 1999). In the 21st century, many long and particularly super long-span bridges were planned in sea-crossing 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 etc. However, due to its advantages mentioned above, the cable-stayed-suspension hybrid bridge becomes a competitive design alternative for these bridges.

The design of cable-stayed-suspension hybrid bridges involves many problems including the static and dynamic characteristics, construction, economy, and wind stability etc. In previous studies, more attentions were paid to the static and dynamic characteristics under the dead and service loads, the economics, etc., (Meng, *et al.* 1999, Xiao 1999, Zen, *et al.* 2002, Hu 2000 and Wang, *et al.* 2001), but few investigations were done on the wind stability of cable-stayed-suspension hybrid bridges (Sato, *et al.* 2000, Fumoto, *et al.* 2004). Just like the suspension and cable-stayed bridges, the cable-stayed-suspension hybrid bridge is also a structural system of great flexibility, and very susceptible to the service load and the wind action. For the sea-crossing bridges in the 21st century, the bridge span becomes more longer, and they are also commonly built in the locations attacked frequently by violent typhoon, and therefore structural deformation and wind stability becomes an important factor controlling their design.

In this paper, by taking the cable-stayed-suspension hybrid bridge, suspension bridge and cable-stayed bridge with main span of 1400 m as examples, the mechanics performance including the static and dynamic characteristics, the aerostatic and aerodynamic stability etc is investigated by 3D nonlinear analysis, and the applicability of the cable-stayed-suspension hybrid bridge in super long-span bridges is also discussed.

2. The sample bridge models

In order to investigate and compare the mechanics performance of the cable-stayed-suspension hybrid bridge, suspension bridge and cable-stayed bridge, three sample bridges with main span of 1400 m are designed, and described respectively as follows.

2.1. Suspension bridge model

Based on the Runyang Bridge, the longest suspension bridge built in China, a sample suspension

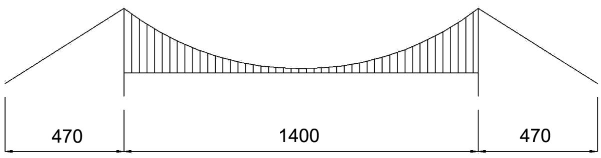

Fig. 1 1400-m suspension bridge model

Table 1 The cross-sectional properties of suspension bridge

Member	E (Mpa)	A (m^2)	J_d (m^4)	I_z (m^4)	I_y (m^4)	M (Kg/m)	J_m ($Kg.m^2/m$)
The deck	2.1×10^5	1.2481	5.034	1.9842	137.7541	18386.5	1.852×10^6
Main cable	2.0×10^5	0.47347	-	-	-	3717	-
Hanger	2.0×10^5	0.00214	-	-	-	16.8	-

Notes: E-modulus of elasticity; A- cross section area; J_d – torsional moment of inertia; I_z – vertical bending moment of inertia; I_y – lateral bending moment of inertia; M – mass per unit length; J_m – mass moment of inertia per unit length

bridge with a center span of 1400 m is designed as shown in Fig. 1. The cable's sag to span ratio is 1/10, the distance of two main cables is 34.3 m, and the spacing of hangers is 16 m. The deck is a streamlined steel box girder of 35.9m wide and 3.0m high. The tower is door-shaped frame with 3 transverse beams, its height is about 209 m from the ground level. The cross-sectional properties of the bridge are given in Table 1.

2.2. Cable-stayed bridge model

Fig. 2(a) shows a side view of the cable-stayed bridge model (Nagai, *et al.* 1998). Center and side spans are assumed to be 1,400 and 680 m respectively. For the side span, three intermediate piers

