*Structural Engineering and Mechanics, Vol. 29, No. 5 (2008) 567-579*
DOI: http://dx.doi.org/10.12989/sem.2008.29.5.567 

# Mechanics feasibility of using CFRP cables in super long-span cable-stayed bridges

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*(Received July 18, 2007, Accepted March 31, 2008)*

**Abstract.** To gain understanding of the applicability of CFRP cables in super long-span cable-stayed bridges, by taking a 1400 m cable-stayed bridge as example, mechanics performance including the static behavior under service load, dynamic behavior, wind stability and seismic behavior of the bridge using either steel or CFRP cables are investigated numerically and compared. The results show that viewed from the aspect of mechanics performance, the use of CFRP cables in super long-span cable-stayed bridges is feasible, and the cross-sectional areas of CFRP cables should be determined by the principle of equivalent axial stiffness.

**Keywords:** cable-stayed bridges; CFRP cable; mechanics performance.

## 1. Introduction

By the end of the last century, 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 bridges. To meet with the navigation requirement and avoid the construction of deep-water foundation, longer and longer span of cable-stayed bridges is being constructed and planned, such as the Stonecutters Bridge (1018 m) in Hong Kong and the Sutong Bridge (1088 m) in China (Xiang and Ge 2002).

As important structural elements of cable-stayed bridges, the stay cables have significant influence on structural performance and appearance. At present, the stay cable is commonly made of conventional high strength steel wires. On the structural performance, the steel cable is relatively heavy, resulting in significant sagging effect due to its self-weight, thus reducing its effective stiffness and making it behave softer under service load. In addition, for the conventional 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 stay cables is generally high.

Continuous attempts are being made to improve conventional cable materials, at the same time engineers and researchers try to develop new engineering materials. Among them, more attention is

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attracted to the CFRP material. Compared to the conventional 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, and other outstanding advantages including excellent corrosion-resistant and fatigue-resistant ability, low thermal expansion coefficient, etc. (Cheng 1999). Although the CFRP material has a high cost and low shear capacity, with the increase of production and development of new anchorage system (Gubinger and Kollegger 2002), these problems are being solved, and the CFRP material is believed to have the greatest potential application prospect. At present, the CFRP material is widely used in the seismic retrofit and rehabilitation of existing concrete bridges. Due to its the highest modulus-density ratio among available structural materials, CFRP is most suitable for application as structural member where maximum stiffness and light weight are required, such as the cables in cable-stayed bridges and suspension bridges. CFRP is being used as the stay cables of cable-stayed bridges in a test manner, and several bridges has been successfully built such as the Stork Bridge in Switzerland, the Herning Footbridge in Denmark, the I-5/Gilman Bridge in America, the Laroin Footbridge in France, the Tskuba bridge in Japan, the Jiangsu University Footbridge in China etc. (Cheng 1999, Hojo and Noro 2002, Kim and Meier 1991, Meier 1996, 1999, Noistering 2000, Ohashi 1991). In addition, some cable-stayed bridges using CFRP cables have been also proposed as design alternatives of long and particularly super long-span bridges.

Comprehensive investigations on the material and mechanics performance, economy, construction, anchorage system, etc. of CFRP cable and its application in cable-stayed bridges have been done (Cheng 1999, Gaubinger and Kollegger 2002, Khalifa 1992, 1996, Kremmidas 2004, Kou *et al.* 2005, Noistering 2000, Xie *et al.* 2005). Due to its great slender and flexible characteristics, cable-stayed bridge is very susceptible to the dynamic action such as wind and earthquake etc. However, little research on the wind stability and seismic behavior of cable-stayed bridges using CFRP cables has been conducted (Kao *et al.* 2006, Cheng 1999, Zhang and Ying 2007).

To gain understanding of the applicability of CFRP cables in super long-span cable-stayed bridges, by taking a 1400 m cable-stayed bridge as example, mechanics performance including the static behavior under service load, dynamic behavior, wind stability and seismic behavior of the bridge using either steel or CFRP cables are investigated numerically and compared, and the applicability of CFRP cables in super cable-stayed bridges is also discussed.

