WIND TUNNEL STUDY ON THE EFFECT OF THE GAP WIDTH IN THE AERODYNAMIC AND AEROELASTIC RESPONSES OF TWIN-BOX DECKS

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ABSTRACT

Twin-box decks have recently been introduced in long-span bridges because this type of slotted cross-section provides flutter critical wind speeds higher than mono-box streamlined decks for flexible structures. The two parallel girders are linked together by means of transverse beams with a central gap between them. Experimental and CFD studies have shown that the length of this central gap plays a key role in the aerodynamic and aeroelastic responses of the deck. In this work, the geometry of the Stonecutters Bridge in Hong Kong (China) has been chosen as an application case to conduct a series of parametric studies based on wind tunnel tests. The tests have been conducted under smooth flow, for a 1:80 geometric scale sectional model able to modify its slot length. For an ample range of gap lengths, the force coefficients and the flutter derivatives have been obtained. It has been found that the slopes of the lift and moment coefficients suffer important changes with the gap length. In the same manner, it has also been found that the gap distance modifies the values of flutter derivatives. Finally, for a long-span bridge example, the critical flutter speeds for different gaps are obtained, aiming to identify the gap length that provides a safer threshold for the flutter phenomenon. The results reported herein permit the assessment of the impact caused by the gap length in the aerodynamic and aeroelastic responses of twin-box decks.

Keywords: twin-box deck, gap distance, Stonecutters Bridge, force coefficients, flutter derivatives, flutter velocity, wind tunnel testing.

1 INTRODUCTION

The advances in long-span bridges design have been driven by the quest for spanning longer distances. The 176 m main span length of the 1826 Menai Suspension Bridge were as impressive as the 1,991 m main span length of the 1998 Akashi Kaikyō Bridge. The engineering achievements that have taken place during these almost two centuries of bridge engineering practice have been mainly linked with improvements in the understanding and modelling of wind actions on cable-supported bridges.

The introduction of the “multi-box deck” concept in long span bridge design is associated to the studies conducted in the 1990s for two flagship bridges: the Akashi Kaikyō and the Messina Bridges [1]. According to Diana et al. [1], slotted deck solutions are required to obtain a low lift deck design since the opening permits the pressure equalisation between the upper and lower side of the deck. Furthermore, streamlined box girders allow for low drag. Other advantages in multi-box decks, besides their feasible aerodynamic response, are the lightweight of the structure, a relatively easy maintenance, and an effective modular construction process.

Consequently, the multi-box deck concept was further studied and developed in the early years of the 21st century. Three outstanding cable supported bridges must be mentioned: the 2009 Stonecutters Bridge which is a 1,018 m span length cable-stayed bridge, the 2009 Xihoumen Suspension Bridge with 1,650 m of span length and the 2012 Yi Sun-sin Suspension Bridge with a span length of 1,545 m.

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The literature on the subject focused on the flutter response, which was much improved compared to mono-box designs, the vortex-induced excitation risk, that is the main drawback of this deck arrangement, as well as Reynolds number effects [2]–[12]. More recently, the effect of the boxes' geometry has also been studied [13], [14], as well as the effect of aerodynamic appendages [15]. The basic conclusion that can be obtained from the published studies is that the aerodynamic response depends mainly on the gap distance between boxes. However, there is not an agreement regarding the identification of a feasible slot size. In fact, the gap to depth ratio (*G*/*D*, being *G* the gap distance and *D* the depth of the girder) of the Stonecutters Bridge is about 4:1, while this ratio for the Xihoumen Bridge is 1.7:1. Furthermore, short gap lengths are generally favoured since construction costs increase with the gap length [12].

In this work, for the cross-section of the Stonecutters Bridge, five different gaps are studied by means of wind tunnel tests. In first place, the results obtained for the force coefficients of the static deck as a function of the gap to depth ratio are reported for the range of angles of attack (-10°, 10°). Then, the set of the eight flutter derivatives that relate the aeroelastic lift and moment with the heave and pitch movements and velocities are presented. The effect of the gap distance is discussed based on the changes in the slopes of the force coefficients as well as the different trends in flutter derivatives. Finally, for a given long-span bridge, the critical flutter speed is calculated for the studied gap widths, assessing the impact that the slot distance has in its aeroelastic response. The results that are reported next belong to a broader scope project whose goal is the identification of the optimal gap width and box geometry in a mathematical sense.