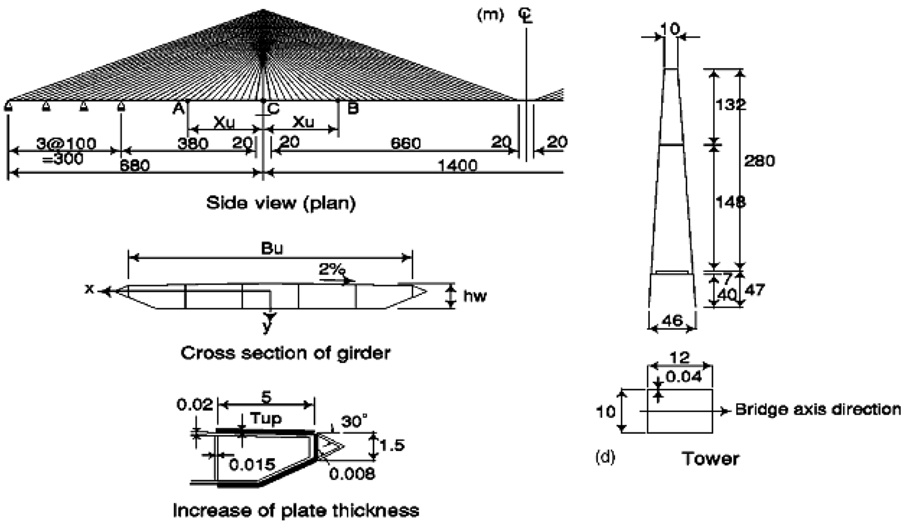

Fig. 2 1400-m cable-stayed bridge model

are installed at a distance of 100 m in order to increase in-plane flexural rigidity of the bridge. The deck shown in Fig. 2(b) is a streamlined steel box girder of 35 m wide and 3.5 m high, and is suspended by diagonal stays anchored to the girder at 20 m intervals. As shown in Fig. 2(c) at the edge of the cross section, the thickness of the plate is increased to cope with the large bending moment from wind load in the girder near the tower. By increasing the thickness of the plate at the edge of the section, out-of-plane flexural rigidity is increased efficiently. The required distance for reinforcement from the tower is defined as Xu seen in Fig. 2(a), which is 80 m herein. Fig. 1(d) shows a front view and the assumed cross section of the tower. Its height from deck level is 280m, which is one-fifth of the center span length. Table 2 gives cross-sectional properties of the girder

Table 2 The cross-sectional properties of girder and tower

Members	E (Mpa)	A (m^2)	I_x (m^4)	I_y (m^4)	I_z (m^4)	M (kN/m)	J_m (Kg.m^2/m)
Girder	2.1×10^5	1.761 (2.046)	3.939 (4.432)	193.2 (261.1)	8.33 (9.739)	26340 (28583)	2.957×10^6 3.712×10^6
Tower	2.1×10^5	1.76	30.67	40.32	39.27	19327	8.574×10^5

Note: Values in parentheses are reinforced values.

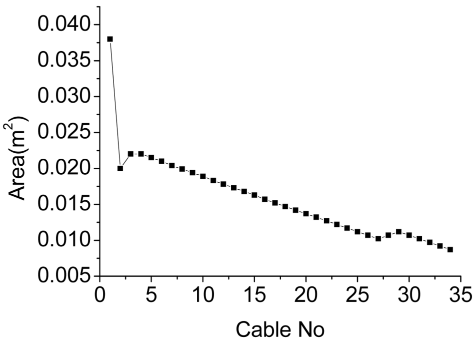

Fig. 3 The cross-sectional areas of stay cables

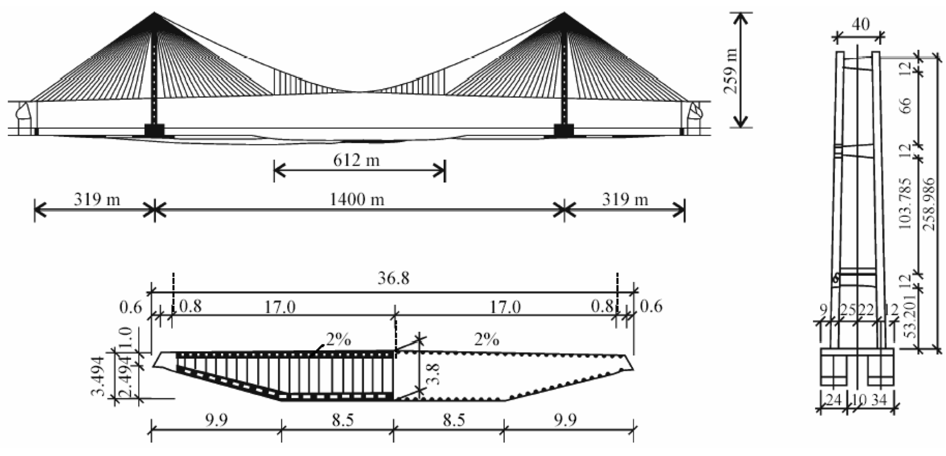

Fig. 4 1400-m cable-stayed-suspension bridge model and tower. The cross-sectional areas of the stay cables are plotted in Fig. 3, in which the 1st stay cable is located near the bridge end, whereas the 34th stay cable is located near the tower.

