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Vortex-induced vibration characteristics of double-slotted box girder of a long-span bridge

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SUMMARY
Double-slotted box girder is a novel main girder for long-span bridges. Wind tunnel tests based on a spring-suspended sectional model were performed to investigate its vortex-induced vibration (VIV) performance and aerodynamic effects. For vertical VIV, aerodynamic forces on the upper and lower surfaces of the upstream box, upper surface of the middle box, and rear regions of the downstream box positively contribute to VIV. The vortex-related flow pattern is illustrated by combining vortex drifting theory and a simplified vortex model, and the front lower surface of the middle box is significantly affected by vortices in the windward slot. For torsional VIV, strong disturbances from wind barriers and balustrades induce large-amplitude torsional VIV with considerable excitation forces. Interactions between slotted airflow and the girder generate stronger torque, and wind pressures on key parts including the windward box's upper surface and leeward box's upper and lower surfaces further promote torsional VIV.

Keywords: Double-slotted box girder, Vortex-induced vibrations, Aerodynamic characteristics

1. Introduction

An increasing number of bridges are constructed with complicated cross-section types to improve their aerodynamic characteristics, thus ensuring long-span bridge safety under extreme wind loads. For instance, a double-slotted box girder was adopted in the Messina Bridge to improve its flutter characteristics (Jurado et al., 2007; Diana et al., 2013). The aerodynamic characteristics of long-span bridges, especially slotted box girder bridges, are more sensitive to vortex-induced vibrations (VIVs) than to flutter instability.In bridge engineering, VIV of streamlined closed-box girder is widely studied (Zhao et al., 2022). To enhance the flutter stability, central-slotted box girders have been widely used in long span bridges. Many investigations showed that there are obvious differences between flow field and aerodynamic force distribution characteristics around streamlined closed-box girder and central-slotted box girder (Zhao et al., 2019). However, investigations on the VIV of double-slotted box girder remain relatively lacking. This study investigates the performance of vertical VIVs and torsional VIVs for a double-slotted box girder through wind tunnel tests on a sectional model, with comprehensive analyses conducted from multiple perspectives.

2. Methods

Using a real double-slotted box girder as a prototype, a spring-suspended sectional model was designed and manufactured with a geometric scale ratio of 1:30. The model is a thin-walled multiple box structure with a length, width, and height of 6.000, 2.267, and 0.167 m, respectively. A strip of 115 pressure taps is arranged around a section in the middle of the model. Additional bridge facilities include railway barriers, highway barriers, balustrades, and maintenance rails. Free vibration tests under uniform flow were conducted in the TJ-3 wind tunnel.

3. Results

Two vertical VIV lock-in regions exist within the range of tested wind velocity. The first lock-in region is selected as the representation to discuss in the following sections. Typical cases were selected: the onset point (pre-VIV stage), the peak response point (extreme amplitude point), the decline point (descent stage), and the vibration cessation point (post-VIV stage).The torsional VIVs' amplitude with different additional structural elements was measured. No VIVs were generated with the installation of maintenance rails. This was in contrast to balustrades and wind barriers, which generate large torsional VIVs. Torsional VIV lock-in ranges for different Scruton numbers were measured. The real structural damping should be greater than 5.7‰ to avoid torsional VIVs and no torsional VIVs are produced while damping is 11‰.

4. Discussion

4.1. Vertical VIV

The analysis results of the wind pressure distribution is shown in Fig. 1. The influence of the distributed aerodynamic force on the general vortex-excited force (VEF) can be described using the product of the correlation coefficient and the fluctuating pressure. The distributed aerodynamic forces on most of zones on the model surface all participate in the process of generate general VEF. This is not observed in the streamlined closed-box girder and the central-slotted box girde. Double-slotted box girder may be more prone to experience VIV than the other sections.

