Study on longitudinal wind load calculation method of cables for cable-stayed bridge

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Abstract: Along with the expanding of span of cable-stayed bridge, wind load becomes a more and more important controlling factor for bridge the design. A very large proportion of the wind load acting on cables has exceeded that acting on deck. There was not any detailed prescript in Chinese code for calculation of longitudinal wind load on cables due to lack of theoretical research and experiment, and conservative simplified calculation was adopted during design, which leads to conservative and uneconomical design of structures. To resolve this problem, cable force experiment was carried out during the design of Sutong Bridge. By comparing with international research results, the calculation formula of longitudinal wind drag coefficient for cables was advanced to fill the blank of bridge wind resistant code of China, and has already been adopted in the *Highway Bridge Wind Resistant Design Code* (JTG/T D60-01-2004) with great significance for bridge engineering.

Key words: cable-stayed bridge; stayed cable; longitudinal; wind load

1 Introduction

Since the reform and opening-up, with Chinese sustained and rapid economic development, the design and construction method of bridges have changed a lot. "Longer, higher, lighter, more flexible" became the trends of modern long-span bridge. However, with the length of bridge span increasing, some factors which didn't show very significant effect to the conventional bridges have become more prominent, and the control factors in design have become more complex and diverse simultaneously. The wind load becomes more and more important control factor during the design of long-span cable-stayed bridge, in which the wind load suffered by cable accounted for a large proportion, and also beyond that suffered by main girder. Due to the lack of theoretical and experimental research, in the past, there were not clearly definitions about wind calculating method of cable-stayed bridge in longitudinal direction in Chinese code. Therefore, the simple calculations used in the design process are always too conservative, which induce poor economic rationality of structure design. In fact, the wind load in longitudinal direction relevant to inclination of cable is much smaller than transverse wind load. So researching reasonable and reliable wind load calculation method of cable-stayed bridge in the longitudinal direction has great significance not only to ensure the safety, advantage, and economy of long-span bridge design, but also to raise the level of bridge wind-resistant design, and it will also become the scientific basis for *Wind-resistant Design Specification for Highway Bridge* (JTG/T D60-01-2004)[1] simultaneously.

2 The rise of the problem

Because of the large number and great length of cables of long-span cable-stayed bridge, the wind load suffered by cable accounted for a large proportion, and beyond that suffered by main girder. Take the world's longest cable-stayed bridge—Sutong Bridge for example, the longest cable of this bridge is up to 580 m and the total number of cables is 272. Therefore, the transverse wind load contributed by cables accounts for a proportion of 60 % ~ 70 %, and about 30 % by the girder, about 5 % ~ 10 % by the pylon. As a result, the long-span cable-stayed bridge design should attach great importance to the wind load of cables, for a reasonable calculation of its direct impact on the structure of the economy and security

In the design process of Sutong Bridge, the wind calculation methods of cables in codes of different countries have been compared. In terms of transverse wind load, European and Japanese codes are the same as the Chinese code in spite of details. But under the action of wind load in longitudinal direction, the calculation methods beside China, Europe and Japan have great differences. Due to no clear definition in the Chinese *Wind-resistant Design Guidelines for Highway*

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Bridge[2], in the past bridge design process, the same value has been taken for cable drag factor in longitudinal direction and cable drag factor in transverse direction, and the loading length adopts the projection length of cable which is perpendicular to the direction of flow. Then the conservative simple formula is shown as follows[2]:

$$F_D = \frac{1}{2}\rho V_d^2 C_H D(L\sin\alpha) \qquad (1)$$

letting $C_D = C_H \sin\alpha$,

we will get $$F_D = \frac{1}{2}\rho V_d^2 C_D DL \qquad (2)$$

Where, F_D is longitudinal wind load; C_D is drag coefficient of cable in longitudinal direction; α is angle of cable in longitudinal direction; ρ is air density; C_H is drag coefficient of cable in transverse direction; D is diameter of cable; L is length of cable; and V_d is static gust wind speed; the subscript D means the longitudinal direction of the bridge; the subscript H means the transverse direction of the bridge and the subscript d means static gust wind.

