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Experimental Studies on VIV Countermeasures for Long-Span Suspension Bridge with Twin-box Girder

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Abstract

Twin-box girder is one of typical main beam sections of large span bridges. The present study attempts to investigate the Vortex-Induced Vibration (VIV) behavior of a twin-box girder bridge with a main span of 1660m by sectional wind tunnel test. The effect of grid plates on suppressing the VIV of twin-box girder model is examined. Test result shows that the vertical VIV of the test model under attack angle of 0°, -3°, ±5° and torsional VIV under attack angle of +3° exceed the allowable value(Chinese specification, JTG/TD60-01-2004). The installation of grid plates provides noticeable improvement on suppressing the VIV of the test model, and its effect depends on the variation of different design parameters, i.e., porosity, b_1/d ratio (the ratio of the width of the plate, b_1, to the gap width, d), composition type and installation position. The optimal design parameters of the grid plates are as follows: The porosity is about 42% to 67%, while the b_1/d ratio is about 0.042 to 0.167, a uniform distribution of grid plates produces better VIV suppression performance as compared to non-uniform composition type. In addition, with the installation of grid plates at the upper side, the VIV behavior can be reduced markedly.

Introduction

It is noted that twin-box girders are becoming increasingly popular in the construction of super-long-span cable-supported bridges due to its capability of enhancing the aerodynamic stability of long-span bridges. There are several twin-box girder long-span bridges that have been constructed in recent years, including the Xihoumen suspension bridge(1650m, China), the Gwangyang suspension bridge(1545m, South Korea), the Hong KongStone Cutters cable-stayed bridge(1018m, China)[1]. Even though long-span bridges with twin-box girders have better flutter performance than those featuring a single-box girder, it is worth noting that the presence of twin-box girders may cause the occurrence of serious VIV[2,3]. The phenomenon of VIV of bridges not only cause discomfort to the drivers but also given rise to long-term fatigue damages in bridge structures[4]. It is therefore of great importance to investigate the performance of VIV of twin-box girders, and identify the most effective method to minimize the VIV-induced impacts on bridges. Although there have been abundant literature concerning the VIV and flow field characteristics of complex twin-box girders, further research is still highly required.

This study comprises two primary objectives, the first is to comprehensively investigate the VIV performance of a twin-box girder bridge; the second is to optimize the design parameters of gird plates. The rest of the paper is organized as follows: first, the research background and details involved in the dynamic and static sectional model experiments of a twin-box girder are briefly introduced. Second, the results and discussions of this study are presented, where the VIV performance of a twin-box girder with a gap ratio of L/D=3.68. In addition, the influence of four design parameters (i.e., porosity, b_1/d ratio, composition type, and installation position) of gird plates on the VIV performance of a twin-box girder is identified. At last, the major conclusions derived in this study are summarized.

Engineering background

In the present study, an exceptionally-long suspension bridge is selected as the research object to investigate the VIV performance and suppression countermeasures of a twin-box girder. This bridge is located in the southern part of China, where has a subtropical oceanic climate and is frequently affected by strong winds. As shown in Fig.1, the selected bridge is a steel twin-box girder suspension bridge with a total length of 2720 m. The girder is 64.1m in width and 4.51m in depth. The main cable is a space cable, and tower is single column tower with a box section fabricated from reinforced concrete. The design wind speed of this bridge is 54.76m/s.

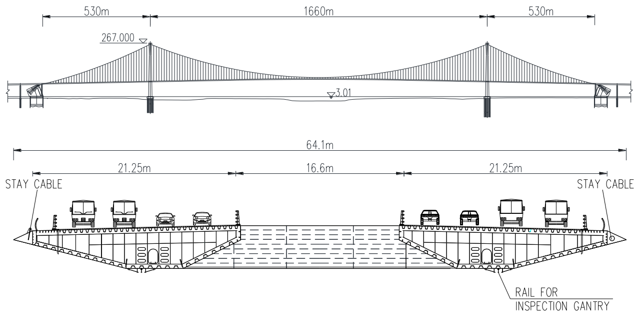

Figure 1. Twin box girder section of Bridge (unit: m)

