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Wind Tunnel Test on Aerodynamic Characteristics of Long-Span Twin Bluff Body Steel Box Girders

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Abstract: Taking a long span twin bluff body steel box girder bridge as the engineering background, wind tunnel pressure tests were carried out to systematically investigate the aerodynamic characteristics of the main girder under eight spacing ratios and various wind angles of attack. Aerodynamic coefficients and Strouhal numbers are adopted as core evaluation indices. An interference factor is introduced to quantitatively analyze the interference effects on drag and lift coefficients. The aerodynamic characteristics of a single box girder were compared with those of twin box girders at different spacing ratios. Meanwhile, the aerodynamic characteristics of the twin bluff box girders are further analyzed. Results indicate that the leeward girder barely affects the windward girder, while the windward girder creates a shielding effect that reduces the leeward girder aerodynamic coefficients. The drag coefficient interference factors of both girders are dominated by suppression effects, and such suppression effects weaken with increasing spacing ratio and angle of attack. The lift coefficients of the leeward girder are lower than those of the single box girder but gradually converge toward the values of the single box girder with increasing angle of attack. Distinct Strouhal numbers are mainly captured under large spacing ratio conditions; under positive angles of attack, the Strouhal number generally decreases with rising spacing ratio.

1. Introduction

Long span cable-stayed bridges and suspension bridges are sensitive to wind loads due to their low natural frequencies and small damping, and are prone to vortex-induced vibration at relatively low wind speeds [1-2]. With relatively smaller spans and greater stiffness, continuous girder bridges are less sensitive to wind loads and less prone to vortex-induced vibration under oncoming flow. However, with the development of bridge construction and the increase in traffic volume, long span twin bluff body steel box girders have been increasingly used in continuous girder bridges, such as

the Gwangyang Bridge in South Korea and the Chongqi Bridge, known as the "First Bridge at the Yangtze River Estuary", which was opened to traffic in China in 2011[3-4]. As spans increase and lightweight, low-damping steel structures are adopted, sensitivity to wind loads increases and vortex-induced vibration occurs frequently.

Growing traffic volume has increased the use of twin parallel girder bridges with higher traffic capacity, accompanied by more complex vortex-induced vibration problems. Extensive research has investigated twin flat steel box girders using model vibration measurement methods. Chen et al. [5-7] and Zhu et al. [8] investigated the vortex-induced vibration characteristics of twin flat steel box girders through sectional model wind tunnel tests. Tan et al. [9-10] and Liu et al. [11] investigated the vortex-induced vibration characteristics of twin flat steel box girders under different wind angles of attack and spacing ratios through elastically suspended sectional model wind tunnel tests. Research on the vortex-induced vibration characteristics of twin bluff body steel box girders remains relatively scarce. Dong et al. [12] and Mao et al. [13] analyzed the mechanism of vortex-induced vibration of twin bluff body steel box girders through pressure-measuring sectional model wind tunnel tests. Overall, research on the vortex-induced vibration characteristics of twin steel box girders mainly uses sectional model wind tunnel tests. Aerodynamic shape, wind angles of attack and spacing affect their vortex-induced vibration characteristics.

Due to the significant aerodynamic interference effect, twin parallel girder bridges differ significantly from a single box girder in wind pressure distribution characteristics and aerodynamic force parameters. This difference directly affects the static wind load distribution and vortex-induced vibration characteristics of the structures [14-16]. Compared with model vibration measurement studies, static model studies provide more accurate, reliable and repeatable results. These provide a basis for studying wind loads on a twin parallel girder bridge and a reference for vortex-induced vibration research. Studies of the aerodynamic characteristics of twin steel box girders under stationary conditions therefore mainly focus on twin flat steel box girders. Laima et al. [17] investigated the aerodynamic characteristics of twin flat steel box girders at different wind angles of attack and the influence of Reynolds number on aerodynamic characteristics. Kwok et al. [18] and Zhu and Xu,[19] investigated the wind pressure distribution, vortex shedding mechanism and aerodynamic characteristics of the deck surface of twin flat steel box girders through synchronous pressure-measuring wind tunnel tests of sectional models. Extensive studies use pressure tests, force tests and numerical simulations, focusing on three-component force coefficients, wind pressure distribution coefficients and Strouhal numbers. Wind angle of attack and different girder spacings are the main influencing factors. These studies provide valuable references for research on the aerodynamic characteristics of twin bluff body steel box girders.

