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Aerodynamic stability of cable-supported bridges using CFRP cables*

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Abstract: To gain understanding of the applicability of carbon fiber reinforced polymer (CFRP) cable in cable-supported bridges, based on the Runyang Bridge and Jinsha Bridge, a suspension bridge using CFRP cables and a cable-stayed bridge using CFRP stay cables are designed, in which the cable's cross-sectional area is determined by the principle of equivalent axial stiffness. Numerical investigations on the aerodynamic stability of the two bridges are conducted by 3D nonlinear aerodynamic stability analysis. The results showed that as CFRP cables are used in cable-supported bridges, for suspension bridge, its aerodynamic stability is superior to that of the case using steel cables due to the great increase of the torsional frequency; for cable-stayed bridge, its aerodynamic stability is basically the same as that of the case using steel stay cables. Therefore as far as the wind stability is considered, the use of CFRP cables in cable-supported bridges is feasible, and the cable's cross-sectional area should be determined by the principle of equivalent axial stiffness.

Key words: Cable-supported bridges, Carbon fiber reinforced polymer (CFRP) cable, Aerodynamic stability
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INTRODUCTION

By the end of the last century, the Akashi Kaikyo Bridge (1990 m) in Japan and the Great Belt Bridge (1624 m) in Denmark represent an outstanding engineering achievement in building suspension bridge with a span approaching 2000 m. Meanwhile, the Normandy Bridge (856 m) in France and the Tatara Bridge (890 m) in Japan made cable-stayed bridge compete with suspension bridge for spans around 1000 m. Into the 21st century, the world's bridge construction entered into a new era of building sea-crossing and island-linking projects. To meet with the navigation requirement and overcome the construction difficulty of deep-water foundation, longer and longer span of cable-supported bridges is being planned, such as the Messina Bridge (3300 m) in Italy and the Gibraltar Bridge between Spain and Morocco (3550 m) for suspension bridges, for cable-stayed bridges such as the Stonecutters Bridge (1018 m) in Hong Kong and the Sutong Bridge (1088 m) in China (Xiang and Ge, 2002).

With the rapid increase of span length, bridges are becoming lighter, slender and more sensitive to wind action, and some new problems are arising. One of the most important things of these is structural design. Generally, the design of super long-span suspension bridges is mainly controlled by structural dead load, with the cables playing an important role in structural dead load. Therefore, using materials with higher tensile strength and lower mass density for the cables can decrease the cable's dead load, save cable materials, decrease the dimensions of substructures, and finally decrease the cost and construction difficulty for suspension bridges. For cable-stayed bridges, the stay cables are also important structural elements, with significant influences on structural performance and appearance. At present, the stay cable is commonly made of traditional steel wires. On the structural performance, the steel cable is relatively heavy, resulting in significant sagging effect due to its self-weight, thus reducing the effective stiffness of the stay cable and making it behave softer under ser-

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vice load. In addition, for the traditional steel cable, corrosion and fatigue are two major problems in bridges with high traffic volume or bridges located in corrosion environment, which cause the premature breakage of the wires inside the cable. Moreover, the cost of replacement and maintenance of the steel cable is generally high.

