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Evaluation of wind effects on a large span retractable roof stadium by wind tunnel experiment and numerical simulation

Man Liu [a], Qiu-Sheng Li [a,b,*], Sheng-Hong Huang [c], Feng Shi [d], Fubin Chen [e]

[a] School of Civil Engineering, Hunan University, Changsha, 410082, China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong
[c] School of Engineering Science, University of Science and Technology of China, Hefei, 230026, China
[d] Changsha Pilot Investment Holdings Group Co., Ltd., Changsha, 410082, China
[e] College of Civil Engineering and Architecture, Changsha University of Science and Technology, Changsha, 410082, China

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ABSTRACT

Retractable roof structures break traditional concepts of indoor and outdoor spaces, which can free indoor activities from weather restrictions and ambient conditions. Thus, such structures have gained great popularity. The length of retractable roof increases with the demand for more flexible and light construction, and such requirements make retractable roof structures more sensitive to wind actions. Hence, this paper presents a combined study of wind tunnel experiment and large eddy simulation (LES) for evaluation of wind effects on a large span retractable roof stadium. The effectiveness and reliability of the adopted LES techniques have been verified by detailed comparisons with the model test results. The main objective of this study is to investigate the wind effects on a large-span retractable roof structure in terms of net pressure coefficients and flow fields for different roof states. Additionally, this study attempts the LES for estimation of the wind effects on the prototype stadium with retractable roof, which can account for the Reynolds number effects and overcome the model space constraints of wind tunnel experiments. The adopted LES techniques have been proven to be an effective tool for evaluations of wind effects on buildings with complex geometries in high Reynolds number turbulent flows. This paper aims at further understanding the wind effects on retractable roof structures and providing useful information for the wind-resistant design of large-span retractable roof stadiums.

1. Introduction

Retractable roofs are structures that can transform from one configuration to another, usually referred to as the unfolded and folded states (Friedman et al., 2011). Retractable roof structures break traditional concept of indoor and outdoor spaces, which can free indoor activities from weather restrictions and air conditions. Hence, such structures can be operated in optimal conditions (Ishii, 2000). Retractable roof structures have the ability to provide a comfortable environment to audiences and players. Therefore, retractable roof structures have gained great popularity among designers in the past decades. Pittsburgh Civil Arena marked the first significant application of retractable roof structure in structural engineering (Lu et al., 2016). Thereafter, an increasing number of buildings have been built with retractable roofs all over the world, such as the Sky Dome in Canada (Allen and Duchesne, 1989), the Fukuoka Dome in Japan (Tanno et al., 1994), the Montreal Olympic Stadium in Canada (Irwin and Wardlaw, 1979), the National Stadium of Singapore Sports Hub (Lewis and King, 2014), the Northwest New Pacific baseball field in Seattle and the Shanghai Qi Zhong Tennis Hall, the Hangzhou Huanglong Sports Center Tennis Hall, the Nantong Sports Exhibition Center Stadium, the National Tennis Center and the Ordos Dongsheng Stadium in China (Lu et al., 2016).

A report written by the working group of the International Association for Shell and Spatial Structures listed 23 retractable roof structures, where the movable part typically spans in excess of 50 m (Kassabian et al., 1999). The length of the retractable roofs increases with the demand for more flexible and light construction, and such requirements normally result in the characteristics of higher flexibility, lighter mass, lower natural frequency and smaller damping of retractable roof structures. As a result, large span retractable roof structures are becoming more sensitive to wind actions than traditional structures. Additionally, large span retractable roof structures are usually used for low-rise

* Corresponding author. School of Civil Engineering, Hunan University, Changsha, 410082, China.
E-mail address: bcqsli@cityu.edu.hk (Q.-S. Li).

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buildings and located within the lower part of the atmospheric boundary layer, hence, experiencing stronger gusty wind with higher turbulence intensity (Chen et al., 2016). Therefore, wind flow patterns around retractable roof structures are extremely complex due to the complicated flow characteristics of separation and reattachment. Besides, the changeable geometric shapes of retractable roofs also contribute to the inaccurately quantifying the wind effects on these structures. Nevertheless, most current wind codes or design standards (American Society of Civil, 2010; Standards Association of, 2002; Architectural Institute o, 2004) do not provide relevant guidelines or information for determination of the wind effects on large span retractable roof structures. It is therefore necessary to investigate the wind-induced effects on large span retractable roof structures.

Three methods, namely: wind tunnel test, full-scale measurement and computational fluid dynamics (CFD), have been widely used to evaluate the wind effects on buildings and structures. Full-scale measurement is considered to be the most direct and reliable approach of assessing the wind effects on buildings and structures. In recent years, a large number of full-scale measurements have been conducted for evaluating the wind effects on large span roofs. For example, Kim et al. (2011) carried out a long-term monitoring of the wind-induced acceleration responses of the World Cup Stadium's roof structure in Jeju-do, Korea in 2011. Full-scale measurements of the wind actions and wind-induced structural responses of the roof of the Guangzhou International Convention & Exhibition Center (GICEC) were conducted during the passage of Typhoon Nuri by Chen et al. (2011). Fu et al. (2015) analyzed the wind-induced pressures and acceleration responses of a long-span steel roof structure during the passage of Typhoon Fanapi. Chen et al. (2016) carried out full-scale measurements of wind effects on a large span cable-suspended roof. These measurements have enhanced the understanding of structural responses and dynamic properties of large span roof structures. However, full-scale measurements of wind effects on structures may be limited by objective conditions such as weather conditions, high cost and site limits, especially it is infeasible to measure the wind effects on structures prior to their constructions.

