Effects of Railings on Torsional Vortex-induced Vibration of a Long-span Bridge Based on Flow Field Visualization

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Abstract. An experimental investigation was conducted to investigate the effects of railings on the torsional vortex-induced vibration (VIV) of a single-box girder bridge. This study undertakes a comparative analysis of the torsional VIV characteristics of a bridge girder in two configurations: with railings and without railings, and provides a detailed analysis of the periodic wake flow features. The results show that the VIV characteristics of the bridge, including the initial wind speed, the peak vibration amplitude, and the lock-in range, are significantly influenced by the presence of railings. Flow field visualization tests reveal that, compared to the bare girder, the girder with railings generates larger-scale vortex structures in the wake and exhibits an altered vortex shedding mode.

Keywords: long-span bridge; vortex-induced vibration; railing; wind tunnel test; flow field visualization

1 Introduction

Advancements in new materials and construction methodologies, coupled with the escalating demands of contemporary traffic systems, have facilitated the construction of cable-stayed and suspension bridges with progressively longer spans. Nevertheless, as the main span increases, it inevitably leads to greater flexibility and reduced damping, making the bridge structure more sensitive to wind effects. Vortex-induced vibration (VIV), a typical type of wind-induced oscillation, which occurs in numerous long-span bridges. While VIV exhibits limited amplitude and is not as devastating as flutter, it can still lead to persistent oscillations with relatively significant amplitudes at low wind velocities. Furthermore, in the context of vehicular traffic, VIV can induce discomfort among drivers, and from a structural perspective, it may contribute to long-term fatigue degradation.

Streamlined closed-box girders have gained prominence in long-span bridges owing to their superior aerodynamic characteristics. Nevertheless, the complete elimination of alternating vortex shedding generated from the trailing edge remains elusive, which can still induce VIVs [1]-[3]. Additionally, the ancillary components to the bridge for traffic safety and routine maintenance purposes—such as railings, dividers and maintenance

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rails—are able to alter the aerodynamic shape of the main girder, thereby exerting a notable influence on the VIV characteristics. In recent decades, an extensive body of research has been dedicated to investigating the impact of bridge ancillary components on the VIV characteristics of bridges [4] . Nguyen et al. (2022) [5] examined the impact of barrier geometry on wind-induced instability of the girder and proposed an optimal shape configuration to augment the aerodynamic stability of the bridge. Yao et al. (2023) [6] discovered that the incorporation of railings significantly degraded the aerodynamic performance of the suspension bridge, resulting in considerable VIVs at wind angles of attack of +3° and +5°.

The main objective of this study is to investigate the effects of the railings on the torsional VIV characteristics and the corresponding periodic flow features of a classic single box girder.

2 Experimental Configuration

2.1 Test models and Flow Conditions

The section model was 830 mm long, 387.5 mm wide, and 50 mm high, at a scale of 1:80, simulating the aerodynamic geometry of a single box girder section of a long-span bridge, as shown in Fig.1. Additionally, the railing consisted of three horizontal bars and 17 vertical columns. The vertical columns were spaced 50 mm apart, and the spacing of horizontal bars is also evenly arranged.

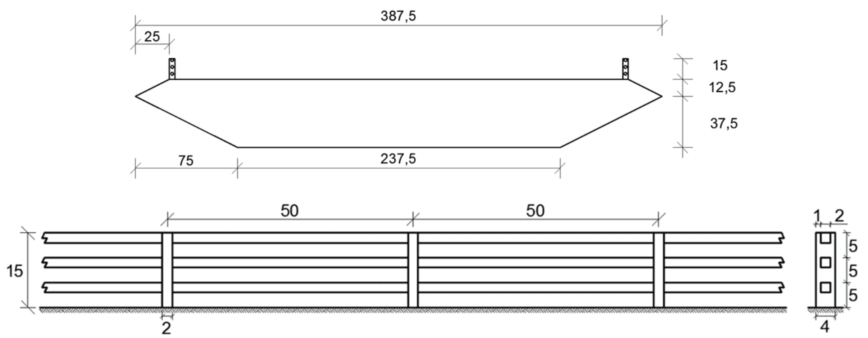


Fig. 1. Geometrical dimensions of (a) the bridge model (b) the railing

The experiment was carried out in a closed-circuit wind tunnel, featuring a test section with dimensions of 5 meters in length and 1 meter in height. The wind tunnel was capable of generating wind velocities ranging from 1.8 to 70 meters per second, with an incremental precision of 0.1 meters per second. In this study, the test wind velocities ranged from 2.0 to 8.2 m/s. The bridge model was installed within the wind tunnel utilizing an external suspension system comprising lever arms and eight coil springs. The torsional frequency of the test model was determined to be 10.8 Hz, with a damping ratio of 0.18%.