2.3. Cable-stayed-suspension hybrid bridge model

The example cable-stayed-suspension hybrid bridge consists of a main span of 1400 m and two side spans of 319 m as shown in Fig. 4, 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 distance of two main cables is 34 m, the cable sag to span ratio is 1/10, 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 3.85 m high. The tower is a door-shaped frame with 3 transverse beams, its height from the deck level is about 194 m. The cross-sectional and material properties of the bridge are given in Table 3.

3. Static performance

By structural three-dimensional nonlinear static finite element analysis, the static performance of the sample bridges is investigated analytically. In the analysis, the traffic lane load is employed, which consists of a uniform load q_k and a concentrated load P_k (China Standard JTG D60). For single traffic lane, q_k is 10.5 kN/m, and P_k is 360 kN. For all the sample bridges, six traffic lanes are loaded together. Considering the reduced effect of multi-lane loading, a uniform load 34.65 kN/m is acted on the whole bridge spans and a concentrated load 1188 kN is acted at the midspan of the center span. Because the maximum displacement at midspan of the center span is an important parameter reflecting the bridge stiffness, and in Table 4, the displacements at midspan of the sample bridges are therefore given.

Table 3 The cross-sectional properties of cable-stayed-suspension hybrid bridge

Members		E (Mpa)	A (m^2)	J_d (m^4)	I_z (m^4)	I_y (m^4)	M (Kg/m)	J_m (Kg.m^2/m)
Girder		2.1×10^5	1.2481	5.034	1.9842	137.754	18386.5	1.852×10^6
Main Cable	CS	2.0×10^5	0.3167	0.0	0.0	0.0	2660.3	0.0
	SS	2.0×10^5	0.3547	0.0	0.0	0.0	2979.5	0.0
Hanger		2.0×10^5	0.0064	0.0	0.0	0.0	50.2	0.0
Stay cable		2.0×10^5	0.008	0.0	0.0	0.0	62.5	0.0
Towers	C	3.3×10^4	30.0	350.0	320.0	220.0	78000	5.7×10^5
	TB	3.3×10^4	10.0	150.0	70.0	70.0	26000	4.7×10^5

Notes: CS- center span, SS- side span, C-tower's Column, TB- tower's transverse beam.

Table 4 The displacements at midspan of the sample bridges

Bridge type	SB	CSB	CSSB
Displacement(m)	1.44	1.10	0.90

Note: SB-suspension bridge, CSB-cable-stayed bridge, CSB-cable-stayed-suspension hybrid bridge

As seen in Table 4, under the same main span and load condition, the displacement of the cable-stayed-suspension hybrid bridge is the smallest among the three sample bridges. It is because that the interaction of the cable-stayed and suspension portions improves efficiently the vertical stiffness of the bridge, and therefore can overcome the deficiency of greater deflections for pure suspension bridge or cable-stayed bridge.

Table 5 gives the important internal forces of the sample bridges. The axial force in the girder at the tower is the largest for the cable-stayed bridge, and for the suspension bridge it is the smallest. Also for the cable-stayed bridge, the vertical bending moments at midspan in the girder and the maximum bending moment in the tower are both remarkably larger than those for the suspension bridge and cable-stayed-suspension hybrid bridge respectively. Therefore, the dimensions of the girder and tower can be greatly reduced for the cable-stayed-suspension bridge. In addition, due to the girder supported efficiently by the stay cables, the maximum tensional forces in main cables are also significantly reduced, and only a half of that for the suspension bridge. Therefore as compared to the suspension bridges, the size of cables and anchorages can be minimized and the materials can also be saved remarkably.

