Engineering Structures 127 (2016) 416–433

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Stress-level buffeting analysis of a long-span cable-stayed bridge with a twin-box deck under distributed wind loads

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ARTICLE INFO

Article history:
Received 29 October 2015
Revised 26 August 2016
Accepted 29 August 2016

Keywords:
Stress-level buffeting analysis
Multi-scale modelling
Long-span cable-stayed bridge
Twin-box deck

ABSTRACT

To accurately predict buffeting-induced stresses in a long-span cable-stayed bridge with a twin-box deck, buffeting analyses should take into account the cross-sectional distribution of both aerodynamic and aeroelastic forces over the surface of the bridge deck. They should also be performed on an accurate multi-scale model rather than a spine-beam model of the bridge. This paper proposes a framework for stress-level buffeting analysis of a long-span cable-stayed bridge with a twin-box deck under distributed wind loads. Methods to obtain distributed aerodynamic and aeroelastic forces on the bridge deck are introduced. The proposed framework synthesizes the buffeting analysis with distributed wind loads and the multi-scale modelling and model updating of long-span bridges. The proposed framework is applied to the Stonecutters cable-stayed bridge in Hong Kong. The responses computed using the proposed buffeting analysis framework are compared with those computed using the sectional-force-based traditional method on a spine-beam model. The comparative results show significant differences in stress distribution on the twin-box deck and the multi-scale model yields larger maximum stress responses compared with the spine beam model.

1. Introduction

Wind induced responses, especially buffeting responses due to turbulent winds, are one of the major sources that lead to fatigue damage in long-span cable-supported bridges [1–6]. Thus, buffeting analyses that can accurately predict fatigue-related stress responses are important for modern cable-supported bridges [7–10]. In the meantime, structure health monitoring (SHM) systems have been installed in a number of long-span cable-supported bridges to monitor and assess bridge functionality and safety [11–13]. However, the number of sensors in an SHM system is always limited, such that not all of the key structural components can be directly monitored. Therefore, to facilitate the effective assessment of stress-related bridge performance and safety, stress-level buffeting analysis is required.

Traditional buffeting analysis methods, either in the frequency-domain [14–16] or the time-domain [1,17,18], are based on integrated sectional aerodynamic and aeroelastic forces rather than distributed forces on the bridge deck. Disregarding the cross-sectional distribution of buffeting forces may affect the accuracy of computed buffeting-induced stress responses. Thus, to accurately predict the buffeting-induced fatigue of bridges, it is imperative to take into account the cross-sectional distribution of aerodynamic and aeroelastic forces. In this study, aerodynamic forces refer to the forces result from the wind around a rigid body, while aeroelastic forces refer to the forces result from the interaction between the wind and motion of an elastic body. The effects of aerodynamic and aeroelastic forces are considered separately for simplification.

Distributed aerodynamic and aeroelastic forces are closely related to wind pressures and their distribution. Aerodynamic pressure time-histories can be obtained from pressure tests of a motionless sectional deck model. Larose [19] and Larose and Mann [20] directly measured the aerodynamic admittance and span-wise coherence of aerodynamic forces based on the simultaneous measurements of unsteady surface pressures on three chord-wise strips of sectional deck models. Hui [21] investigated the admittance and span-wise coherence of aerodynamic forces induced by turbulent winds on a twin-box deck by wind tunnel pressure tests of the sectional deck model with seven pressure-tapped strips. Nevertheless, these studies focused on the integrated aerodynamic forces rather than distributed pressures. Zhu and Xu [22] have recently investigated the characteristics of distributed aerodynamic forces on the surface of a motionless twin-box bridge deck model. The aerodynamic admittances and span-wise correlation

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http://dx.doi.org/10.1016/j.engstruct.2016.08.050
0141-0296/

of the distributed aerodynamic forces have been identified and analyzed. However, the distribution of aeroelastic forces and the framework for a buffeting analysis with these distributed forces have not been developed.

Aeroelastic pressures can be acquired from pressure tests on an oscillating deck model. Haan and Kareem [23] investigated the turbulence effects on the pressure distribution over an oscillating rectangular prism using a forced-vibration test system and a pressure-tapped model. Argentini et al. [24] obtained distributed aerodynamic admittance and derivatives using a forced-vibration pressure test of a sectional model. Their studies show that the forced-vibration tests with a pressure-tapped model are capable of obtaining both aerodynamic and aeroelastic pressure distributions. The buffeting induced pressure distribution has the advantages of providing more information about fluid-structure interaction. Nevertheless, forced-vibration tests may not be able to fully represent real fluid-structure interaction as the mass of the fluid-structure system is not simulated and the motion of the model is pre-set and not induced by incoming winds. Besides, a full set of measured distributed aeroelastic stiffness and damping matrices of the deck section is rarely available. Thus, a more convenient method to obtain the distributed aeroelastic stiffness and damping matrices is worth studying. Liu et al. [8] proposed a method of distributing traditional sectional aeroelastic forces to the nodes of a multi-scale finite element (FE) model to enable buffeting-induced stress analysis of a long-span suspension bridge. However, the proposed distribution method is not based on measured wind pressures from either wind tunnel tests or field measurements. It is based on the rigid body motion relationships between the motions at the nodal lines and those at the center of elasticity of the deck section. Therefore, this distribution method does not reflect real fluid-structure interaction mechanism.

