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Vortex-induced vibration performance and suppression mechanism of spanwise spoilers for separated twin rectangular box girders

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SUMMARY

Vortex-induced vibration (VIV) of separated twin rectangular box girders is investigated based on the Optics Valley suspended monorail cable-stayed bridge in Wuhan. Sectional model tests and smoke-wire flow visualization are conducted to examine VIV responses, flow structures, and the effectiveness of spanwise spoiler baffles (SSBs). The original girder exhibits pronounced vertical VIV at attack angles of −3°, 0°, and +3°, with the strongest response at 0°, while the VIV lock-in wind-speed range shows weak angle sensitivity. Smoke-wire images reveal that a large-scale gap vortex in the central slot under dynamic conditions is the dominant excitation source. With SSBs installed, VIV amplitudes are reduced by over 70%, owing to suppressed gap vortex formation and induced spanwise phase differences in vortex shedding, which significantly reduce the resultant aerodynamic forces.

Keywords: *separated twin rectangular box girders; wind tunnel test; vortex-induced vibration; vibration suppression measures*

1. INTRODUCTION

Vortex-induced vibration (VIV) not only compromises the serviceability of bridges but may also lead to fatigue damage under long-term cyclic loading. Separated twin rectangular box girders, consisting of two parallel quasi-rectangular sections separated by a central slot, have been applied in engineering practice, such as the Wuhan Optics Valley Sky Rail cable-stayed bridge. Owing to the complex aerodynamic interference between the upstream and downstream box sections, this structural configuration is prone to large-amplitude VIV under wind excitation(Laima et al, 2013).

Existing studies on tandem rectangular cylinders (Duan et al, 2025) or separated twin box girders (Zhu et al, 2025) have mainly focused on independently arranged cylinders or streamlined cross-sections. For the separated twin rectangular box girder with pronounced bluff-body characteristics and a fixed central slot, systematic investigations on VIV behavior and suppression measures remain limited. Moreover, current aerodynamic control strategies are largely based on two-dimensional flow control concepts, whereas three-dimensional flow control offers advantages in both control efficiency and economic feasibility by disrupting spanwise aerodynamic coherence(Chen et al, 2019).

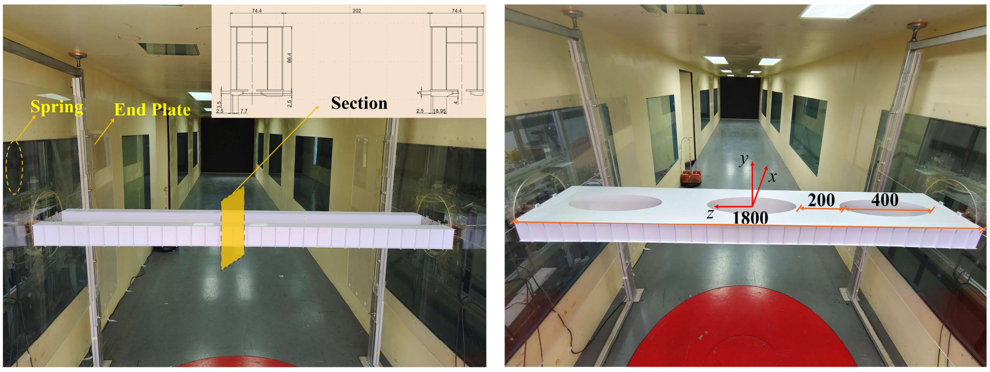
Accordingly, this study proposes the installation of spanwise spoiler baffles (SSBs) in the central slotted region as a three-dimensional aerodynamic control measure. Wind tunnel tests are conducted to investigate the VIV characteristics and flow features, with emphasis on the suppression performance and underlying mechanisms of SSBs.

2. EXPERIMENTAL SETUP

Wind tunnel tests were conducted in the CSU-WT4 wind tunnel at Central South University, with a turbulence intensity below 1%. A 1:20 scale sectional model with a spanwise length of 1.8 m was employed. The cross-section comprises two parallel quasi-rectangular box girders with a total width of 0.351 m, a height of 0.086 m, and a central slot width of 0.20 m, as illustrated in Fig.

1a.

The sectional model was elastically suspended to permit vertical and torsional degrees of freedom, with displacement responses measured using laser displacement sensors. Wind attack angles of −3°, 0°, and +3° were investigated for both the original configuration and the model equipped with SSBs. As shown in Fig. 1b, the SSBs feature elliptical openings designed to match the elliptical bridge towers of the Wuhan Optics Valley Sky Rail cable-stayed bridge. Smoke-wire flow visualization experiments were also conducted to investigate the flow characteristics under both static and dynamic conditions.