According to the conventional practice about middle-span cable-stayed bridge in the past, the drag coefficient in the longitudinal direction of cable is:

$$C_D = C_H \sin\alpha \qquad (3)$$

The drag coefficient of cable in the longitudinal direction defined in European code is:

$$C_D = 1.2\sin^3\alpha \qquad (4)$$

The drag coefficient of cable in the longitudinal direction defined in Japanese code[3]:

$$C_D = 0.7\sin^3\alpha \qquad (5)$$

Eq. (3) ~ Eq. (5) show there are great differences between the simple calculation method adopted in our country in the past and the methods used in Europe and Japan. The formulas used in Europe and Japan are similar, they are all $C_D = C_{D0}\sin^3\alpha$, and the difference only appears in the different values in selection of coefficient C_{D0}. For the small-span and middle span cable-stayed bridge, the difference between loads effect obtained from different calculation methods is small. However, it cannot be ignored for the super long-span cable-stayed bridges, such as Sutong Bridge.

Table 1 shows the comparison of structure reactions obtained by different wind load calculation methods in the longitudinal direction of Sutong Bridge with floating system[4].

Table 1 shows that the difference of moment at the bottom of pylon and longitudinal displacement of girder obtained by different calculation methods are great. It directly controls the size of base, the selection of expansion joint and the determination of structure system.

Table 1 Comparison of structure reaction under wind load of Sutong Bridge

Items	Moment at the bottom of pylon /(MN·m)	Longitudinal displacement of girder /m
Eq. (3)	5 361	1.350
Eq. (4)	4 378	1.054

In order to ensure the scientific rationality of the design of Sutong Bridge and provide scientific data for *Wind-resistant Design Specification for Highway Bridge*[1], the China Highway Planning and Design Institute (HPDI) and Tongji University jointly organized and implemented the cable loading test, studied the calculation method of cable in the longitudinal direction as a special subject.

3 Relevant regulations analysis of abroad wind-resistant code

The above section shows both in Europe and Japan, $C_D = C_{D0}\sin^3\alpha$ is used for calculating the drag coefficient of cable in the longitudinal direction. This calculation method rooted in the theory of wind response, the calculation model is shown as Fig. 1.

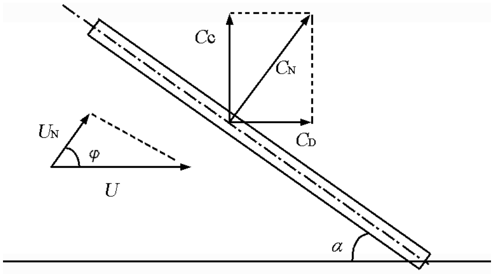


Fig. 1 Calculation model of longitudinal wind load drag force factor

In the action of longitudinal wind in the horizontal plane, the vertical wind load reacts on cable (the diameter is D) can be expressed as following form:

$$F_N = \frac{1}{2}\rho U_N^2 C_{D0} DL \qquad (6)$$

Where, F_N is the wind load perpendicular to the axis; C_{D0} is drag coefficient of cable perpendicular to flow; U_N is the projection of longitudinal wind speed perpendicular to the axis direction of cable, the subscript N means the vertical direction of the cable.

For $U_N = U\cos\varphi$, the Eq. (6) become:

$$F_N = \frac{1}{2}\rho U^2 \cos^2\varphi C_{D0} DL \qquad (7)$$

Use the non-dimensional form of expression, Eq. (8) will be got:

$$C_N = \frac{F_N}{\frac{1}{2}\rho U^2 DL} = C_{D0}\cos^2\varphi = C_{D0}\sin^2\alpha \quad (8)$$

Assuming that the role of axial wind load of cable can be ignored, so the drag coefficient of wind load in the horizontal plane can be approximately expressed as:

$$C_D \approx C_N\cos\varphi = C_{D0}\sin^3\alpha \quad (9)$$

The drag coefficient of vertical wind load is:

$$C_C \approx C_N\sin\varphi = C_{D0}\sin^2\alpha\cos\alpha \quad (10)$$

The drag coefficient of wind load in the longitudinal direction in the European code is: $C_D = C_{D0}\sin^3\alpha$, in which, $C_{D0} = 1.2$, and it comes from the theoretical result of wind engineering by origin and is determined by the envelop of control value considering a certain safety factor.