Experimental set-up

An aerodynamic sectional model test is carried out in the wind tunnel of Southwest Jiaotong University (Type: XNJD-1). The dimensions of the test section is 2.4m×2.0m×16.0m (W×H×L), and the attainable wind speed ranges from 1m/s to 45.0m/s (turbulent intensity<0.5%). The size of the sectional model is2.095 m (length)×0.776 m (width)×0.09 m (height). The suspension system consists of 8 springs and supporting frames, which allows the sectional model to rotate and move vertically. The frequencies and masses of the test model are modified by adjusting spring lengths and adding mass blocks at two ends of the models. Schematic diagram of model test is shown in Fig.2. The detailed test parameters were shown in Tab. 1

Figure 2. Aerodynamic sectional model test

parameters	Prototype	Scaling	Model
L(m)	146	λ_L = 1:70	2.10
B(m)	64.1	λ_L = 1:70	0.917
H(m)	4.5	λ_L = 1:70	0.065
m(kg/m)	49073	λ_m = 1:70^2	20.981
J_m(kg-m^2/m)	43179800	λ_J = 1:70^4	3.768
f_v (Hz)	0.0989	λ_f =14:1	1.47
f_t (Hz)	0.2182	λ_f =14:1	3.26
ξ_v (%)	-	$\lambda\xi$ = 1	0.4
ξ_t (%)	-	$\lambda\xi$ = 1	0.32

Tab.1 Parameters for sectional model wind tunnel tests

VIV performance of twin-box girder

This study deals primarily with the VIV of a bridge deck in the completion stage unless otherwise specified. According to Chinese specification JTG/TD60-01-2004, the amplitude limitations of VIV (first-order bending mode) in the completion stage are defined as follows:

$$[h_a] = 0.04/f_v = 0.04/0.0989 = 0.404\text{m} \quad (1)$$

$$[\theta_a] = 4.56/f_t B = 4.56/(0.2182 \times 64.1) = 0.326° \quad (2)$$

Fig.4 illustrates respectively the vertical responses of the bridge deck at a damping ratio of 0.4% and the torsional responses at a damping ratio of 0.32% under different attack angles (α) and wind speeds (transferred in real situation). As can be seen (Fig. 4a), the vertical VIV of the bridge occurs in all five wind attack angles and the resultant maximum amplitudes consistently exceed the allowable value (0.404m, Chinese specification) by a large amount. The most undesirable situation is found at a wind attack angle of -3°, in which the peak vertical response reaches 0.7 m with a corresponding lock-in wind speed at 5.94 m/s. Likewise, it is shown in Fig.4b that the occurrence of torsional VIV can be found in all the considered wind attack angles. Noted that the peak amplitude of torsional VIV under the attack angle of +3° exceeds the allowable value (0.326°, Chinese specification). The maximum torsional response occurs at a wind attack angle of +3°, with a peak amplitude of 0.378° and a lock-in wind speed at 13.48 m/s.

Design parameters of gird plates

The results presented hereinabove suggest that the VIV of the twin-box girder bridge is significant. It is therefore of great interest to applying some necessary countermeasures to suppress the VIV phenomenon. Early literature address that strong vortices generated at the central gap are one of the critical factors for inducing the large amplitude of VIV[5]. In this case, gird plates are employed which are deemed as new effective VIV suppression countermeasures for twin-box girders. The grid plats are installed at the central gap of the main girder with a function to block airflow as they interfere with the generation of large-scale vortices at the central gap. In the present study, systematic assessment on the performance of grid plats in VIV suppression is carried out, in which the influence of four design parameters are examined respectively. A shown in Fig.5, a gird plate consists of several equal sized flat plates. It has four major design parameters, namely porosity(R), b_1/d ratio (i.e., the ratio of the width of the plate, b_1, to the gap width, d), composition type (i.e., uniform and non-uniform), and installation position (i.e., upper, lower, both upper and lower). The porosity of a gird plate(R) can be defined as

$$R = 1 - n.b_1/d \times 100\% \quad (3)$$

where b_1 is the width of each flat plate of the gird plate, n is the number of flat plates, d is the width of the gap of the twin-box girder model or the length of the connection box. The experimental setups for a series of wind tunnel tests are summarized in Tab.2.