## 2. Description of the sample bridge

Fig. 1(a) shows the side view of a 1400-m 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 are installed at a distance of 100 m in order to increase in-plane flexural rigidity of the bridge. The four stay cable planes are fan-shaped, and in each stay cable planes, there are $2 \times 34$ stay cables. The deck shown in Fig. 1(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. 1(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. 1(a), which is 80 m herein. Fig. 1(d) shows a front view and the assumed cross section of the tower. Its height from

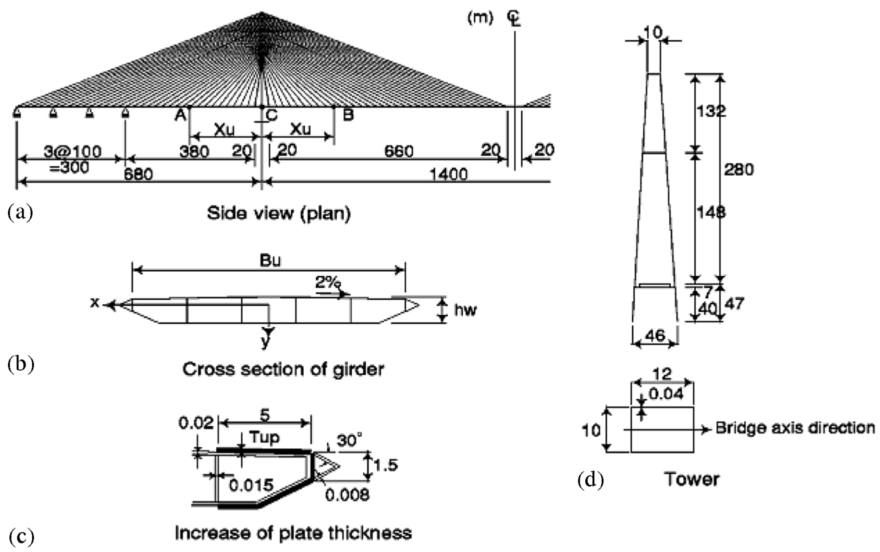



Fig. 1 1400-m cable-stayed bridge model

Table 1 The cross-sectional properties of the bridge

| Members | $A$ (m$^2$) | $J_d$ (m$^4$) | $I_y$ (m$^4$) | $I_z$ (m$^4$) |
|---|---|---|---|---|
| Girder | 1.761<br>(2.046) | 3.939<br>(4.432) | 193.2<br>(261.1) | 8.33<br>(9.739) |
| Tower | 1.76 | 30.67 | 40.32 | 39.27 |

Notes: $A$ = cross section area, $J_d$ = torsional moment of inertia, $I_y$ = lateral bending moment of inertia, $I_z$ = vertical bending moment of inertia, Values in parentheses are the values of the reinforced cross section.

Table 2 The cross-sectional areas of steel stay cables

| Cable No. | Area (m$^2$) | Cable No. | Area (m$^2$) |
|---|---|---|---|
| 1 | 0.038 | 18 | 0.0147 |
| 2 | 0.02 | 19 | 0.0142 |
| 3 | 0.022 | 20 | 0.0137 |
| 4 | 0.022 | 21 | 0.0132 |
| 5 | 0.0215 | 22 | 0.0127 |
| 6 | 0.021 | 23 | 0.0122 |
| 7 | 0.0204 | 24 | 0.0117 |
| 8 | 0.0199 | 25 | 0.0112 |
| 9 | 0.0194 | 26 | 0.0107 |
| 10 | 0.0189 | 27 | 0.0102 |
| 11 | 0.0183 | 28 | 0.0107 |
| 12 | 0.0178 | 29 | 0.0112 |
| 13 | 0.0173 | 30 | 0.0107 |
| 14 | 0.0168 | 31 | 0.0102 |
| 15 | 0.0163 | 32 | 0.0097 |
| 16 | 0.0157 | 33 | 0.0092 |
| 17 | 0.0152 | 34 | 0.0087 |

deck level is 280 m, which is one-fifth of the center span length. Table 1 gives the cross-sectional properties of the girder and towers, and the cross-sectional areas of the steel stay cables are given in Table 2, in which the 1st stay cable is located near the bridge end, whereas the 34th stay cable is located near the tower.

Based on the bridge, two bridge models using CFRP cables are designed, except for the stay cables, other design parameters are remained the same. The cross-sectional areas of CFRP cables can be determined by the principle of either equivalent cable stiffness or equivalent cable strength, which is described as follows (Cheng 1999):

Equivalent cable strength:

$$[\sigma]_{CFRP}A_{CFRP} = [\sigma]_{steel}A_{steel} \tag{1}$$

Equivalent cable stiffness:

$$E_{CFRP}A_{CFRP} = E_{steel}A_{steel} \tag{2}$$

Where $[\sigma]_{CFRP}$, $[\sigma]_{steel}$ are the allowable tensile stress of CFRP and steel respectively; $E_{CFRP}$, $E_{Steel}$ are the elastic modulus of CFRP and steel respectively; $A_{CFRP}$, $A_{Steel}$ are the cross-sectional areas of CFRP and steel cables respectively. The material properties of CFRP and steel cables used herein are given in Table 3.

