J. Wind Eng. Ind. Aerodyn. 132 (2014) 27–36

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

An experimental study on the unsteady vortices and turbulent flow structures around twin-box-girder bridge deck models with different gap ratios

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ARTICLE INFO

Article history:
Received 1 January 2014
Received in revised form
4 June 2014
Accepted 7 June 2014
Available online 5 July 2014

Keywords:
Twin-box-girder
Bridge deck model
Gap ratio
Unsteady vortex
Flow structure
PIV
Pressure

ABSTRACT

In the present study, an experimental investigation was conducted to characterize the unsteady vortices and turbulent flow structures around twin-box-girder (TBG) bridge deck models with and without cross beams. While the oncoming wind speed was fixed at $U_\infty = 8.0$ m/s (i.e., the corresponding Reynolds number, $Re = 1.01 \times 10^4$, based on the height of the box girder) during the experiments, the gap width between the TBG was varied to have four different gap ratios (i.e., the ratio of the gap width between the TBG to the deck height). The corresponding test cases were classified into two categories: the cases with relatively small gap ratios (i.e., gap ratio = 0.85 and 1.70) and the cases with relatively large gap ratios (i.e., gap ratio = 2.55 and 3.40). In addition to measuring the surface pressure distributions around the TBG bridge deck models using an array of digital pressure transducers, a high-resolution particle image velocimetry (PIV) system was utilized to perform detailed flow field measurements to quantify the evolution of the unsteady vortex structures around the TBG bridge deck models. The measurements reveal that as the gap ratio increases, the vortex shedding moves from the trailing edge of the leeward box to the rear edge of the windward box, which simultaneously increases the turbulent kinetic energy in the gap region and the fluctuating pressures on the leeward box. The vortex dimensions and the core-to-core distances between two neighboring vortices are also affected by the gap ratio. Combining with the estimation of the pressure field and the measured fluctuating pressure coefficient distributions on the TBG models, it is found that the TBG bridges with larger gap ratios will dramatically strengthen the fluctuating pressure coefficients on the leeward box which are greatly higher than those for the small gap ratio cases. Moreover, for large gap ratio cases, the test model with cross beams also has higher fluctuating pressure coefficients on the leeward box which just decrease a little comparing with the test model without cross beams.

1. Introduction

As the bridge span increases, modern cable-stayed and suspension bridges are becoming more flexible and have little damping capability. While single box steel girders usually cannot meet the requirements of the aerodynamic stability for long-span bridges as the girder width increases, twin-separated box steel girders, which are composed of two parallel longitudinal girders with an open gap between them, are found to be able to improve the aerodynamic stability for long-span bridges. For twin-box-girders (TBG) bridges, the two parallel girders are usually connected by transverse cross beams. So far, several super-long-span bridges have been constructed by using the TBG section configuration, which include the Xihoumen suspension bridge (main span: 1650 m, China), the Gwangyang suspension bridge (main span: 1545 m, Korea), the Hong Kong Stonecutters cable-stayed bridge (main span: 1018 m, China) and Edong cable-stayed bridge (main span: 926 m, China). While the super-long-span bridges with TBG configuration have better flutter performance (i.e., higher critical flutter speed than those with single box girders (Ge and Xiang, 2008)), the flow characteristics around such kind of bridge decks are more complicated due to the effects of the gap between the two separated box girders.

While the TBG configuration is relatively new for long-span cable-supported bridges, in the past decade several investigations have been conducted on TBG bridges. Diana et al. (2004, 2006) conducted wind tunnel tests to investigate the aerodynamic forces (i.e., the static aerodynamic coefficients, flutter derivatives, admittance

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http://dx.doi.org/10.1016/j.jweia.2014.06.015
0167-6105/

functions) of the multiple box deck of the Messina Strait Bridge and proposed a numerical model to reproduce the aerodynamic forces induced by the vortex shedding. Kwok et al. (2012) conducted wind-induced pressure measurements around a sectional twin-deck bridge model to study the effects of gap-width on the aerodynamic forces and vortex shedding mechanisms. They found that, for larger gap-width configurations, the downstream deck was supposed to be immersed in the wake of the upstream deck. Large mean positive pressures were recorded at the upstream windward surface of the downstream deck, which results in a significant increase of the drag force acting on the deck. They also found that the effect of the gap-width on the lift force and pitching moment is smaller than that of the angle of wind incidence on the lift force and pitching moment; however, both the gap-width and the angle of wind incidence have an evident effect on the drag force.

Ogawa et al. (2002) investigated the aerodynamic characteristics of a TBG section that could be adapted for a super-long span suspension bridge. They found that the steady pitching moment characteristics and flutter stability could be greatly improved by attaching rails on the bottom of the fairing and attaching vertical plates to the lower flange of the girder. Larsen et al. (2008) conducted an investigation on the vortex characteristics of a twin box bridge section at different Reynolds numbers. They found that the vortex shedding of TGBs became stronger than that of mono box girders because the fluctuating pressure on the downwind box was dramatically larger than that on the upwind box; specifically, the vortices shed from the upwind box would impinge onto the downwind box, resulting in higher fluctuating pressures than those on the upwind box where the vortices were shed. The analytical results indicated that the guide vanes were efficient devices for inducing high speed flow in the wake region of the upwind box to prevent vortex formation. It was also found that, the flutter critical wind speed can be dramatically increased for the TBG bridge deck, which was highly desirable for very long span cable supported bridges comparing with a mono box deck with the same span. However, the down side of TBG bridge decks was the vortex shedding which would cause higher fluctuating pressures on the downwind box (Larsen et al., 2008).

