

## **A simulation study on passive control of the buffeting vibration of a multi-tower bridge**

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### **ABSTRACT**

Wind is one of the most important dynamic loads that affect the safety and usability of a long-spanned bridge. While structural control can offer a reliable contribution to suppressing some vibration of civil structures, this paper is focusing on the buffeting control of multi-tower bridges using viscous fluid dampers.

In order to study the effectiveness of this control strategy, the Jiashao Bridge, a cable-stayed bridge with six towers, is taken as an example in this paper. The spatial finite element model of the six-tower cable-stayed bridge is established in ANSYS, and the modal analysis following a large deflection static analysis is conducted. Then a time-domain buffeting analysis on the bridge is also conducted using a simulated 3D turbulence wind field. Furthermore the buffeting responses of the bridge with viscous fluid dampers are analyzed, and they are also compared with the responses without viscous fluid dampers aiming to investigate the control performance. Results show that the viscous fluid dampers has notable effects on reducing the displacements of the girder at middle span at both vertical and transverse directions, whereas the impact is not significant for the girder at other spans. It is also indicated that the base reactions of the towers are reduced, especially the base reactions of Tower2 and Tower5, and the maximum decreasing ratio reaches 41%.



Fig. 1 View of Jiashao Bridge

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## **1. INTRODUCTION**

Long span bridges must satisfy at the same time spanning very long distances and limited responses against external loads. In all these loads, wind buffeting is regarded as one of the most important dynamic excitation for long span flexible bridges owing to the low frequency content which characterize its spectrum (Domaneschi et al. 2015). In recent years, cable-stayed bridges are usually employed for overcoming large distances, and in general, they have low frequencies and damping ratio associated with their fundamental oscillation modes. Therefore, when subjected to dynamic loads, these bridges may experience large amplitudes of bending and torsional oscillation. Especially, if a cable-stayed bridge was built in a wind prone area, the bridge would experience large deflection due to mean wind and considerable vibration due to aerodynamic effects. Serious vibrations may cause fatigue damage in structural members such as stay cables and steel deck, and thereby increasing the maintenance cost of the bridge.

The buffeting of long-span bridges is a type of vibration motion induced by wind turbulence, and to date an amount of research work had been conducted on investigating the buffeting response analysis of long-span bridge (Gu 2012; Kim and Yhim 2014). At the same time, the suppression of the oscillation has also become one of the major concerns in bridge engineering. A number of methods exist for improving the performance of the long span bridges. Xing et al. (Xing et al. 2013) designed a TMD-type counterweight in which the counterweight originally designed for reducing the live load-induced displacements at the central span is taken as the mass block, and investigated the control performance by taking Sutong Cable-Stayed Bridge as example. Wen and Sun (Wen and Sun 2015) taken the Third Nanjing Bridge as example to investigate mitigating multimode buffeting of cable-stayed bridges by using distributed active tuned mass dampers (ATMDs), and they optimized the placements of ATMDs and sensors and developed a control model and schemes. Wang et al. (Wang et al. 2014) numerically analyzed the buffeting displacement of Sutong Bridge, and investigated optimal design of the multiple tuned mass dampers (MTMD). Heo et al. (Heo and Joonryong 2014; Heo et al. 2014) built two laboratory-scale model of cable-stayed bridge, and experimentally studied a semi-active control of with MR-damper, where both Lypunov and Clipped-optimal control algorithms were applied. Domaneschi and Martinelli (Domaneschi and Martinelli 2013) established a model of an existing suspension bridge in the ANSYS finite element code, and assessed the efficacy for the bridge protection of passive and on/off Skyhook semi-active control laws. And in 2015, they (Domaneschi et al. 2015) suppressed the wind buffeting response of suspension bridge with optimal designed TMD scheme and a hybrid control schemes which adopt tuned mass dampers and hysteretic dampers at the same time.