According to the material properties given in Table 3, the cross-sectional areas of CFRP stay cables can be determined as follows:

Equivalent cable strength:

$$A_{CFRP} = A_{steel} \tag{3}$$

Equivalent cable stiffness:

$$A_{CFRP} = 1.25A_{steel} \tag{4}$$

Table 3 The cable's material properties

| Cable type | $\rho$ (kN/m$^3$) | $\sigma$ (Mpa) | $[\sigma]$ (Mpa) | $E$ (Gpa) |
|---|---|---|---|---|
| Steel | 77.0 | 1960 | 980 | 200 |
| CFRP | 16.0 | 2450 | 980 | 160 |

Note: $\rho$ = weight density; $\sigma$ = the ultimate tensile stress; $[\sigma]$ = the allowable tensile stress; $E$ = elastic modulus.

## 3. Static behavior under service load

By three-dimensional geometric nonlinear finite element analysis (Zhang *et al.* 2002), the static behavior under service load of the bridge of using either steel or CFRP cables is investigated analytically. In the analysis, the traffic lane load is employed, which consists of a uniform load $q_k$ and a concentrated load $P_k$. For single traffic lane, $q_k$ is 10.5 kN/m, and $P_k$ is 360 kN. For all the cases, six traffic lanes are loaded together. Considering the reduced effect of multi-lane loading and the impact effect of traffic load, a uniform load 36.38 kN/m and a concentrated load 1247.4 kN are acted on the bridge. Table 4 presents the maximum displacements of the girder and towers, which are the important parameters reflecting the bridge stiffness. The maximum internal forces in the

Table 4 The maximum displacements of the towers and girder under service load (m)

| Cable type | Steel | CFRP[1] | CFRP[2] |
|---|---|---|---|
| Longitudinal displacement at tower's upper end | 0.228 | 0.335 | 0.227 |
| Vertical displacement of the girder | 0.965 | 1.253 | 0.965 |

Note: 1 = equivalent cable strength; 2 = equivalent cable stiffness.

Table 5 The maximum internal forces in the girder and towers under service load

| Cable type | | Steel | CFRP[1] | CFRP[2] |
|---|---|---|---|---|
| Girder | Vertical bending moment ($\times 10^5$ kN.m) | 2.972 | 2.852 | 2.768 |
| | Axial force ($\times 10^5$ kN) | 1.935 | 1.809 | 1.798 |
| Towers | Bending moment ($\times 10^5$ kN.m) | 2.154 | 2.148 | 2.141 |
| | Axial force ($\times 10^5$ kN) | 3.150 | 2.862 | 2.833 |

girder and towers are given in Table 5.

In the case of equivalent cable strength, as compared to the bridge using steel cables, the maximum displacements of the girder and towers are both increased significantly. The fact is that in the case of CFRP cables, due to lower elastic modulus and the same cross-sectional areas, the supporting efficiency of stay cables and further the vertical stiffness of the bridge are therefore decreased. On the contrary, in the case of equivalent cable stiffness, the maximum displacements are very identical to those of the bridge using steel cables. It can be due to that the vertical stiffness under the two cases is almost the same.

As seen in Table 5, as CFRP cables are used, the internal forces in the girder and towers are all decreased, the static performance is therefore improved, but the case of equivalent cable stiffness is more favorable statically.

Through the above analysis and comparison, it can be concluded that considering the static behavior, the use of CFRP cables in super long-span cable-stayed bridges is feasible, and determination of the cross-sectional areas of CFRP cables by the principle of equivalent cable stiffness is favorable statically.

## 4. Dynamic behavior

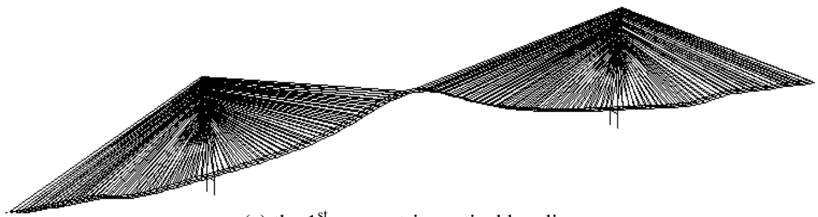
On the equilibrium position of the bridge in completion, the first 20 modes of the bridge using either CFRP or steel cables are computed by dynamic characteristics finite element analysis, in which the subspace iteration method is adopted and structural geometric nonlinearity is also considered (Zhang *et al.* 2002). Table 6 shows the modal properties of the girder, and the modal shapes of main modes of the bridge are plotted in Fig. 2.