Continuous attempts are being made to improve traditional cable materials; at the same time engineers and researchers try to develop new engineering materials. Among them, more attention is attracted to the CFRP material. Compared to the traditional cable material of high strength steel, CFRP has properties of about 2 times higher tensile strength, about 80% of the elastic modulus, only about 20% of the mass density of steel, with other outstanding advantages including excellent corrosion-resistant and fatigue-resistant ability, low thermal expansion coefficient, etc. (Cheng, 1999). Although CFRP material has high cost and low shear capacity, with the increase of production and development of new anchorage system, these problems are being solved, and CFRP material is believed to have the greatest potential application prospect. At present, CFRP material is widely used in the seismic retrofit and rehabilitation of existing concrete bridges. As CFRP has the highest modulus-density ratio among available structural materials, it is most suitable for application as structural member where maximum stiffness and light weight are required, such as in the cables in cable-stayed and suspension bridges. Its high stiffness-mass density ratio can reduce the longitudinal deformation of the cables under loads and the sagging effect due to the self-weight. The outstanding fatigue resistant property of CFRP also satisfies the typical loading conditions of the cable-stayed bridge with large cyclic load amplitudes. The excellent corrosion resistance of CFRP makes it more economical for maintenance as compared to steel. Therefore, the feasibility of using CFRP cables in long-span cable-supported bridges attracts increasing attention from civil engineers (Meier, 1992; Meier and Meier, 1996; Noisternig, 2000). The first application of CFRP cables in a real cable-stayed bridge is the Stork Bridge in Switzerland in 1996, but only two of the 24 cables are made of CFRP (Cheng, 1999). A few cable-stayed pedestrian bridges using CFRP stay cables have been successfully built for research purpose such as the Herning Footbridge in Denmark, the Laroin Footbridge in France, etc. Also, some cable-stayed bridges using CFRP stay cables have been proposed as design alternatives. But for suspension bridges, the actual application of CFRP material as main cables has not been reported until now.

Comprehensive studies on the material and mechanical performance, economy, construction, anchorage system, etc. of the CFRP cable and its application in cable-stayed bridges have been done (Cheng, 1999; Kremmidas, 2004; Kao and Kou, 2005; Kou *et al*., 2005; Xie *et al*., 2005). However, very little research on the wind stability of cable-supported bridges using CFRP cables has been conducted (Kao *et al*., 2006; Nonuaki *et al*., 1999; Cheng, 1999; Fang and Xiang, 1999). Due to their great flexibility, cable-supported bridges are very susceptible to wind action, with the wind stability generally becoming an important controlling factor of their design and construction. For long-span suspension bridges, increasing structural dead load can greatly improve their gravity stiffness, and thus the mechanical performance. Therefore, use of CFRP material with lower elastic modulus and mass density in the main cables seems to be not advisable. Whether or not the wind stability of suspension bridges using CFRP cables becomes worse needs to be further investigated. Fang and Xiang (1999) investigated the aerostatic stability of super long-span suspension bridges using CFRP cables, and concluded that the aerostatic stability worsens with use of CFRP cables. But in his study, the cable cross-sectional area was determined by the principle of equivalent cable strength. In addition to this method, the cable cross-sectional area can also be determined by the principle of equivalent axial stiffness (Cheng, 1999). Nonuaki *et al*.(1999) investigated the flutter characteristics of a dual cable suspension bridge of 3000 m center span using advanced composites by the direct flutter FEM. Cheng (1999) investigated the flutter stability of a cable-stayed bridge using CFRP stay cables. But in their studies, the important effect of nonlinear wind-structure interaction was neglected.

In this work, based on the Runyang Bridge and Jinsha Bridge, a suspension bridge using CFRP cables and a cable-stayed bridge using CFRP stay cables were designed. Numerical investigations on the aerodynamic stability of the two bridges were conducted by 3D nonlinear aerodynamic stability analysis, and the feasibility of using CFRP cables in cable-supported bridges was also discussed based on the wind stability.

AERODYNAMIC STABILITY OF SUSPENSION BRIDGE USING CFRP CABLES

Description of the sample bridge

In this work, the Runyang Bridge taken as example is the longest suspension bridge as of 2005 in China. The bridge has a 1490 m main span and two 470 m side spans, as shown in Fig.1 (Chen and Song, 2000). The cable's sag to span ratio is 1/10, and the spacing of the two cables is 34.3 m. The deck is a steel streamlined box girder of 3.0 m height and 35.9 m width. The concrete door-shaped towers are about 209 m high. For the purpose of discussion, a same span length of suspension bridge using CFRP cables is designed. Except for the material and sectional properties of the cables and hangers, other design parameters of the two bridges are kept the same. Structural material and sectional properties for the two cases are presented in Table 1.

