Influence of structural parameters on dynamic characteristics and wind-induced buffeting responses of a super-long-span cable-stayed bridge

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Abstract: A 3D finite element (FE) model for the Sutong cable-stayed bridge (SCB) is established based on ANSYS. The dynamic characteristics of the bridge are analyzed using a subspace iteration method. Based on recorded wind data, the measured spectra expression is presented using the nonlinear least-squares regression method. Turbulent winds at the bridge site are simulated based on the spectral representation method and the FFT technique. The influence of some key structural parameters and measures on the dynamic characteristics of the bridge are investigated. These parameters include dead load intensity, as well as vertical, lateral and torsional stiffness of the steel box girder. In addition, the influence of elastic stiffness of the connection device employed between the towers and the girder on the vibration mode of the steel box girder is investigated. The analysis shows that all of the vertical, lateral and torsional buffeting displacement responses reduce gradually as the dead load intensity increases. The dynamic characteristics and the structural buffeting displacement response of the SCB are only slightly affected by the vertical and torsional stiffness of the steel box girder, and the lateral and torsional buffeting displacement responses reduce gradually as the lateral stiffness increases. These results provide a reference for dynamic analysis and design of super-long-span cable-stayed bridges.

Keywords: cable-stayed bridge; dynamic characteristics; finite element (FE) method; wind field simulation; buffeting response; parameter effects; elastic connection device

1 Introduction

Due to increasing global economic development together with improved theory of bridge design and construction methods, long-span bridge engineering has made many excellent achievements since the end of the 20th century. Moreover, cable-stayed bridges have proliferated all over the world due to their strong span ability. Abroad, the longest cable-stayed bridge is the Tatara bridge, with a main span of 890 meters. The Normandy bridge, with the main span of 856 meters, ranks second. Moreover, the Russky Island bridge, with a main span of 1104 meters, is under construction. As with the rapid development of bridge engineering abroad, bridge construction in China has also made great progress. Currently, there are seven completed cable-stayed bridges with spans of more than 600 meters in China. The Sutong cable-stayed bridge (SCB) has a main span of 1088 meters and is the longest cable-stayed bridge in the world; it has become a new milestone in the history of the cable-stayed bridge.

With the increase of the main span, cable-stayed bridges are becoming more and more flexible. As a result, they are increasingly vulnerable to earthquakes, winds, vehicles and other heavy loads. Structural dynamic characteristics including natural frequencies and vibration mode shapes are the basis for conducting structural dynamic analysis. As an important technique to obtain the structural dynamic characteristics, modal analysis on long-span bridges has become one of the key research issues in bridge engineering (Abdel-Ghaffar, 2000; Maceri and Vairo, 2003; Almutairi et al., 2006; Karoumi, 2007; Loh and Chang, 2007; Xu et al., 2009; Wang et al., 2010a). Scanlan and Jones (1990) considered that the self-excited aerelastic force had a very important influence on the buffeting response of bridges.
Katsuchi et al. (1999) made a further development of Scanlan's theory by taking the aerodynamic admittance into account during the buffeting analysis. Chen et al. (2001) studied the buffeting response of large span cable-stayed bridges, and indicated that the aerodynamic coupling of the vibration mode should be considered during the structural response analysis. Ding et al. (2003) used a finite element (FE) CQC method for analyzing the aerodynamic mode coupling effect. Xu and Zhu (2008) analyzed the coupled stayed bridge based on some strong motion records. Hua identified the buffeting response with the pseudo excitation method.

As is well known, the structural design parameters are closely related to the dynamic characteristics of long-span cable-stayed bridges. At present, most research on static and dynamic analysis focuses on wind resistance, seismic resistance, FE modeling and dynamic analysis. Ye and Hu (2004) carried out a study of seismic displacement control for super-long-span cable-stayed bridges. Ren and Peng (2005) conducted experimental and analytical studies on dynamic characteristics of a large span cable-stayed bridge. Guo and Xu (2007) studied the dynamic performance of a cable-stayed bridge tower with a multi-stage pendulum mass damper under wind excitations. Siringoringo and Fujino (2007) identified the dynamic characteristics of a curved cable-stayed bridge based on some strong motion records. Hua and Chen (2008) analyzed the coupled flutter of long-span bridges by full-order and multimode methods, and then presented an equation which leads to a single-parameter searching technique without iteration to determine the conditions of flutter instability. Bartoli and Mannini (2008) analyzed the flutter behavior of several types of bridges and investigated the influences of the structural damping ratio and natural frequency on the structural flutter instability. Briseghella and Busatta (2010) conducted dynamic characteristic analysis on a curved cable-stayed bridge using both the operational modal testing and the FE modeling techniques. However, very little research about the parametric effects on the dynamic characteristics and buffeting responses of cable-stayed bridges has been conducted, especially on super-long-span cabled-stayed bridges such as the SCB.

In this study, the SCB is used as an example of a super-long cable-stayed bridge. A 3D FE model was established for the SCB using ANSYS. Based on the model, modal analysis was performed to obtain the structural dynamic characteristics using the subspace iteration method. By using the spectral representation method and the fast Fourier transform (FFT) technique combined with measured data, turbulent winds at the SCB site are simulated. During the simulation, the measured wind spectrum model, therefore, the wind field simulation results in this study can be employed to validate values from current design specifications (Wang et al., 2013). The effects of important design parameters and key structural measures on the dynamic characteristics of the bridge are investigated. The objective is to provide theoretical references for dynamic analysis and design of super-long-span cable-stayed bridges.

2 Bridge description

Located in the eastern part of Jiangsu province, the SCB, as shown in Fig. 1, will be the longest cable-stayed bridge in the world when it is completed. The project is very complex, and the highest construction standards as well as the most complex and advanced techniques are being used in its design and construction.

The SCB is a double-tower double-cable-plane steel-box-girder cable-stayed bridge with a main span of 1088 m, as shown in Fig. 2. A streamlined flat steel-box-girder is employed as the deck and the whole width is 41.0 m. Without counting in the wind mouth, the widths of the roof and bottom are 35.4 m and 9.0 + 23.0 + 9.0 m, and the height of the deck at centerline is 4.0 m. Parallel wire cables are adopted, and the basic distance of the cables are 16 m at the main span, 12 m at the side span, and 2 m at the towers. The total number of cables on the bridge is $4 \times 34 \times 2 = 272$. The longest cable is about 577 m long, and the largest size is PES7-313. The main towers are inverted Y-shaped, including upper, middle, lower tower columns, and lower beams. The full height of the towers is 300.4 m, and the height of the towers above the deck is 230.41 m. There are only horizontal wind-resistant bearings and vertical viscous dampers with limit function between towers and the deck. 131 bored piles with a length of 117 m are adopted as the foundation of the main towers, and the inner diameter of the steel tubes is 2.8 m. The layout of the piles is quincunx. The pile caps with plane size of 51.35 m × 48.1 m are dumbbell-shaped. The thickness of the pile cap varies from 5.0 to 13.3 m. There is a connection

Fig. 1 View of SCB