From the comparison with the suspension bridge and cable-stayed bridge, it is concluded that the cable-stayed-suspension hybrid bridge has greater structural stiffness and less internal forces, and therefore has better static performance.

4. Dynamic characteristics

On the equilibrium position of the sample bridges in completion, the first 20 modes of the sample bridges are calculated by the dynamic characteristics finite element analysis, in which the subspace iteration method is adopted and structural geometric nonlinearity is also considered(Zhang, *et al.* 2002). Table 6 shows natural frequencies of the main modes for the sample bridges.

As seen in Table 6, the modal frequencies of the cable-stayed bridge are the greatest among the sample bridges, whereas for the suspension bridge, they are the smallest. As for the cable-stayed-suspension hybrid bridge, its modal frequencies are all between the cable-stayed bridge and

Table 5 The internal forces of the sample bridges

Members	Internal force	SB	CSB	CSSB
Girder	Maximum axial force(kN)	688	313000	59600
	Vertical bending moment at midspan ($\times 10^4$kN·m)	1.28	11.9	1.30
Tower	Maximum bending moment($\times 10^3$kN·m)	4.53	41.7	8.71
Main cable	Maximum tensional force($\times 10^5$kN)	3.16	\	1.61

Table 6 Natural frequencies of the sample bridges (Hz)

Modes	SB	CSB	CSSB	Modal Shape
Vertical bending	0.1294	0.1830	0.1858	1-S
	0.1849	0.2625	0.2171	2-S
	0.2473	0.3912	0.3100	3-S
Lateral bending	0.0517	0.0558	0.0689	1-S
Torsion	0.2625	0.3959	0.3382	1-S

Note: S-symmetric.

suspension bridge, and but much greater than those of suspension bridge. It is because that, as compared to the suspension bridge, the cable-stayed portion helps a great deal to improve the vertical and particularly the torsional stiffness of the bridge, and higher modal frequencies are consequently achieved for the cable-stayed-suspension hybrid bridge. It can be also concluded that under the same main span, structural stiffness of the cable-stayed bridge and cable-stayed-suspension hybrid bridge is both greater than that of the suspension bridge.

5. Aerostatic stability

Under the wind attack angle of 0º, the aerostatic behaviors of the sample bridges are investigated

