Influences of structural system characteristics on the dynamic characteristics and wind-induced buffeting response of multi-tower cable-stayed bridge

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Abstract—This study explores the dynamic characteristics and the nonlinear wind-induced buffeting response of the bridge based on a six-tower cable-stayed bridge, the Jiashao Bridge. The effect of structural system characteristics (number of anchor piers and different conditions of longitudinal constraints) on the dynamic characteristics and the wind-induced buffeting performance of multi-tower cable-stayed bridges has been studied in detail. The analysis indicates that the different amounts of anchor piers have a limited effect on changing the overall stiffness of the bridge, but have an obvious effect on the buffeting displacement response of the side spans to which they belong. As for the condition of longitudinal constraints between the girder and towers, it mainly changes the vertical and transverse bending stiffness of the girder which means with the enhancement of the longitudinal constraints, the bending stiffness of the girder increases, and meanwhile significantly influence the transverse buffeting response of the girder.

1. Introduction

In the construction scheme of cross-sea projects, the multi-tower cable-stayed bridges have the arrangement form of multiple towers with long spans, which can avoid establishing deepwater foundation on the basis of ensuring navigability [1]. Compared with conventional cable-stayed bridges, the main components (cables, towers and the girder) of multi-tower cable-stayed bridges are more sensitive to live load and temperature-induced effect [2]. Hence, using a reasonable structural system to improve structural stiffness and reduce temperature-induced effects is the key point for the design. The previous literature [3] provides conceptual design and practice of multi-tower cable-stayed bridges and identified various possible stiffening measures for the insufficient stiffness of the system, including improving the span arrangement, setting anchor piers at the side spans, adopting rigid towers, setting stiffening cables between towers, increasing the stiffness of the main girders and cables and so on. Three typical methods, adding longitudinal constraints between the girder and towers, adopting larger-scale cables and towers and setting up rigid hinge setting in the midspan of the girder, were adopted by the
Millau Viaduct Bridge [4] in France, the Rion-Antirion Bridge [5] in Greece and the Jiashao Bridge in China.

The stiffness strengthening and constraint characteristics of the multi-tower cable-stayed bridges are mainly aimed at reducing the structural live load effect and temperature-induced effect. Therefore, the analysis in this paper focuses on the effects of the structural characteristics on the dynamic characteristics and wind-induced buffeting performance.

2. Analysis of the dynamic characteristics

2.1. Overview

The Jiashao Bridge, which is a six-tower cable-stayed bridge, crosses Hangzhou Bay, along the highway between Jiaxing and Shaoxing in China. The total length of the bridge is 2680m with the span arrangement of 70m + 200m + 5 ×428m+ 200m + 70m. It is the longest multi-tower cable-stayed bridge in the world. To solve the problems of low vertical stiffness and large temperature-induced deformation of the girder, four types of strengthening measures were adopted in the design: (1) longitudinal supports were set at the joints between towers and girder; (2) anchor piers were set at the side spans; (3) rigid hinges were set in the midspan of the girder; (4) longitudinal constraints were set at the secondary side towers (Tower 2 and Tower 5).

2.2. Dynamic analysis model

As shown in Fig 1, a three-dimensional finite element model of the Jiashao Bridge has been created in the commercial software package ANSYS (ANSYS 2009). The girder, bridge towers and piers are simulated by Timoshenko’s beam elements. Considering the geometric stiffness of cables under dead load, the Ernst equivalent modulus of elasticity is adopted [6].

2.3. Results of dynamic characteristics

The main results of the modal analysis are listed in Table 1 which shows that: (1) The first mode is the coupling mode of the symmetric vertical bending of girder and symmetric longitudinal bending of towers. (2) No longitudinal floating mode appears as the longitudinal constraints between the girder and towers have been set. (3) The global third mode is the first mode of towers indicates that the tower bridge owns small longitudinal bending stiffness. (4) The first mode of transverse bending of the girder is appeared at the 21st global mode. (5) The first torsional mode of the girder appears at the 43rd global mode. The torsional frequency is strongly related to flutter instability. It implies better aerodynamic stability with a higher first-order torsional frequency of the girder[6], a larger ratio of first-order torsional frequency to first-order vertical bending frequency of the girder, and wider space of double-girders. For the Jiashao Bridge, the first torsional mode of the girder appears later, and the ratio to the first vertical bending mode is 4.996, which indicates that the structure has adequate wind-resisted stability.

3. Simulation of the wind fields and analysis method of buffeting response

3.1. Simulation of 3D fluctuating wind fields

The simulation of 3D fluctuating wind fields is constituted by eight one-dimensional independent multivariable stochastic wind fields, in the vertical and transverse directions of the girders and six
transverse directions of the towers. The spacing of simulation points on the girder is arranged at equal intervals of 30m along the span direction and the spacing of simulation points on towers is arranged at equal intervals of 10m along the vertical direction. The time histories of fluctuating wind speed are obtained by using a modified Deodatis simulation method [7]. The transverse and vertical wind spectrum using Kaimal spectrum and Lumley-Panofsky spectrum, respectively. The velocity cross-spectrum of fluctuating wind uses the Davenport coherence function [8]. The time histories of fluctuating wind speed and the Comparison of the power spectrum and target power spectrum at the middle point of the girder are shown in Fig 2 and Fig 3.