2.2 Measurement Apparatus

As illustrated in Fig. 2, two laser displacement sensors were mounted on one lateral surface of the sectional model for the purpose of measuring wind-induced torsional responses. The displacement signals were subsequently captured and recorded through a dedicated data acquisition system. The torsional displacements of the bridge model were quantified as follows:

$$\alpha = 180 \times (y1 - y2)/\pi d \quad (1)$$

where α represents the torsional displacement of the test model; y1 and y2 represent the vertical displacements measured by two laser displacement sensors; and d is the horizontal distance between these two displacement sensors.

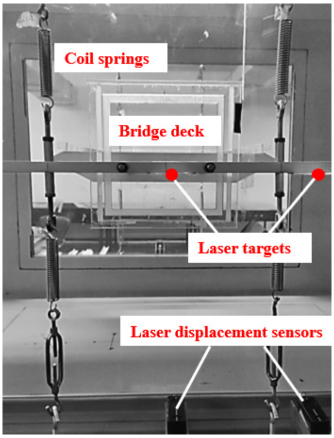


Fig. 2. Testing system

The flow field velocity was measured using a two-dimensional (2D) PIV system comprising a digital CCD camera, a double-pulsed Nd:YAG laser (380mJ, 532nm wavelength), a seeding generator and a Laser pulse computer controlled synchronizer. Two flow field measurement planes were selected in the wake of the bridge model: the x-y plane and the x-z plane, the directions of the defined coordinate axes are shown in Fig.3.

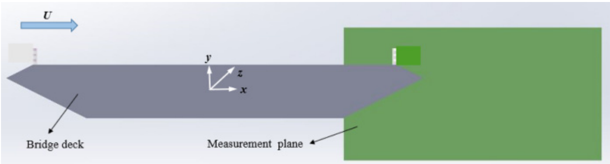


Fig. 3. x-y measurement plane

3 Test Results

3.1 VIV Response

Fig. 4 presents a comparison of the torsional VIV displacements of the bridge model in two scenarios: one with the presence of railings and the other without. The incorporation of railings resulted in an expansion of the VIV lock-in range, a delay in the initial wind velocity of VIV, and an augmentation of the peak dimensionless torsional response, RMS(α), from 0.26 to 0.43. It demonstrates that adding railings adversely affects the VIV performance of the bridge structure due to the increased overall bluffness of the bridge deck.

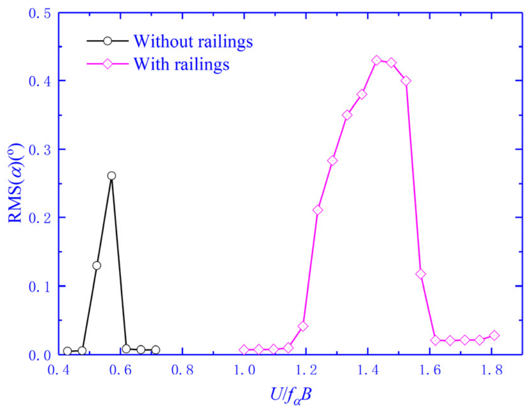
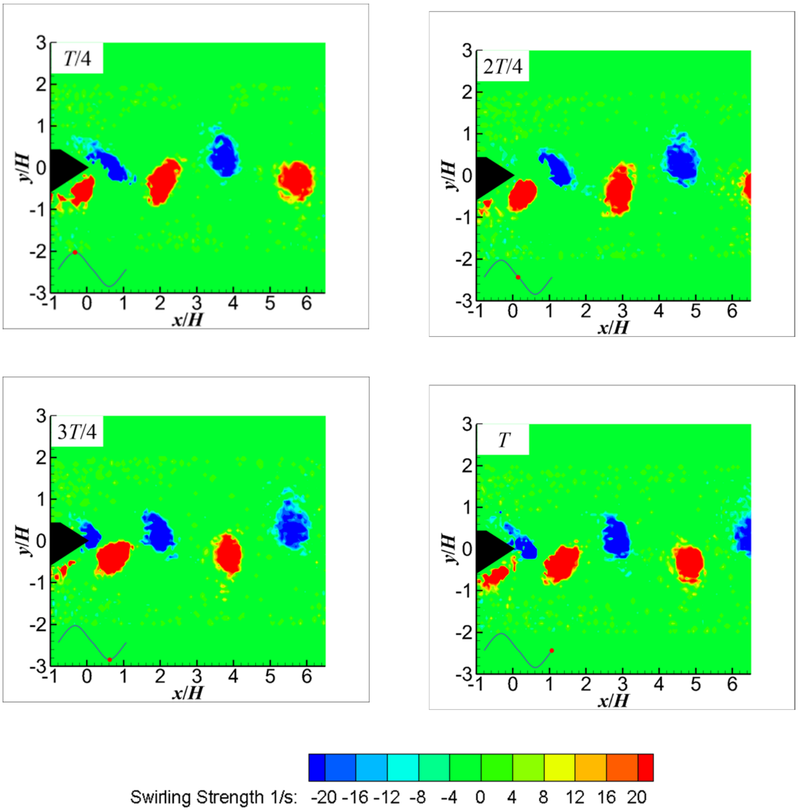