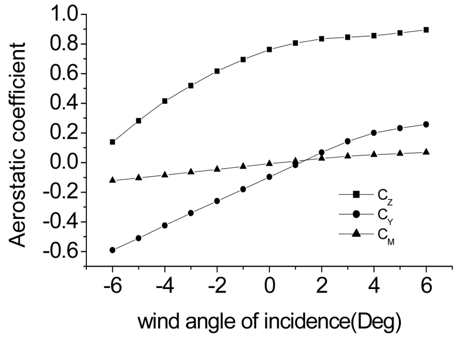

Fig. 5 Aerostatic coefficients versus wind angle of incidence

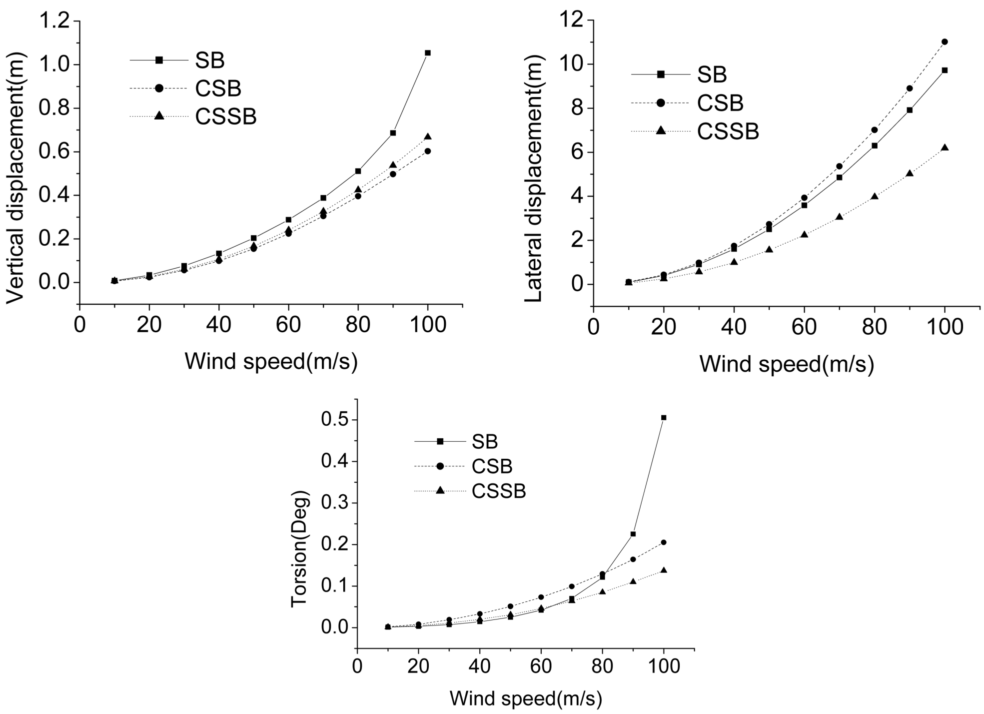

Fig. 6 Evolutions of the deck's displacements at midspan with wind speed

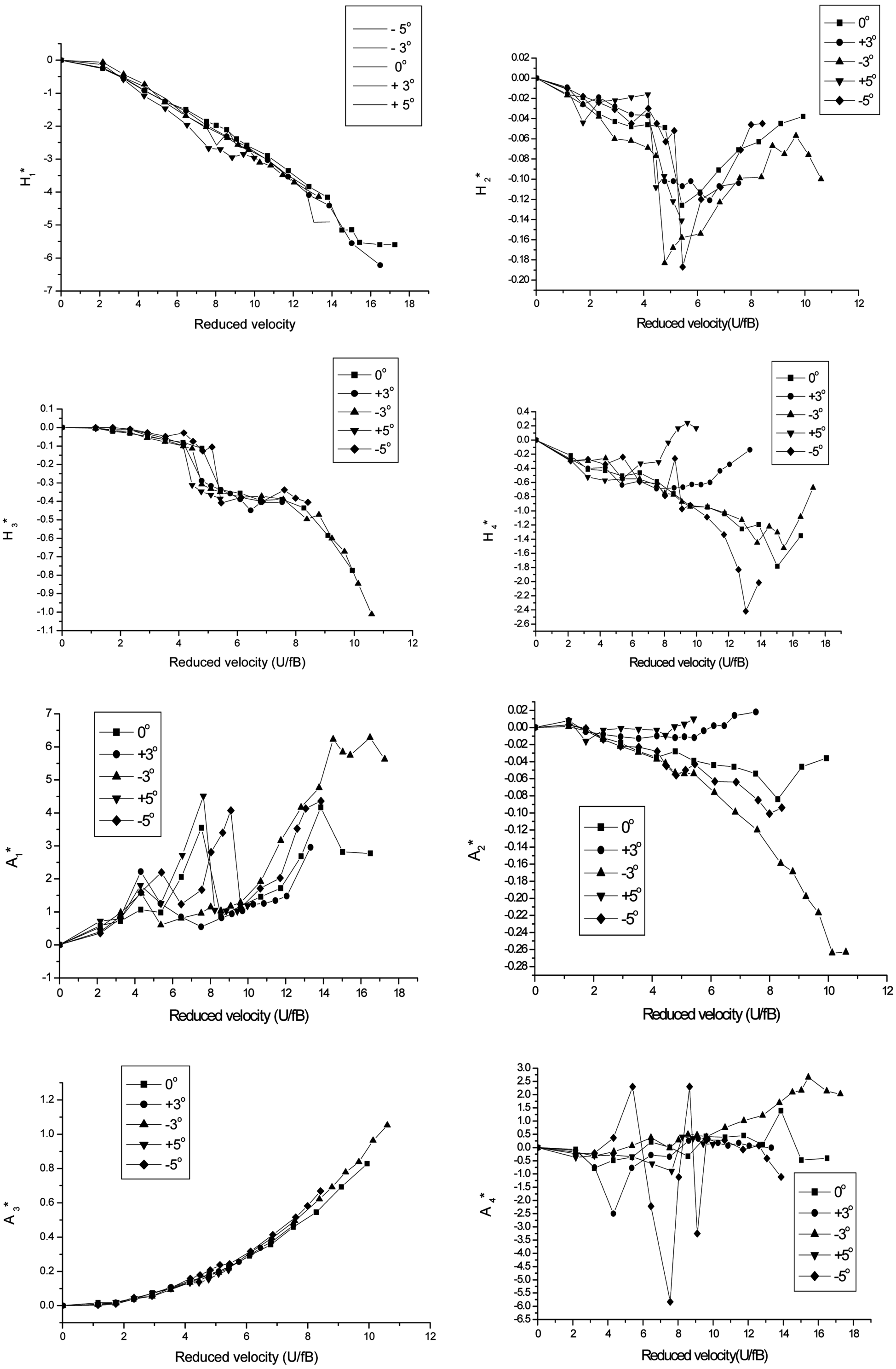

Fig. 6 Flutter derivatives at varying angles of wind incidence versus the reduced velocity

by three-dimensional nonlinear aerostatic analysis (Zhang, *et al.* 2002). In the analysis, the drag, lift and twist moment components of the aerostatic load are considered to be acted on the deck, because the girder's cross-sectional aerodynamic shape of the cable-stayed bridge and cable-stayed-suspension hybrid bridge is very similar to that of the Runyang Bridge, and the aerostatic coefficients obtained from the sectional-model wind tunnel test of the Runyang Bridge (Chen and Song 2000) are used herein, as shown in Fig. 5; for the cables, hangers and towers, only the drag component is considered, and the corresponding drag coefficient is 0.7 for the cables and hangers and 2.0 for the towers. Evolutions of the deck's displacements at midspan with wind speed are plotted in Fig. 6.

As found in Fig. 6, when the wind speed is over 90 m/s, the vertical and torsional displacements of suspension bridge are increased sharply, which means that the critical condition of aerostatic instability is reached. As for the cable-stayed bridge, its lateral and torsional displacements are both greater than those of the cable-stayed-suspension hybrid bridge, however their vertical displacement are very identical. In the whole range of wind speeds investigated, displacements of the cable-stayed-suspension hybrid bridge are the smallest among the sample bridges, and also structural instability does not happen. Therefore viewed from the aspect of aerostatic stability, the cable-stayed-suspension hybrid bridge is superior to the cable-stayed bridge and suspension bridge.

