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Aerodynamic instability performance of twin box girders for long-span bridges

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ABSTRACT

Twin box girders are a popular choice among long-span bridge engineers, and the aerodynamic performance of such a system is critical to the stability of a bridge under wind excitation. Two groups of twin-box girders with six representative slot width ratios varying from 0% to 100% were utilised to investigate the influence of different wind fairing shapes on aerodynamic instability performance for both torsional divergence and flutter of the girders. The girders with two wind fairing shapes for various slot ratios were investigated by wind tunnel tests and theoretical analyses. Based on the experimental results of static wind loads and critical flutter wind velocities, the symmetry of wind fairing only showed an influence on the development pattern of drag force coefficients and the flutter performance was only significantly affected when the slot width ratio was over 40%. It is also shown that the effect of structural stiffness variation caused by the change of slot width ratio cannot be neglected in stationary torsional divergence analysis. The flutter performance of twin box girders with asymmetric wind fairing is sensitive to slot width ratio due to the existence of optimal slot width, which is opposite to the case with symmetric wind fairing, especially when this ratio is over 40%. Different aerodynamic damping parts contributing to the torsional aerodynamic damping and the participation level of each degree of freedom (DOF) were analysed through a two-dimensional three degree of freedom (2D-3DOF) method, and the results indicate that the improvement in flutter performance can be mainly attributed to the decrease in aerodynamic negative damping Part F (caused by the couple effect of the torsional and vertical motion) and the increase of participation level in heaving motion at the flutter onset. Particle Image Velocimetry (PIV) techniques were further employed to reveal that the change in central slot width ratio and the symmetry of wind fairing have a great influence on the vortices' characteristics, especially in the central slot region when the slot ratio is over 40%. This was determined by observing the flow structures around the deck sections in terms of wind velocity field and vortex characteristics.

1. Introduction

As a new type of girder section for long-span, or even super long-span bridges, multi-box girders can significantly improve flutter performance and are therefore gradually gaining popularity with bridge engineers. The Xihoumen suspension bridge in China with a central span of 1650 m (Yang et al., 2007) and the Messina Straits Bridge in Italy with a main span of 3300 m (Diana et al., 2004) are considered to be two good examples of the use of this innovative structural form. Greater attention has been placed on the aerodynamic performance of super long-span bridges with multi-box as this kind of flexible structure shows a higher sensitivity to wind excitation. The understanding of stationary aerodynamic instability and flutter performance of multi-box girders has been significantly enhanced over the last several decades. Theoretical methods for stationary aerodynamic instability analysis have been gradually improved and the calculation of results based on the optimal iteration method have suggested that the increase of the central slot width ratio can improve the stationary aerodynamic stability of twin-box girders (e.g. Boonyapinyo et al., 1994; Cheng et al., 2002; Zhang et al., 2013). Similarly, theoretical and experimental investigations have suggested that an increase of the centre slot width will also improve the flutter stability of multi-box girders (e.g. Larsen and Astiz (1998); Sato et al., 2002). However, despite the efforts made in the past, aerodynamic stabilisation of long-span bridges with multi-box girders is still a challenge for structural and wind engineers. In order to explore the aerodynamic stabilisation mechanism of twin-box girders with

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various slot width ratios, the aerodynamic effects of the centre slots should be systematically investigated with a series of typical slot widths.

Wind fairings at the edges of a cross-section can ease the flow separation and smooth the airflow around the main girder. However, it is necessary to select a reasonable angle for wind fairing in geometrical shape optimisation in order to effectively improve the aerodynamic performance. Most of the previous studies have concentrated on the wind fairing of a single box girder and the results obtained through wind tunnel tests have indicated that a wind fairing with a sharper angle is helpful in enhancing the flutter stability of a single box girder (e.g. Meng et al., 2011; Yang et al., 2015). Moreover, significant distinction may be found in the aerodynamic performance of multi-box girders with different wind fairing shapes when wind fairings are divided into symmetric and asymmetric ones. In Yang et al. (2015), the flutter performance of twin-box girders with different wind fairing shapes was investigated using wind tunnel tests and then compared to the results of the researches by Larsen and Astiz (1998) and Sato et al. (2002). Reasons for discrepancies in these results were analysed from two critical aspects-the structural dynamic characteristic parameters and the aerodynamic shapes. In a few recent studies, aerodynamic forces and surface pressure distributions of twin-box girders have been reported. Due to lack of a good field measurement of flow structures and forces, the importance of a capable Particle Image Velocimetry (PIV) technique has highlighted for reliably observing flow field transformation during the flutter phenomenon in wind tunnel tests (e.g. Diana et al., 2004; Kwok et al., 2012; Zhu and Xu, 2014; Chen et al., 2014; Yang et al., 2014). Additionally, Acampora et al. (2014) have found that the static drag coefficients that were back-calculated from full-scale vibration measurements are in good agreement with wind tunnel measurement results. However, the influence of wind fairing shapes on stationary aerodynamic instability is still uncertain and studies on the aerodynamic performance of twin-box girders with different wind fairing shapes are very limited.

