Study on integrated aerodynamic measures for improving flutter and vortex-induced vibration performance of flat steel box girders

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Integrated aerodynamic measures for improving the flutter and vortex-induced vibration (VIV) performance of flat steel box girders (FBGs) were studied with a long-span suspension bridge. The critical flutter wind speed and VIV response of the FBG were first evaluated through 1 : 60 scale section model wind tunnel tests, including aerodynamic measures such as an upper central stabiliser, inner guide vanes at the maintenance vehicle tracks and horizontal stabilisers. Results indicated that adding an upper central stabiliser improved the flutter stability of the FBG but increased the VIV amplitude. Setting inner guide vanes at the maintenance vehicle tracks eliminated VIV under vertical and torsional damping ratios of 0.28% and 0.21% respectively, but significantly reduced the critical flutter wind speed. Horizontal stabilisers alone did not improve wind-induced stability. The combined use of the upper central stabiliser and guide vanes mitigated each other's advantages: guide vanes reduced the flutter stability improvements of the upper central stabiliser, whereas the latter compromised the VIV suppression effectiveness of the guide vanes. However, a combined configuration of horizontal stabilisers, upper central stabilisers and guide vanes significantly enhanced flutter and VIV performance. The optimised section exhibited no VIV, with critical flutter wind speeds increasing by over 14.8% across all angles of attack compared to the original section. Computational fluid dynamics simulations revealed that large vortex shedding in the wake region induced periodic aerodynamic forces, which primarily triggered VIV. While the upper central and horizontal stabilisers enhanced vortex shedding on the upper surface of the girder, the resulting aerodynamic forces interfered with periodic forces from wake vortex shedding, effectively suppressing VIVs.

Keywords: Combined aerodynamic measures, computational fluid dynamics, flat steel box girder, flutter, vortex-induced vibrations, wind-induced stability, wind tunnel tests.

THE span of suspension bridges has been continuously increasing due to advancements in high-performance materials[1]. Flat steel box girders (FBGs), characterised by their lightweight, high sectional stiffness, and excellent stability, have become the preferred main girder type for long-span bridges[2]. For long-span bridges, flutter stability and vortex-induced vibration (VIV) performance are critical factors in determining the feasibility of a design scheme[3,4]. Both flutter stability and VIV performance are indispensable for ensuring the success of bridge designs.

It is well known that FBGs exhibit lower flutter stability compared to split box girders[5,6]. Furthermore, as bridge spans increase, the inherent damping ratio of real bridges, in the absence of dampers, tends to remain low, posing significant challenges to the VIV performance of bridges[7,8]. However, numerous aerodynamic shape factors affect the wind-induced stability of bridge sections, and the mechanisms behind VIV and flutter are fundamentally different[9–12]. Therefore, studying the flutter stability and VIV performance of long-span and even ultra-long-span FBG suspension bridges, along with exploring holistic aerodynamic optimisation measures is paramount.

In the study of flutter stability and aerodynamic optimisation measures for FBGs, Larsen[13] studied the effects of railings, maintenance vehicle tracks, and deck pavement on the critical flutter wind speed of the main girder, concluding that these auxiliary structures negatively impact flutter stability. Wang *et al.*[14] conducted a series of comparative wind tunnel tests and found that maintaining the inclined web angle of FBGs below 16° improves the critical flutter wind speed of bridges. Ge[15] found that installing an upper central stabiliser on single-box girders effectively increases the critical flutter wind speed. Mei *et al.*[16] conducted optimisation tests on the flutter stability of a streamlined steel box girder with a width-to-height ratio of 12.4 : 1, showing that an appropriately sized upper central stabiliser effectively enhances its critical flutter wind speed. Subsequent researchers have further explored the mechanism of flutter optimisation using upper central stabilisers as an effective aerodynamic measure[17,18]. Li *et al.*[19] proposed an active control system named the twin-winglet system, which installs winglets at the wind fairings of FBGs. This system provides real-time feedback based on bridge deck movements and adjusts the rotation of the winglets, serving as an aerodynamic aid to enhance flutter stability.

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