6. Aerodynamic stability

Under wind attack angles of 0^o, aerodynamic stability of the sample bridges is investigated by three-dimensional nonlinear aerodynamic stability analysis (Zhang, *et al.* 2002) , and the critical wind speeds of aerodynamic instability are presented in Table 7. In the analysis, the deck's aerodynamic derivatives as shown in Fig. 6 are obtained from the sectional-model wind tunnel test of the Runyang Bridge (Chen and Song 2000), the first 20 modes are involved, and the modal damping ratio is taken as 0.5%.

Table 7 The critical wind speeds of the sample bridges

Bridge type	SB	CSB	CSSB
The critical wind speed (m/s)	68.4	108.8	92.7

As found in Table 7, aerodynamic stability of the cable-stayed-suspension hybrid bridge and particularly the cable-stayed bridge is both better than that of the suspension bridge. The fact can be explained from the natural frequencies given in Table 6. As compared to the suspension bridge, the vertical bending and especially torsional frequencies are greatly increased, and the increase of torsional frequency is helpful to improve the wind stability of the bridge. Therefore considering the aerodynamic stability, the cable-stayed bridge and cable-stayed-suspension bridge are both superior to the suspension bridge.

7. Conclusions

In this paper, by taking the cable-stayed-suspension hybrid bridge, suspension bridge and cable-stayed bridge with main span of 1400 m as examples, the mechanics performance including the static and dynamic characteristics, the aerostatic and aerodynamic stability etc is investigated by 3D nonlinear analysis, and the comparison among the sample bridges is also made. The results show that the cable-stayed-suspension hybrid bridge has greater structural stiffness, less internal forces and better wind stability, and is favorable to be used in super long-span bridges.

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