Fig. 4. Comparison of torsional VIV response with and without railings

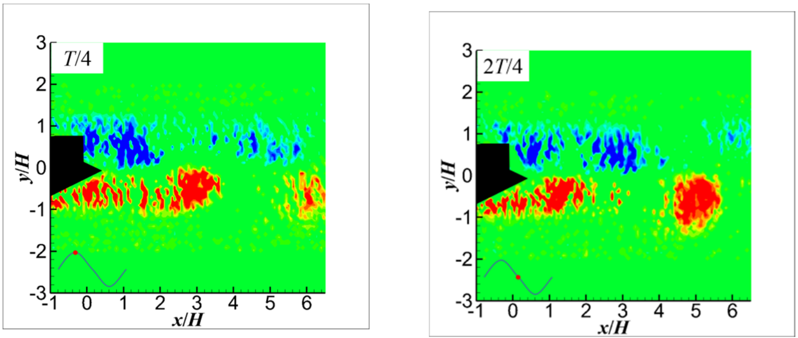
3.2 Flow Field Visualization Results

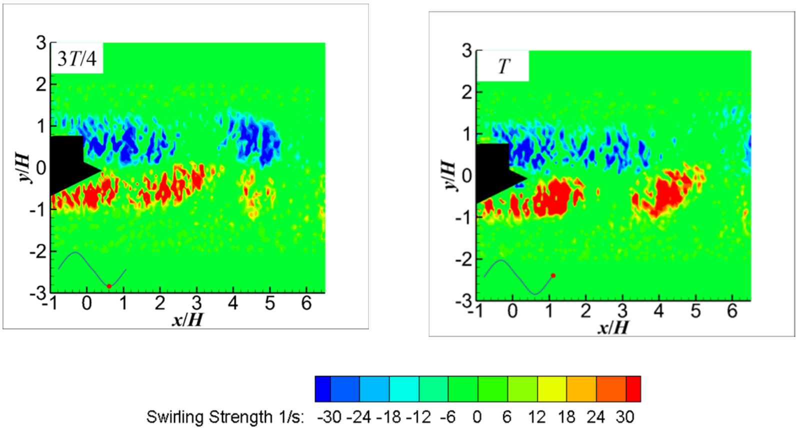
As illustrated in Figure 4, the bridge girder, both without and with railings, demonstrated notable torsional VIVs. Specifically, the girder without railings exhibited significant VIVs at a reduced wind speed of U/fαB=0.52, whereas the girder with railings displayed significant VIVs at a reduced wind speed of U/fαB=1.33. These two wind speeds were selected for PIV tests to investigate the wake flow field characteristics of the bridge girder under torsional VIVs. The evolution process of the wake spanwise (z-axis) vortex is shown in Fig.5. It can be observed from Fig.5(a) that, for the bare girder, during one period of torsional VIV, alternating spanwise vortex structures are shed from the upper and lower trailing edges of the box girder. At T/4, when the main girder reaches its maximum counterclockwise torsional angle, the vortex structure at the upper trailing edge begins to shed. At 3T/4, as the main girder reaches its maximum clockwise torsional angle, shedding occurs from the lower trailing edge. The alternating vortices are symmetrical in shape, strength, and shedding position, indicating a "2S" vortex-shedding mode. Fig. 5(b) shows that when the main girder with railings undergoes torsional VIVs, the scale of spanwise vortices in the wake region significantly increases.

Additionally, the shedding mode changes: within one torsional vibration period, spanwise vortices are shed twice from both the upper and lower trailing edges of the box girder, corresponding to a "2P" vortex-shedding mode.



