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Study on Aerodynamic Characteristics of A New Suspension Bridge with Twin-box Girder

H.L. Liao [123], J.X. Wang [13], C.M. Ma [123]

[1]Department of Bridge Engineering, Southwest Jiaotong University, Chengdu 610031, China

[2]key Laboratory for Wind Engineering of Sichuan Province, Chengdu 610031, China

[3]Research centre for Wind Engineering, Southwest Jiaotong University, Chengdu 610031, China

Abstract

A new suspension bridge with twin-box girder of 1660m, Lingding Channel Bridge which is the main channel bridge of Shenzhen-Zhongshan Thoroughfare, have been investigated in aerodynamic characteristics through a series wind tunnel test and numerical analysis. The present study includes measurement of static coefficient of main girder under orthogonal wind, vortex-induced vibration(VIV) and flutter sectional model test with a geometric scale of $\lambda_L = 1:70$, and nonlinear static wind stability analysis. The above work showed that the main wind- resistance problem of Lingding Channel Bridge is vortex-induced vibration, and the VIV can be effectively controlled by grids with 50% porosity. Although this countermeasure will make the flutter critical wind speed of the bridge reduce 16.1%, and 3.4% for the static stability critical wind speed, the indicators will still be able to meet the wind- resistance requirements.

Introduction

Shenzhen-Zhongshan Thoroughfare, with a total length of 24 km, is a cluster Engineering made up by bridge, island, tunnel and underground communication. It is a major transportation infrastructure project which would be established by China. The project can reduce the traffic time of Shenzhen to Zhongshan from 2 hours to 20 minutes[1]. Lingding Channel Bridge(Figure 1), a steel twin-box girder suspension bridge with a main span of 1660m, the main channel bridge of Shenzhen-Zhongshan Thoroughfare. This bridge will be built on the Lingding sea. Because this area is located in the typhoon path, the typhoon will land at the bridge site frequently. Furthermore, the bridge structure is novel in design, and there is no clear standard of the wind load, so it is urgent to study the wind-resistance performance of this bridge[2]. This paper mainly introduces a series of wind tunnel tests and numerical analysis about the Lingding Channel Bridge. Main aspects of wind resistance performance of the Lingding Channel Bridge were studied, including measurement of static coefficient of main girder under orthogonal wind, vortex-induced vibration(VIV) and flutter sectional model test with a geometric scale of $\lambda_L = 1:70$, and nonlinear static wind stability analysis.

Figure 1. Lingding Channel Bridge

Details of the Bridge

Figure 2. schematic diagram of bridge location

Lingding Channel Bridge is located between Xinlong Zhongshan and south of Shenzhen Airport, and 30km away from Humen Bridge in the north, 40km away from Hong Kong - Zhuhai - Macao Bridge in the south, as shown in figure 2. The project area belongs to the subtropical maritime monsoon climate zone, where the climate is complex and volatile, and disastrous weather is frequent. The main bridge of Lingding Channel Bridge is 2720m in length and consists of 530m (side span) + 1660m (main span) + 530m (side span). The main beam is twin-box girder section with a width 64.1m, height (from center line) of 4.5m[3]. The main cable is the space cable, the width of the lateral bridge is 61.0m, and the span of the cable is 12.8m. The tower is single column cable tower with a box section made of reinforced concrete. The height of the tower is 263.0m. The main bridge and the main section were shown in figure 3. According to the general report of the meteorological observation and wind parameters of the bridge between Shenzhen and Zhongshan, the average wind speed of 10min is 39.1m/s. With reference to the measured data of the Hong Kong-Zhuhai-Macao Bridge, the wind speed in the channel position is about 10% more than that in the shore. So the basic wind speed (120 years of recurrence) of Lingding Channel Bridge at the height of 10m is 43.98 m/s. The design elevation of the bridge is 91.966m and the water level is 0.52m. Therefore, the design wind speed(120 years of recurrence) of the bridge deck is 58.6m/s.