Most of these researches above focused on conventional three-span cable-stayed bridges with two towers, but recently the multi-span cable-stayed bridges with three or more towers have been a design trend (Jia et al. 2015; Ni et al. 2005; Okamoto and Nakamura 2011). Compared with the conventional cable-stayed bridges, the multi-span cable-stayed bridges have more spans and more towers, so the vibration properties are sure to be more complicated. Hence, it is necessary to investigate the unique features of the buffeting response of the multi-tower cable-stayed bridges and the corresponding

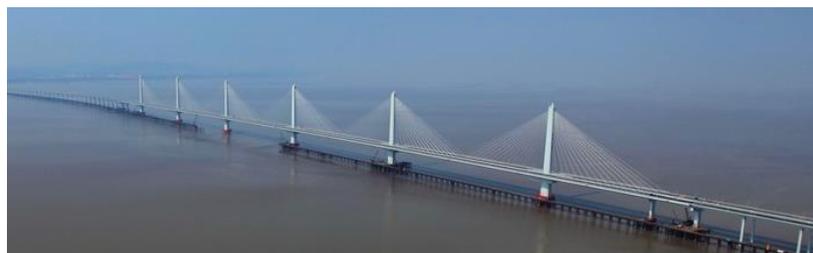
control strategies.

This paper investigates the wind-induced buffeting responses of the Jiashao Bridge, a multi-tower cable-stayed bridge, without and with viscous fluid dampers. The remainder of this paper is organized as follows. First, the structural information of the Jiashao Bridge is described, and its dynamic properties are presented using a finite element model (Section 2). Next, the wind field of the bridge is simulated in time domain, and the buffeting responses are analyzed considering the aerodynamic properties of the bridge (Section 3). Finally, the performance of the bridge with and without viscous dampers are compared (Section 4) and the major conclusions are described (Section 5).

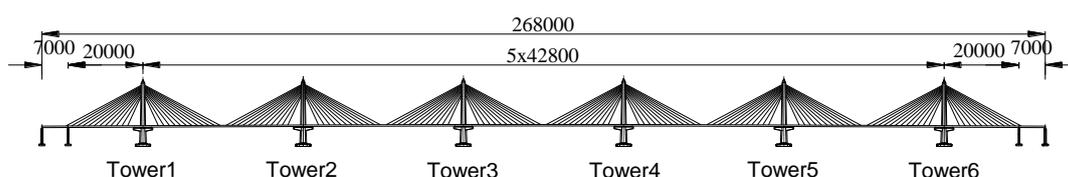
## 2. STRUCTURAL GEOMETRY AND NUMERICAL MODEL

### 2.1 BRIDGE DISCRIPTION

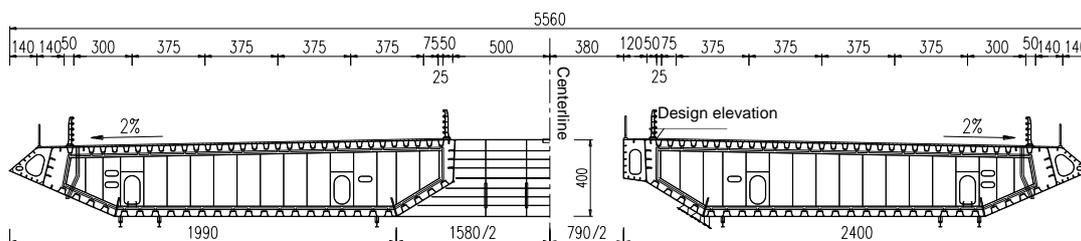
Connecting Jiaxing and Shaoxing City, the Jiashao Bridge is the longest multi-span cable-stayed bridge in the world with the span arrangement of 70m+200m+5×428m+200m+70m, as shown in Fig.1. The bridge construction was initiated in December 2008 and opened to traffic on July 2013.



(a) View of Jiashao Bridge



(b) Elevation of Jiashao Bridge (centimeters)



(c) Cross section of the steel box girder (centimeters)

Fig.1 The Jiashao Bridge

The Jiashao Bridge is a steel box-girder cable-stayed bridge. As shown in Fig.1(c), the bridge used a cross section composed of two orthotropic steel boxes. The width of the cross section is 55.6m which is the largest among the multi-tower bridges all over the world, and the height at the centerline is 4.0m. The six main towers, which are made of concrete, are single columns and sword-shaped. Between the bridge girder and the towers, two longitudinal constraints are applied at the Tower 2 and Tower 5 respectively, in order to restrict the bridge deck from moving in the longitudinal direction.