2 FORMULATION

2.1 Force coefficients

The force coefficients of the deck arrangements considered in this study are obtained according to the following formulation:

$$C_D = \frac{D}{\frac{1}{2}\rho U^2 B}, \quad C_L = \frac{L}{\frac{1}{2}\rho U^2 B}, \quad C_M = \frac{M}{\frac{1}{2}\rho U^2 B^2}, \tag{1}$$

where ρ is the air density, U is the wind velocity, B is the width of the deck cross-section, and L, D and M are the lift and drag forces and moment per unit length, respectively, following the sign convention depicted in Fig. 1.

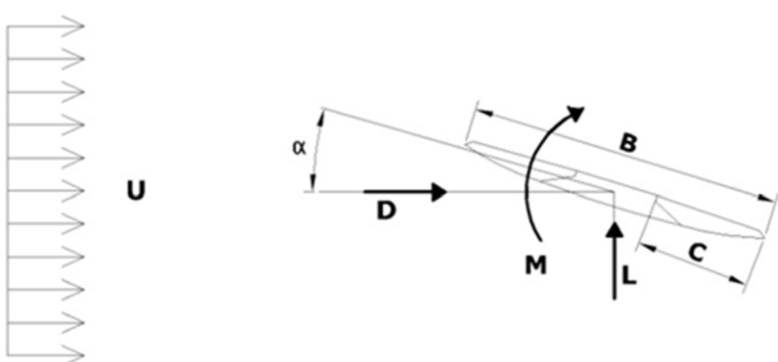


Figure 1: Force coefficients sign convention.

2.2 Aeroelastic forces

Flutter derivatives are non-analytical parameters which relate motion-induced forces and the velocities and movements of the structure. These parameters have been traditionally identified using wind tunnel tests. According to Simiu and Scanlan [16], the aeroelastic forces on a bridge deck, considering two degrees of freedom (heave and pitch) can be written as follows:

$$L^{ae} = \rho U^2 B \left[K H_1^* \frac{\dot{h}}{U} + K H_2^* \frac{B\dot{\alpha}}{U} + K^2 H_3^* \alpha + K^2 H_4^* \frac{h}{B} \right], \tag{2}$$

$$M^{ae} = \rho U^2 B^2 \left[K A_1^* \frac{\dot{h}}{U} + K A_2^* \frac{B\dot{\alpha}}{U} + K^2 A_3^* \alpha + K^2 A_4^* \frac{h}{B} \right], \tag{3}$$

where L^{ae} is the aeroelastic force per unit of span length, M^{ae} is the aeroelastic moment per unit of span length, $K = (B\omega)/U$ is the reduced frequency, B the deck width and ω the circular frequency of oscillation, h is the heave displacement and $\dot{h}$ is its time derivative, α in the torsional rotation and $\dot{\alpha}$ its time derivative, H_i^* and A_i^* $(i = 1, \dots, 4)$ are the flutter derivatives.

3 WIND TUNNEL CAMPAIGN

3.1 Experimental set-up

Wind tunnel tests have been conducted at the aerodynamic wind tunnel of the University of La Coruña, which is a low turbulence, open circuit class, facility with a 2 x 1 x 1 m^3 test chamber. The sectional model has been fabricated at a 1:80 geometric scale, reproducing the geometry of the Stonecutters Bridge. An in-house system has been designed to allow fixing the boxes at different positions on a rigid frame to obtain the different gap distance arrangements. The gap to depth ratios considered in this study are the following: 0, 0.28:1, 2.08:1, 3.96:1 and 7.48:1, which are named respectively as gaps A, B, C, D and E. In Table 1, the total width of the studied deck configurations at real scale are provided. The width, *C*, of a single box is 19.5 m at real scale (see Fig. 2).

Table 1: Total width of the studied twin-box arrangements.