In the case of equivalent cable strength, as compared to the bridge using steel cables, the vertical bending frequency is slightly decreased, and but the lateral bending and torsional frequencies are increased. As mentioned above, due to lower elastic modulus and the same cross-sectional area, the supporting efficiency of stay cables and further the vertical stiffness of the bridge are therefore decreased. At the same time, due the light weight of CFRP cables, structural mass of the bridge is slightly decreased, but the decrease is very limited. The vertical bending frequency is thus

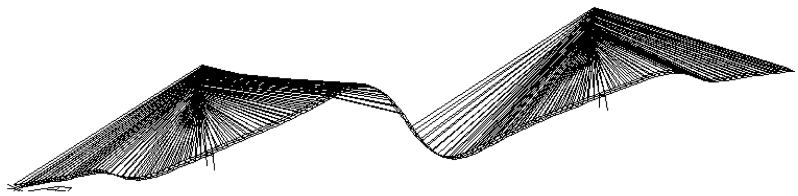
Table 6 The modal properties of the girder

| Modes | Natural frequency (Hz) | | | Modal shape* |
|---|---|---|---|---|
| | Steel | CFRP[1] | CFRP[2] | |
| Vertical bending | 0.1830 | 0.1816 | 0.1965 | 1-S |
| | 0.2153 | 0.2107 | 0.2264 | 1-AS |
| | 0.2625 | 0.2591 | 0.2763 | 2-S |
| | 0.3084 | 0.3055 | 0.3223 | 2-AS |
| | 0.3912 | 0.3807 | 0.4096 | 3-S |
| | 0.4506 | 0.4350 | 0.4687 | 3-AS |
| Lateral bending | 0.0558 | 0.0593 | 0.0591 | 1-S |
| | 0.1595 | 0.1657 | 0.1657 | 1-AS |
| | 0.3023 | 0.3162 | 0.3157 | 2-S |
| | 0.5082 | 0.5311 | 0.5083 | 2-AS |
| Torsion | 0.3959 | 0.4267 | 0.4522 | 1-S |
| | 0.4713 | 0.4991 | 0.5416 | 1-AS |

Note: The number represents the modal order; S = Symmetric; AS = Antisymmetric

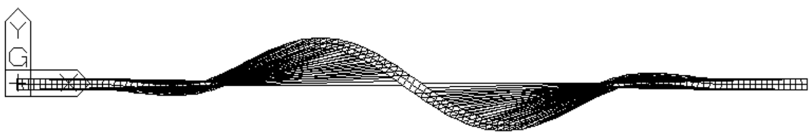


(a) the 1st symmetric vertical bending



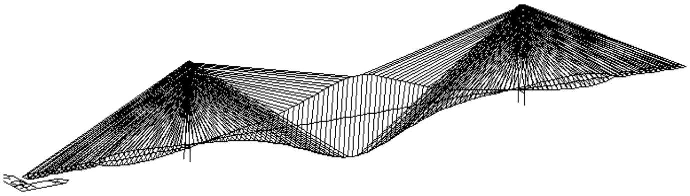
(b) the 1st antisymmetric vertical bending

(c) the 1st symmetric lateral bending

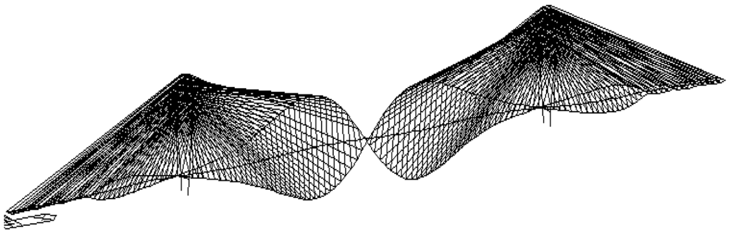


(d) the 1st antisymmetric lateral bending

Fig. 2 Modal shapes of main modes of the bridge



(e) the 1st symmetric torsion



(f) the 1st antisymmetric torsion

Fig. 2 Continued

decreased. The lateral and torsional stiffness of cable-stayed bridges is developed from the towers and girder, and therefore the lateral and torsional stiffness of the bridge are basically identical under the cases of using steel and CFRP cables. Due to the same stiffness and lower mass, the lateral bending and torsional frequencies are thus increased. In the case of equivalent cable stiffness, structural frequencies and in particular the torsional frequencies are increased greatly. In this case, due to the same cable stiffness, the vertical stiffness of the bridges is almost the same. However due to the light weight of CFRP stay cables, structural mass is decreased slightly, and the vertical bending frequencies are thus increased. Determination of the cross-sectional areas of CFRP cables by the principle of equivalent cable stiffness has the effect of stiffening the structure by increasing its natural frequencies.