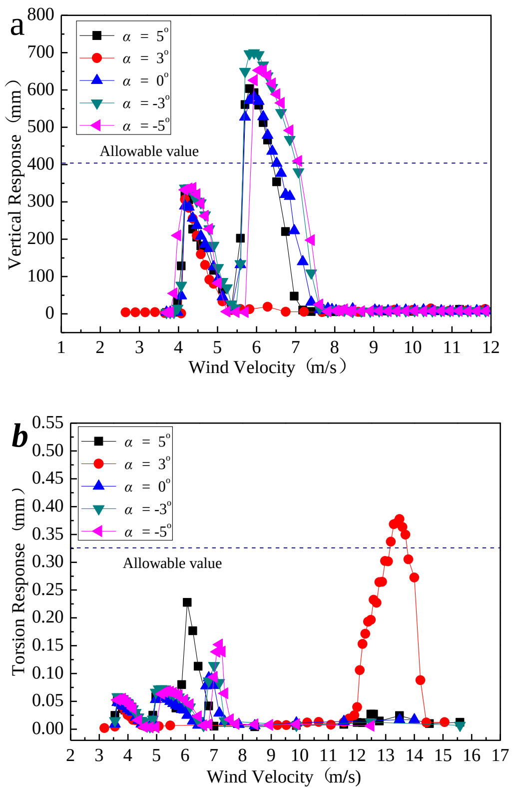

Figure 4. VIV responses of the model(a) vertical responses (b) torsional responses

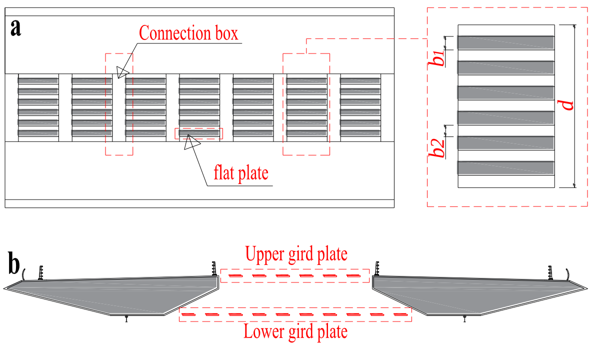

Figure 5. Structure diagram of gird plate

Influence of Porosity

The results in regard to the effect of porosity of gird plates on VIV suppression are illustrated in Fig.6, in which the magnitude of porosity ranges from 0% to 83% (C1–C9). As can be seen in

Fig.6a, the vertical VIV response reduces noticeably with the installation of gird plates. With a porosity of 42%, 50% and 67% (C5-C7), the grid plates generate the best vibration suppression performance and no VIV occurs in the main girder. Fig.6b shows that torsional responses associated with different porosities of grid plates. It is shown that, with a grid porosity of 0% and 17% (C1 and C2), the behavior of torsional VIV is somewhat intensified as compared to the case with the installation of grid plate. The optimal performance of suppression of torsional VIV is found with a grid porosity of 42%, 50%, 67% and 75% (C5-C8). In general, it is found that there is an optimal porosity range of grid plate in terms of suppressing the vertical and torsional VIV of test model. The optimal value of grid plate associated with vertical VIV is 42%–67%, while the corresponding value for torsional VIV is 42%–75%.

	Design parameters	Parameters				
		R (%)	b_1 (mm)	b_1/d	n	Position
C1	Porosity	0%	20	0.084	12	Upper
C2		17%	20	0.084	10	Upper
C3		25%	20	0.084	9	Upper
C4		33%	20	0.084	8	Upper
C5		42%	20	0.084	7	Upper
C6		50%	20	0.084	6	Upper
C7		67%	20	0.084	4	Upper
C8		75%	20	0.084	3	Upper
C9		83%	20	0.084	2	Upper
C10	b1/d ratio	50%	10	0.042	12	Upper
C11			20	0.084	6	Upper
C12			30	0.125	3	Upper
C13			40	0.167	6	Upper
C14			60	0.25	3	Upper
C15			120	0.5	2	Upper
C16	Compositio n type	50%	20	0.084	6	Upper
C17			20	0.084	6	Upper
C18			20	0.084	6	Upper
C19	Installation position	50%	20	0.084	6	Upper
C20			20	0.084	6	Lower
C21			20	0.084	6	Upper and lower

Table.2 Testing cases of VIV countermeasures.

