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Short Note

Parameter sensitivity study on flutter stability of a long-span triple-tower suspension bridge

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ABSTRACT

The flutter instability is the most hazardous wind-induced vibration for the long-span suspension bridge. In this study, the first-built long-span triple-tower suspension bridge in China, the Taizhou Yangtze River Bridge, is taken as an example. The three-dimensional flutter stability analysis of the bridge is conducted based on ANSYS, and the parametric analysis on the structural flutter stability is performed. The parameters studied in this paper include the sag-to-span ratio, the stiffness of the main girder, the dead load of the main girder, the rigid central buckle, the longitudinal stiffness of the middle tower and the cable system. The result shows that the torsional stiffness of the main girder, the sag-to-span ratio of cables, the central buckle and the cable system has significant influence on the flutter stability of the bridge. Among the sensitive parameters found in this paper, the influence of the cable system is prominent. However, the influences of the stiffness of the main girder, the longitudinal stiffness of the middle tower and the dead load of the deck are limited. The results can provide the reference information for wind resistance design of long-span triple-tower suspension bridges in the future.

1. Introduction

Flutter is a self-excited vibration induced by wind, and the flutter instability is the most hazardous wind-induced vibration for the long-span bridge as the bridge oscillates in a divergent and destructive manner at some critical wind velocity (Simiu and Scanlan, 1996). Since the collapse of the old Tacoma Narrow Bridge in 1940, the flutter instability of the long-span bridge has been paid special attention. With the increase in the bridge span, flutter instability potentially occurs for fairly low wind velocity because of the large flexibility and low structural damping (Scanlan and Tomko, 1971; Scanlan and Jones, 1990). Consequently, the research on the flutter stability of long-span bridges is of great significance and has become one of the key issues in bridge wind engineering (Scanlan, 1978).

The objective of the flutter analysis is to evaluate the lowest critical flutter wind velocity as well as the corresponding flutter frequency. In general, flutter analysis can be conducted in either frequency domain or time domain. Great achievements have been made in this field based on the long-term collaboration of the bridge engineers and the aerodynamic scientists. Several methods have been proposed for flutter analysis of bridges, such as the full-order flutter analysis method (Miyata and Yamada, 1990; Dung et al., 1998; Ge and Tanaka, 2000; Ding et al., 2002), the multimode flutter analysis technique (Xie and Xiang, 1985; Agar, 1989; Namini et al., 1992; Tanaka et al., 1992; Jain et al., 1996; Katsuchi et al., 1999; Zhang and Sun, 2004; Chen, 2007; Hua et al., 2007), etc. The full-order method employed in this study is not based on the structural modal but the system model of the interaction between the structures and aerodynamic forces, meanwhile, the overall influences of structural modal without modal analysis in advance is considered.

However, most research on aerodynamic stability analyses are focused on two-tower suspension bridges (Abdel-Ghaffar, 2000; Jurado and Hernández, 2004; Zhang and Sun, 2004; Almutairi et al., 2006; Wang et al., 2011). The triple-tower suspension bridge is totally a new type of structural form. Unlike a two-tower suspension bridge, a triple-tower suspension bridge has a dominant middle tower between main spans to alleviate the strain of main cables and anchors at two ends of the bridge. The middle tower is a vertical pivot for supporting main cables through the saddle seats of the bridge. Compared to a two-tower suspension bridge, structural characteristics of a triple-tower suspension bridge are

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strikingly different owing to the addition of a middle tower and an additional main span. Yoshida et al. (2004) studied the parameters influencing the deformation characteristics of a four-span suspension bridge which had two main spans of 2000 m in length each. Based on the preliminary design of Taizhou Yangtze River Highway Bridge (the Taizhou Bridge for short), Zhang (2010) studied the structural parameters on the aerodynamic stability of three-tower suspension bridge, In general, few research on the triple-tower bridges are conducted, especially on the aerodynamic stability.

The Taizhou Bridge is taken as an example in this paper. After a three-dimensional (3-D) finite element (FE) model is established based on ANSYS, the flutter analysis of the bridge is conducted using the full-order method, and the design parameter sensitivity analyses on the structural flutter stability are carried out. Results show that the torsional stiffness of the main girder, the sag-to-span ratio of cables, the central buckle and the cable system have significant influence on the flutter stability of the bridge. However, the influences of the sectional area of the middle tower and the dead load of the deck are very limited. The objective of this study is to provide theoretical reference for flutter analysis of triple-tower suspension bridges.