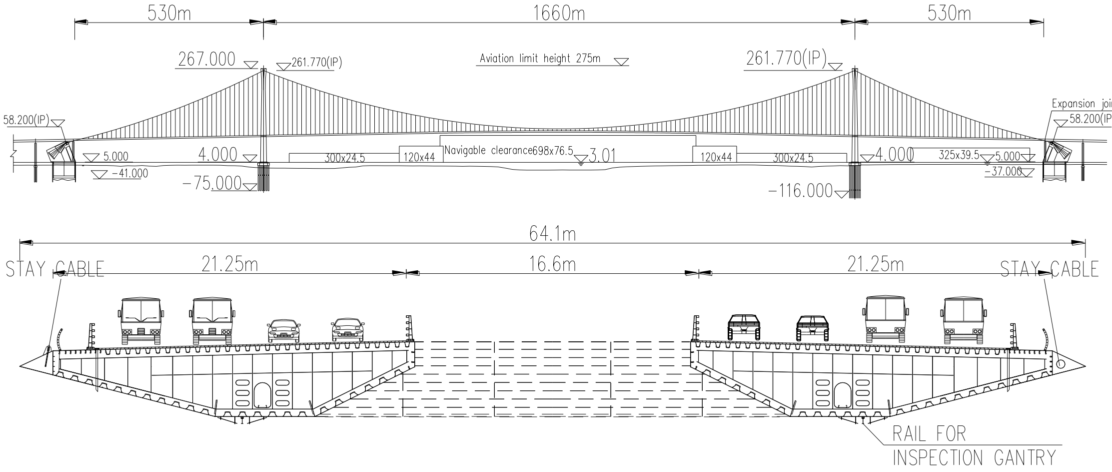

Figure 3. Twin-box girder section of Lingding Channel Bridge (m)

Sectional Model Wind Tunnel Testing

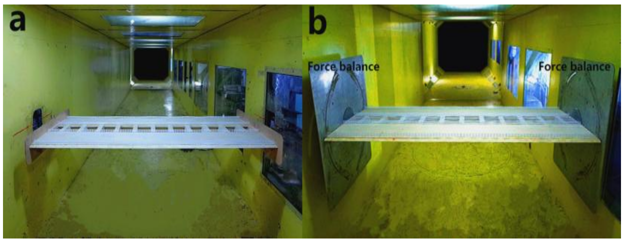

Figure 4. Wind tunnel test(a) 1:70 dynamic sectional model test(b) 1:70 static sectional model test

Both dynamic sectional model test and static sectional model test were carried out in the wind tunnel: XNJD-1(figure 4). The dimension of the test section is 2.4m×2.0m×16.0m (W×H×L), with wind speed adjustable from 1m/s to 45.0m/s (turbulent intensity<0.5%). Specialized device in wind tunnel test is used in testing aerodynamic model of bridge, as shown in figure 4(a). The model is suspended on the support by eight springs. Two dimension vibration systems can rotate and also can move vertically. In the test section, there is a side wall support and force balance system designed for the bridge section model static force test and connected with the data acquisition system(Figure 4(b)). The detailed test parameters are shown in table 1.

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_s(kg/m)	49073	λ_m = 1:70^2	20.981
J_{ms}(kg-m^2/m)	43179800	λ_J = 1:70^4	3.768
$f_{V\text{-}S\text{-}1}$(Hz)	0.0989	λ_f =14:1	1.47
$f_{T\text{-}S\text{-}1}$(Hz)	0.2182	λ_f =14:1	3.26
m_A(kg/m)	106200	λ_m = 1:70^2	45.046
J_{mA}(kg-m^2/m)	29298100	λ_J = 1:70^4	2.556
$f_{V\text{-}A\text{-}1}$(Hz)	0.0818	λ_f =14:1	1.65
$f_{T\text{-}A\text{-}1}$Hz)	0.1795	λ_f =14:1	3.60
ξ_v (%)	-	$\lambda\xi = 1$	0.3
ξ_t (%)	-	$\lambda\xi = 1$	0.36

Table 1 Similarity scales and setup parameters for sectional model wind tunnel tests

VIV Performance

Vortex-induced vibration(VIV) is a major challenge for long-span bridges in terms of structural safety and serviceability. It is well known that when the air flow through the bridge section, it will produce periodic vortex shedding near the section[4]. When the frequencies of vortex shedding are close to the bending or pitching natural frequencies of the bridge, it may induce large-amplitude vibrations, resulting in the discomfort of the drivers and long-term fatigue damages in bridge structures.