Furthermore, traditional FE models that reduce bridge decks into beam elements with equivalent sectional properties are not sufficient for stress-level buffeting analyses, and accurate FE models built in detailed geometry with plate/shell/solid elements are required. On the other hand, the computation capacity for such analyses shall be considered as the large number of degrees of freedom (DOF) resulting from such fine modelling can cause difficulties in the dynamic analyses. To deal with this problem, multi-scale modelling methods that can simulate long-span bridges with a simplified global model and detailed local models concurrently have been developed [25,26].

In view of the problems outlined above, this paper proposes a practical framework to perform buffeting-induced stress analysis using the multi-scale model of a long-span cable-stayed bridge with distributed aerodynamic and aeroelastic forces. In this framework, distributed aerodynamic forces are obtained from pressure tests of a motionless sectional model, and distributed aeroelastic forces are acquired based on the quasi-static assumption and the sectional aeroelastic forces. How to apply the buffeting-induced stress analysis with these distributed wind loads to a multi-scale model constructed with sub-structuring method is then discussed. In the end, the details of applying this framework to the Stonecutters cable-stayed bridge in Hong Kong are then presented. The results of the analyses with the proposed framework are presented and discussed. The difference between the proposed framework and the traditional framework is examined.

2. Framework of buffeting analysis with distributed wind loads

2.1. Key issues in buffeting analysis with distributed wind loads

As shown in Fig. 1, traditional buffeting analyses were performed with integrated sectional wind forces on the beam-element model of a bridge deck while the proposed framework considers distributed wind forces on a much detailed FE model. The finite element (FE) model, the aerodynamic and aeroelastic characteristics used in the proposed framework are all different from those in the traditional buffeting analyses.

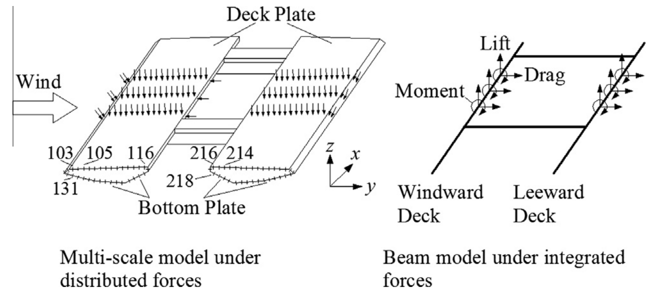

Fig. 1. Distributed wind forces on a multi-scale model v.s. integrated forces on a beam model of a twin-box deck.

The governing equation of a coupled wind-bridge system under distributed dynamic wind loads can be written as

$$\mathbf{M}_{str}\ddot{\mathbf{u}} + (\mathbf{C}_{str} + \mathbf{C}_{se})\dot{\mathbf{u}} + (\mathbf{K}_{str} + \mathbf{K}_{se})\mathbf{u} = \mathbf{F}_b \tag{1}$$

where $\mathbf{M}_{str}$, $\mathbf{C}_{str}$ and $\mathbf{K}_{str}$ are the mass, damping and stiffness matrices of the multi-scale FE model of a bridge, respectively; $\mathbf{C}_{se}$ and $\mathbf{K}_{se}$ are the distributed aeroelastic damping and stiffness matrices, respectively; $\mathbf{F}_b$ is the distributed aerodynamic force vector; $\mathbf{u}$ is the displacement vector; a dot on $\mathbf{u}$ represents the first-order derivative with respect to time and two dots represent the second-order derivative.

As the multi-scale modelling technique of long span bridges has been presented by the authors and their colleagues [27,28], the remaining key issues in the stress-level buffeting analysis with distributed wind loads are (1) how to obtain the distributed aerodynamic force vector; (2) how to obtain the distributed aeroelastic damping and stiffness matrices; and (3) how to solve the above governing equation efficiently with a multi-scale FE model. The solutions to these three issues are presented in the following subsections.

2.2. Cross-spectral density matrix of distributed aerodynamic forces

To determine the cross-spectral density matrix of distributed aerodynamic forces, three aerodynamic properties should be obtained: pressure coefficients; pressure admittance functions; and the coherence functions of pressures. The pressure coefficients can be naturally obtained from the wind pressure test of a motionless deck model. The method to identify pressure admittance functions and span-wise pressure coherence functions have been proposed by Zhu and Xu [22]. The essential formulations in the method are summarized as follows.

The aerodynamic pressure on a surface point i of a bridge deck can be expressed as [22]

$$P_{b,i}(t) = \frac{1}{2}\rho\overline{U}^2 \cdot \left[2C_{pi}(\alpha_0)\cdot\chi_{pui}\cdot\frac{u(t)}{\overline{U}} + C'_{pi}(\alpha_0)\cdot\chi_{pwi}\cdot\frac{w(t)}{\overline{U}}\right] \tag{2}$$

where ρ is the density of air; $\overline{U}$ is the mean speed of the incoming wind flow; C_{pi} and C'_{pi} are the pressure coefficient and its derivative with respect to the angle of incidence, respectively; u and w are the longitudinal and vertical turbulence component, respectively; α_0 is the mean angle of incidence; χ_{pui} and χ_{pwi} are the aerodynamic pressure admittance functions of the fluctuating pressure at the ith surface point of the bridge deck with respect to the fluctuating wind u and w, respectively.