Compared with twin flat steel box girders, static model research on the aerodynamic characteristics of twin bluff body steel box girders remains insufficient. Liu et al. [20] revealed the aerodynamic interference mechanism of twin bluff body steel box girders by investigating several spacing ratios using numerical simulations and wind tunnel tests. However, their study considered only one wind angle of attack. Chen et al. [7] studied the effects of spacing ratios and wind angles of attack for twin bluff body steel box girders, where the test wind angles of attack ranged from −10° to 10°, yet only three spacing ratios were examined. Sectional model wind tunnel pressure tests are therefore needed to fully understand the overall and local aerodynamic characteristics of twin bluff body steel box girders.

This study uses a sea-crossing three-span twin bluff body steel box girder bridge in China as the engineering background. Through static model wind tunnel pressure tests, it investigates the variation laws of the aerodynamic coefficients and Strouhal number of twin bluff steel box girders. It aims to provide a basis for wind load design and support research on the vortex-induced vibration characteristics of twin bluff steel box girders.

2. Design of Wind Tunnel Test Scheme

2.1 Test model and setup

Taking a three-span continuous steel box girder bridge located in a coastal area of China as the research background, this study conducts calculations in accordance with the Wind-resistant Design Specification for Highway Bridges. The bridge is located in an open-coastal terrain, so the terrain roughness at the bridge site can be conservatively classified as terrain Category A with a corresponding roughness coefficient of 0.12. The bridge adopts a span arrangement of 123 + 178 + 123=424 m, and the main girder is a bluff body steel box girder. The height of the main girder is 4.5 m, the width of the main girder is 13 m, and the net spacing is 0.65 m. The tests were performed in the low-speed test section of the STDU-1 wind tunnel at Shijiazhuang Tiedao University, which has a width of 4.4 m, a length of 24.0 m and a height of 3.0 m. Based on the actual cross section dimensions of the steel box girder and in combination with the blockage ratio requirements specified in the Wind Resistant Design Specification for Highway Bridges, the scale ratio of 1:25 was finally selected for model fabrication, with a maximum blockage ratio of 4.39% that meets the requirement of being less than 5%.

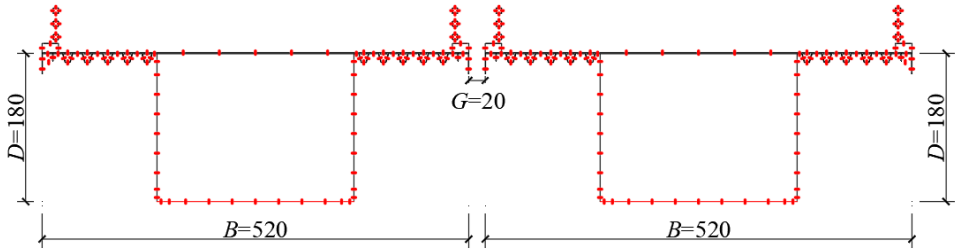


Figure 1: Dimensions and pressure tap arrangements for models (unit: mm)

As shown in Figure 1, The number of surface wind pressure taps of the steel box girder model is 104, respectively. Since the wind pressure changes sharply at the corners of the model surface, the pressure taps near the corners were appropriately densified. The test was conducted in a uniform flow field with a test wind speed of 10 m/s. In the experiment, the DTC series micro-ESP pressure scanning valve and DTC Initium data acquisition system produced by Pressure Systems were used to collect the wind pressure information at the pressure tap, with a sampling frequency of 330 Hz and a sampling time of 30 s.