Table 1. The main results of modal analysis of the Jiashao Bridge

| Mode number | frequency/Hz | Mode shape | Mode number | frequency/Hz | Mode shape |
|-------------|--------------|------------|-------------|--------------|------------|
| 1           | 0.2274       | G-SV-1+TW-SL | 21          | 0.7087       | G-SR-1+TW-SR |
| 2           | 0.2615       | G-AV-1+TW-AL | 33          | 0.8956       | G-AR-1+TW-AR |
| 3           | 0.2894       | TW-SR-1     | 43          | 1.1361       | G-T-1      |
| 4           | 0.2907       | TW-AR-1     | 44          | 1.1389       | G-T-2      |
| 16~19       | 0.6779       | P-L         | 45          | 1.1391       | G-T-3      |

Note: G = girder; TW = towers; P = anchor piers; S = symmetrical; A = asymmetrical; V = vertical bending; R = transverse bending; L = longitudinal; T = torsional; F = Longitudinal floating; others can be seem as congruous.

3.2. Time-domain procedure of wind-induced buffeting

In the analysis of wind-induced buffeting response, the wind load generally consists of three components: the steady aerodynamic forces due to the average wind speed, the buffeting forces due to the fluctuating wind and the self-excited forces due to flow-solid coupling.

\[ L = L_{st} + L_b + L_{se} \]
\[ D = D_{st} + D_b + D_{se} \]
\[ M = M_{st} + M_b + M_{se} \]  

Fig. 2 The vertical wind speed time histories of the simulation point

Fig. 3 Time histories and correlation functions of transverse wind speed in the midspan of the girder

(a) auto-spectrum of the simulation point  
(b) Auto-correlation of the simulation point
where $L$, $D$, $M$ represent the three components of resisting force, lifting force and torque under the specified coordinate system. The subscripts $st$, $b$ and $se$ represent the steady aerodynamic forces, the buffeting forces and the self-excited forces.

The specific steps in the non-linear time-domain buffeting analysis include: (1) Calculate the steady aerodynamic forces and the buffeting forces by measured static three-part force coefficients and the corrected Scanlan buffeting forces model [7], respectively. (2) Calculate the self-excited forces by the Scanlan self-excited forces model [9], and define their aerodynamic stiffness terms and aerodynamic damping terms based on, for example, flutter derivatives and wind speed data. (3) Apply the wind load to the model to perform a time-history analysis, in which geometric and aerodynamic nonlinearity have been taken into consideration. (4) Analyze the results of the buffeting response [10].

4. Influences of structural system characteristics on the dynamic characteristics and buffeting response

4.1. Influences of the anchor piers

In order to analyze the influence of the number of anchor piers on the buffeting performance of a multi-tower cable-stayed bridge, this section establishes a comparative model which includes two anchor piers (model 1) and three anchor piers (model 2) based on the basic model of the Jiashao Bridge. The layout of the two anchor piers is shown in Fig 4. The main dynamic characteristics results of the two anchor piers are shown in Table 2 which indicate that: (1) The frequency of the vertical bending mode of the main beam, the side bending mode of the main tower, and the transverse bending mode of the main beam slightly increase with the number increasing of the anchor piers; (2) The frequency of the torsional mode of the girder decreases slightly with the increase of the number of anchor piers; (3) The main modes of anchor piers are longitudinal. Therefore, the number of the anchor piers has a limited impact on the overall stiffness of the multi-tower cable-stayed bridge.

A further buffeting response analysis of model 1 has been carried out based on the analysis of the dynamic characteristics. Meanwhile, the comparative analysis is taken between these two models which shows there is a negligible difference in the longitudinal and transverse buffeting response of the towers by setting transition piers, but it generates a significant influence on the buffeting displacement response of the girder. Fig 5a and Fig 5b show the comparison results of the RMS (root mean square) buffeting displacement of the girder and towers (Tower 3 as an example) with one (original model), two and three anchor piers. It’s obvious that the anchor pier mainly affects the buffeting displacement response of the side spans to which they belong. The increasing of the anchor piers makes the side spans gradually form a multi-span continuous beam, which leads to a decrease in buffeting response. In general, the more anchor piers, the smaller the buffeting displacement response of the side span.

| Mode number | frequency/Hz | Mode shape | Mode number | frequency/Hz | Mode shape |
|-------------|--------------|------------|-------------|--------------|------------|
| 1           | 0.2280       | G-SV-1+TW-SL | 23          | 0.7088       | G-SR-1+TW-SR |
| 2           | 0.2641       | G-AV-1+TW-AL | 36          | 0.8958       | G-AR-1+TW-AR |
| 3           | 0.2894       | TW-SR-1     | 45          | 1.1307       | G-T-1      |
| 4           | 0.2910       | TW-AR-1     | 46          | 1.1333       | G-T-2      |
| 16~19       | 0.6779       | P-L         | 47          | 1.1334       | G-T-3      |