## 2.2 FINITE ELEMENT MODEL

The three-dimensional (3D) finite-element model (FEM) of the Jiashao Bridge is established based on ANSYS, as shown in Fig.2. In this model, a double-girder model is used to simulate the bridge deck system. The bridge deck, bridge towers and piers are all modeled as Timoshenko's beam elements with 6 degrees of freedom (DOFs) at each node, which account for transverse shear deformation, biaxial bending and axial strain. The stay cables are simulated using 2-node truss element which accounts for only tension and no compression. In order to consider the geometric stiffness of the stay cables under dead loading, the Ernst equivalent elastic modulus is used.

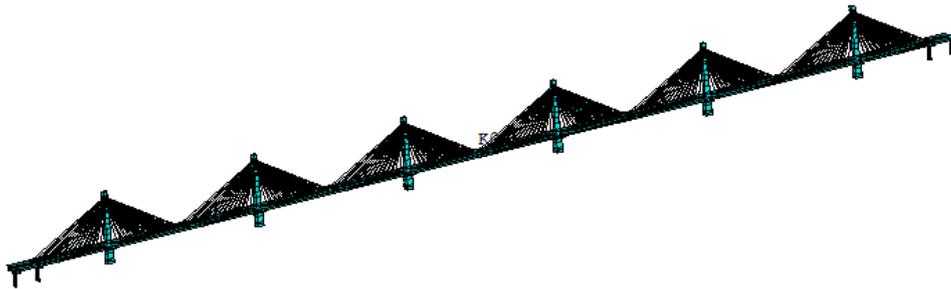
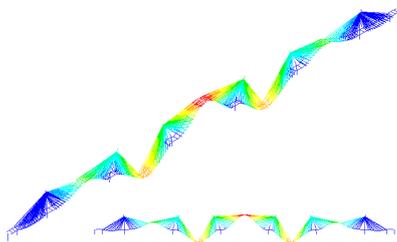
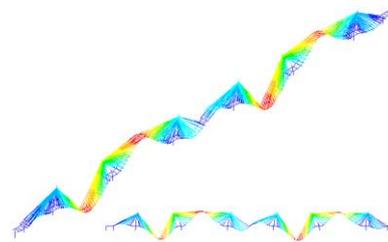


Fig. 2. Spatial FE model of the Jiashao Bridge

## 2.3 DYNAMIC PROPERTIES OF THE BRIDGE



(a) 1st symmetric vertical bending of bridge deck + symmetric longitudinal bending of bridge tower(0.227Hz)



(b) 1st anti-symmetric vertical bending of bridge deck + anti-symmetric longitudinal bending of bridge tower(0.262Hz)