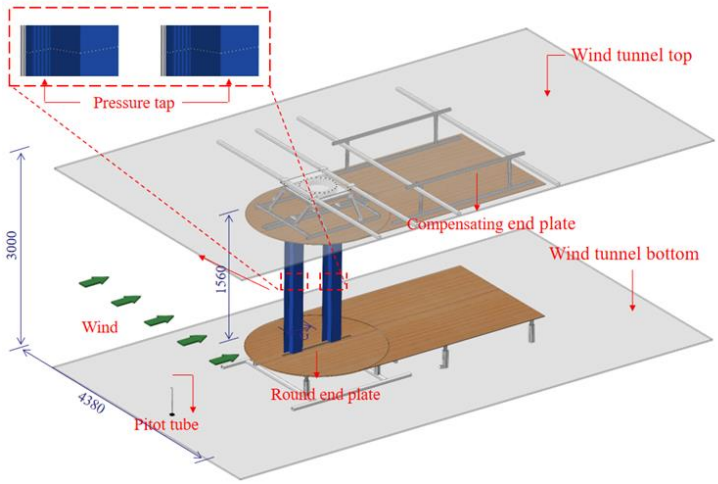


Figure 2: Diagram of the experimental setup

The installation of the test model setup is shown in Figure 2. The model has a length L of 1.56 m, a cross-section height D of 0.18 m and a width B of 0.52 m. The steel box girder model is fixed between the upper and lower circular end plates of the fixture through steel pipes inside the model, and the upper and lower circular end plates are independent of the compensation end plates. The rotation of the bottom turntable drives the circular end plates and the model to rotate together, thus realizing the adjustment of the wind angle of attack. The wind angles of attack of the test cases range from −5° to 5° at an interval of 1°. The spacing ratios of the test models are set as *G/B*=0.05, 0.1, 0.3, 0.5, 0.75, 1.0, 1.25 and 1.5.

2.2 Parameter definition

The instantaneous dimensionless wind pressure coefficient *Cp(i)* of the pressure taps on the surface of the girder model is defined as:

$$C_p(i) = \frac{P_i - P_o}{0.5\rho U^2} \tag{1}$$

Where *Pi* is the instantaneous wind pressure at the pressure tap on the surface of the main girder model; P_0 is the static pressure at the reference point in front of the main girder model; ρ is the air density; U is the incoming wind speed in front of the main girder model. The mean wind pressure coefficient *Cp* can be obtained by averaging the wind pressure coefficient time history.

The drag coefficient C_D and the lift coefficient C_L of the main girder are defined as:

$$C_D = \frac{F_D}{0.5\rho U^2 D} \tag{2}$$

$$C_L = \frac{F_L}{0.5\rho U^2 B} \tag{3}$$

The Strouhal number (*St*) is a dimensionless parameter characterizing vortex shedding frequency, and its calculation formula is expressed as:

$$St = \frac{fB}{U} \tag{4}$$

Where f is the vortex shedding frequency, which is obtained by the fast Fourier transform of the lift coefficient time history of the main girder.

The interference factor is used to quantify the difference in the three-component force coefficients between twin box girders and a single box girder. The closer the interference factor is to 1, the smaller the influence of aerodynamic interference on the aerodynamic forces of the twin box girders; the farther it is from 1, the greater the influence of such interference.

$$IF_D = \frac{C_D \text{ of twin box girders}}{C_D \text{ of single box girder}} \tag{5}$$

$$IF_L = \frac{C_L \text{ of twin box girders}}{C_L \text{ of single box girder}} \tag{6}$$

Where F_D and F_L are the drag force and lift force per unit length in the wind axis system, respectively; *B* and *D* are the width and height of the main girder, respectively. As shown in Figure 3, the positive value of the drag coefficient indicates that the main girder experiences a force in the direction of the tailwind, while a negative value indicates the opposite. The positive value of the lift coefficient indicates that the main girder experiences an upward force due to crosswinds, while a negative value indicates the opposite. α represents the wind angle of attack, and it is defined as the

positive wind angle of attack when the incoming speed blows obliquely upward from the left side of the main girder.