While these previous studies revealed are very useful, more work is still needed to improve our understanding of the underlying physics of the flow structures around complex multiple-box girders, especially the behavior of the unsteady vortex shedding and turbulent flow characteristics around multiple-box girders. In the present study, experiments were conducted to investigate the flow characteristics around fixed TBG models with different gap ratios. In addition to measuring the surface pressure distributions around the TBG bridge deck models using an array of digital pressure transducers, a high-resolution particle image velocimetry (PIV) system was utilized to perform detailed flow field measurements to quantify the evolution of the unsteady vortex structures around the TBG bridge deck models. The detailed flow field measurements were correlated with the measured pressure distributions around the test models to elucidate the underlying physics and to quantify the influence of the gap ratio on the evolutions of the unsteady vortices and turbulent flow structures around the test models. It should be noted that this study only focused on the flow characteristics and aerodynamic forces of the fixed TBG bridge deck models, which are different from the vortex-induced vibration, and the corresponding flow characteristics and aerodynamic forces under occurrence of vortex-induced vibration.

2. Experimental setup and test models

The experimental study was conducted in a closed-circuit low-speed wind tunnel located in the Aerospace Engineering Department of Iowa State University. The tunnel has a test section with a 1.0×1.0 ft^2 (30.48×30.48 cm^2) cross section, and the walls of the test section are optically transparent. The tunnel has a contraction section upstream of the test section with honeycombs, screen structures, and a cooling system installed to provide uniform, low-turbulence flow in the test section. The turbulence level of the oncoming flow at the entrance of the test section is about 0.8% as measured by a hotwire anemometer.

2.1. Test models

Fig. 1 shows the TBG test models used in the present study. The test models have a height of $H=18.240$ mm and width of $L=78.125$ mm for each box girder. The angle of attack of each box girder was set to zero. During the experiments, the total deck width was changed according to the different gap widths between the girders, and the corresponding gap ratio was varied from 0.85 to 3.40 (i.e., 0.85, 1.70, 2.55 and 3.40). It should be noted that the test model with the gap ratio of 1.70 for the present study is a scaled-down version of the model reported in Laima et al. (2013) (with a scale factor of 4.806) from where the detailed information of the test model is given. The speed of the oncoming airflow was fixed at $U_\infty=8.0$ m/s during the experiments, with a corresponding test model Reynolds number of $\mathrm{Re}=1.01\times10^4$ based on the height of the box girder and the oncoming wind speed.

Since the gap between the two box girders is shaded by the cross beams for the acquisition PIV images, the deck model #1 without cross beams (Fig. 1(a)) was used at first to measure the flow structures in the gap between the two girders. Then, the deck model #2 (Fig. 1(b)) with cross beams was used to investigate the effects of the gap width on the flow structures around the test model. The laser illumination plane for the PIV measurements was set at the same position for the test models with or without cross beams, specifically, at the middle plane of the 4th gap.

As shown in Fig. 2, a total amount of 62 pressure taps (i.e., 31 for each box) were arranged around the TBG models. The pressure taps were located in the same cross section as the PIV measurement plane. For each pressure tap, the pressure measurements

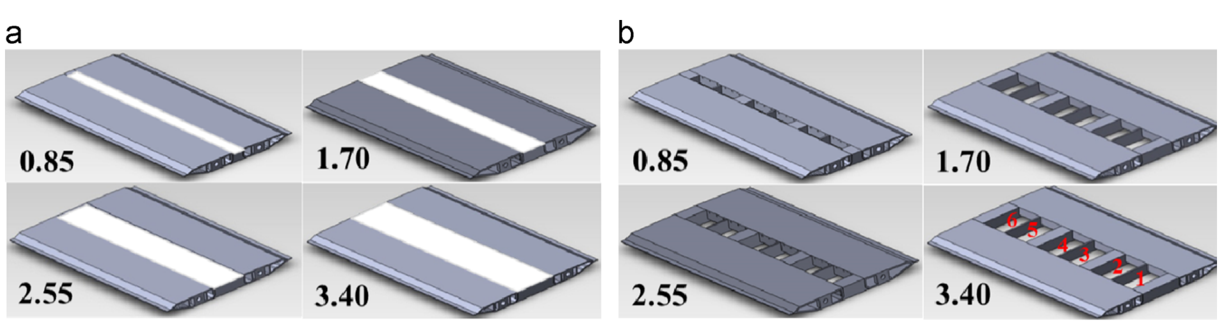

Fig. 1. Testing deck models with different gap ratios, (a) model #1, (b) model #2.