Attack Angle	-5°	-3°	0°	3°	5°
Lock-on frequency(Hz)	0.099	0.099	0.099	0.099	0.099
Lock-on wind speed（m/s）	6.16	5.94	5.94	4.36	5.82
Maximum amplitude(m)	0.66	0.70	0.58	0.30	0.61
Allowable value(m)(Based on Chinese specification)	0.404	0.404	0.404	0.404	0.404
Exceeding percentage	65%	75%	45%	-25%	53%

Table 2 Heaving VIV characteristics of original section model

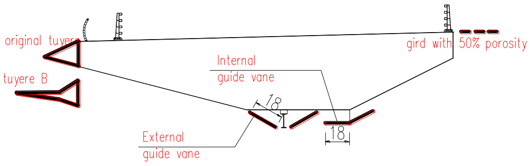

Figure 5. Four vibration suppression measures(external guide vane, internal guide vane, tuyere B, gird with 50% porosity)

As shown in table 2, VIVs in heaving DOF of the original section model occurred under all the five wind attack angle(-5^o, -3^o, 0^o, +3^o, +5^o), and exceed the allowable value due to Chinese specification JTG/TD60-01-2004[5]. The most unfavourable one occurs at the wind attack angle of -3° and the corresponding wind speed is around 5.94 m/s. It is therefore necessary to take some countermeasures to suppress VIV. The suppression effect of guide vane, grid with 50% porosity and tuyere were investigated, the details were shown in figure 5. The of VIV versus wind speeds were shown in figure 6. Meanwhile, the VIV responses of most unfavorable case of original section model was plotted for comparison as well As shown in figure 6, external guide vane, internal guide vane and tuyere B have no obvious effect on VIV suppression of the main beam. The VIV can be effectively controlled only when the grids with 50% porosity were installed at the upper side of the gap.

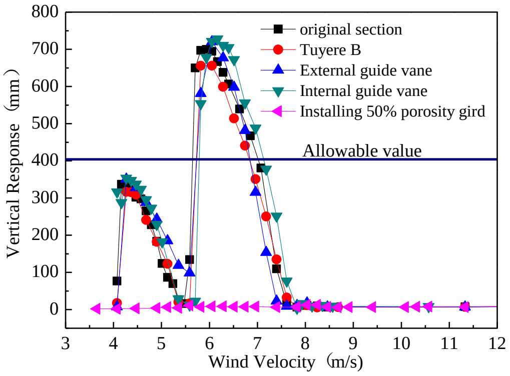

Figure 6. Heaving VIV responses of the original section with four VIV countermeasures,α =-3°

Aerodynamic Flutter Instability

Flutter is a dangerous self-excited divergent vibration. When the wind speed reaches a bridge's flutter critical wind speed, the vibrating bridge can constantly absorb energy from the wind through the feedback of the airflow, which will gradually increase the amplitude of vibration until the structural collapse. In bridge wind resistance design, flutter critical wind speed must be higher than the equivalent flutter check wind speed. The critical wind speed of Lingding Channel Bridge was predicted by the wind tunnel test with sectional model, and the experimental results were checked with the allowable flutter speed of 83.7m/s due to the Chinese code[5]. Considering the sensitivity of the flutter critical wind speed to wind attack angle, the tests were conducted in the uniform flow field under five angles of attack (α): 0°, +3° and -3°, +5° and -5°. When the wind directly flows towards the bottom surface of the main beam, the wind attack angle is positive. For each working condition, the wind speed starts from 0 m/s with an increment of 0.2 m/s. When the wind speed is greater than 1.2 times of the flutter check wind speed, the flutter stability of the bridge meets the requirements.

Attack Angle	Flow	Check wind speed（m/s）	Critical wind speed V-S-1/T-S-1（m/s）		Change percentage（%）	Critical wind speed V-A-1/T-A-1（m/s）		Change percentage（%）
			Original	with Gird		Original	with Gird	
-5°	Smooth	83.7	100.1	90.8	-9.2	113.2	98.2	-13.3
-3°	Smooth	83.7	103.0	91.2	-11.5	115.0	100.5	-12.6
0°	Smooth	83.7	107.4	95.1	-11.4	120	102.2	-16.1
3°	Smooth	83.7	100.2	91.5	-8.7	110.8	98.7	-11.6
5°	Smooth	83.7	95.7	90.9	-5.0	104.1	95.5	-8.3

Table 3 Flutter critical wind speed of Lingding Channel Bridge

The results of the critical wind speed of flutter were shown in Table 3. Compared with the original section, the critical flutter speed of the section with 50% porosity grid will decrease 8.3%~16.1%, which may indicate that the grid has adverse effects on the flutter performance of Lingding Channel Bridge.

