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Investigation of the wind-resistant performance of seismic viscous dampers on a cable-stayed bridge

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ABSTRACT

Wind and seismic resistance design are two critical elements in structural design of long-span cable stayed bridges. In order to investigate the influences of the originally equipped seismic viscous dampers on the wind-resistant performance of bridges, full bridge aeroelastic wind tunnel tests have been carried out on the overall scaled model of Hangzhou Bay Cable Stayed Bridge. It is found that the bridge exhibits good wind-resistant performance, while seismic viscous dampers have very minor effects on the vertical buffeting displacement of the mid-span girder. The study also shows that optimizing the damper parameters could only slightly improve the ability of the dampers to reduce wind vibrations. Therefore, when designing long span cable stayed bridges, the bridge seismic design and wind-resistant design can be carried out separately, without considering the wind-resistant effects of the dampers which aim at dissipating earthquake energy.

1. Introduction

In recent years, many long-span bridges have been constructed and opened to traffic. Well-known examples are Runyang Bridge (a suspension bridge with a main span of 1490 m), Jiangyin Bridge (a suspension bridge with a main span of 1385 m), Sutong Bridge (a cable-stayed bridge with a main span of 1088 m), Third Nanjing Bridge (a cable-stayed bridge with a main span of 648 m), and Hangzhou Bay Bridge (a cable-stayed bridge with a main span of 448 m), etc. [1–4]. Among the various types of dynamic responses, wind-induced vibration is one major concern during the design, construction and later operational service stages for these long-span flexible bridges, which often locate at open river or ocean areas with unfavorable wind environments. In extreme cases, if dealt with improperly, destructive structural failure may occur when subject to strong winds.

To evaluate and ensure the wind-resistant performances, there have been many researches carried out to study particularly wind-induced flutter and buffeting responses, which may be generally divided into three categories, i.e., theoretical analysis [5–8], in-situ monitoring of wind characteristics and structural responses [9–11] and wind tunnel tests[3,4,12] (and their combinations or comparisons with numerical simulations). Among these studies, wind tunnel tests would provide the most valuable information to improve the aerodynamic behavior of long-span bridges during the design stage. It is pointed out that compared to the sectional model tests, full bridge aeroelastic wind tunnel tests are more reasonable in case of cable-stayed bridges because the tower-girder-cable interaction can impose either positive or negative effects on the wind response depending on the bridge design and on the type of wind excitation [13]. To meet the wind safety requirements, two vibration mitigation measures can be adopted whenever necessary, including improving the bridge cross-section's aerodynamic configuration, increasing the structural overall stiffness and adding extra damping through mechanical measures. For example, tuned mass dampers (TMDs) are adopted to control wind-reduced vibrations of the Great Belt East Bridge and their effectiveness is proved through a full bridge aeroelastic model [14]; for the trans-Tokyo Bay Highway Crossing Bridge, TMDs are employed specially to control vibrations related to the first and second vertical flexural modes [15].

In the design stage of Hangzhou Bay Bridge, it has been proved that the bridge can meet the wind-resistant design requirements through both sectional model and full bridge aeroelastic wind tunnel tests in various smooth and turbulent flow test conditions. Thus, no particular mitigation measures are needed to reduce wind-induced vibration. However, structural analysis indicated that energy dissipation devices such as viscous dampers should

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be equipped to reduce the seismic responses of girders or towers subjected to potential earthquakes.

To our knowledge, there has been no study reported to investigate the influences of viscous dampers (that are installed to mitigate seismic bridge responses) on the wind-resistant performance of bridges. The motivation of this study is to gain more insight into this influence. If the viscous dampers favor the bridge's wind-resistant performance, in order to make the best of the viscous dampers, the damper parameters can be adjusted and optimized to simultaneously mitigate the bridge responses subjected to wind and seismic excitations. On the other hand, if the viscous dampers have adverse wind-resistant effects, the original scheme of seismic scheme should be reconsidered and redesigned.

2. Hangzhou Bay Cable Stayed Bridge

The Hangzhou Bay Crossing Bridge is located in the coastal area of Zhejiang Province in China, spanning the Hangzhou Bay area and connecting Haiyan city and Cixi city. The Hangzhou Bay's horn-shaped terrain forms a narrow "tube effect", which would cause complicated weather conditions, especially harsh wind field characteristics. Corresponding to a recurrence interval of 100 years, the wind speed 10 m above the mean sea tide height can reach 31.9 m/s. The total length of the Hangzhou Bay Crossing Bridge is around 35.7 km, currently the world's longest cross-sea bridge. Hangzhou Bay Cable Stayed Bridge is a double pylon cable-stayed bridge over the north navigation channel. The stay cables are arranged in double inclined cable planes. A streamlined closed steel box girder is adopted for the bridge girder and two diamond-shaped reinforced concrete pylons for bridge towers. One auxiliary pier and one transitional pier are symmetrically set on each side. The bridge has an overall length of 908 m (70 m + 160 m + 448 m + 160 m + 70 m). A schematic representation of the bridge is shown in Fig. 1. To simplify the expression, in this study, Hangzhou Bay Cable Stayed Bridge is simply denoted as Hangzhou Bay Bridge.