The cross-sectional areas of CFRP cables and hangers as presented in Table 1 are determined by the equivalent axial stiffness, and calculated by the following equation (Cheng, 1999):

$$E_{\mathrm{CFRP}}A_{\mathrm{CFRP}}=E_{\mathrm{Steel}}A_{\mathrm{Steel}}, \tag{1}$$

where E_{CFRP}, E_{Steel} are the elastic modulus of CFRP and steel respectively; A_{CFRP}, A_{Steel} are the cross-sectional areas of CFRP and steel cables respectively.

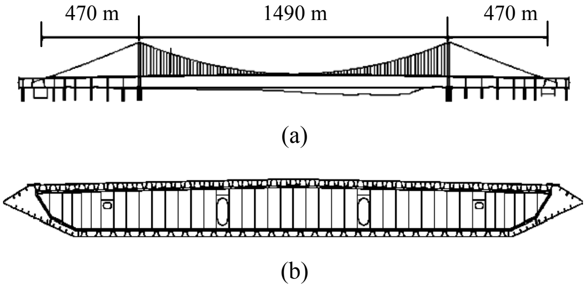

Fig.1 General layout of the Runrang Bridge. (a) Elevation; (b) Cross-section of the stiffening girder

Aerodynamic stability analysis

Wind tunnel test revealed that the bridge is prone to wind instability under positive wind attack angle (Chen and Song, 2000). Therefore in the following analysis, the common wind attack angles of 0° and +3° are selected. Aerodynamic stability of the bridge using CFRP and steel cables was investigated by 3D nonlinear aerodynamic stability analysis (Zhang *et al.*, 2002), and the critical wind speeds of aerodynamic instability are presented in Table 2. In the analysis, the bridge is idealized to a 3D finite element model as shown in Fig.2, in which the deck and towers are modeled by 3D beam elements, and the hangers and cables are modeled by 3D bar elements, with rigid beams provided to model the connections between the deck and the hangers. The deck's aerodynamic derivatives are obtained from the sectional-model wind tunnel test of the bridge (Chen and Song, 2000), the first 20 modes are involved, and the modal damping ratio is taken as 0.5%.

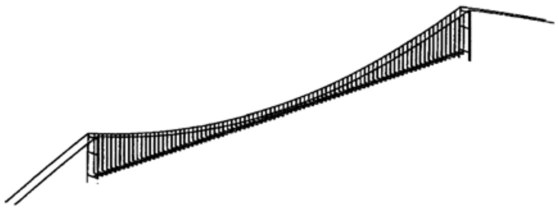

Fig.2 3D finite element model of the Runyang Bridge

Table 1 Structural material and sectional properties

Members		E ($\times10^5$ 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)
Deck		2.10	1.24810	5.034	1.9842	137.7541	18386.5	1.852×10^6
Cable	Steel	2.00	0.47347	–	–	–	3817.4	–
	CFRP	1.65	0.57390	–	–	–	895.3	–
Hanger	Steel	2.00	0.00214	–	–	–	16.8	–
	CFRP	1.65	0.00259	–	–	–	4.0	–

Note: E: elastic modulus; A: cross-sectional area; J_{d}: polar moment of inertia; I_z: moment of inertia for vertical bending; I_y: moment of inertia for lateral bending; M: mass per unit length; J_{m}: polar mass moment of inertia per unit length

Table 2 Effect of cable materials on the critical wind speed under wind attack angles of 0° and +3°

Wind attack angle	Critical wind speed (m/s)	
	Steel cables	CFRP cables
+3°	40.1	47.0
0°	69.6	79.9