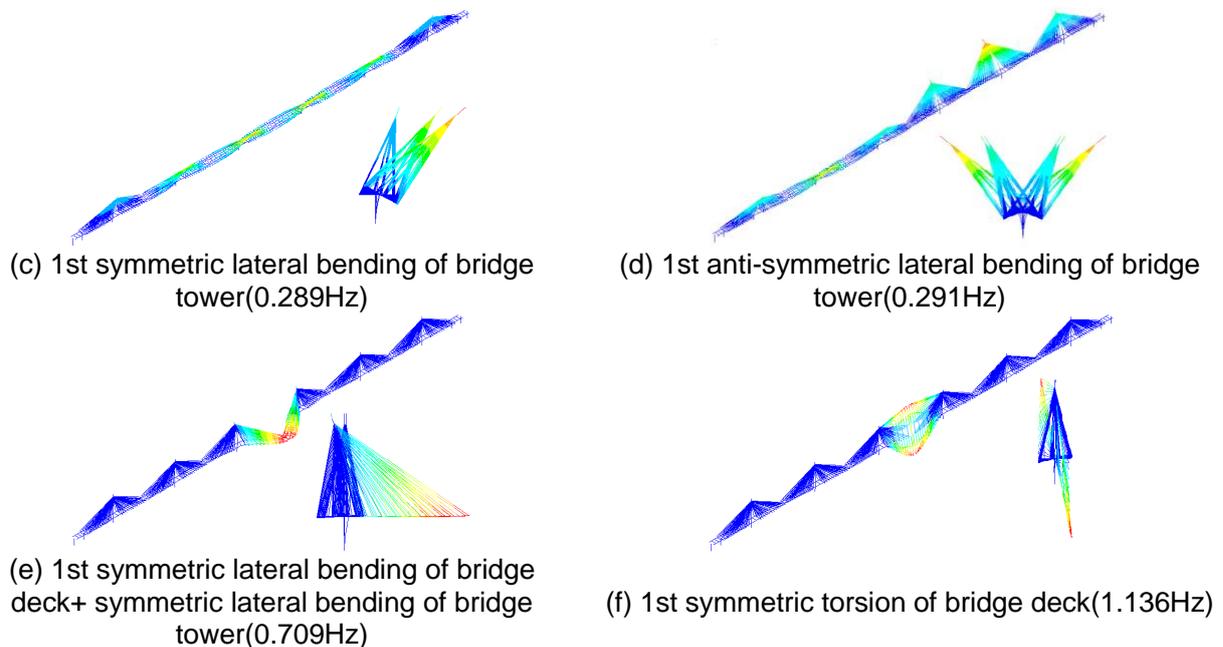


Fig. 3. Mode shapes of the bridge

The multi-tower cable-stayed bridge is a flexible structure, which exhibits prominent geometric nonlinearity. To obtain the frequencies and mode shapes of the Jiashao Bridge, the prestressed modal analysis is performed following a large deflection static analysis based on ANSYS. In this analysis, LANCZOS eigenvalue solver is used, and some of the main vibration modes are shown in Fig.3. It illustrates that the vertical bending mode appears earlier than the lateral bending vibration because the in-plane stiffness of the bridge deck is weaker than the out-plane stiffness. The Fig.3 also reveals that the longitudinal floating mode doesn't occur due to the longitudinal constraints between the bridge girder and the Tower 2/Tower 5.

### 3. BUFFETING RESPONSE OF THE MULTI-TOWER CABLE-STAYED BRIDGE

#### 3.1 WIND FIELD GENERATION

The turbulent component of the wind field is generally a function of the orography and environment. In this work, a three dimensional wind field is used as the base to derive the wind forces on the bridge, and the wind field is simulated as spatially correlated process acting in the horizontal and transversal directions. The autospectra adopted for transversal and vertical components are Kaimal spectrum and Panofsky spectrum, respectively. And it should be noted that the coherence between the longitudinal and vertical components is disregarded in the present study. Fig.4 shows the fluctuating velocity (Fig.4 (a)) and the corresponding spectrum (Fig.4 (b)), and it can be seen from the figure that the simulated spectrum is in well agreement with the targets.