## 5. Wind stability

### 5.1 Aerostatic stability

Under the wind attack angle of $0^{o}$ and $\pm 3^{o}$, with the increasing of wind speed, aerostatic behavior of the bridge using either CFRP or steel cables is investigated numerically by three-dimensional nonlinear aerostatic analysis (Zhang *et al*. 2002). In the analysis, the aerostatic drag, lift and twist moment components are considered for the deck, because the girder's aerodynamic shape of the bridge is very similar to that of the Runyang Bridge, and therefore the aerostatic coefficients of the Runyang Bridge (as shown in Fig. 3) are employed herein (Chen and Song 2000); for stay cables and towers, only the aerostatic drag component is considered, and the corresponding drag coefficient is 0.7 for stay cables and 2.0 for towers. Evolutions of the deck's maximum displacements in the central span with wind speed are plotted in Fig. 4, Fig. 5 and Fig. 6.

Under wind attack angle of $0^{o}$, in the case of equivalent cable strength, as compared to the bridge using steel cables, the lateral, torsional displacements are almost identical, but the vertical

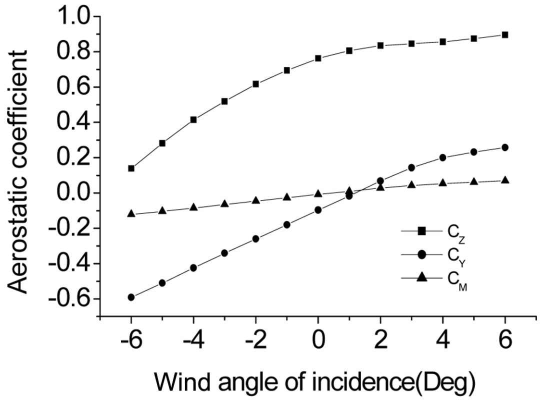



Fig. 3 Aerostatic coefficients versus wind angle of incidence

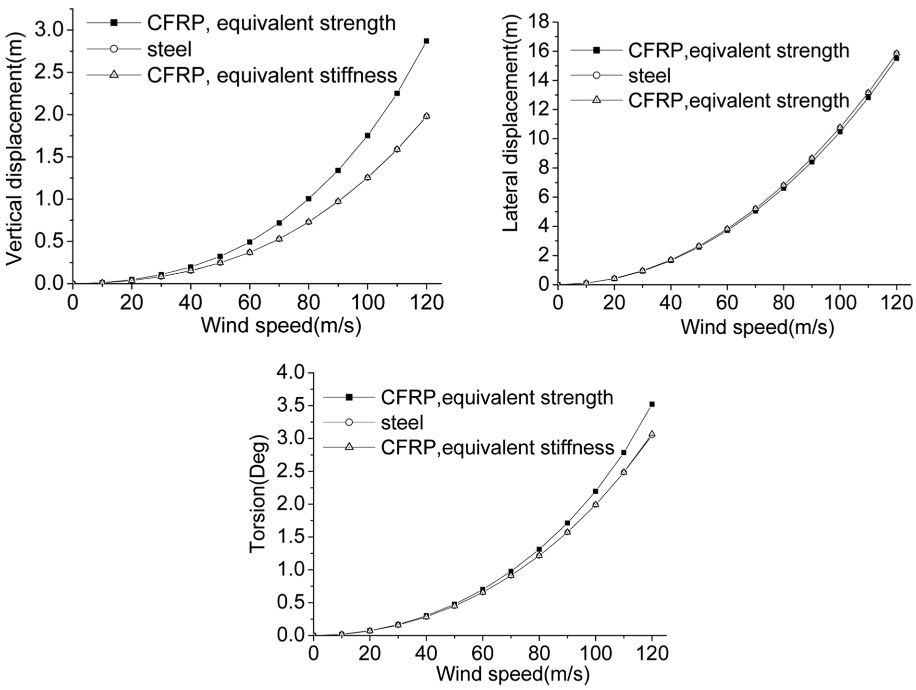



Fig. 4 Evolutions of the deck's maximum displacements in the central span with wind speed under wind attack angle of +3°

displacement is increased. The fact is that in the case of CFRP cables, due to lower elastic modulus and the same cross-sectional area, the vertical stiffness is therefore decreased, however the lateral and torsional stiffness are basically unchanged. In the case of equivalent cable stiffness, as known from Eq. (4), compared to steel cable, the cross-sectional area of CFRP cable is increased by 25%, and the stay cable's diameter is thus increased 11.8%. With the increase of vertical projected height, the drag component of aerostatic load is increased consequently, which leads to greater lateral and further torsional deformations. The vertical stiffness of the bridge using either steel or CFRP cables is almost the same, and therefore the vertical displacements are very identical.

