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Field measurements of wind pressures on a 600 m high skyscraper during a landfall typhoon and comparison with wind tunnel test

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ABSTRACT

As high-rise structures are constantly emerging worldwide, wind effects on wind-sensitive structures are correspondingly getting increasing concerns, especially in tropic cyclone prone areas. This paper presents the analyzed results from field measurements of wind effects on a 600 m high skyscraper located in Shenzhen during a landfall typhoon. Field monitoring of wind-induced pressures on the skyscraper was conducted by a structural health monitoring system. The major objective of this study is to further understand typhoon-generated wind pressures on super-tall buildings. In addition, wind tunnel test of simultaneous pressure measurements on the building model was performed. Full-scale and wind tunnel measurements of wind-induced pressures on windward, leeward and side faces of the super-tall building were analyzed and compared. A whole range of characteristic properties, including pressure coefficient, probability distribution, peak factor, power spectral density, and correlation of cladding pressures were presented and discussed. The findings of this study are expected to be of interest and practical use to professional and researchers involved in the wind-resistant designs of super-tall buildings in tropic cyclone prone regions.

1. Introduction

The rapid development of economics, advances in construction materials and technologies continue to propel skyscrapers to new heights and pose new design challenges for structural engineers. It is foreseeable that wind-resistant design of skyscrapers is not an easy task since those buildings are generally wind-sensitive due to the enhanced structural flexibility and stronger wind speed at higher altitudes, in particular in tropic cyclone prone regions. Tropic cyclone is one of the most destructive natural disasters in the world. As reported by Hong Kong Observatory (HKO), tropic cyclones are formed approximately 28 times each year in the Western Pacific Ocean and the South China Sea. The China Central Meteorological Bureau reported that the south-east coastal regions of China are exposed to tropic cyclones or typhoons with an average of nine times making landfall each year during 1951–2008, with each often causing great economic losses and heavy causalities (Xiao et al., 2011).

Although structural assessments of high-rise buildings in tropic cyclone prone regions, as well as other areas impacted by extreme wind events, generally reveal satisfactory global structural performance under wind loading, extensive damages to cladding, especially glass, were frequently reported (Williams and Kareem, 2003). Occurrences of wind-induced glass breakage in tall buildings (Kareem, 1986; Pande et al., 2002; Williams and Kareem, 2003) have emphasized the need for a better understanding of the nature of wind loads on claddings. Wind-induced pressures on external surfaces of a building exposed to an atmospheric boundary layer may result from the turbulence in approach flow, flow separation and reattachment, vortex shedding in the wake, building motion and possible impingement of vortices shed by upstream objects (Kareem and Cermak, 1984). Thus, wind pressures on building claddings fluctuate spatio-temporally in a complicated manner. The assessment of wind pressures on high-rise buildings can be implemented via numerical simulation by computational fluid dynamics (CFD) techniques, wind tunnel test, or filed measurement. In recent years, CFD has undergone a rapid development and became an important complementary tool to the traditional approaches (full-scale measurement and wind tunnel test) in wind engineering (Blocken, 2014). More importantly, CFD has some particular advantages over those experimental means. It can provide detailed information on the relevant flow variables in the whole computational domain under well-controlled conditions. However, despite the increasing computing power and advanced numerical techniques, there are still some difficulties and limitations to be overcome or improved. Especially, the validity and accuracy of computational results

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of CFD may need further verification or improvement based on wind tunnel test results or field measurements (Blocken, 2014; Yan and Li, 2016).

Wind tunnel tests are the most commonly used techniques for the wind-resistant design of tall buildings. For example, synchronous multi-pressure sensing system (SMPSS) can provide information of the space-time characteristics of wind pressure fields over building surfaces. Such information is required for design of building cladding, window glass, mullions and other exterior architectural features. Over the past decades, wind tunnel tests have been widely used to investigate the characteristics of wind pressures on tall buildings (Melbourne, 1980; Holmes, 1981, 1988; Kareem and Cermak, 1984; Kareem, 1988, 1990; Tanaka et al., 2012). Melbourne (1980) compared the wind pressure measurements on the CAARC Building Model tested at six wind tunnel laboratories, in simulated boundary layer wind flows, and explored the differences of the wind pressure distributions. Kareem (1990) investigated the influence of turbulence on the space-time structure of random pressure fields on the surface of prismatic bluff bodies exposed to turbulent boundary layer flows. Tanaka et al. (2012) conducted a series of wind tunnel experiments to investigate the wind pressures acting on tall buildings due to architects' and structural designers' challenging demands for novel and unconventional expressions. Though wind tunnel testing is a main tool for the wind-resistant design of tall buildings, it is difficult to reproduce the exact field conditions such as incident turbulence, terrain characteristics and Reynolds number etc. in conventional wind tunnels. Therefore, to verify the reliability of wind tunnel test techniques, refine numerical models and improve codes of practice, on site monitoring of wind effects on tall buildings is necessary.

