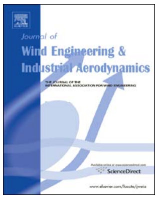
J. Wind Eng. Ind. Aerodyn. 155 (2016) 159–173

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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



Wind effects on a cable-suspended roof: Full-scale measurements and wind tunnel based predictions

Bo Chen [a,*], Teng Wu [b], Yilong Yang [a], Qingshan Yang [a], Qingxiang Li [c], Ahsan Kareem [d]

[a] Beijing's Key Laboratory of Structural Wind Engineering and Urban Wind Environment, School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China
[b] Department of Civil, Structural and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY 14126, USA
[c] Guangdong Provincial Academy of Building Research, Guangzhou 510500, China
[d] Department of Civil & Environmental Engineering & Earth Sciences, University of Notre Dame, IN 46556, USA

ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form
7 June 2016
Accepted 7 June 2016

Keywords:
Cable-suspended roof
Full-scale measurement
Wind-induced response
Modal parameter
Wind tunnel test

ABSTRACT

Full-scale measurements of wind effects on a long-span cable-suspended roof were carried out. The wind-induced response data were analyzed in the time-frequency domain based on the wavelet transformation, and modal frequencies and amplitude-dependent damping ratios were identified with the random decrement technique. The damping ratios were noted larger with increasing response amplitude especially in the fundamental mode. The identified modal frequencies from the full-scale measurements were lower than those from the original finite element model (FE model). The identified modal parameters were then used to update the FE model with an artificial neural networks (ANNs) based scheme. The dynamic response from the roof was computed from the updated FE model of the structure where the wind loads input was obtained from simultaneous pressure measurement in wind tunnel tests. In view of the uncertainties surrounding both full scale measurements and wind tunnel based predictions, these comparisons show good agreements at least at two locations. Both the dynamic response from full-scale measurements and numerically predicted analyses demonstrated significant contributions from multi-mode effects. The computed response spectra at selected locations were similar to those from the full-scale measurements, suggesting a validation of the predictions.

1. Introduction

Long-span roofs are quite sensitive to oncoming turbulent winds due to their flexibility. These roofs are usually low-rise and are located within the lower part of the atmospheric boundary layer, and hence experiencing strong gusty wind with high turbulence intensity. The wind flow patterns around the roofs are extremely complex due to the flow separation and reattachment. In addition, other factors such as irregular geometric shape of structure and effects of surrounding buildings contribute to the uncertainties in accurately quantifying the wind loads on these roofs. As a consequence of the complexity involved, dynamic wind effects on the roofs are usually calculated from a structural finite element model (FE model) where the input of the fluctuating wind pressures are obtained from wind tunnel tests. However, it is not easy to establish a FE model with high accuracy since the long-span roofs are constructed with complex structural systems. Full-scale measurements of wind effects on long-span roofs are needed for better understanding of the actual characteristics of the wind-induced response, verifying wind tunnel based numerical simulation, updating the FE model if necessary, and enhancing the future structural design.

Full-scale measurements provide a most reliable approach of assessing the aerodynamic and dynamic properties of buildings and bridges. A large number of full-scale measurements on the wind velocity, wind pressure, and wind-induced response have been conducted for studying the wind effects on high-rise buildings or bridges (e.g., Tamura et al., 2002; Satake et al., 2003; Macdonald and Daniell, 2005; Li et al., 2007; Fu et al., 2008; Wang et al., 2010; Chen et al., 2011b; Bashor et al., 2012; Chen et al., 2013). These measurements have greatly enriched our knowledge of natural winds in terms of wind spectrum, turbulence intensity, and enhanced our understanding of dynamic properties of full-scale structures in terms of the modal parameters. Full-scale measurements of wind-induced response of long-span roofs have also been reported (Chen et al., 2011a, Liu et al., 2011, Fu et al., 2015). Tieleman (1996) compared the pressure coefficients of the Texas Tech experimental building from the wind tunnel tests with those from the full-scale measurements. The study highlighted the importance of the small-scale turbulence, which is usually

---

* Corresponding author.
E-mail address: chenbohrb@163.com (B. Chen).

http://dx.doi.org/10.1016/j.jweia.2016.06.006

overlooked in the wind tunnel simulation for an accurate duplication of the fluctuating pressure coefficients at corners and leading edges of roofs. Magalhaes et al. (2008) compared the modal parameters of a suspended roof based on the ambient vibration test with finite element results. The structure investigated had a small damping ratio of around 0.5%. Kim et al. (2011) examined the dependency of modal properties on the vibration amplitude and temperature of a steel truss in a stadium. The study showed approximately 5% decrease of the natural frequencies and more than 200% increase of the damping ratios with five times increase in the vibration amplitude. This study also showed that the relative difference in the natural frequencies between the measured and FE model results was within 5%. Chen et al. (2011a) investigated the characteristics of amplitude-dependent damping ratios of a beam string roof structure with nonlinear energy dissipation. Comparison of the field measurements and the numerical analysis results indicated that the relative differences of the first several vertical vibration modes are in a range between 1.0% and 8.6%. Martins et al. (2014) measured the effects of wind velocity and temperature on the modal parameters of a suspended roof. The 10-min root-mean-square (RMS) acceleration was found approximately nonlinearly proportional to the 10-min mean wind velocity with a power of 2.5.