The drag coefficient of wind load in the longitudinal direction in the Japanese code is: $C_D = C_{D0}\sin^3\alpha$, in which, $C_{D0} = 0.7$, and it bases on the research of widely used cables with pit on surface in Japan, (its drag coefficient value is less than that with helix surface), the design control factor is design wind speed rather than the low wind speed with the combination of live load.

Therefore, from the results of calculation equation analysis, the European code is more conservative than Japanese code.

4 Research on the force measurement test of cables in transverse direction for Sutong Bridge[5]

4.1 Testing method

Three surface types of cables were selected, which was in upright status in the uniform flow, to conduct the testing for drag factor in TJ-2 wind tunnel by using force measurement balance. The three types of cable surface were smooth surface, surface with pits on, surface with helix lines which also had 9 types of pitches or diameters. The different control values of drag factor in transverse directions for Sutong Bridge were provided through the comparison tests with different cable surface situations. In order to eliminate the effect of Reynolds number, the testing used the cable model with diameter ration of 1∶1, and the wind speed varied from 15 m/s to 55 m/s.

4.2 Testing equipment

The test was conducted in the TJ-2 wind tunnel which was a part of state key laboratory for disaster reduction in civil engineering in Tongji University. In the test, the cable was in upright status, and there were two balances located at the end of the cable, which worked simultaneously. In the addition of floating box balance with 6-weight to measure force at the bottom of the cable, in the hanging wall of wind tunnel, there was also a cassette balance with 6-weight to measure force. The range of testing in the resistance direction was 0 ~ 20 kg, and measurement error is less than 20 g. In order to decrease the errors caused by three-dimensional flow at the end of cable, compensation model which has the same diameter as cables was placed at the top of the model. The photo of testing model is shown as Fig. 2.

Fig. 2 Experiment instrument of transverse wind load

4.3 Testing conclusions

The results of different surface types of cables obtained by force measurement testing in the action of wind load in the transverse direction are shown as Fig. 3.

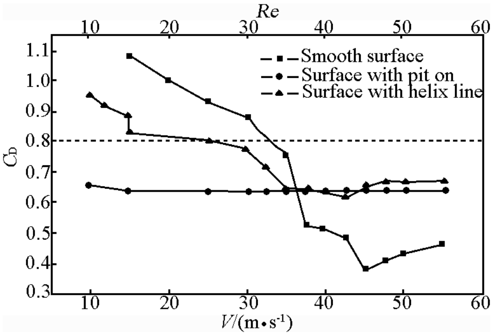


Fig. 3 Drag force coefficient for different cable surface

From the above figure, the following conclusions can be got:

1) The smooth surface cable has the minimum drag coefficient value in the design wind speed, and in lower wind speed, the smooth surface cable has the biggish drag coefficient value.

2) The drag coefficient of cable with helix line is a bit bigger than that with pit on.

3) With enlarging the distance of the pitch and the diameter, the drag coefficient of cable with helix line become reducing.

4) While the wind speed in the deck is 25 m/s (combination with the live load), the control design

value of the drag coefficient can be selected as 1.0.

5) While the wind speeds up to the design wind speed, the control design value of the drag coefficient can be selected as 0.8.

The above research conclusions have already been adopted by *Wind-resistant Design Specification for Highway Bridge* (JTG/T D60-01-2004) in item 4.4.5[1].