Influence of b_1/d ratio

A wide range of b_1/d ratios are considered in this section, varying from 0.042 to 0.5. The porosity of grid plate is maintained with a value of 50%. Fig.7 presents the comparison results with respect to varying b_1/d ratios. For the vertical response of the test model, Fig.7a indicates that the phenomenon of vertical VIV vanishes with a b_1/d ratio = 0.042, 0.084, 0.125, or 0.167 (C10-C13). With a further increase in the b_1/d ratio, the vertical VIV occurs(C14 and C15). Moreover, Fig.7b shows the results of torsional response with different b_1/d ratios. It is found that with a b_1/d ratio of 0.042, 0.25 and 0.5 (C10, C14 and C15), the peak amplitudes of torsional VIV are 0.43°, 0.38°, and 0.33° which exceed the allowable value. For the remaining cases (C11-C13), the peak amplitudes of torsional VIV are approximately around 0.17°, which are well below the allowable value.

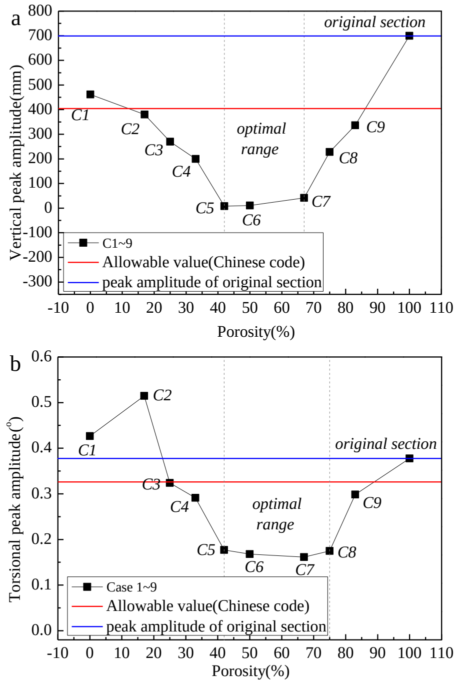

Figure 6. VIV responses of grid plates with different porosity(a)vertical responses (α= -3°) (b)torsional responses (α= +3°)

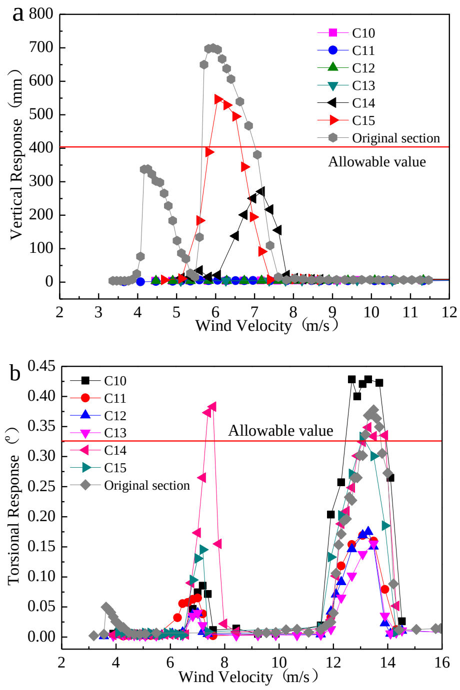

Figure 7. VIV responses of gird plates with different b_1/d ratios (a)vertical responses (α= -3°) (b)torsional responses (α= +3°)

Influence of composition type

To investigate the effect of composition type of gird plates on vibration suppression, three different composition types of grid plates are adopted in this section, i.e., a uniform (C16) and two non-uniform composition types (C17, C18). The porosity of grid plates is kept with a value of 50%. As can be found in Fig.8a, no distinct vertical VIV phenomenon is observed in C16 with uniform composition of grid plates. On the other hand, the results for C17 and C18 exhibit a typical vertical VIV with a peak magnitude of 0.24m and 0.17m, respectively. For torsional response, it is found that the peak amplitude for C17 and C18 are 0.42 °, and 0.43 °, which exceed the allowable value. By contrast, the result for C16 exhibit a weak torsional VIV, which meets the requirement in Chinese specification.