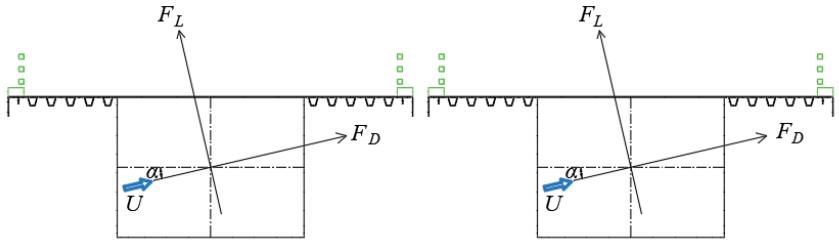


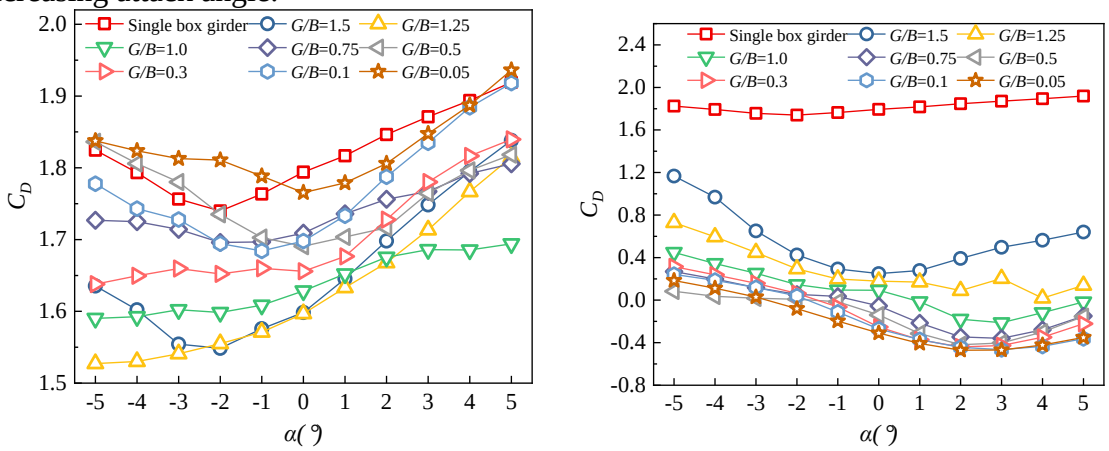
Figure 3: Definition of wind angle of attack and aerodynamic forces

3. Aerodynamic Characteristics Analysis

3.1 Aerodynamic Force Coefficient

To clarify the variation law of aerodynamic coefficients of twin bluff body steel box girders with wind angles of attack, the curves of aerodynamic coefficients versus wind angles of attack were plotted.

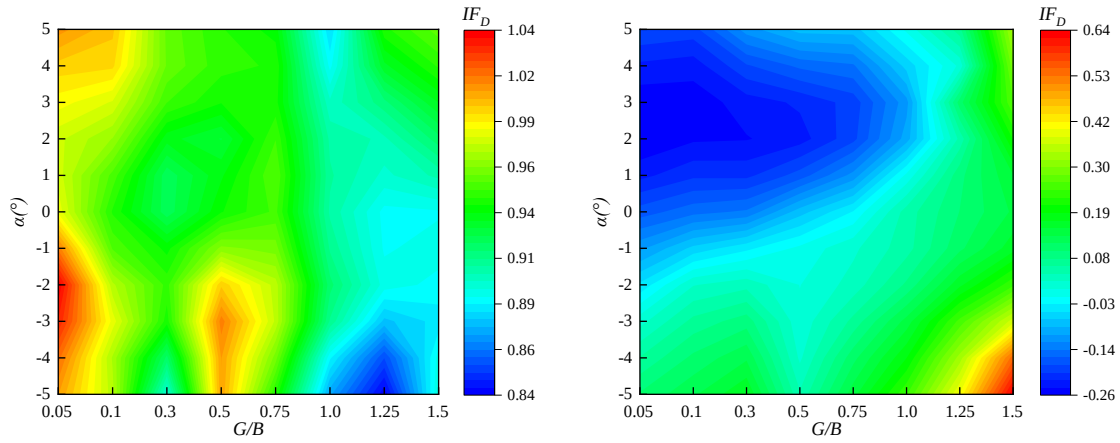
Figure 4 shows the differentiated responses of drag coefficient to angles of attack. The windward drag coefficient increases monotonically only at G/B = 0.3, 1.0, and 1.25, and first decreases then increases at other spacing ratios. Ranging from 1.527 to 1.936, the windward drag coefficient reaches its minimum at G/B = 1.25, $\alpha = -5°$ and maximum at G/B = 0.05, $\alpha = 5°$. Within $0° \leq \alpha \leq 4°$, it stays below the single box girder value for all spacing ratios, and exceeds the single box girder value only at very small spacing ratios under partial attack angles. The leeward drag coefficient ranges from −0.471 to 1.167 (minimum at G/B = 0.05, α = 2 °, maximum at G/B = 1.5, $\alpha = -5°$), remains lower than the single box girder value at all attack angles, and exhibits a first-decrease-then-increase pattern with increasing attack angle.