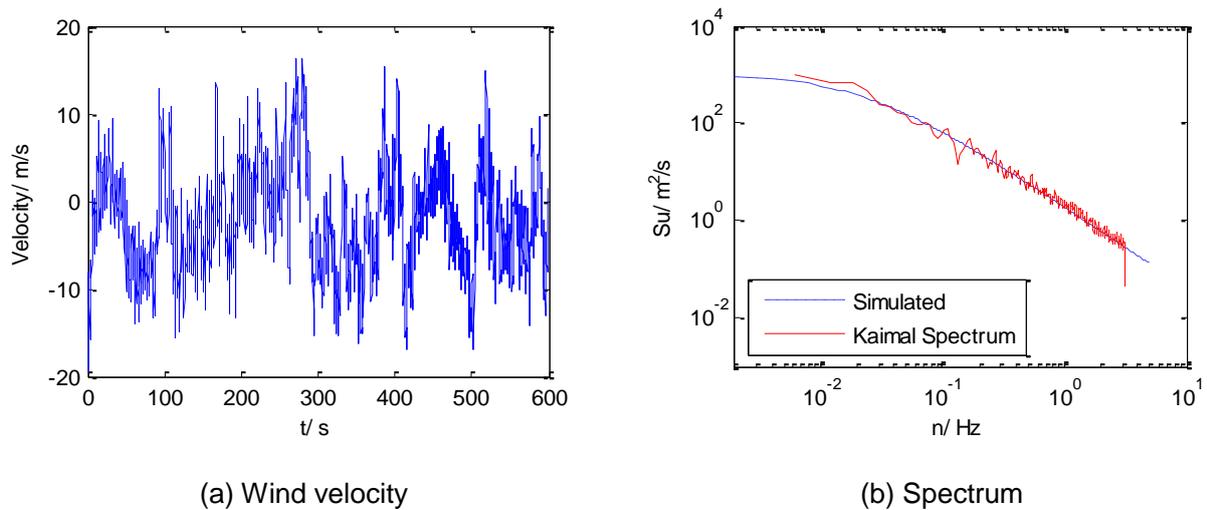


Fig. 4. Fluctuating wind velocity of Point 40

### 3.2 BUFFETING RESPONSES OF THE BRIDGE

During the time-domain buffeting analysis, the modeling of unsteady self-excited force usually requires the flutter derivatives to express the indicial functions or rational functions. The procedure can be simplified and implemented in ANSYS, where the self-excited forces on the bridge girder are modeled by the Matrix27 element (Xing et al. 2013; Wang et al. 2013). The Matrix27 element has 144 coefficients, and represents an arbitrary element whose geometry is undefined but whose elastic kinematic response can be specified by stiffness, damping, or mass coefficients in matrix form. Therefore it can simulate the self-excited forces if the aeroelastic stiffness and damping coefficients are obtained.

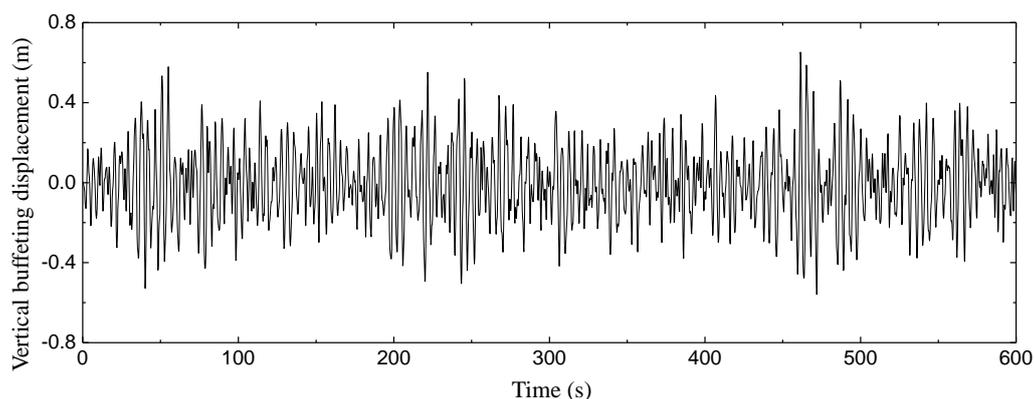


Fig. 5. Time histories of the vertical buffeting displacements of a point at bridge deck

Prior to the buffeting response analysis, nonlinear static analysis under the dead load of the bridge is carried out. First, a large deflection nonlinear static analysis is performed based on ANSYS. The effects of the stress stiffness and large deflection are,

therefore, obtained through the nonlinear static analysis. After these effects are activated and then added to the stiffness matrix of the structural system, the time-domain buffeting analysis is then started with the deformed shape of the bridge under its dead load. The buffeting responses of the Jiashao Bridge were calculated at the design wind velocity of 49.72m/s at the bridge deck for the return period of 100 years. Fig.5 shows the time-histories of vertical buffeting displacements of a point at the bridge deck, which is located in the middle of the girder span between Tower 3 and Tower 4.