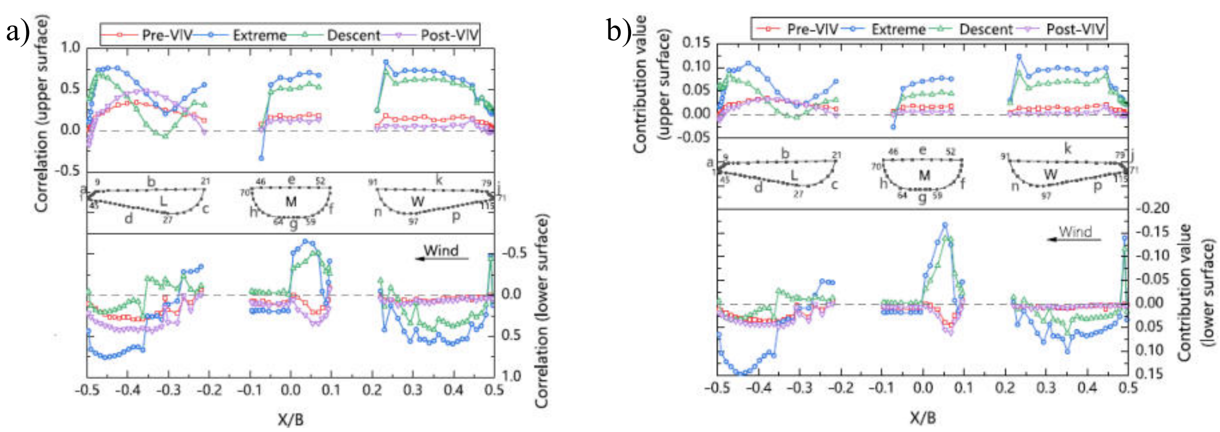

Figure 1 Aerodynamic characteristics of the double-slotted box girder (a) Distribution of correlation coefficient. (b) Distribution of contribution values.

Hu et al. (2021, 2022) elucidated that the potential lock-in region for vertical VIV of a streamlined closed-box girder occurs when vortices shed from the leading edge arrive at the trailing edge after n complete vibration periods (n = 1, 2, 3...). The simplified vortex are summarized in Fig. 2. Through the ansysis of the phase lag, there are vortices drifting periodically on the upper and lower surfaces of the downstream box. The characteristics of vortex on the upper surface corresponds well with the simplified vortex model of streamlined closed-box girder. The periodic vortex drifting on the downstream box is one of the causes for the occurrence vertical VIV .

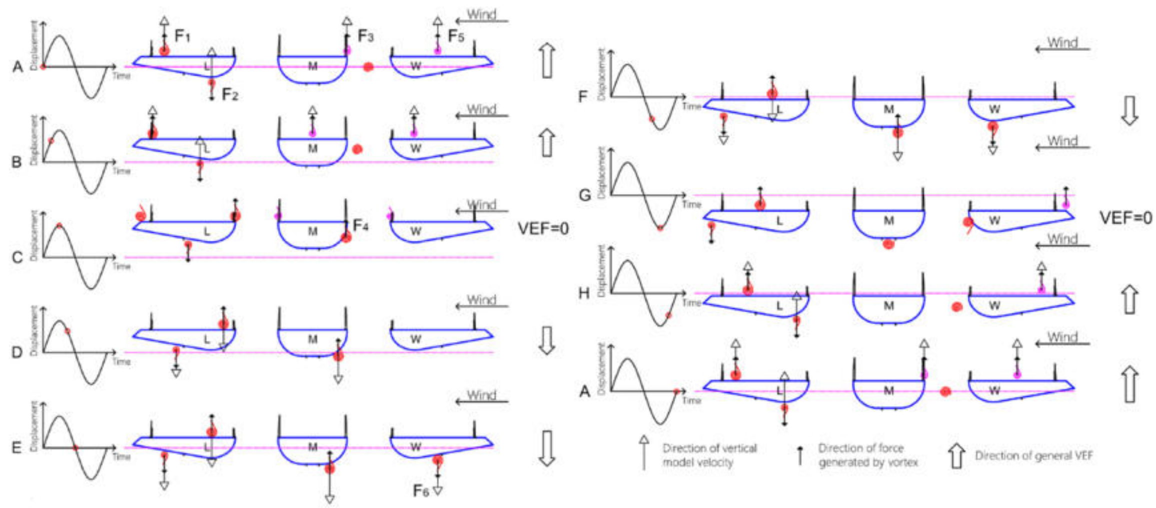

Figure 2 Schematic of simplified vortex flow pattern during vertical VIV.

4.2. Torsional VIV

The relationship between the distributed VEFs and the overall aerodynamic force is displayed in Fig. 3. The wind barriers on the highway deck would greatly amplify the correlations between the local VEFs on the upper surface and the overall VEFs. However, a cover plate with 30% porosity can reduce the correlations between the distributed wind pressures and the overall VIVs compared with Case A. The local VEFs of the upper surface of the windward, upper, and lower surfaces of a leeward girder dominate the torsional VIVs of a double-slotted box girder to a large extent. The regions of II to IV, V to VI, and X to XI were the key regions where the local VEFs promoted torsional VIVs significantly for the double-slotted box girder. The wind barriers on the highway and railway deck surfaces were more sensitive to the torsional VIVs.

