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On the effects of the gap on the unsteady pressure characteristics of two-box bridge girders

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ABSTRACT

This experimental study focuses on the unsteady pressure characteristics of two-box bridge decks. Models with vertical plates and gratings in several gap length configurations are investigated and compared with single-box cross sections. The results demonstrate that, with respect to unsteady pressure characteristics, the upstream box is barely affected by the slot and behaves similarly to the single-box model. In contrast, the unsteady pressure characteristics of the dowstream box are defined mainly by the characteristics of the slot and the geometry of its cross section. The upstream box geometric configuration plays only a minor role in the definition of the unsteady pressure characteristics of the dowstream box. An equivalent Theodorsen function to be used in the calculation of aerodynamic derivatives of two-box girders is proposed. Using this function, it is demonstrated that the only aerodynamic derivative that is aerodynamically dependent on the gap length is A_2^*. These findings suggest that the results of single-box investigations can be extended to two-box cross sections.

1. Introduction

Increasing span lengths have posed several challenges to bridge engineers in the last decades. One challenge is the problem of aerodynamic stabilization. Torsional and heaving natural frequencies of bridges decrease and approach each other as span lengths increase [1,2]. This combination is an important trigger for flutter instability. Furthermore, the need for more aesthetical and comfortable solutions, with reduced environmental impacts, has become an important issue [3]. As a result, configurations of bridge decks that used to be suitable for a certain range of spans no longer address the requirements for the modern longer spans. This problem has led to the creation of new cross sections, imposing new challenges to designers and researchers.

In this scenario, a cross section that provides stable solutions is based on the concept of a two-box girder [3]. Such a cross section is composed of two separated boxes that behave as a single rigid body. The unicity is achieved using transverse beams, which should be rigid enough to prevent the two decks from twisting independently beyond an acceptable limit. In addition to aerodynamic advantages, two-box girders may also result in considerably lighter structures compared with opaque decks. The reduced weight also contributes to economic attractiveness.

There is a direct correlation between gap length and flutter stability in two-box girder bridges [4–9]. The reduction of the relative density of the deck increases the total torsional damping of the cross section [10]. Moreover, openings in the deck reduce the destabilizing pitching moment originated from the twist [10] as well as the quasi-static coefficients of aerodynamic resistance to torque and lift [11]. The combination of these factors increases flutter onset speeds. These findings highlight the major roles that the slot may play in stabilizing two-box girders.

The mechanisms of such aerodynamic stabilization, however, have not been fully clarified [12–14]. Depending on the characteristics of the deck as a whole and the gap length, flutter onset may even decrease [13,14]. Analyses to determine correlations with the characteristics of one of the boxes were attempted by Yang et al. [14], leading to the conclusion that central-slotting is not always able to improve the stability, which would depend on the aerodynamic characteristics of that single-box and the gap length. When gratings are used, the situation becomes even complicated, since the effects of gratings have been shown to depend on Reynold's number [5,15,16].

Gap lengths have been usually referred to as a ratio to the width B^* of one box. Studies have accounted for good aerodynamic stability of cross sections with gap lengths longer than $0.25B^*$ [13]. Nevertheless, since costs increase with gap length, short gaps are preferred. As a consequence, typical values have been limited to no longer than $1.0B^*$, as in the Stonecutters Bridge in Hong Kong,

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with gap length of $0.73B^*$, and the proposed Kitan Straits bridge in Japan, with a gap length of $0.34B^*$ [7].

Because unsteady pressure characteristics have intrinsic relationships with aerodynamic derivatives and the onset of flutter [17–19], establishing relationships between unsteady pressure characteristics and the geometry of decks must contribute to flutter stabilization efforts. However, collecting such information in real bridge projects or even in wind tunnel experiments can be complicated and expensive, which might explain the scarcity of such data in the technical literature.

Based on all above considerations, this study investigates how the geometry of a deck – two-box girders, in this case – is related to the unsteady pressure characteristics that develop along the surface of the body. Through an experimental investigation in wind tunnel, the influence of the slot on the unsteady pressure characteristics of two-box girders is studied. A wide range of gap lengths is tested. Gratings and vertical plates are also considered in the analyses, along with measurements obtained from single-box models. In addition to the conclusions of the study, the wind tunnel test results should contribute to the technical literature and will be made available for future studies of long-span bridges.

Of course, further investigations are necessary to completely clarify the relationships among unsteady pressure characteristics, aerodynamic derivatives and flutter stabilization. Such work is not the objective of this study, which is restricted to the effects of gap length on the unsteady pressure characteristics of certain two-box girders. Even though the study was not directly designed to enhance the understanding on the potential contribution of two-box girders on flutter stabilization, efforts in this sense may benefit from the results reported herein. This fact is an additional motivation for the study.

It is concluded that the gap is decisive for defining the unsteady pressure characteristics of the downstream box, regardless of the configuration of the upstream box. Moreover, the significant role played by the solidity ratio in the composition of the aerodynamic derivatives is highlighted.