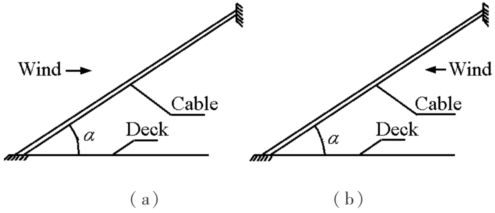
5 Research on the force measurement testing of cables in longitudinal direction for Sutong Bridge[5]

5.1 Testing method

According to the results of above force measurement testing of cable in the transverse direction, three surface types of cables were chosen, which was in incline status in the uniform flow, to conduct the testing for drag factor in the TJ-2 wind tunnel by using force measurement balance. The three types of cable surface are smooth surface, surface with pits on, surface with helix lines which also had 2 kinds of diameters. The test simulated the incline angle of the cable and simulated two situations of the flow. Firstly, the flow pointed to the up direction of cable. Secondly, the flow pointed to the decline direction of cable, which is shown in Fig. 4. Comparing the drag coefficients of all cables in each of the tilt angle during the testing, selecting the largest drag factor as the control value of each testing tilt angle, according to the final testing control value of each tilt angle, fitting the function—the relationship between the drag factor and the changes of the angle. In order to eliminate the effect of Reynolds number, the test was carried out using the cable model with diameter ration of 1∶1, and the wind speed varied from 15 m/s to 55 m/s.

5.2 Testing equipment

The testing was conducted in the TJ-2 wind tunnel. In the testing, the cable was in incline status, and there were two balances located at the end of cable. At the bottom of the cable, there was a floating box balance with 6-weight to measure force. The force measurement range of this balance is 0 ~ 20 kg, and measurement error is less than 20 g. There was another cassette balance in the hanging wall of wind tunnel with 6-weight to measure force. The range of this balance in the resistance direction is 0 ~ 50 kg and measurement error is less than 60 g. The two balances worked simultaneously in the role of wind load.



(a) (b)

(a) The flow pointed to the up direction of cable

(b) Flow pointed to the decline direction of cable

Fig. 4 Sketch of longitudinal wind load act on the cables

Based on the changing of inclination angles, the respective lengths of models were 3.2 m, 2.2 m, and 1.7 m. In order to decrease the errors caused by three-dimensional flow at the end of cable, compensation model which had the same diameter was placed at the top of the model. Besides, a wind-resistance cover was installed between the hanging wall of the wind tunnel and the cable model to eliminate the effect of the action, with the brace and balance suffered for wind load. The testing equipment photo is shown as Fig. 5.

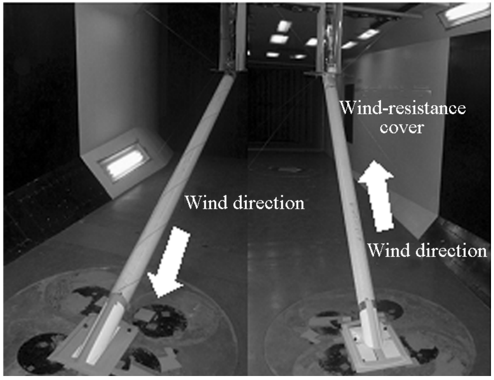


Fig. 5 Experiment instrument of longitudinal wind load

5.3 Testing conclusions

The results from different cable surface and different inclination angles in the wind tunnel tests with design wind speed in the longitudinal direction are shown as Fig. 6. In order to ensure the reliability of the data obtained by testing, the numerical simulation is conducted simultaneously using CFD (computational fluid dynamics) method. The two results agree with each other well.

From Fig. 6, it can be concluded as follows:

1) In most cases, the value of drag coefficient of cable with aerodynamic measure is greater than that of smooth surface.

2) With increasing of inclination angles (absolute value), the value of drag coefficient increases monotonously.

3) The smaller of the inclination angle, the more gently changes appear to the relationship between the drag coefficient and Reynolds number.

4) The drag factor of cable with helix line is a bit bigger than that with pits on.

5) In the condition of the same inclination angle

and the same wind speed, the value of drag coefficient increases with the increasing of pitch diameter.