A number of schemes such as peak-picking, frequency domain decomposition, stochastic subspace identification (SSI), random decrement technique (RDT), Hilbert-Huang transform (HHT), and wavelet transform (WT) have been developed to identify the modal parameters based on the full-scale or experimental data. Among them, HHT and WT are more suitable for analyzing non-stationary data (Huang et al., 1998; Gurley and Kareem, 1999). Kijewski and Kareem (2003) investigated the influence of the center frequency and end effects on the identified modal parameters based on the Morlet wavelet transform. Chen et al. (2004) utilized the empirical mode decomposition (EMD) and Hilbert transformation (HT) to identify modal parameters of Tsing Ma Bridge under a strong typhoon. Yan and Miyamoto (2006) compared the WT with HHT approaches, and showed that WT was more effective in identifying the modal parameters with very closely spaced modes. Typically, an accurate damping ratio is more difficult to obtain compared to the modal frequency (Kijewski et al., 2006a). RDT can result in a free-decay vibration signal from an ambient vibration response (Ibrahim, 1977). Jeary (1986) utilized the RDT method to evaluate the structural damping under random loads. Tamura and Suganuma (2006) proposed an improved RDT scheme that can account for the amplitude dependence of the damping ratio. More recently, Spence and Kareem (2014) have offered a data-driven approach for modeling damping in structures.

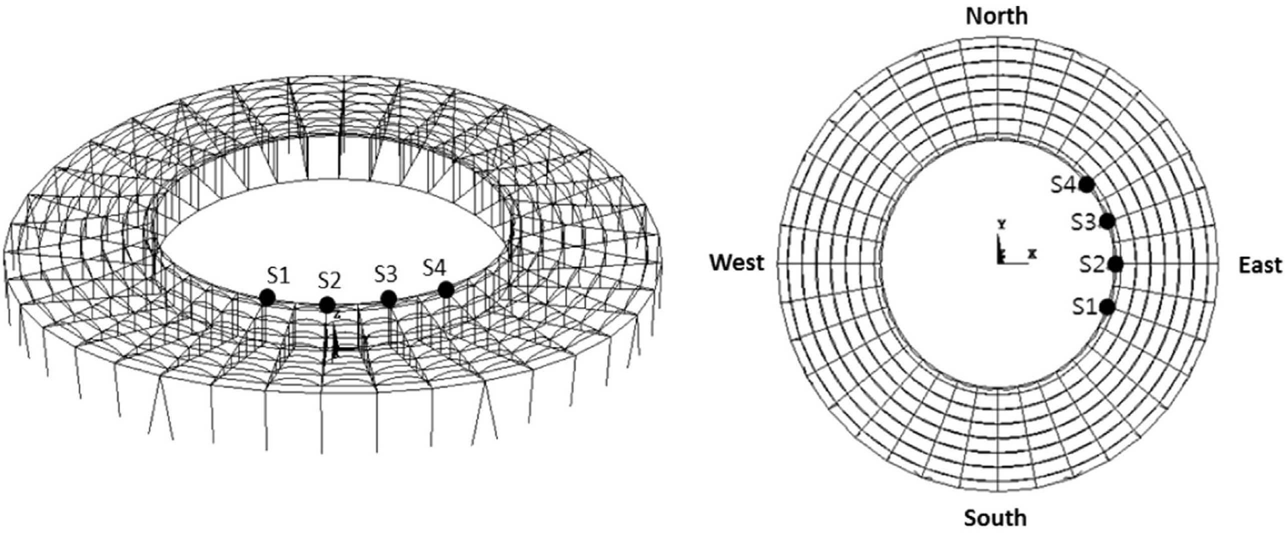
The Bao'an stadium discussed here is a long-span cable-suspended structure with light mass and low stiffness. It is located in Shenzhen city, which is a typhoon-prone area near the South China Sea. Full-scale measurements are employed to investigate the wind effects on the cable-suspended roof, and to identify the natural frequencies and amplitude-dependent damping ratios of the structural system. Furthermore, the measured wind-induced response and identified modal parameters are compared to the results of the numerical simulation with the FE model of the structure subjected to the wind pressure input obtained from the wind-tunnel tests.

The structure investigated is extremely complicated, and presents several challenges in the full-scale measurements and the wind-tunnel based predictions, e.g., the nonlinear geometric and three-dimensional spatial effects, accounting for the difference between the post-construction and design pre-stresses of the cables, and accurate simulation of the wind loads in the wind tunnel tests on this low-rise open building.

2. Wind characteristics and wind-induced response from full-scale measurements

2.1. Bao'an stadium with cable-suspended roof

The Bao'an stadium shown in Fig. 1 was built to host the 26th Summer Universiade game in 2011 in Shenzhen, China. The outer and inner rings of the roof structure are elliptical, with 230 m, 237 m and 122 m, 129 m for the long and short axes of the outer ring and inner ring, respectively. The saddle-shape roof of the stadium is supported by 36 pairs of suspended cable trusses between the outer steel ring and the inner pre-tensioned cable ring. The radial cable trusses are connected by steel beams. Tensioned membranes, transferring wind loads to the cable trusses, are embedded into the roof surface. The lowest height of the south and north roof eaves is 23.8 m from the ground, and the highest height



(a) FE model

(b) Location of accelerometers

Fig. 1. The finite element model of the stadium and placement of accelerometers.