Combinations of theoretical and experimental approaches were considered when determining the aerodynamic instability performance for twin-box girders with various slot width ratios and different wind fairing shapes. Wind tunnel experiments were first performed on two groups of spring-supported rigid sectional models which had six representative slot ratios and symmetric or asymmetric wind fairings. These experiments were conducted to promote the understanding of stationary aerodynamic instability and flutter performance of twin-box girders. Based on the experimental observations, a two-dimensional three degree of freedom (2D-3DOF) flutter analysis method was applied to elaborately clarify the flutter mechanism by investigating the formation of aerodynamic damping and the participation level of motions in different DOFs. A PIV technique was employed to measure the surrounding flow pattern and to further investigate the wind velocity field and vortex characteristics around twin box girders with different wind fairing shapes.

2. Stationary aerodynamic performance

2.1. Experimental set-up

Wind tunnel experiments on the stationary aerodynamic forces of two rigid sectional models of simplified twin box girders without deck facilities (with reference to the stiffening girder of the Xihoumen suspension bridge in China at 1:100 geometric scale ratio but with both the symmetric (SY) and asymmetric (AS) wind fairings) were performed in the TJ-2 Boundary Layer Wind Tunnel of Tongji University, China. The sectional models are 0.14 m wide

Table 1
Structural parameters of force-measured models.

Slot ratio	Slot width D (unit:m)	Deck width B_s (unit:m)	Total width B (unit:m)	Working section length L (unit:m)	Compensation section length L_b (unit: m)
0%	0.000	0.280	0.280	1.080	0.540
20%	0.056	0.280	0.336	1.080	0.540
40%	0.112	0.280	0.392	1.440	0.400
60%	0.168	0.280	0.448	1.440	0.400
80%	0.224	0.280	0.504	1.620	0.400
100%	0.280	0.280	0.560	1.620	0.400

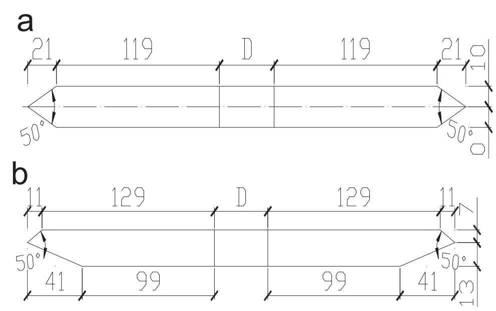

Fig. 1. Sectional model diagrams of static wind loads measurement with working sections (unit:mm): (a) SY section, and (b) AS section.

Fig. 2. Force-measured model.

for each single girder ($B_s/2$) and 0.02 m high (H), resulting in an aspect ratio of $14B_s/H$. The main parameters and geometric dimensions of the two models (SY and AS sections) are listed in Table 1 and illustrated in Fig. 1, respectively.

A force-balance system consisting of an identical suspension system (called a compensation section) was installed on one side of the tunnel to vertically support the two ends of the working section (see Fig. 2), which allowed accurate adjustment of wind attack angles from $-12°$ to $+12°$ with an increment of 1°. In order to exclude negligible model vibrations during testing, the resulting natural frequency of the restrained sectional model was approximated as 25 Hz. Six test configurations were investigated, with gap width (D) to two single girders (B_s) ratios of 0%, 20%, 40%, 60%, 80% and 100%, corresponding to prototype scale gap widths equivalent to 0 m, 5.6 m, 11.2 m, 16.8 m, 22.4 m and 28.0 m, which represent different design schemes for the prototype bridge.

2.2. Static wind loads of twin box girders

As shown in Fig. 3, the three components of wind loads per unit span acting on the deformed deck are drag force, lift force and