Fig.4 The model with two anchor piers (unit: m)
5

(a) vertical RMS buffeting displacement

(b) transverse RMS buffeting displacement

(c) torsional RMS buffeting displacement

Fig. 5a Influences of anchor piers on buffeting displacement response of the girder

(a) longitudinal RMS buffeting displacement

(b) transverse RMS buffeting displacement

Fig. 5b Influences of anchor piers on buffeting displacement response of Tower 3

4.2. Influences of longitudinal constraints between towers and girder

Two models have been established based on the original Jiashao Bridge to analyze the different buffeting performance caused by different longitudinal constraints between the girder and towers. One is fully constrained in each tower which is Model 3. The other, Model 4, is releasing all longitudinal constraints. Table 3 and Table 4 list main analysis results of the dynamic characteristics of the fully constrained model and the fully released model. According to Table 3 and Table 4, it can be found that the longitudinal constraints of the tower girder have a greater influence on the vertical bending mode of the girder. Stronger longitudinal constrains give the girder a higher frequency of vertical bending. Meanwhile, the longitudinal constraints of the girder and towers affect the transverse bending mode of the girder certainly, the stronger the longitudinal constraints, the higher the frequency of the transverse bending of the girder. However, the longitudinal constraints have less effect on the torsional mode of the girder and the transverse bending mode of towers.

A further buffeting response analysis of the fully constrained model and the fully released model have been carried out as shown in Fig 6a and Fig 6b. The results of the analysis indicate that: (1) The
longitudinal constraints slightly affect the longitudinal and torsional displacement response of the girder.

(2) The longitudinal constraints affect deeply the transverse displacement responses of the girder as the transverse buffeting displacement response of the girder of the fully constrained model has been dramatically reduced while it is basically the same as the original model of the fully released model. (3) The longitudinal constraints have little effect on the longitudinal and transverse displacement response of the towers. Taking tower 3 as an example, the RMS buffeting displacement on the top of the tower of the fully constrained model, partially constrained model (the original model) and the fully released model gradually decreases, which is also consistent with the results of the dynamic characteristics analysis.

Table 3 The main results of modal analysis of the fully constrained model

| Mode number | frequency/Hz | Mode shape       | Mode number | frequency/Hz | Mode shape       |
|-------------|--------------|------------------|-------------|--------------|------------------|
| 1           | 0.2376       | G-SV-1+TW-SL     | 28          | 0.8598       | G-SC-1+TW-SR     |
| 2           | 0.2694       | G-AV-1+TW-AL     | 33          | 0.9524       | G-AC-1+TW-AR     |
| 3           | 0.2895       | TW-SR-1          | 43          | 1.1366       | G-T-1            |
| 4           | 0.2910       | TW-AR-1          | 44          | 1.1397       | G-T-2            |
| 16~19       | 0.6779       | P-L              | 45          | 1.1398       | G-T-3            |

Table 4 The main results of modal analysis of the fully released model

| Mode number | frequency/Hz | Mode shape       | Mode number | frequency/Hz | Mode shape       |
|-------------|--------------|------------------|-------------|--------------|------------------|
| 1           | 0.1704       | G-SV-1+TW-SL     | 23          | 0.7071       | G-SC-1+TW-SR     |
| 2           | 0.1725       | F+G-AV-1+TW-AL   | 31          | 0.8558       | G-AC-1+TW-AR     |
| 3           | 0.2894       | TW-SR-1          | 43          | 1.1357       | G-T-1            |
| 4           | 0.2907       | TW-AR-1          | 44          | 1.1384       | G-T-2            |
| 16~19       | 0.6779       | P-L              | 45          | 1.1387       | G-T-3            |

Fig. 6a Influences of the longitudinal constraints on buffeting displacement response of the girder.
5. Conclusion

In this paper, the dynamic characteristics and wind-induced buffeting response of a six-tower cable-stayed bridge are analyzed through the nonlinear time-domain method, with emphasis on the influence to the wind-induced buffeting responses caused by the structural system characteristics (number of anchor piers and different conditions of longitudinal constraints). The main conclusions are as follows:

1. The change of structural system characteristics will have a certain impact on the dynamic characteristics of the structure, and the wind-induced buffeting response of the girder and towers is closely related to the dynamic characteristics of the structure. Hence, different structural system characteristics will show the different influences on the buffeting response of the structure.

2. The setting of anchor piers mainly affects the buffeting displacement response of the side span where it is located, and the increasing number of the anchor piers can decrease the buffeting displacement response of the side span.

3. The longitudinal constraints of the girder and towers have relatively little effect on the vertical and torsional buffeting displacement response of the girder, and the longitudinal and transverse buffeting response of towers. But it could significantly affect the transverse buffeting displacement of the girder.

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