Twin-box arrangement	Width to depth ratio	Total width (m)
Gap A	0	39
Gap B	0.28	40
Gap C	2.08	47.2
Gap D	3.96	53.3
Gap E	7.48	68

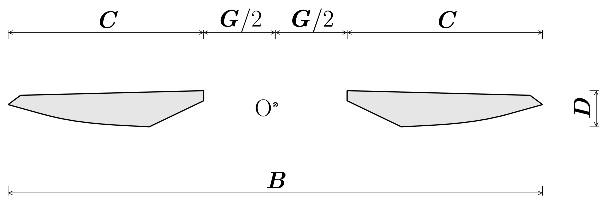


Figure 2: Geometry of the twin-box deck. Gap distance, *G*, variable.

In Fig. 2, the main dimensions of the model are presented, while in Fig. 3 the considered gaps are shown graphically, which provides a clear idea of the amplitude in the gap distances considered herein.

In Fig. 4, two images of the sectional models corresponding to gaps C and E are presented, along with another image of the gap E sectional model in the wind tunnel ready for testing.

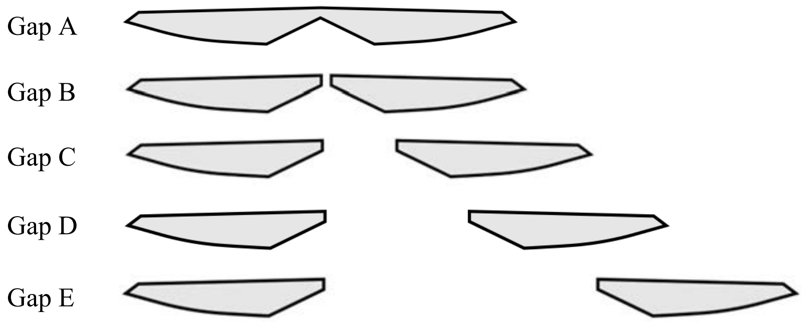
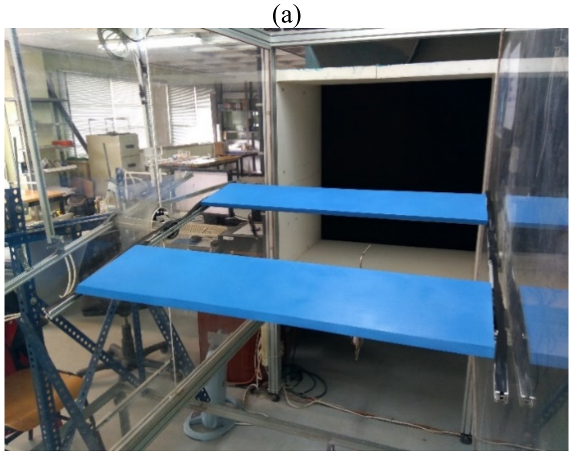


Figure 3: Studied gaps.

(a)



(b)

Figure 4: Sectional models. (a) Detail of gap C and Gap E models; and (b) Gap E sectional model inside the test chamber.

3.2 Force coefficients results

The wind tunnel tests of the static sectional models have been conducted at a Reynolds number of 2.45e+05, considering the width of a single box as the reference dimension. Reynolds number sensitivity studies were conducted for the Gap D case, finding negligible differences in the force coefficient values for the range of studied Reynolds numbers (3.26e+04, 3.26e+05). The force coefficients as a function of the angle of attack are reported in Fig. 5 for the five gap to depth ratios considered in this investigation. In all the cases, the force coefficients are moderate at low angles of attack.

The slopes of the lift and moment coefficients provide qualitative information concerning the expected flutter response of a bridge deck, since positive low value slopes are associated to a feasible aeroelastic performance [17]. In this respect, in all the cases, the slopes of the lift and moment coefficients are positive, and they decrease as the gap distance augments, which signals the positive effect caused on the flutter velocity due to the increase in the gap distance. It can also be appreciated the different trend in the drag coefficient of Gaps A and B, compared to Gaps C, D and E, since the short gap in the former ones prevents the air flow in the slot in the streamwise direction. The results reported herein are in general agreement with the ones reported in the literature for similar gap to depth ratios [7].