#### 4. PERFORMANCE OF THE BRIDGE WITH VISCOUS FLUID DAMPERS

Viscous fluid dampers are typically used in the long-span cable-stayed bridges with fully floating system, in which the viscous fluid dampers provide longitudinal links between the bridge deck and towers, so as to effectively reduce the large displacements of the bridge deck when subjected to dynamic loads. In this section, a simulation study is performed to investigate the effects of viscous fluid dampers on the buffeting control of the multi-tower cable-stayed bridge with the application of partially longitudinal constraint system. The damping force of a viscous fluid damper can be described as follows:

$$f = c|v|^\alpha \text{sgn}(v) \quad (1)$$

Where  $c$  is the damping coefficient of the damper;  $\alpha$  is the velocity exponent of the damper;  $v$  is the relative velocity across the damper. And the damper can be modeled in ANSYS using COMBIN37 element. As shown in Fig. 6, the viscous fluid dampers are placed at the Tower 1, Tower 3, Tower 4 and Tower 6, which are not constrained with the main girder in longitudinal direction.

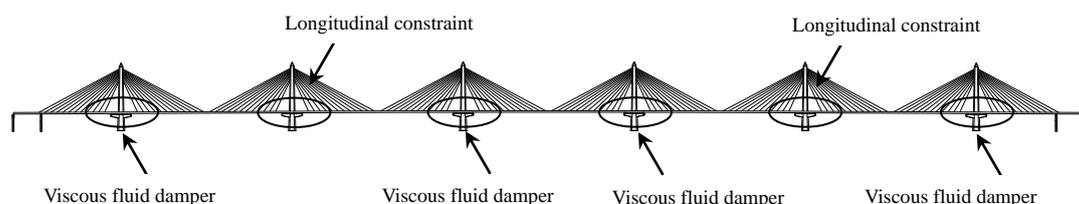


Fig. 6. Arrangement of the viscous fluid dampers in the bridge

The comparison of the buffeting response of the bridge without and with viscous fluid dampers are shown in Table 1, in which the parameters of the viscous fluid dampers are set to be:  $\alpha=0.3$ ,  $c=4000 \text{ kN}\cdot(\text{s/m})^{-0.3}$ . Considering the symmetry of the bridge, only half of the structure's responses are presented in the table. It can be seen that both the vertical and transversal displacements of the middle span are reduced, and the maximum decreasing ratios are 23.05% and 41.46% respectively. As for towers, decreasing ratio of top displacement of Tower3 is larger than the other two. However, while comparing the decreasing ratios of the bottom moments, the value of Tower2 is larger than the other two. The table also indicates that by implementing these viscous fluid dampers, the responses of different spans and towers numerically

changed to be close to each other, which may be useful in the bridge design.

Table 1 Comparison of the bridge's buffeting responses with and without dampers

Response quantity	Position	Without dampers $f_0$	With dampers $f_1$	Decreasing ratio $(f_0-f_1)/f_0 \times 100\%$
Vertical displacements of the main girder	Middle of the span between Tower1 and Tower 2	0.1640m	0.1424m	13.18%
	Middle of the span between Tower2 and Tower 3	0.1814m	0.1431m	21.13%
	Middle of the span between Tower3 and Tower 4	0.2106m	0.1621m	23.05%
Transeversal displacements of the main girder	Middle of the span between Tower1 and Tower 2	0.0027m	0.0026m	4.11%
	Middle of the span between Tower2 and Tower 3	0.0027m	0.0025m	6.46%
	Middle of the span between Tower3 and Tower 4	0.0047m	0.0028m	41.46%
Longitudinal top displacements of Towers	Tower1	0.0659m	0.0617m	6.42%
	Tower2	0.1136m	0.0932m	17.93%
	Tower3	0.1144m	0.0880m	23.09%
Longitudinal bottom moments of Towers	Tower1	$5.0983 \times 10^8 \text{N}\cdot\text{m}$	$4.6731 \times 10^8 \text{N}\cdot\text{m}$	8.34%
	Tower2	$1.1288 \times 10^8 \text{N}\cdot\text{m}$	$6.3608 \times 10^8 \text{N}\cdot\text{m}$	43.65%
	Tower3	$7.2532 \times 10^8 \text{N}\cdot\text{m}$	$5.5937 \times 10^8 \text{N}\cdot\text{m}$	22.88%