(a) Windward of twin box girder (b) Leeward of twin box girder

Figure 4: Drag coefficients of twin box girders versus wind angle of attack

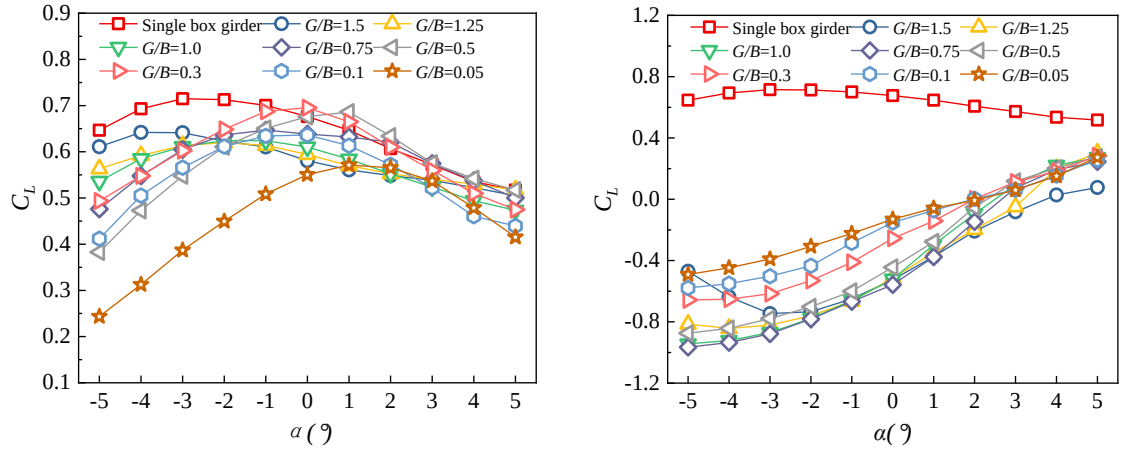
Figure 5 shows the interference factors of drag coefficients for windward and leeward box girders. The windward box girder shows an almost overall suppression effect, strongest at G/B = 1.25, α = −5 °. The leeward box girder also shows an overall suppression effect, strongest at G/B = 0.05, α = 2 °. The suppression effect is generally higher in the positive wind angle of attack range than in the negative range, and weakens gradually with increasing spacing ratio in the positive range.



(a) Windward of twin width girder (b) Leeward of twin box girder

Figure 5: Interference factor of drag coefficient for twin box girders

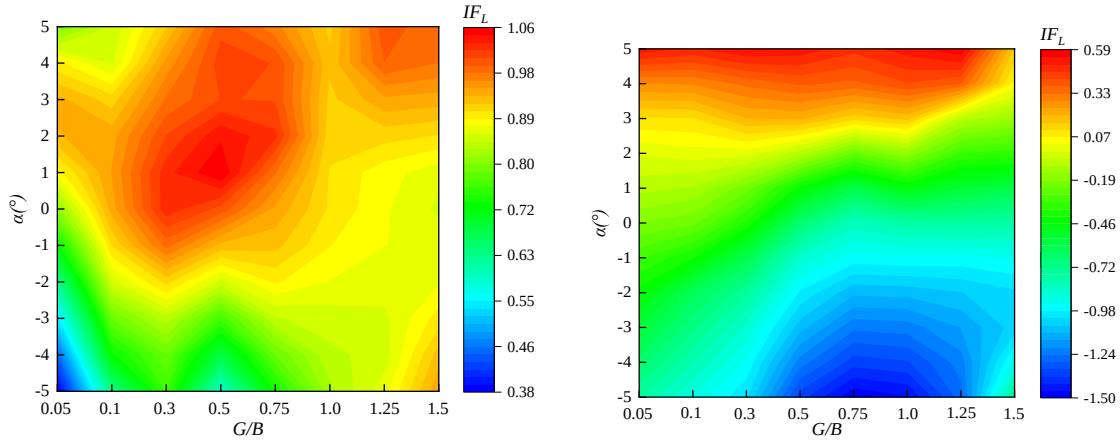
Figure 6 shows the differentiated responses of lift coefficient to angles of attack. The windward lift coefficient ranges from 0.243 to 0.695, with the minimum at $G/B = 0.05$, $\alpha = -5°$ and the maximum at $G/B = 0.3$, $\alpha = 0°$. It remains smaller than the single box girder value at all spacing ratios under negative attack angles, and is also lower at most spacing ratios within $0° \leq \alpha \leq 5°$. The windward lift coefficient first increases and then decreases with rising attack angle. For windward girders with $G/B > 0.5$, the lift coefficient increases with spacing ratio at negative wind angles of attack but shows the opposite trend at positive angles. For the leeward girder, the lift coefficient ranges from −0.966 to 0.302 (minimum at $G/B = 0.75$, $\alpha = -5°$; maximum at $G/B = 1.25$, $\alpha = 5°$) and stays below the single box girder value at all spacing ratios. At negative attack angles, it first decreases and then increases with growing spacing ratio, whereas no clear trend appears at other angles.