Static coefficient

The static coefficient is a non-dimensional coefficient which represents the force of the structure under wind load, including resistance coefficient C_D(Equation1), lift coefficient C_L(Equation2), and moment coefficient C_M(Equation3). It reflects the quasi-static aerodynamic effect of the wind on the bridge. The static coefficients of the main girder at different attack angles(-12° ~+12°) were measured by the static model test of the main girder, which provides the calculation parameters for the calculation of the aerostatic stability. Test speed: U=10m/s and 12m/s. Static coefficients of Lingding Channel Bridge as shown in figure 7. As can be seen in figure 7, the resistance coefficients of the main girder section increased after installing girds with 50% porosity.

$$C_D(\alpha)=F_D(\alpha)\Big/\left(\frac{1}{2}\rho U^2HL\right) \tag{1}$$

$$C_L(\alpha)=F_L(\alpha)\Big/\left(\frac{1}{2}\rho U^2BL\right) \tag{2}$$

$$C_M(\alpha)=M_Z(\alpha)\Big/\left(\frac{1}{2}\rho U^2B^2L\right) \tag{3}$$

Where H, B and L are the height, width and length of the segment model, respectively, corresponding to the height, width and length of the original bridge are 4.51m, 64.1m and 147m

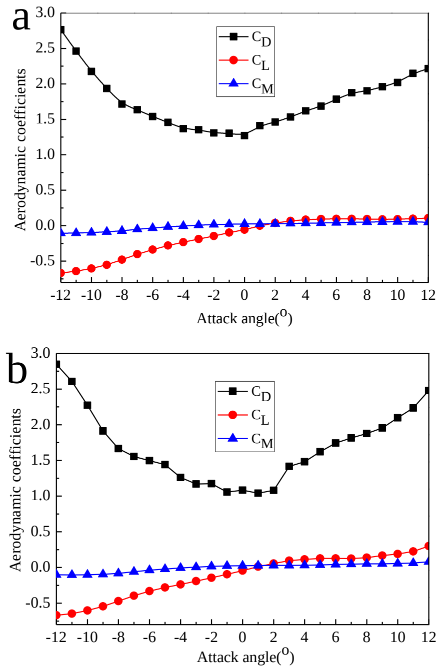

Figure 7. Static coefficients of main beam(a)original section(b) install grid plates with 50% grid porosity at central gap

Aerostatic stability

The aerostatic stability of bridge structures includes lateral buckling and torsional divergence. When the wind speed reaches the critical wind speed of the aerostatic stability of the bridge, the main girder will not be able to maintain the original equilibrium state and overturn. Such a situation would cause devastating damage to the structure and therefore must be avoided. The critical wind velocity of aerostatic instability of Lingding Channel Bridge was calculated by ANSYS, and the results were checked with the allowable critical velocity of aerostatic instability due to the Chinese code. The nonlinear finite element method based on the static coefficient was used to analysis the wind load and displacement of the structure in this paper. The aerostatic stability analysis results of Lingding Channel Bridge were shown in figure 8. The aerostatic stability analysis results of Lingding Channel Bridge with girds with 50% porosity were shown in figure 9. The calculated critical wind speed is 91.2m/s(original bridge) and 88.1m/s(installing girds with 50% porosity), respectively. The calculated wind speeds are greater than the allowable wind speed 70.3m/s. It is can be seen that the bridge has enough static wind stability.