5.4 Testing data fitting

Assuming $\alpha = 0°$, $C_D \approx 0$, based on the results of testing with inclination angles $\alpha = \pm 20°$, $\pm 40°$, $\pm 60°$ and $\alpha = 90°$, curve fitting ,which is shown as, is conducted by the relationship between drag factor and inclination angle, and the final formula is shown as follows:

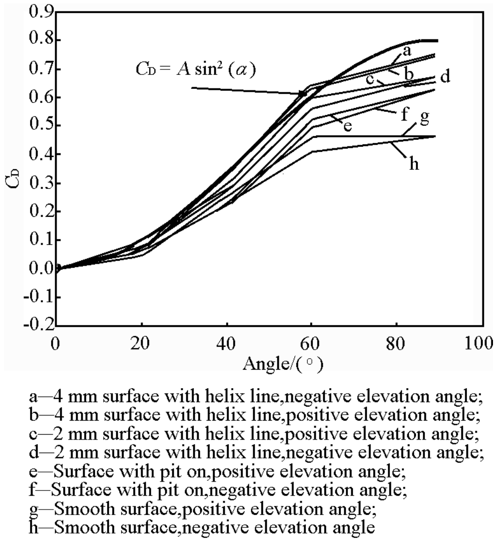


Fig. 6 Drag force coefficient for different obliquity and surface of cables

$$C_D = A\sin^2(\alpha) \qquad (11)$$

Where, with the wind speed of 25 m/s, for deck (combination with the live load), the control design value of the drag coefficient can be selected as 1.0.

In terms of transverse wind load, in the case of inclination angle of $\alpha = 90°$, $C_D = A$. So, the Eq. (11) can act as unity formula in calculating drag factor of cable in both longitudinal and transverse direction.

The research conclusions above have already adopted by *Wind-resistant Design Specification for Highway Bridge* (JTG/T D60-01-2004) in item 4.4.6.[1]

6 Comparing with the wind-resistant code in Europe

Under the action of wind load in the longitudinal direction, the drag coefficient, in different inclination angles are shown as Fig. 7 curved according to the research results of Sutong Bridge and the code of Europe respectively.

According to the total wind load obtained by the above two methods of calculating drag coefficient (take the cables of Sutong Bridge in main span for example), the drag coefficient obtained from results of Sutong Bridge is 5 % greater than that regulated in European code. Comparing with the sum of the wind load afforded by the pylon and girder in the longitudinal direction, the results of Sutong Bridge is 8.5 % higher[6].

According to the comparison results above, the result of Sutong Bridge is more conservative than Europe code. However, considering the uncertainty of test and theoretical analysis, the difference between them is acceptable.

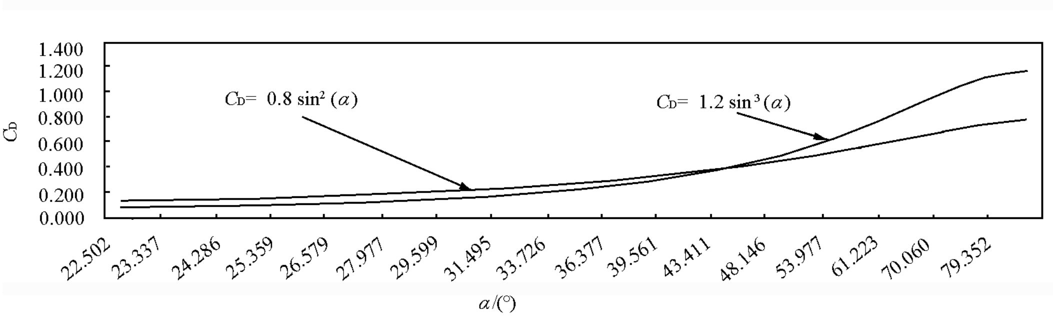


Fig. 7 Comparison of longitudinal wind drag force coefficient between Euro-code and Sutong Bridge researches

7 Conclusions

1) Whether the calculations of wind load of cable for long-span cable-stayed bridge is reasonable or not directly affects the scientific rationality of bridge structure design. Therefore, the special research of wind load of cable is necessary.

2) The results obtained from the force measurement testing of cables for Sutong Bridge filled the blank of our national wind-resistant design code, the results were adopted by *Wind-resistant Design Specification for Highway Bridge* (JTG/T D60-01-2004). It is a very significant value for practising guide, and it is also a creative achievement in the field of bridge wind-resistant design.

(cont. on p. 58)