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Wind tunnel and full-scale study of wind effects on a super-tall building

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ABSTRACT

This paper presents the analyzed results from a combined wind tunnel and full-scale study of the wind effects on a super-tall building with a height of 420 m in Hong Kong. In wind tunnel tests, mean and fluctuating forces and pressures on the building models for the cases of an isolated building and the building with the existing surrounding condition are measured by the high-frequency force balance technique and synchronous multi-pressure sensing system under two typical boundary layer wind flow fields. Global and local wind force coefficients and structural responses are presented and discussed. A detailed study is conducted to investigate the influences of incident wind direction, upstream terrain conditions and interferences from the surroundings on the wind loads and responses of the high-rise structure. On the other hand, full-scale measurements of the wind effects on the super-tall building have been performed under typhoon conditions. The field data, such as wind speed, wind direction, structural acceleration and displacement responses have been simultaneously and continuously recorded during the passage of 12 typhoons since 2008. Analysis of the field measured data is carried out to investigate the typhoon effects on the super-tall building. Finally, the model test results are compared with the full-scale measurements for verification of the wind tunnel test techniques. The comparative study shows that the wind tunnel testing can provide reasonable predictions of the structural resonant responses. The resonant displacement responses are comparable to the background displacement responses so that the contribution of the background responses to the total displacement responses should not be underestimated. The outcome of the combined wind tunnel and full-scale study is expected to be useful to engineers and researchers involved in the wind-resistant design of super-tall buildings.

1. Introduction

The development of new light-weight materials and advanced construction techniques in recent years has resulted in the emergence of many super-tall buildings, which are generally wind-sensitive structures. A statistical report from the Council on Tall Building and Urban Habitat (2013a, 2013b) reveals that 77 tall buildings over 300 m have been built throughout the world, and there are other 100 tall buildings over 300 m, which may be completed in the next 6 years. Due to the fast urban developments in some countries and regions, more super-tall buildings will be built in the future. For these high-rise

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structures, wind loads generally control the structural design, resulting in a greater emphasis on understanding the structural behavior of super-tall buildings under strong wind actions, in particular in typhoon or hurricane-prone regions. Therefore, it is necessary to conduct comprehensive investigations of the wind effects on super-tall buildings.

Over the past three decades, numerous field measurements of structural dynamics characteristics and wind-induced responses of tall buildings and high-rise structures have been carried out (Jeary, 1986; Ohkuma et al., 1991; Littler and Ellis, 1992; Tamura and Suganuma, 1996; Tamura, 1998; Campbell et al., 2007; Pirnia et al., 2007; Ni et al., 2009; Hernandez et al., 2012), including the observation of the structural performance of Burj Khalifa in Dubai (Kijewski-Correa et al., 2013), the monitoring program on three Chicago super-tall buildings by the University of Notre Dame (Kijewski-Correa, 2003) and the field measurements of the wind effects on more than ten super-tall buildings in Hong Kong, mainland China and Taiwan by the City University of Hong Kong (Li et al., 1998, 2003, 2004a, 2004b, 2005, 2006, 2011). These studies provided useful information on the wind characteristics above city central districts. The dynamic properties such as natural frequencies, mode shapes and damping ratios of a number of tall buildings were identified and the characteristics of wind-induced structural vibrations were investigated. However, reliable field measurements of the wind effects on super-tall buildings (building height >400 m) have rarely been carried out during strong windstorms such as tropical cyclones. Therefore, there is an urgent need to conduct such studies to further the understanding of the wind effects on super-tall buildings and the behaviour of these buildings under tropical cyclones. Hence, the measurement results of the wind effects on a super-tall building in Hong Kong during 12 typhoons are presented and discussed in this paper.

Wind tunnel testing is an important tool to evaluate the wind effects on buildings and structures. However, it is sometimes difficult to reproduce the exact field conditions such as incident turbulence and terrain characteristics in wind tunnel tests. Therefore, validations of wind tunnel predictions against full-scale measurements are always desirable to evaluate the accuracy of model test results and the adequacy of the techniques used in wind tunnel tests as well as to provide better understanding of the physics. However, such validations are quite rare for super-tall buildings, in particular under typhoon conditions. In this study, wind tunnel tests for investigating the wind effects on the super-tall building in Hong Kong are conducted by the high-frequency force balance (HFFB) technique and synchronous multi-pressure sensing system (SMPSS). Moreover, the model test results are compared with the field measurements for verification of the wind tunnel test techniques.

Over the last two decades, the technique of GPS has been widely applied in many areas of practice, especially in monitoring large-scale structures, such as dams, tall buildings and bridges. For example, the deformations of tall buildings were measured using kinematic GPS by Lovse et al. (1995), Kijewski-Correa and Kareem (2001), Tamura et al. (2002), Li and Wu (2007), Kijewski-Correa and Kochly (2007) and Yi et al. (2013). On the other hand, Ashkenazi and Roberts (1997), Brown et al. (1999), Fujino et al. (2000), Nakamura (2000) and Wong et al. (2001), among others, applied the GPS technique to measure the displacement responses of bridges to wind. Celebi and Sanli (2002) and Chan et al. (2006) evaluated the dynamic measurement accuracy of the GPS technique for applications in civil engineering. Psimoulis et al. (2008) investigated the ability of GPS to measure the dynamic characteristics of civil engineering structures. The GPS technique has been regarded as a viable means to obtain the mean, background and resonant responses of tall buildings.

The super-tall building under consideration in this study is 420 m high with 88 floors, located near the seashore in Hong Kong Island. In order to monitor the wind effects on the high-rise structure, a wind and movement monitoring system, including anemometers, accelerometers, GPS and pressure sensors, was installed in the super-tall building (Yi et al., 2013). The wind speed, wind direction, wind-induced pressures on cladding, structural acceleration and displacement responses were recorded simultaneously by the monitoring system during a number of tropical cyclones since 2008. This paper presents the analyzed results from a combined wind tunnel and full-scale study of the wind effects on the super-tall building in Hong Kong. The field measurements by themselves can provide valuable results of the wind effects on the super-tall building located in a typhoon-prone area. Furthermore, the field data are useful to evaluate the accuracy of the model test results and the adequacy of the techniques used in wind tunnel tests. The model tests generate detailed and additional results that are not available from the full-scale measurements, so that the understanding of the wind effects on the super-tall building can be improved. The output generated from this combined wind tunnel and full-scale study is expected to be useful for the wind-resistant design of super-tall buildings in typhoon or hurricane-prone regions.

2. Wind tunnel experiments

2.1. Experimental setup

In this study, wind tunnel experiments using SMPSS for pressure measurement and HFBB for global force measurement on two models of the super-tall building were conducted. The models were 1:400 scaled reproduction of the external surface of the super-tall building. The wind tunnel experiments were carried out in the boundary layer wind tunnel at the City University of Hong Kong. The dimensions of the working section of the wind tunnel are 4 m wide $\times$ 2 m high. Two typical boundary layer wind flow fields representing coastal area flow environment (denoted as BL1 in this paper) and urban flow environment (called BL2 hereafter) were simulated for the model tests by means of placing a barrier at the entrance of the wind tunnel, triangular shaped spires and arrayed cubic roughness elements with different sizes on the tunnel floor upstream of the building models. The mean wind speed profiles of the two typical boundary layer flows were found to