(a) Original girder

(b) Girder with SSBs

Figure 1 Cross-sections of the original girder and the girder equipped with SSBs

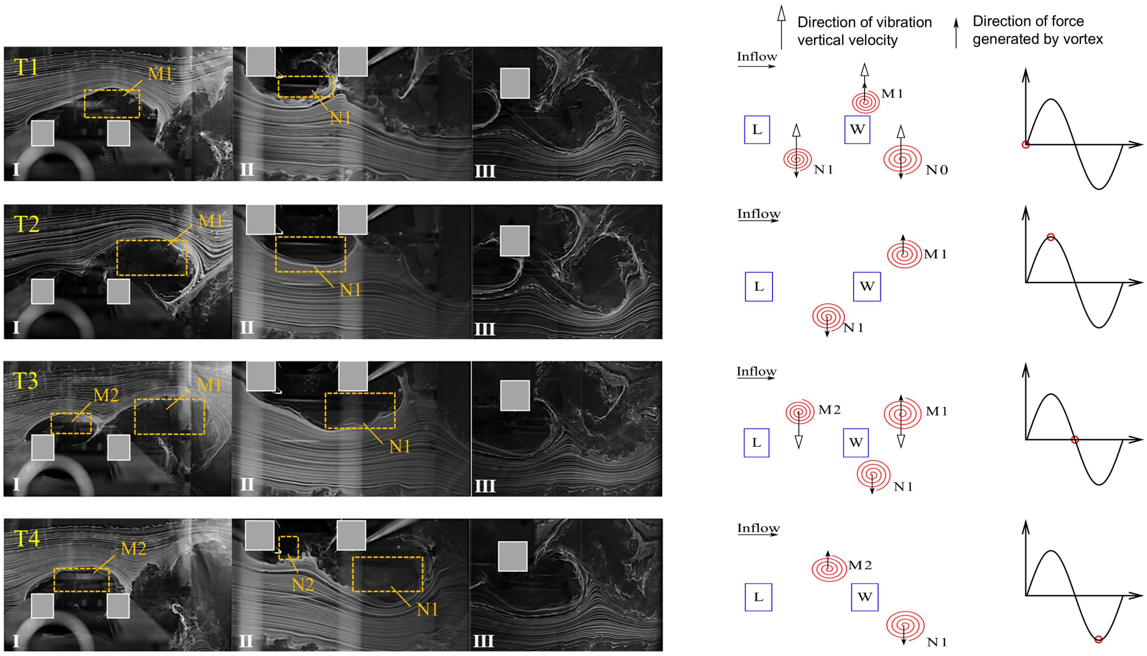
3. RESULTS AND DISCUSSION

3.1. VIV Characteristics of the Original Structure

The separated twin rectangular box girder exhibits pronounced vertical VIV at wind attack angles of −3°, 0°, and +3°, with the most significant response occurring at 0°. The VIV lock-in wind-speed range remains nearly identical across all attack angles, indicating that the overall VIV behavior is only weakly dependent on the angle of attack (Fig. 3).

Smoke-wire flow visualization reveals distinct flow features under static and dynamic conditions. Under static conditions, the flow around the two boxes resembles a single-bluff-body regime with alternate vortex shedding in the wake. In contrast, under dynamic conditions within the lock-in regime, a large-scale gap vortex develops in the central slotted region. This gap vortex originates from the upstream box, evolves coherently with the structural motion, and convects downstream before merging into the wake (Fig. 2a).

Based on the simplified vortex model proposed by (Hu et al, 2025), the phase-resolved analysis indicates that the gap vortex provides the primary aerodynamic energy input as the girder approaches maximum displacement, while its contribution diminishes after convecting into the wake (Fig. 2b). This confirms the central gap vortex as the dominant excitation source for the large-amplitude VIV.



(a) Smoke-wire flow visualization (b) Simplified vortex model

Figure 2 Flow field characteristics of the original girder during VIV: (a) smoke-wire visualization (I: upper region; II: lower region; III: wake region); (b) simplified vortex model

3.2. Vibration Suppression Effects and Mechanism

The VIV responses of the girder with SSBs are presented in Fig. 3. The maximum RMS displacements at wind attack angles of −3°, 0°, and +3° are reduced by 72.9%, 73.2%, and 71.3%, respectively. Despite a slight widening of the lock-in range, the consistent reduction ratios demonstrate the stable suppression performance of SSBs.