Wind tunnel test is an effective way and a relatively mature technique in wind engineering, which can overcome the limitations of full-scale measurement such as weather and site restrictions, time-consuming, etc. Hence, wind tunnel test has been widely used in wind engineering. A large number of wind tunnel tests have been conducted on large span roof structures during the past decades (Irwin and Wardlaw, 1979; Chen et al., 2011; Biagini et al., 2007; Uematsu et al., 2001; Yasui et al., 1999; Suzuki et al., 1997; Vickery and Majowiecki, 1992). The wind effects on large span roof structures can be characterized as: complicated and temporal-spatial distributions of fluctuating wind pressures, multi-mode vibrations of wind-induced responses (Chen et al., 2016; Li et al., 2016; Mannini et al., 2016; Liu and Ishihara, 2015; Yan and Li, 2015a; Huang et al., 2014; Ding and Tamura, 2013). Although wind tunnel tests can provide acceptable results for wind related practices, it is actually difficult to reproduce the exact wind field conditions such as incident turbulence, terrain characteristics and the Reynolds numbers. In addition, scaled wind tunnel experiments may fail to capture the maximum and minimum pressures due to limited pressure taps used in model tests (Lu et al., 2012).

CFD based numerical simulation has become a complementary tool to evaluate the wind effects on large span roof structures due to fast development of computer power and computational techniques in recent years. Lu et al. (2012) carried out a numerical simulation study to investigate wind effects on a long-span complex building in 2012. By comparing their results between wind tunnel experiment and the numerical simulation, their recommended CFD technique has been validated to be an effective and useful tool for designers to assess the wind effects on long-span complex structures at design stage. Hence, the same numerical technique is adopted in this study for estimation of the wind effects on a retractable roof structure.

To the knowledge of the authors, all the studies mentioned above put emphasis on the wind-induced pressures and responses of large span roof structures, the wind effects on retractable roof structures have rarely been reported in literature. A retractable roof structure usually has a specific predetermined motion process, i.e., it moves on a particular trail from the unfolded state to the folded state or the other way around (Friedman et al., 2011). The dependence of the wind actions on building shapes makes the generalizations of the wind effects on retractable roof structures almost impossible, because every roof state corresponds to a unique set of wind effects (van Hooff and Blocken, 2010). Thus, it is required to evaluate the wind effects on a retractable roof structure at different retractable states.

Since damage to roofs has been identified as one of the main reasons for the extensive damage to large span roof structures during many violent storms (Wu et al., 2015), this study focuses on the effects of wind on the large span retractable roof of a stadium located at a typhoon-prone region in China. A combined study of wind tunnel experiments with a length scale of 1:200 and CFD numerical simulations (scale-down and full-scale) is presented in this paper. The model test results provide the estimations of the wind effects on the large span retractable roof, which are also used to evaluate the accuracy of the numerical predictions and the adequacy of the technique used in the CFD simulation. In the numerical simulation of this study, the inflow turbulence generator (DSRFG approach) (Huang et al., 2010) and the engineering oriented subgrid-scale (SGS) model (Huang and Li, 2010) proposed by two of the authors are integrated into the large eddy simulation (LES) algorithm to predict the flow fields around and wind effects on the large span retractable roof structure. Since the LES of this study considers the full-scale size of the stadium, Reynolds numbers of the wind flows around the stadium in the simulation are greater than 10^8. The main objective of this study is further understanding the wind effects on a large span retractable roof structure by means of wind tunnel test and numerical simulation in order to apply such knowledge to the design of other similar structures in the future. The results presented in this paper are expected to be of interest and useful to designers and professionals involved in designing retractable roof structures. Additionally, the full-scale size (prototype) simulation adopted in this study can account for the Reynolds number effects as well as overcome space constraints of wind tunnel experiments. Furthermore, a comparative study between the model experimental measurements and the numerical predictions can validate and improve the LES technique.

The content of this paper is divided into four sections. Section 2 presents a brief introduction of the retractable roof stadium considered in this study, and then provides the details about the wind tunnel experiment for the stadium, thereafter, briefly introduces the numerical simulation method based on LES. In section 3, the LES results and comparisons with the wind tunnel experiments are presented. Finally, conclusions of the combined study of the numerical simulation and wind tunnel test for a retractable roof structure are summarized in the last section.

2. Methodology

The large span retractable roof stadium considered in this study consists of two parts: retractable roof and fixed structure. The retractable roof is composed of eight petal like components, which has four retractable states, i.e., 0°, 15°, 30°and 45°, as shown in Fig. 1 a,b,c,d, respectively. The highest height of the retractable roof is 40.25 m from the ground, while the maximum diameter of the fixed structure is 110.20 m. This stadium is located in Hangzhou, China, a typhoon-prone area. Hence, wind effects on the stadium are of main consideration in the design of this complex structure. Since the retractable roof is more sensitive to wind actions than the fixed structure, the following sections will put emphasis on the wind effects on the retractable roof.