To control the seismic responses, a set of energy dissipation system is installed on the Hangzhou Bay Bridge. A total of 8 nonlinear viscous dampers are placed transversely on each auxiliary pier and transitional pier, and four viscous dampers are placed longitudinally at the cross beams of the two pylons, as shown in Fig. 2.

3. Full bridge aeroelastic model wind tunnel test

3.1. Description of the full-bridge aeroelastic model

As shown in Fig. 3, the full bridge aeroelastic model of Hangzhou Bay Bridge was manufactured at a geometric scale of 1:100. All the similar parameters are derived from this geometric scale. The wind speed ratio and frequency ratio are accordingly 1/10. Model design also considered the consistency of various aerodynamic parameters. The total length and height of the model are 9.08 m and 1.83 m, respectively.

Since this wind tunnel test is to study the wind-resistant performance of the bridge after installing seismic viscous dampers, in addition to meet the general wind tunnel test requirements, the model must also be consistent with the seismic mitigation bridge system. Due to the limited installation space, the small size of viscous dampers and difficulties in fabrication, the two transverse dampers on the same auxiliary pier or transitional pier are combined into one, where a beam was used to connect two pier columns, and similarly, the two longitudinal dampers on pylon columns are also combined into a single one. The damping coefficient of the combined damper is twice that of the original damper. In order to investigate various damper arrangement cases as introduced in Section 3.2, the damper connections are designed to be removable. To prevent upward drift of the main girder during the testing process and to ensure the transverse and longitudinal dampers function normally, two-directional roller bearings were designed. The installation of dampers on the aeroelastic model is shown in Fig. 4.

Viscous dampers are velocity-dependent passive energy dissipation devices which do not possess inherent rigidity [2]. The produced damper force F, given in Eq. (1), depends on relative velocity between damper ends as follows;

$$F = CV^{\alpha} \tag{1}$$

where C is damping coefficient, α is damping index, V is relative velocity between damper ends. Damping index takes value between 0 and 1. This constant value designates the damper type. The device is friction type, linear viscous and nonlinear viscous damper for $\alpha = 0$, $\alpha = 1$ and for $0 < \alpha < 1$, respectively. To obtain the characteristic of the viscous damper in the scale model, a quasi-static test was

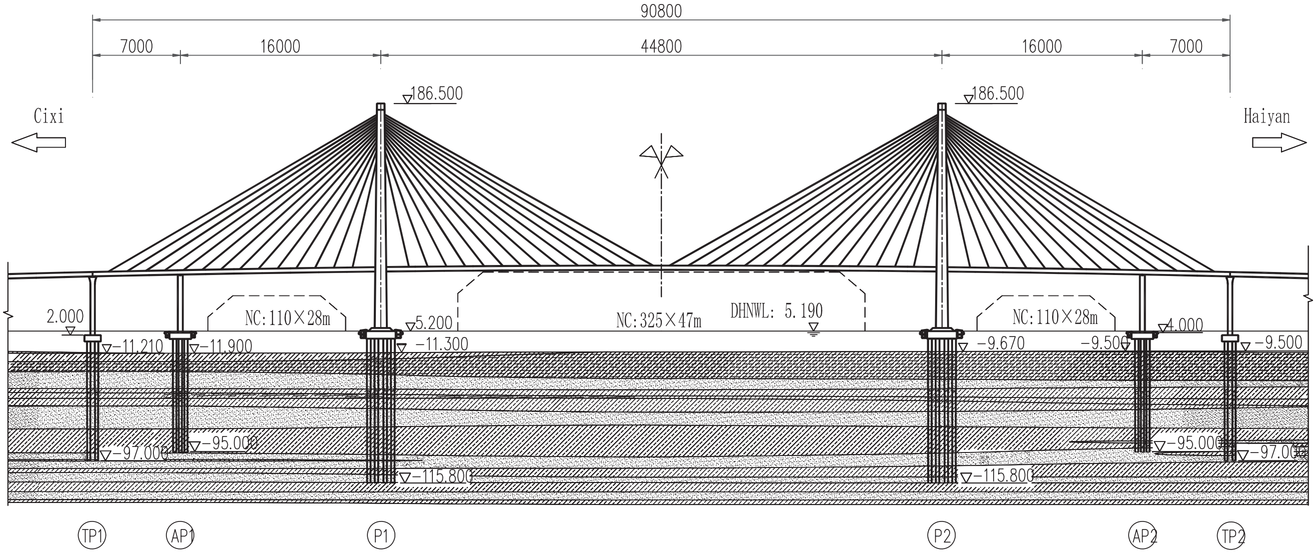

Fig. 1. Cable-stayed bridge over the north navigation channel (unit: cm). NC – navigation clearance; DHNWL – highest water level; TP1,TP2 – Transitional piers; AP1, AP2 – auxiliary piers; P1, P2 – pylons.