2. Bridge description

The Taizhou Bridge, as shown in Fig. 1, is a triple-tower suspension bridge crossing the Yangtze River. The bridge connects Taizhou City with Changzhou City in China. Fig. 2(a) shows that each of the two main spans is 1080 m, which is the longest main span in triple-tower suspension bridges in the world. The typical streamline flat steel box girders were used in the bridge, as shown in Fig. 2(b). The sag-to-span ratio of the cable is 1/9. The double suspender system is used and the longitudinal distance between two adjacent suspenders is 16 m.

Fig. 1. Taizhou Bridge.

The length of a standard segment of the main girder is 16 m. Q345qD steel was used in the main girder. To decrease the weight of the dead loads and improve the ventilation inside the box girder, the truss structure was adopted as the transverse clapboard with the distance of 3.6 m.

The two side towers are reinforced concrete structures with an overall height of 178 m. Vertical and lateral bearings were installed on lower cross beams of side towers. The middle tower is a variable cross-section steel tower with a portal frame in the lateral view and herringbone type in the longitudinal direction. Lateral supports are installed at the joints of the middle tower and the main girder to resist wind loads. Elastic restraints made of steel stranded wires were installed to control the relative displacement between the main girder and the tower. The material and sectional parameters of the bridge are shown in Table 1.

3. Finite element (FE) model of the bridge for flutter analysis

3.1. Initial FE model of Taizhou Bridge

According to the bridge design, the initial FE model of the Taizhou Bridge was established based on ANSYS, as shown in Fig. 3.

In the FE model, the main girders and three towers were modeled by spatial beam elements with 6 degrees of freedom (DOF) at each node. The stiffness and the mass of the steel box girder were lumped on the middle nodes. The element stiffness was taken as its actual stiffness, while the element density was taken as the transformed density of the dead loads including the first and second phases of the bridge deck. The higher and lower tower columns were divided into 46 elements in total, and the higher and lower cross beams of the towers were all divided into 12 elements. The main cable and the suspender were simulated spatial truss elements with 3 DOFs at each node, and the main cable was also meshed to match the nodes of the suspender. The truss elements were assigned tension-only, and the nonlinearity of the back cable stiffness due to gravity was approximated by using the equivalent modulus of elasticity (Ernst, 1965).

As seen in the bridge design, the deck and two side towers were coupled in 3 DOFs, including the vertical displacement, the transverse displacement and the rotation around longitudinal direction. As for the middle tower, only the lateral DOF was coupled with the steel box girder. The spring element was used

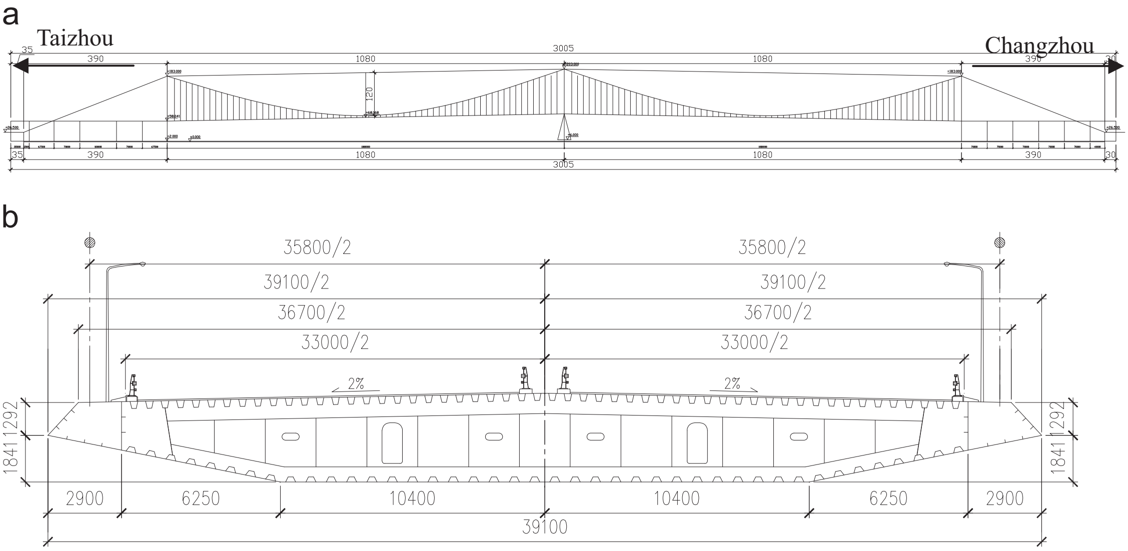

Fig. 2. Schematic description of Taizhou Bridge: (a) elevation (unit: m) and (b) section of the girder (unit: cm).