In the case of CFRP cables used, the critical wind speeds are increased by 17.2% under wind attack angle of +3°, and 14.8% under wind attack angle of 0°, as compared to the case of using steel cables. Therefore viewed from the aerodynamic stability, the CFRP cables are confirmed analytically to be superior to steel cables. The improvement of aerodynamic stability can be explained from the simplified formula of critical wind speed expressed as

$$V_{\mathrm{cr}}=\eta_{\mathrm{s}}\eta_{\alpha}V_{\mathrm{c0}},\quad V_{\mathrm{c0}}=2.5Cf_{\mathrm{t}}B,$$
$$C=\sqrt{\mu\frac{r}{b}},\ \mu=\frac{m}{\pi\rho b^2},\ b=\frac{B}{2},\ r=\sqrt{\frac{I_{\mathrm{m}}}{m}},\tag{2}$$

where η_{s} is the modified coefficient of cross section shape; η_{α} is the modified coefficient of wind attack angle; V_{c0} is the critical wind speed of the coupled flutter of a thin plate; f_{t} is the fundamental torsional frequency; B is the width of the deck; μ is the density ratio of the bridge to air; m is the mass of the deck and cables per unit length; ρ is the mass density of air; I_{m} is the mass inertia of the deck and cables per unit length.

The mass of the bridge is about 26020 kg/m in the case of steel cables, whereas in the case of CFRP cables, it is about 20180 kg/m, and decreased by 22.4%. Similarly, the mass moment of inertia of the bridge is about 2.97×10^6 kg·m^2/m in the case of steel cables, whereas in the case of CFRP cables, it is about 2.12×10^6 kg·m^2/m, and decreased by 28.6%. The coefficient C is therefore decreased by 13.7%. Because the CFRP cable is designed by the principle of equivalent axial stiffness, the structural stiffness under the two cases is almost the same. With the same stiffness and much lower mass and mass moment of inertia, structural natural frequencies, which are inversely proportional to the mass and mass moment of inertia, are therefore increased, as shown in Table 3.

Table 3 Effect of cable materials on structural natural frequencies (Hz)

Mode type	Structural natural frequencies (Hz)		Mode shape
	Steel cables	CFRP cables	
Vertical bending	0.1260	0.1305	1-S
	0.0999	0.1033	1-AS
	0.1723	0.1875	2-S
	0.1898	0.1925	2-AS
	0.2427	0.2476	3-S
	0.2916	0.2970	3-AS
Lateral bending	0.04979	0.0508	1-S
	0.1249	0.1278	1-AS
Torsion	0.2410	0.3123	1-S
	0.2408	0.3153	1-AS

Note: S: symmetric; AS: antisymmetric

As CFRP cables are used, the natural frequencies of both vertical and lateral bending modes are increased by less than 9% as compared to the case of using steel cables, and particularly the torsional frequency is remarkably increased by 29.6%. Although the coefficient C is decreased, the increase in the fundamental torsional frequency is more than 2 times of reduction of the coefficient C, and therefore the critical wind speed is greatly increased. Viewed from the aspect of aerodynamic stability, the use of CFRP cables in long-span suspension bridges is feasible.

AERODYNAMIC STABILITY OF CABLE-STAYED BRIDGE USING CFRP STAY CABLES

Description of the sample bridge

The Jingsha Bridge is a three-span cable-stayed bridge with a 500 m center span and two 200 m side spans as shown in Fig.3 (Song, 1998). The deck is Π-shaped, 27.0 m wide and 2.0 m high. The H-shaped towers are 137 m high. The two cable planes are inclined and fan-shaped. Based on the bridge, a same span length of cable-stayed bridge using CFRP stay cables is designed, and the cross-sectional areas of CFRP stay cables are determined by Eq.(2). Except for the material and sectional properties of the stay cables, other design parameters of the two bridges remain the same.

Aerodynamic stability analysis

Under wind attack angles of 0° and ±3°, aerodynamic stability of the bridge using CFRP and steel stay cables is investigated by 3D nonlinear aerody-