2. Experimental approach

The investigations were based on wind tunnel tests of harmonically oscillating models in the Kyoto University Bridge Engineering Laboratory. Pressure distributions were measured and analyzed. The discussions of the results focused on the role played by the slot in the formation of unsteady pressure characteristics in two-box cross sections.

For the analysis of pressure distributions in harmonically oscillating bodies, the pressure signals can be divided into two components: the mean and fluctuating pressure components. The mean pressure distributions are obtained by averaging the pressure signals along the entire acquisition time span. The fluctuating components are the variation in the pressure signals. In this study, the discussion is restricted to the fluctuating pressure components, which correspond to the so-called unsteady pressure characteristics.

The information is discretized according to the non-dimensionalized (normalized by the half width b) x widthwise coordinate. This parameter is defined as x^* and ranges from -1 to $+1$, where 0 is the center of the cross section. For every normalized location x^*, the fluctuating pressure components can be expressed by two parameters. The first parameter is the full amplitude (negative peak to positive peak) of the unsteady pressure fluctuation, normalized by the dynamic pressure of the flow, i.e., $\widetilde{C}_p(x^*)$. The second parameter is the phase difference between the maximum relative angle of attack of the model and the negative pressure peak in its upper surface, i.e. $\psi(x^*)$.

The wind tunnel used in the experiments was a room-circuit Eiffel-type tunnel, with a working section 1.8 m in height and 1.0 m in width. Two types of models: a single-box model and a two-box model were used. The single-box model was a $B/D = 20$ rectangular cylinder (where B is the width and D is the thickness) made of wood. The model was 950 mm long, 300 mm wide and 15 mm thick, limited by two endplates 200 mm in height and 500 mm in the chordwise direction. The base model of the two-box models was composed of two rectangular cylinders, with a side ratio of $B^*/D = 20$ each (B^* is the width of one box), made of duraluminium, 950 mm long, 150 mm wide and 7.5 mm thick. They were arranged in eight different gap length configurations, as follows: $0B^*$, $0.1B^*$, $0.25B^*$, $0.5B^*$, $1.0B^*$, $1.5B^*$, $2.0B^*$ and $3.0B^*$, with a rotational pivot fixed at the halfway point of both cylinders. Gratings with 35% of permeabilities and vertical plates were installed in the configurations with gap lengths of $1.0B^*$ and $2.0B^*$. The vertical plates were made of naval wood with a thickness of 3 mm and a height of D and were affixed to the upper surface of the models, at the middle of the chordwise direction of each box, according the cases investigated. Two endplates 200 mm high and 900 mm in the chordwise direction limited the models in the wind tunnel.

The models were instrumented with 30 equidistant pressure taps, placed on the upper surface of the models, along the chordwise direction at the center of their spans. The pressure measurements were performed in a smooth flow, with turbulence less than 0.5%, via the forced heaving/torsional 1-DOF (degree of freedom) oscillation method. For both motions, the frequency of the forced oscillation was set to $f = 2$ Hz. The amplitude of oscillation in the torsional system was $2\varphi_0 = 4^\circ$; in the heaving system, the amplitude was $2\eta_0 = 20$ mm. Forced vibrations were used because bridges exhibit harmonic motions during flutter instability [20].

For the single-box models, the reduced wind velocities, defined by $U/f \cdot B$, ranged from $U/f \cdot B = 5$ to $U/f \cdot B = 25$, in steps of 5. For the two-box models, the wind velocities U were chosen so that the resulting reduced wind velocities, U_r, defined by the equation below, ranged from $U/f \cdot B^* = 10$ to $U/f \cdot B^* = 50$, in steps of 10.

$$U_r = \frac{U}{f \cdot B^*} \tag{1}$$

where U_r is the reduced wind velocity; U is the wind velocity; f is oscillation frequency; B^* is the width of one box.

The pressure signals were acquired with a sampling rate of 1000 Hz over 100 s. The signals were carried from the pressure taps through a set of silicone tubes and delivered to the *ZOC 17* sensor box, located outside of the wind tunnel and connected to the computer system used in the data acquisition. The tubing system was kept as short as possible (around 1800 mm for each tube), so that the phase lag between the pressure signals arriving in the sensor box and the corresponding pressure signals at the surface of the models could be minimized.

Prior to the experiments, the phase lag of the tubing system was estimated in 8°. The technique used in this estimation was based on the measurement of a controlled pressure fluctuation made inside the wind tunnel test chamber. The pressure fluctuation was controlled through a system composed of a rotating shutter located between the wind tunnel fan and the model. The rotation of the system resulted in a synchronized sequence of opening and closing that induced controlled pressure fluctuations in the wind tunnel test chamber [21]. A comparison between the measurements obtained concomitantly from the tubing system and from a reference measurement apparatus with no phase lag provided the phase lag of the tubing system. A hot-wire probe was used to acquire velocity fluctuations for the reference measurement apparatus (see Fig. 1).