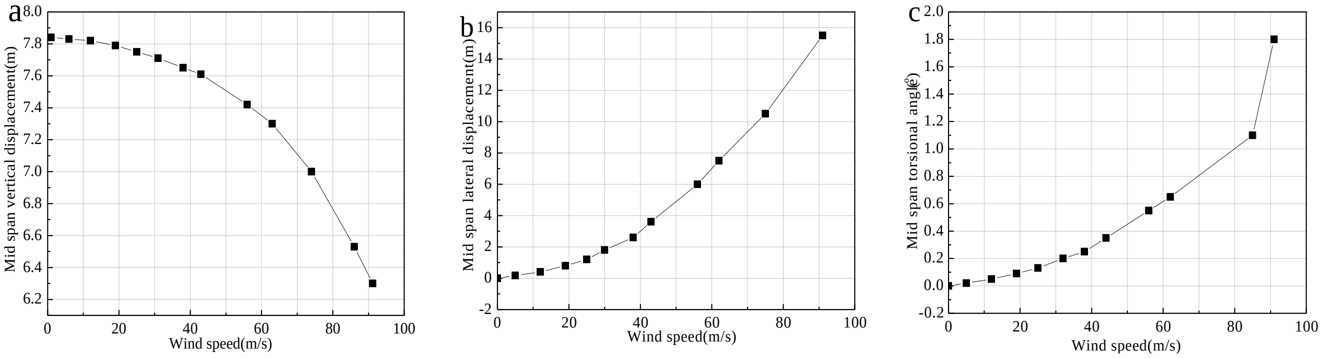

Figure 8. The mid span displacement (original bridge)(a)vertical displacement(b)lateral displacement(c) torsional angle

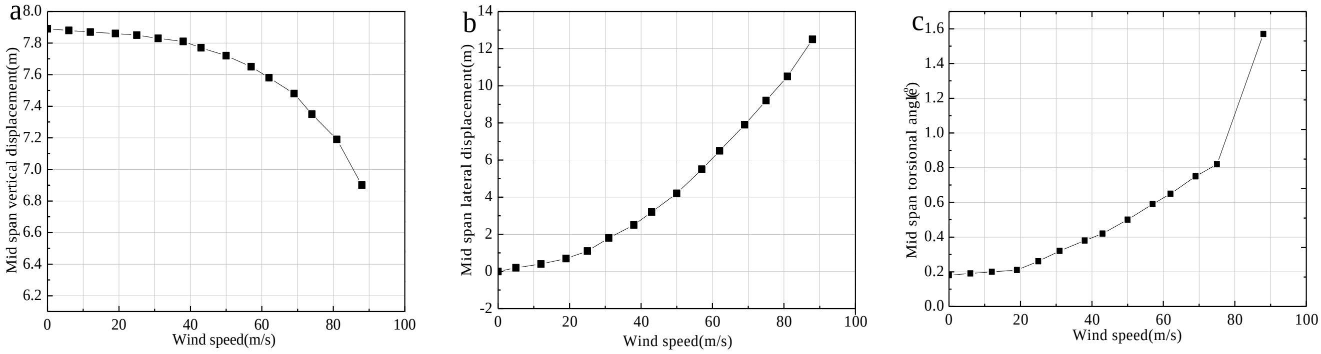

Figure 9. The mid span displacement (installing girds with 50% porosity)(a)vertical displacement(b)lateral displacement(c) torsional angle

Conclusions

Based on a series of studies on the Lingding Channel Bridge, the following conclusions can be drawn:

- The vortex-induced vibration sectional test with a geometric scale of λ_L=1:70 shows that the heaving VIVs of the original girder under four attack of angle(α = 0 °, - 3 ° and ±5 °) exceed the allowable value. External guide vane, internal guide vane and tuyere B were proved to have no effect on vortex-induced vibration(VIV) of the main girder. The VIV can be effectively controlled when grids(50% porosity) were installed at the upper side of the gap.
- The flutter test shows that the critical wind speed of the Lingding Channel Bridge is much higher than the allowable wind speed(83.7m/s). Therefore, the flutter performance of Lingding Channel Bridge could meets the wind- resistance requirements.
- The critical wind speed of static stability is 91.2m/s. In order to suppress the VIVs, the critical wind speed will change to 88.1m/s after installing girds with 50% porosity at the upper side of the gap. Two critical wind speeds are both higher than the allowable speed(70.3m/s).
- Above all, the main wind- resistance problem of Lingding Channel Bridge is VIV, and grid is an effective countermeasure. But this countermeasure may has adverse effects on flutter performance and static stability. Further research is needed for more accurate results.

Acknowledgments

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