(a) Bare girder

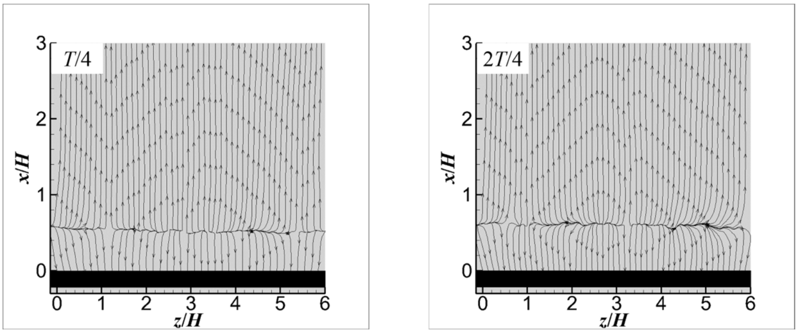


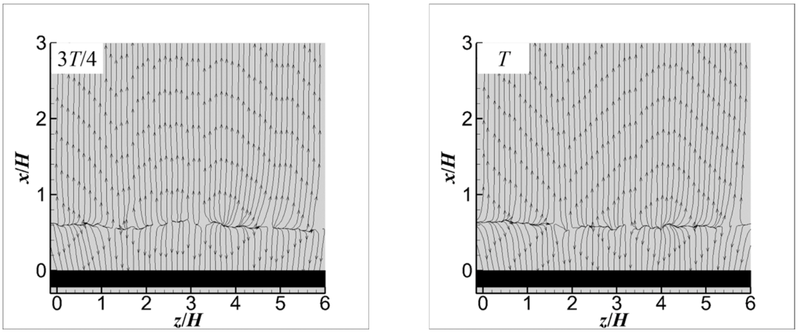


(b) Girder with railings

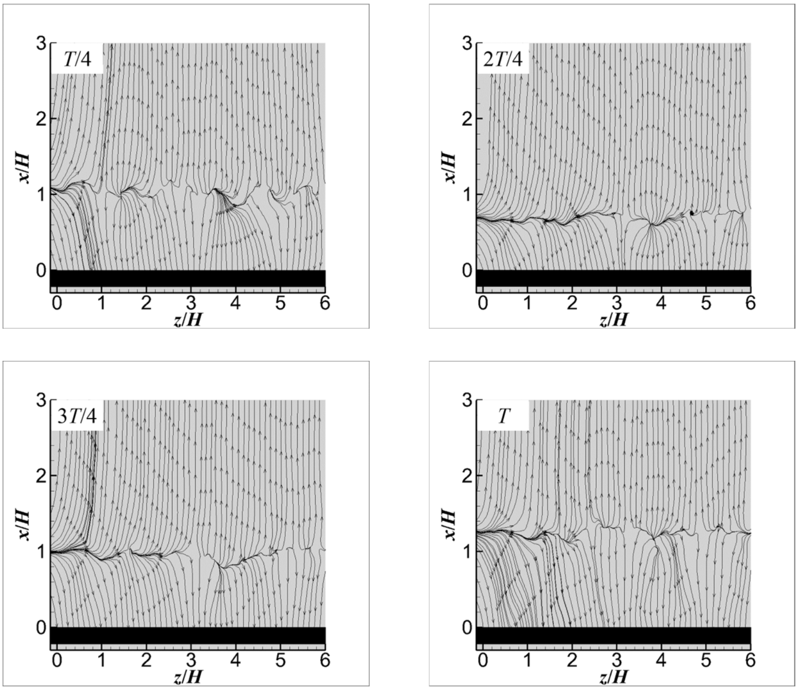
Fig. 5. Evolutionary process of wake spanwise vortex

Fig.6 shows the wake streamline of the bridge girder in the x-z plane. It can be seen from Fig.6(a) that the wake recirculation region of the bare girder remains stable in both length and shape at all times. Throughout one torsional VIV period, the wake region width of the bare girder consistently maintains approximately 0.6H (H is the height of the girder), with velocity streamlines displaying a well-organized distribution along the flow direction (x-axis), indicating a strong two-dimensional flow characteristic. In contrast, the wake recirculation region of the main girder with railings (Fig.6(b)) shows an increased length, and the edges of the recirculation region exhibit an irregular spanwise distribution. It suggests that the addition of railings on the girder surface enhances the three-dimensional characteristics of the wake flow to some extent.





(a) Bare girder



(b) Girder with railings

Fig. 6. Evolutionary process of wake streamline

4 Conclusions

In this study, wind tunnel experiments were conducted to investigate the effects of railings on the torsional VIV of a single-box girder bridge. The torsional VIV characteristics and flow field behavior of the bridge girder without and with railings, were analyzed in detail. The major conclusions are as follows:

- The addition of railings inevitably alters the aerodynamic profile of the bridge girder, thereby affecting the torsional VIV performance of the bridge. Specifically, the presence of railings expands the VIV lock-in range, increases the peak VIV response, and delays the onset wind speed of torsional VIV.
- For the bare girder, during one period of torsional VIV, alternating spanwise vortex structures are shed once from the upper and lower trailing edges of the box girder, representing a typical '2S' mode. With the addition of railings, counter-rotating spanwise vortices shed alternately twice per torsional vibration period, corresponding to a '2P' mode.
- The addition of railings increases the width of the wake recirculation region of the main girder and cause the edge of the recirculation region irregular, indicating an enhancement of the three-dimensional characteristics of the wake flow.

In future research, a comprehensive investigation will be conducted into the influence of other bridge components, including maintenance rails and dividers, on the vortex shedding modes of the bridge girder. This analysis will provide a foundation for optimizing the design of bridge ancillary facilities.

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