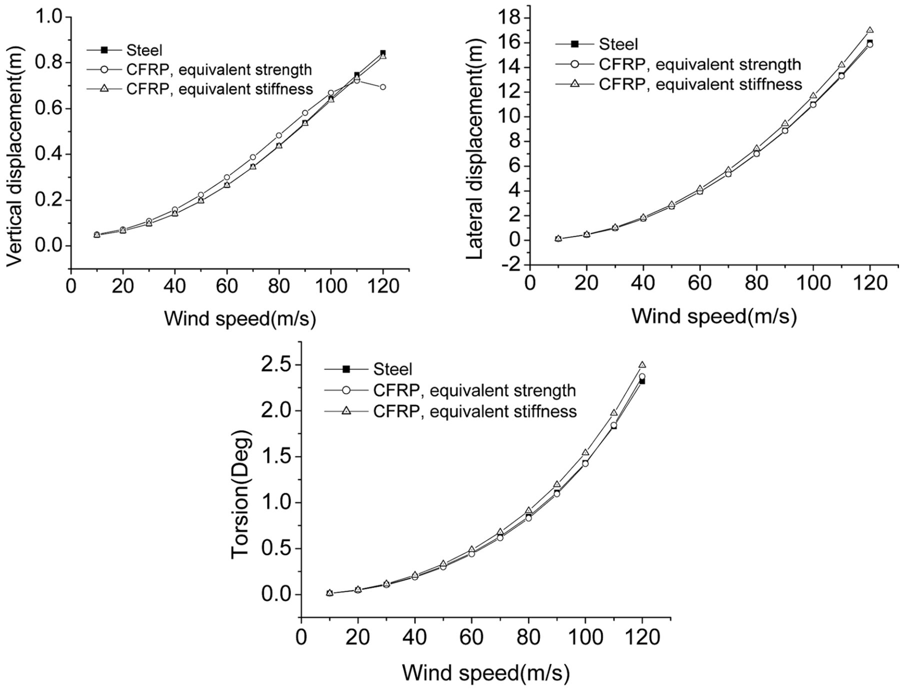



Fig. 5 Evolutions of the deck's maximum displacements in the central span with wind speed under wind attack angle of 0°

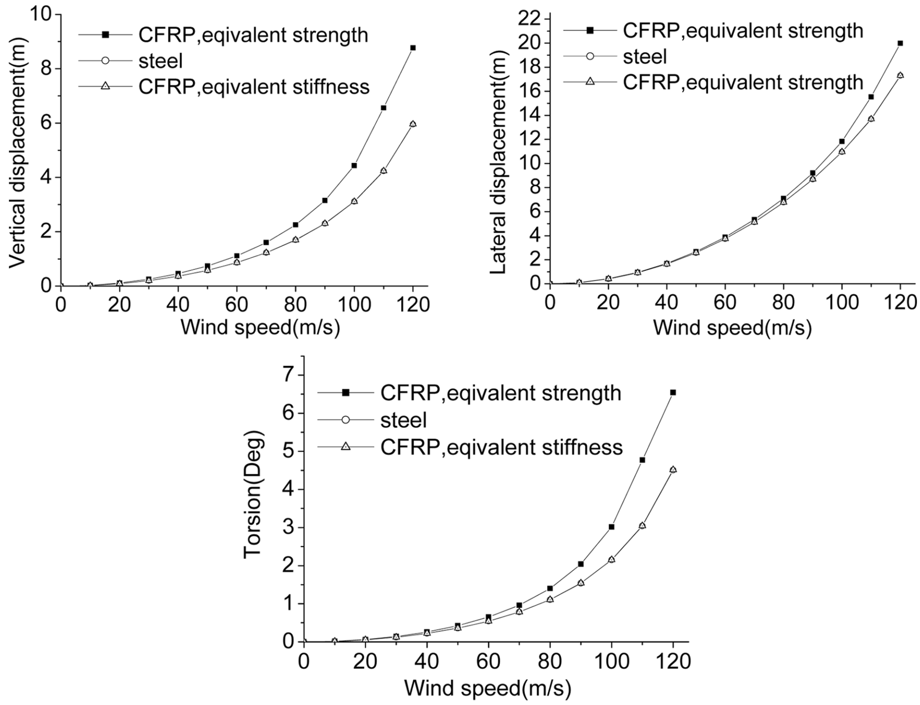



Fig. 6 Evolutions of the deck's maximum displacements in the central span with wind speed under wind attack angle of −3°