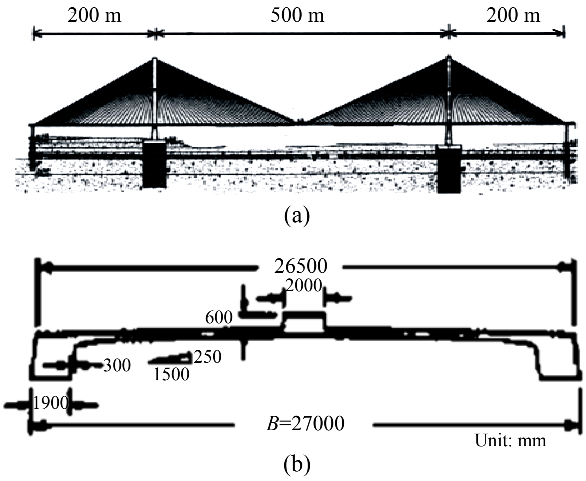

Fig.3 General layout of the Jingsha Bridge. (a) Elevation; (b) Cross-section of the stiffening girder

namic stability analysis (Zhang *et al.*, 2002), and the critical wind speeds of aerodynamic instability are presented in Table 4. In the analysis, the bridge is idealized to a 3D finite element model as plotted in Fig.4, in which the columns and transverse beams of towers and the girder are modeled by 3D beam elements, and the stay cables are modeled by 3D bar elements. The deck is idealized to a three-girder finite element model. The deck's aerodynamic derivatives are obtained from the sectional-model wind tunnel test of the bridge (Song, 1998), the first 10 modes are involved, and the modal damping ratio is taken as 1.0%.

In the case of CFRP stay cables used, the critical wind speed is decreased, but the decrease is very little. The fact can be also explained by Eq.(2). Due to the decrease of structural mass, structural frequencies are slightly increased, as shown in Table 5. Because the increase of the fundamental torsional frequency is very limited, it is less than the decrease amplitude of the coefficient C, so the critical wind speed is decreased. Viewed from the aspect of aerodynamic stability, the use of CFRP stay cables in long-span cable-stayed bridges is also feasible.

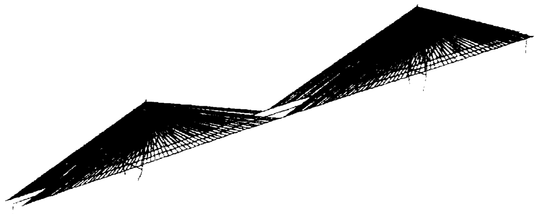

Fig.4 3D finite element model of the Jingsha Bridge

Table 4 Effect of stay cable materials on the critical wind speed under wind attack angles of 0° and ±3°

Wind attack angle	Critical wind speed (m/s)	
	Steel stay cables	CFRP stay cables
−3°	75.5	75.0
0°	87.4	87.0
+3°	93.1	91.0

Table 5 Effect of stay cable materials on structural natural frequencies (Hz)

Mode No.	Structural natural frequencies (Hz)		Mode shape
	Steel stay cables	CFRP stay cables	
2	0.1841	0.1870	1-S-V
3	0.2472	0.2510	1-AS-V
4	0.3520	0.3576	1-S-L
5	0.3951	0.4065	1-S-T
6	0.4435	0.4557	2-S-V
9	0.5105	0.5164	2-AS-V
10	0.5202	0.5332	1-AS-T

Note: S: symmetric; AS: antisymmetric; V: vertical bending; T: torsion; L: lateral bending

CONCLUSION

In this work, based on the Runyang Bridge and Jinsha Bridge, a suspension bridge using CFRP cables and a cable-stayed bridge using CFRP stay cables are designed, in which the cable's cross-sectional area is determined by the principle of equivalent axial stiffness. The aerodynamic stability of the two bridges using either CFRP or steel cables is investigated analytically, and some conclusions are drawn for the bridges using CFRP cables as follows:

(1) Due to the increase of the torsional frequency for suspension bridge, its aerodynamic stability is superior to the case using steel cables. But for cable-stayed bridge, its aerodynamic stability is basically the same as that of the case using steel stay cables.

(2) Considering the better wind stability, the cable's cross-sectional area should be determined by the principle of equivalent axial stiffness.

(3) Viewed from the wind stability, the use of CFRP cables in cable-supported bridges is feasible

under the current span length. But for longer span, it needs to be further studied.

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