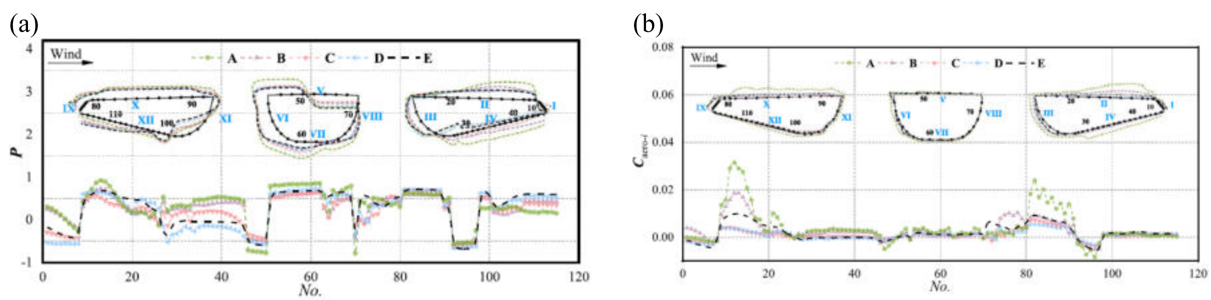

Figure 3 Aerodynamic characteristics of the girder (Case A: all elements; Case B: excluding highway barriers; Case C: balustrade and maintenance rails only; Case D: maintenance rails only; Case E: all elements with 30% porosity cover plate). (a) The correlation coefficient; (b) The contribution values of the pressure coefficient.

Large Eddy Simulation(LES) is utilized to analyze the flow pattern characteristics (Fig. 4). The wind flows across the slotted parts and interacts with the girder and additional elements, resulting in a large torque moment, while wind flow impacts the balustrades on the leeward highway deck, which would exhibit the VIV response. Furthermore, after the barriers were installed, the torque moment effects were enlarged to a large extent while the wind flowed across the slotted parts. When the slotted part was covered by a plate with 30% porosity. The wind flow at the lower girder surface could pass through a few small-sized vortices and the torque moment effect was depressed.

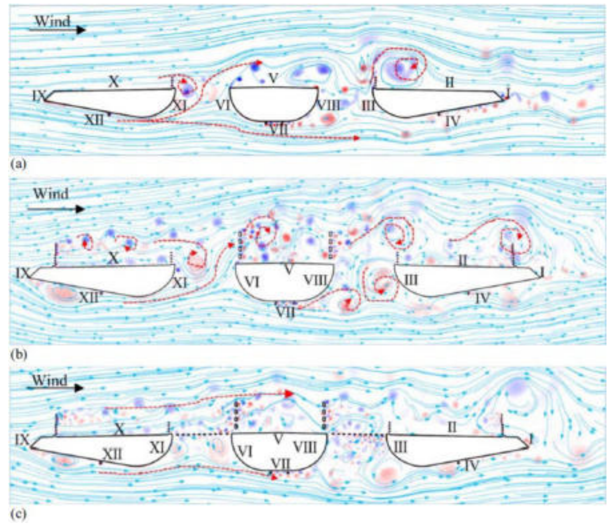

Figure 4 Flow pattern around the double-slotted box girder: (a) flow pattern in Case B; (b) flow pattern in Case A; and (c) flow pattern in Case E

5. Conclusions

1) When vertical VIV occurs, the contributions of most zones are positive. The double slots may weaken the performance of the bridge against VIVs. A vortex periodically drifts on the upper surface of the downstream box. However, different aerodynamic contribution mechanisms may exist on the upper surface of the girder, particularly in the upstream and middle boxes.

2). When torsional VIV occurs, maintenance rails have limited effects. In contrast, the installation of balustrades and wind barriers induces large torsional VIV amplitudes. The use of a cover plate with 30% porosity is considered a reasonable measure to suppress torsional VIVs. The wind pressure characteristics in the key regions of the upper surfaces of the windward and leeward girders make greater contributions to the overall vortex-induced forces than in the other regions.

6. Acknowledgement

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