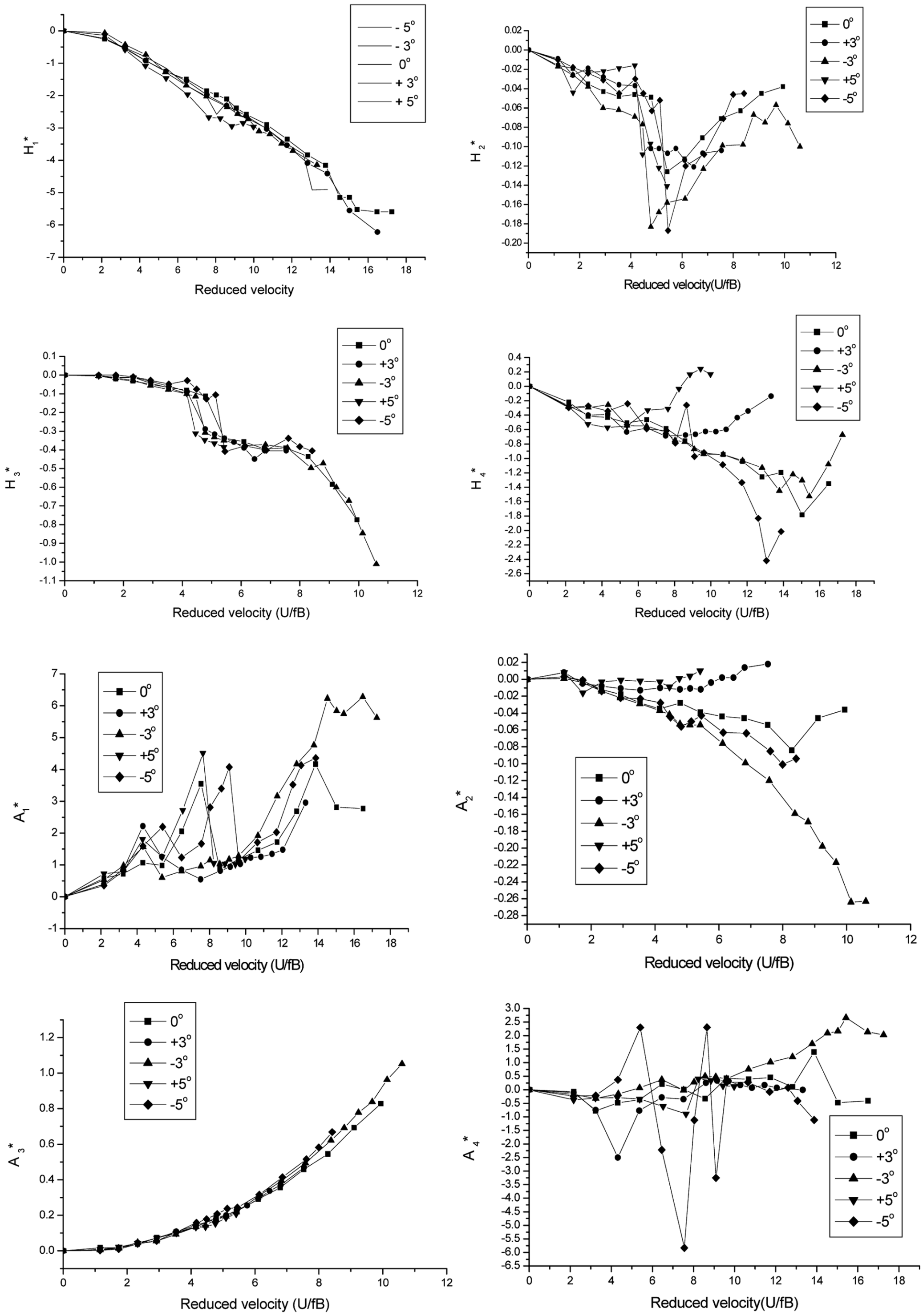



Fig. 7 Flutter derivatives at varying angles of wind incidence versus the reduced velocity

Table 7 The critical wind speed of aerodynamic instability (m/s)

| Wind attack angle | Steel | CFRP[1] | CFRP[2] |
|---|---|---|---|
| −3° | 121.7 | 122.4 | 126.6 |
| 0° | 108.8 | 107.8 | 114.5 |
| +3° | 97.0 | 99.6 | 99.9 |

Under wind attack angle of ±3°, in the case of equivalent cable strength, as compared to the bridge using steel cables, structural displacements are all increased, especially the vertical displacements. However in the case of equivalent cable stiffness, structural displacements are almost identical to those of the bridge using steel stay cables. The reason is also the same as mentioned above.