## 5. CONCLUSIONS

The buffeting responses of the Jiashao Bridge in China without and with fluid dampers are analyzed in time-domain. From the analytical results of the present study the following conclusions are drawn:

1. The shape of the bridge's first mode is symmetric vertical bending of bridge deck and symmetric longitudinal bending of bridge tower, and the frequency of the first mode is 0.227Hz. The buffeting responses of the bridge are approximately symmetrically distributed, and the responses of the middle span are larger than the others.
2. The installations of viscous fluid dampers are beneficial for the reductions of the buffeting responses. The efficacy of the middle span is more significant than the other spans, and the maximum decreasing ratios at vertical and transeversal direction are 23.05% and 41.46% respectively.

## Acknowledgment

The authors are grateful for the joint supports of the National Natural Science Foundation of China (No. 51408389), Natural Science Foundation of Jiangsu Province (No. BK20140281), Scientific Program of Chinese Ministry of Housing and Urban-Rural

Development (No. 2014-K2-034), Jiangsu Province Key Laboratory of Structure Engineering (ZD1304) and Qing Lan Project.

## REFERENCES

- Domaneschi, M., Martinelli, L., and Po, E. (2015). "Control of wind buffeting vibrations in a suspension bridge by TMD: Hybridization and robustness issues." *Comput Struct*, 155, 3-17.
- Domaneschi, M., and Martinelli, L. (2013). "Optimal passive and semi-active control of a wind excited suspension bridge." *Struc. Infrastruct E.*, 9(3), 242--259.
- Gu, M. (2012). "Some important aspects of wind-resistant studies on long-span bridges." *Science China Technological Sciences*, 55(12), 3334--3343.
- Heo, G., Kim, C., and Lee, C. (2014). "Experimental test of asymmetrical cable-stayed bridges using MR-damper for vibration control." *Soil Dyn Earthq Eng*, 57, 78-85.
- Heo, G., and Joonryong, J. (2014). "Semi-active vibration control in cable-stayed bridges under the condition of random wind load." *Smart Mater. Struct.*, 23, 0750277(19p).
- Jia, S., Zhao, L., and Li, B. (2015). "Geometric Closure Control of the Main Channel Girder of Jiaying-Shaoxing Bridge." *J. Highway Transp. Res. Dev. (English Ed.)*, ASCE, 9(1), 63-70.
- Kim, B., and Yhim, S. (2014). "Buffeting Analysis of a Cable-Stayed Bridge Using Three-Dimensional Computational Fluid Dynamics." *J. Bridge Eng., ASCE*, 19(11), 04014044.
- Ni, Y. Q., Wang, J. Y., and Lo, L. C. (2005). "Influence of Stabilizing Cables on Seismic Response of a Multispan Cable-Stayed Bridge." *Comput-Aided Civ Inf*, 20(2), 142 - 153.
- Okamoto, Y., and Nakamura, S. (2011). "Static and seismic studies on steel/concrete hybrid towers for multi-span cable-stayed bridges." *J Constr Steel Res*, 67(2), 203-210.
- Wang, H., Hu, R. M., Xie, J., and Li, A. Q. (2013). "Comparative study of buffeting performance of Sutong Bridge based on design and measured spectrum." *J. Bridge Eng., ASCE*, 18(7), 587-600.
- Wang, H., Tao, T., and Cheng, H. (2014). "A simulation study on the optimal control of buffeting displacement for the Sutong Bridge with multiple tuned mass dampers." *J. Zhejiang Univ.-Sc. A*, 15(10), 798-812.
- Wen, Y., and Sun, L. (2015). "Distributed ATMD for Buffeting Control of Cable-Stayed Bridges Under Construction." *Int. J. Str. Stab. Dyn.*, 15(03), 1450054.
- Xing, C., Wang, H., Li, A., and Xu, Y. (2013). "Study on Wind-Induced Vibration Control of a Long-Span Cable-Stayed Bridge Using TMD-Type Counterweight." *J. Bridge Eng., ASCE*, 19(1), 141-148.