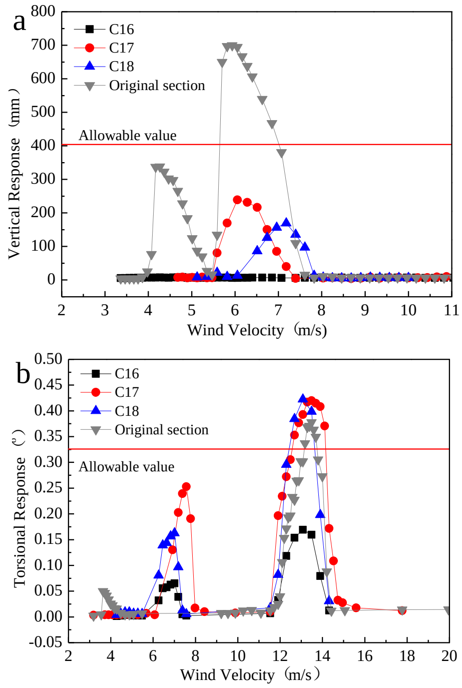

Figure 8. VIV responses of gird plates with different composition types (a)vertical responses (α= -3°) (b)torsional responses (α= +3 °)

Influence of installation position

In addition, a further study on the effect of installation position of grid plates is undertaken. Gird plates with a porosity of 50% are placed at upper side (C19), lower side (C20), both upper and lower sides of the gap (C21). Fig.9 shows respectively the results of vertical and torsional responses associated with different installation position of grid plates. Fig.9a indicates that the installation of grid plates on the upper side tends to improve the vertical response performance as no evident VIV of the test model is observed in C19 and C21. For C20, the occurrence of vertical VIV is found with a peak amplitude of 0.32m and a lock-in wind speed of 7.19m/s. Fig.9b shows that torsional VIV is observed in all cases. Nevertheless, the peak amplitude of torsional VIV is reduced considerably when grid plates are installed on the upper side(C19).

Conclusions

- The vertical VIV of the twin-box girder is found under five attack angles (α=0°, ±3°, ±5°), while the torsional VIV occurs under an attack angle of +3 °. The peak amplitude of vertical VIV is 73.01% higher than the allowable value, and the corresponding value of torsional VIV is 15.95% higher than the allowable value.
- The VIV suppression performance of the grid plates depends greatly on the four design parameters (i.e. porosity, b_1/d ratio, composition type and installation position). For the effects of porosity and b_1/d ratio, there appears to be an optimal range where the VIV suppression of grid plates can be considerably enhanced. The optimal value of porosity is about 42%–67%, while and optimal value of b_1/d ratio is about 0.042–0.167. For the effect of composition type of grid plates, a uniform distribution of grid plates produces better VIV suppression performance as compared to non-uniform composition type. In addition, with the installation of grid plates at the upper side, the VIV behavior can be reduced markedly.

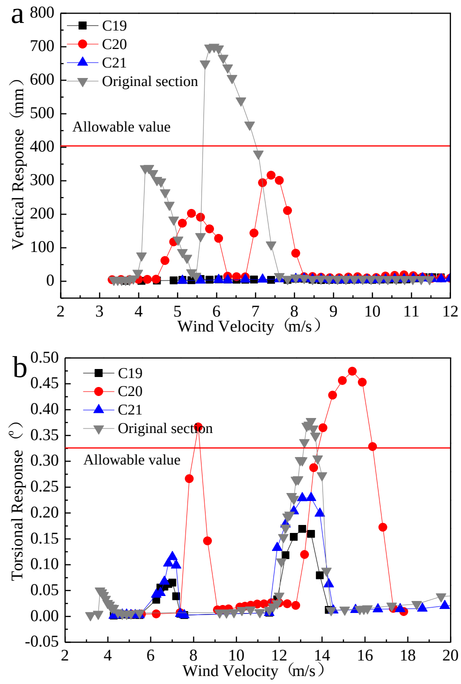

Figure 9. VIV responses of gird plates with different installation position.(a)vertical responses (α= -3°) (b)torsional responses (α= +3°)

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