Within the wind speeds investigated, the aerostatic instability does not happen for all three cases, however the case of equivalent cable strength seems more susceptible to aerostatic instability than other two cases. Therefore considering the aerostatic stability, the use of CFRP cables in long-span cable-stayed bridges is also feasible, and determination of the cross-sectional areas of CFRP cables by the principle of equivalent cable stiffness is more favorable.

### *5.2 Aerodynamic stability*

Under wind attack angles of 0° and ±3°, aerodynamic stability of the bridge using either CFRP or steel cables is investigated numerically 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 girder's aerodynamic derivatives as show in Fig. 7 are obtained from the 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%.

In the case of CFRP cables, the critical wind speed is increased, particularly in the case of equivalent cable stiffness. The improvement of aerodynamic stability can be attributed to the increase of the fundamental torsional frequency as presented in Table 6. Therefore considering the aerodynamic stability, the use of CFRP cables in long-span cable-stayed bridges is also feasible, and determination of the cross-sectional areas of CFRP cables by the principle of equivalent cable stiffness is favorable aerodynamically.

## 6. Seismic behavior

In order to investigate the seismic behavior of super log-span cable-stayed bridges using CFRP cables, seismic response of the bridge using either steel or CFRP cables is conducted by response spectrum analysis. In the analysis, the bridge site is classified as the Zone, the design spectrum is taken from China Code for Seismic Design for Highway Engineering; the maximum earthquake ground acceleration in the longitudinal direction is 0.1 g, 50 modes are involved, the modal damping ratio is 0.5%, and the complete quadratic combination (CQC) method is employed; the uniform seismic excitation is considered, and the vertical, longitudinal and transverse components of ground excitation are acted to the bridge supports. The maximum displacements and internal forces of the girder and towers under the dead load and seismic action are given in Tables 8 and 9 respectively.

As compared to the case of steel cables, structural displacements are slightly decreased, and in

Table 8 The maximum displacements of the girder and towers under seismic load (m)

| | Cable type | Steel | CFRP[1] | CFRP[2] |
|---|---|---|---|---|
| Towers | Longitudinal displacement | 0.029 | 0.028 | 0.028 |
| | Lateral displacement | 0.044 | 0.031 | 0.034 |
| Girder | Longitudinal displacement | 0.012 | 0.011 | 0.011 |
| | Lateral displacement | 0.649 | 0.636 | 0.641 |
| | Vertical displacement | 0.175 | 0.180 | 0.172 |

Table 9 The maximum internal forces of the girder and towers under seismic load

| | Cable type | Steel | CFRP[1] | CFRP[2] |
|---|---|---|---|---|
| Girder | Axial force ($\times 10^5$ kN) | 1.681 | 1.525 | 1.568 |
| | Shear force (kN) | 7178 | 6572 | 6687 |
| | Transverse bending moment ($\times 10^5$ kN.m) | 3.780 | 3.709 | 3.722 |
| | Vertical bending moment ($\times 10^5$ kN.m) | 1.624 | 1.785 | 1.576 |
| Tower | Axial force ($\times 10^5$ kN) | 2.958 | 2.626 | 2.797 |
| | Shear force (kN) | 932 | 769 | 829 |
| | Transverse bending moment ($\times 10^5$ kN.m) | 1.974 | 1.787 | 1.828 |
| | Longitudinal bending moment ($\times 10^5$ kN.m) | 1.791 | 1.692 | 1.725 |

particular the internal forces are remarkably reduced in the case of CFRP cables. It can be attributed to the fact that structural mass and further the seismic load are decreased due to the light weight of CFRP cables. Therefore, viewed from the aspect of seismic behavior, the use of CFRP cables in super long-span cable-stayed bridges is also feasible.

## 7. Conclusions

In this paper, by taking a 1400 m cable-stayed bridge as example, mechanics performance including the static behavior under service load, dynamic behavior, wind stability and seismic behavior of the bridge using either steel or CFRP cables are investigated numerically, and the applicability of CFRP cables in super cable-stayed bridges is discussed. The results show that viewed from the aspect of mechanics performance, the use of CFRP cables in super long-span cable-stayed bridges is feasible, and the cross-sectional areas of CFRP cables should be determined by the principle of equivalent cable stiffness.

## Acknowledgements

The writer would like to thank to Zhejiang Provincial Science Foundation of China for their financial support. The aerodynamic coefficients and flutter derivatives employed in this paper are obtained from wind tunnel results provided by Tongji University, the writer also appreciate Prof. A.R. Chen and J.Z. Song, and the State Key Laboratory for Disaster Reduction in Civil Engineering of Tongji University for their support.

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