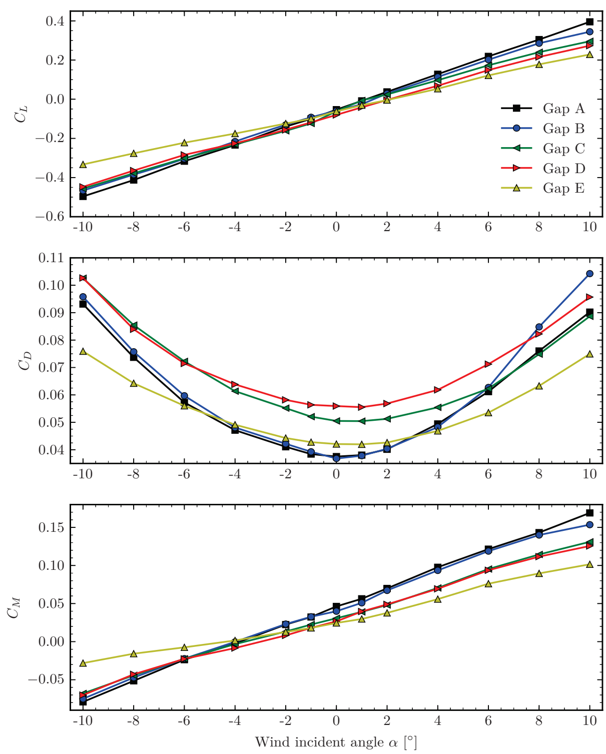


Figure 5: Force coefficients vs. angle of attack for different gap to depth ratios.

3.3 Flutter derivatives

The flutter derivatives that appear in eqns (2) and (3) are identified by means of dynamic wind tunnel tests. The differences in the studied gap ratios have produced sectional models with very different mass moments of inertia. Consequently, the dynamic properties of the dynamical system had to be adjusted by modifying the stiffness of the sectional model supporting system. The flutter derivatives were identified using the Ibrahim Time Domain (MITD) method proposed by Sarkar et al. [18] and Jurado et al. [19].

In Fig. 6, the eight flutter derivatives related with the heave and pitch degrees of freedom, H_i^* and A_i^* $(i = 1, \ldots, 4)$, are presented as a function of the reduced velocity $U^* = U/(fB)$, being f the frequency of the oscillation. The flutter derivatives for the different gap to depth

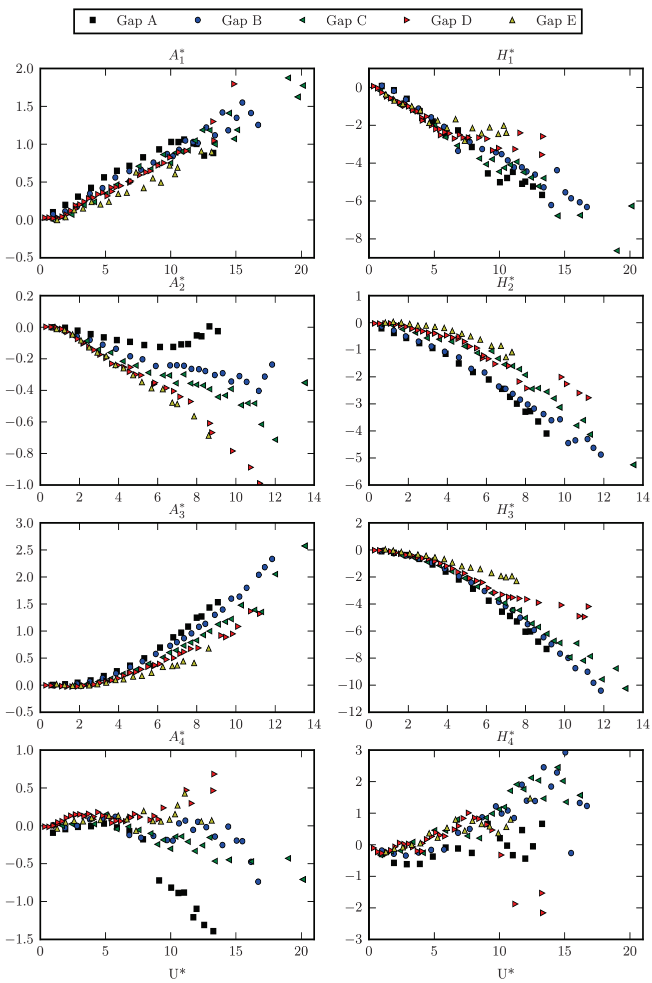


Figure 6: Flutter derivatives for Gaps A, B, C, D and E.