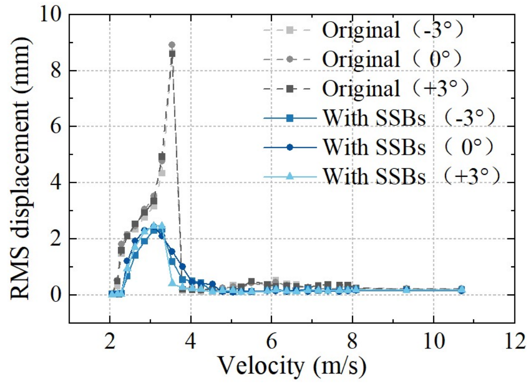
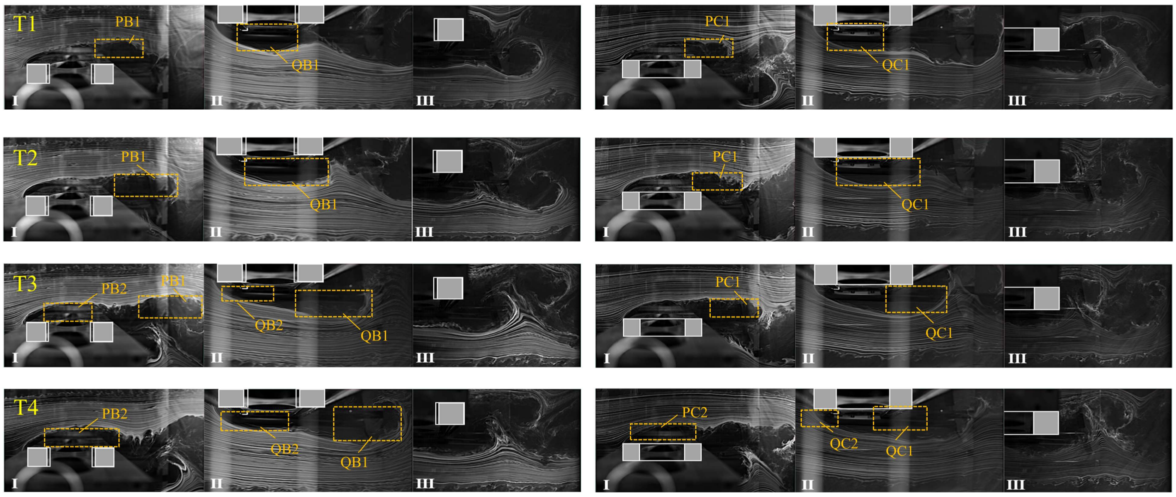


Figure 3 RMS displacement responses of the original girder and the girder with SSBs at different wind attack angles

Smoke-wire flow visualization provides insight into the suppression mechanism. As shown in Fig. 4a, at Section B (with baffle coverage), the boundary layer separates from the upstream box and bypasses the structure directly toward the wake, with no evident gap vortices observed throughout the vibration cycle. This flow pattern resembles the single-bluff-body regime observed under static conditions for the original configuration. A comparison between Sections B and C

(Figs. 4a and 4b) reveals a phase difference of approximately T/4 in vortex shedding, indicating that the SSBs disrupt the spanwise coherence of vortex shedding.

The suppression mechanism of SSBs can be attributed to two synergistic effects: (1) suppression of gap vortex formation, cutting off the primary energy transfer path; and (2) disruption of spanwise aerodynamic coherence, reducing the resultant aerodynamic force. This dual mechanism accounts for the consistent suppression efficiency across multiple attack angles.



(a) Section B with baffle coverage

(b) Section C at baffle opening

Figure 4 Smoke-wire flow visualization of the girder with SSBs during VIV: (a) Section B (with baffle coverage); (b) Section C (at baffle opening). (I: upper region; II: gap region; III: wake region)

4. CONCLUSIONS

(1) The original separated twin rectangular box girder exhibits pronounced vertical VIV at wind attack angles of −3°, 0°, and +3°. The large-scale gap vortex in the central slotted region is identified as the dominant excitation source, exhibiting strong energy coupling with structural motion.

(2) Installation of spanwise spoiler baffles (SSBs) in the central slotted region reduces VIV responses by over 70% at all tested attack angles, demonstrating stable suppression performance.

(3) The suppression mechanism is attributed to dual effects: suppression of gap vortex formation and disruption of spanwise aerodynamic coherence through phase differences in vortex shedding. SSBs represent an effective three-dimensional aerodynamic control strategy for this type of structure.

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