(a) Windward of twin box girder (b)Leeward of twin box girder

Figure 6: Lift coefficients of twin box girders versus wind angle of attack

Figure 7 shows the interference factors of lift coefficients for windward and leeward box girders. The windward box girder shows an overall suppression effect, strongest at $G/B = 0.05$, $\alpha = -5°$. The leeward box girder also shows a suppression effect, strongest at $G/B = 0.75$, $\alpha = -5°$. The interference effect weakens gradually with increasing wind angle of attack.



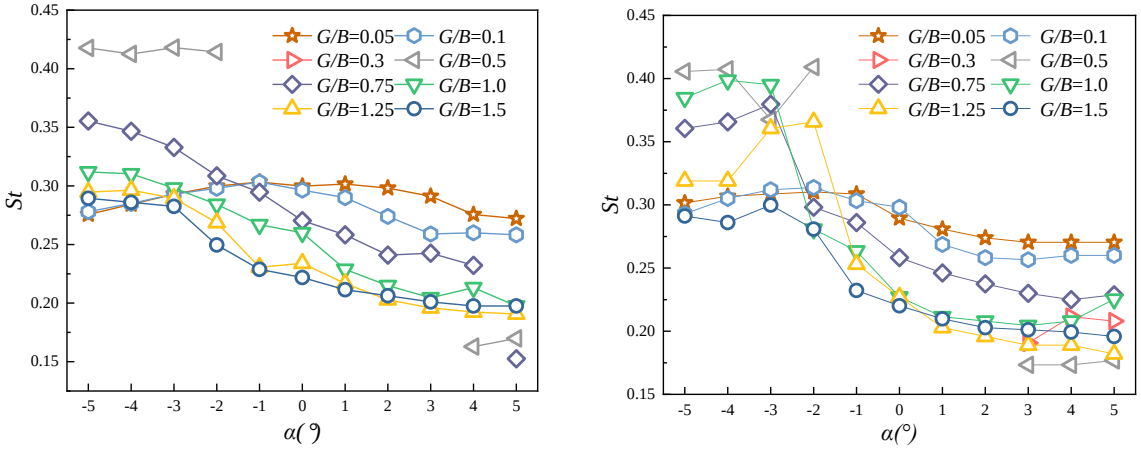
(a) Windward of twin width girder (b) Leeward of twin box girder

Figure 7: Interference factor of lift coefficient for twin box girders

3.2 Vortex Shedding Characteristics

Based on wind tunnel tests, this chapter analyzes the Fourier amplitude spectra of lift coefficients for windward and leeward box girders of twin bluff steel box girders under different spacing ratios and wind angles of attack. And reveals the coupled regulation mechanism of spacing ratio and wind angle of attack on vortex shedding frequency.

As shown in Figure 8 the variation curves of the Strouhal number of the windward box girder with wind angle of attack indicate that St exist at all wind angles of attack except for G/B = 0.3 and 0.5, and the amplitude of the St decreases gradually with the increase of the spacing ratio at positive wind angles of attack. For G/B = 0.5, the St only exists when the absolute value of the wind angle of attack is large. For the leeward box girder, the St decreases with the increase of the spacing ratio at positive wind angles of attack except for G/B = 0.3, 0.5 and 1.25. For G/B = 0.3, the St only exists at large wind angles of attack, while for G/B = 0.5, it only exists when the absolute value of the wind angle of attack is large.



(a) Windward (b) Leeward

Figure 8: Variation curves of Strouhal number with wind angle of attack at different spacing ratios for twin steel box girders

4. Conclusions

Wind tunnel tests were employed to systematically explore the aerodynamic characteristics of twin

bluff body steel box girders with various spacing ratios. The main conclusions are summarized as follows:

(1) The leeward girder has little influence on the windward girder, whereas the windward girder exerts a shielding effect on the leeward girder. Consequently, the drag coefficient of the leeward girder is lower than that of the single box girder. The suppression effect on the drag coefficient of the leeward girder is generally stronger at positive wind angles of attack and weakens as the spacing ratio increases.

(2) The windward girder exerts a shielding effect on the leeward girder. The lift coefficients of the leeward girder are lower than those of the single box girder but gradually approach them as the wind angle of attack increases. Aerodynamic interference primarily manifests as a suppression effect on the lift coefficients of both girders. This interference weakens as the angle of attack increases.

(3) Clear Strouhal numbers can be identified for most angles of attack, except under certain spacing-ratio conditions. For both girders, the Strouhal number generally decreases with increasing spacing ratio at positive angles of attack.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declarations

Competing interest

Non-financial competing interests.

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