ratios considered in this study are very similar amongst them due to the similar deck typology. The most noticeable differences can be found for the A_2^* flutter derivatives, since the larger the gap distance, the higher the negative value of this flutter derivative. This is in agreement with the findings in [12], and explains the improved aeroelastic performance of twin-box decks since the larger the gap is, the higher the aerodynamic damping related with the velocity of rotation for the aeroelastic moment. In addition, differences can be found for the flutter derivatives H_2^* and H_3^*, where the longer the gap distance, the lower the absolute value of the flutter derivatives for the same reduced velocity.

3.4 Critical flutter velocity

Aiming to assess the impact of the gap length in the flutter response of long-span bridges, the critical flutter speed is computed using the code FLAS [20] for the five different deck arrangements whose flutter derivatives were presented in Section 3.3. The structural properties of the studied bridge are similar to the ones reported in [14] for the Xihoumen suspension bridge, and are summarized in Table 2.

In Table 3, the results obtained for the critical flutter speed adopting the flutter derivatives of the five gap ratios studied herein are presented. It can be noticed how the critical flutter speed increases for longer gap ratios. In fact, for gaps D and E, no critical flutter speed is obtained in the range of reduced velocities for which the flutter derivatives were obtained from wind tunnel tests. Because of this, the lower limit provided in Table 2 corresponds to the upper bound of reduced velocities for which flutter derivatives were available combined with frequency of oscillation of 0.18 Hz.

The increment in the critical flutter speed is mainly related with the changes in the A_2^* flutter derivative. As the gap increases, for the same reduced velocity the negative value of A_2^* also increases, providing a greater contribution to the aerodynamic stability.

Table 2: Structural parameters of the application example.

Parameter	Value
Mass (T/m)	28.2
Mass moment (Tm^2/m)	9980
Bending frequency (Hz)	0.1007
Torsional frequency (Hz)	0.1995
Bending damping	0.005
Torsional damping	0.005

Table 3: Critical flutter speed.

Twin-box arrangement	Critical flutter speed (m/s)
Gap A	54.97
Gap B	79.33
Gap C	99.96
Gap D	>115
Gap E	>97

4 CONCLUSIONS

The key concepts and fundamental findings in this work are summarized next:

- A brief description of the main reasons for the development of the multi-box deck concept has been provided in the introduction, along with a several examples of this type of bridges. Also, the fundamental bibliography on the subject has been mentioned.
- Five different gap to width ratios in the range (0, 7.48) have been considered in this research work. The experimental set-up has been introduced, and the experimental results obtained for the force coefficients and the flutter derivatives have been presented.
- It has been found that the slopes of the lift and moment coefficients decrease as the gap distance between the boxes augments. This is indicative of a more feasible aeroelastic behaviour in terms of flutter response.
- The flutter derivatives show that the changes in the A_2^* flutter derivative are responsible for the higher critical flutter speed associated to longer gap distances since larger gaps present A_2^* with higher absolute value, hence higher aerodynamic damping.
- The critical flutter speed for the five considered deck arrangements has been calculated. It has been found that the critical speed increases with the slot length. For gaps D and E, the critical flutter speed is not reached in range of reduced velocities for which flutter derivatives were obtained from wind tunnel tests, thus a lower bound for the flutter speed is provided.
- Moderate gaps may provide dramatic increments in the flutter speed for a given bridge. In this application example, the Gap C case, which corresponds to a gap to depth ratio 2.08:1, nearly doubles the critical flutter speed of the mono-box case, gap A.

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