Full-scale measurement of wind pressures on structures is regarded as a definite requirement both for the confirmation of design theories or codes and verification of wind tunnel experimental techniques. In the past decades, wind pressure effects on low-rise buildings have received increasing attention, such as those studied by Eaton and Mayne (1975), Levitan and Mehta (1992), Hoxey and Richards (1993), Tieleman et al., 1994; Kawai and Nishimura, 1996; Stathopoulos et al. (1999), Li et al. (2012). Although there have been fewer field measurement studies of wind pressures on tall buildings compared to those on low-rise buildings, these previous field investigations enhanced the understanding of wind effects on tall buildings. For examples, in early 1970s, wind pressure measurements were carried out by the Building Research Establishment (U.K.) on Royex House and Vickers Building in London (Newberry et al., 1970, 1973). Holmes (1975) conducted a full-scale experiment using the Menzies building at Monash University in Australia, and the observations were intended both for comparison with wind tunnel test results and for information leading to possible modification of the design methods of estimating gust factors for along-wind structural loading. Dalgliesh and his co-workers (Dalgliesh, 1975; Dalgliesh et al., 1983) conducted extensive measurements on the Commerce Court Tower in Toronto, recording wind induced pressures, acceleration response and window deflections. Subsequently, several full-scale wind pressure measurement investigations on high-rise structures in Japan, including the Chiba Port Tower, World Trade Center building, Yokohama KN Building and Kasumigaseki Building, were conducted (Kawabata et al., 1990; Kanda and Ohkuma, 1990; Ohkuma et al., 1991). Most of those studies recognized the importance for further full-scale wind pressure measurements with the need for performing the internal pressure estimation and for obtaining comprehensive wind speed profile information (Kanda and Ohkuma, 1990).

Although the dynamic performance of high-rise buildings under winds has been broadly investigated by full-scale measurements, there have been very rare opportunities to conduct a comprehensive field investigation of wind pressures on super-tall buildings (such as those with building height up to 600 m) under strong windstorm conditions. Therefore, there is a pressing need to conduct such a study. In this paper, Ping An Finance Center (PAFC) with 600 m in height, located in Shenzhen, a typhoon prone region and equipped with a structural health monitoring (SHM) system, is an ideal testbed to explore the characteristics of wind pressures on super-tall buildings. Field monitoring of wind pressures on PAFC was conducted during the passage of Typhoon Nida. In addition, wind tunnel test of pressure measurement on a 1:500 scale model of PAFC was performed to provide detailed information on the wind pressures on the skyscraper. Furthermore, the model experimental results are compared with the field measurements for verification of the wind tunnel test results. In this study, a whole range of characteristic properties, including pressure coefficient, probability distribution, peak factor, power spectral density and correlation of wind pressures on PAFC are presented and discussed. The field measurements provide valuable, but limited information on the wind pressures on PAFC under typhoon condition. On the other hand, the wind tunnel test generates detailed and additional results that are not available from the field measurements. So, the combined study of the field measurements and the model test aims to enhance the understanding of the wind pressures on a 600 m high super-tall building and provide useful information for the wind-resistant design of future skyscrapers.

2. Introduction of PAFC and Typhoon Nina

2.1. PAFC

PAFC (Fig. 1), with a total height of 600 m, is located in Shenzhen where is frequently subjected to the attack of tropical cyclones. To resist horizontal loads induced by strong winds, this super-tall building incorporates three lateral force resisting systems, including reinforced concrete core-tube (embedded steel column), mega-frame (including belt trusses), brace and outrigger truss. The lengths of the building base in longitudinal and transverse directions are 56.4 m × 56.4 m, leading to an aspect ratio (height to width) of 10.6 which exceeds 7, the limiting value specified in the Technical Specification for Concrete Structures of Tall

Fig. 1. Ping an finance center.