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Dynamic characteristics and wind-induced responses of a super-tall building during typhoons

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ABSTRACT

This paper presents the field measurement results of dynamic characteristics and wind-induced responses of a 420 m high tall building in Hong Kong during the passage of typhoons. The field data such as wind speed, wind direction, acceleration and displacement responses were simultaneously and continuously recorded from a monitoring system installed in the super-tall building. The outputs of accelerometers and GPS mounted in the building are compared to examine the accuracy of the GPS. The multipath effects are extracted by a combination of Empirical Mode Decomposition (EMD) and wavelet method, and then are removed by a high pass finite impulsive response (FIR) digital filter to improve the performance of the GPS. After obtaining the accurate GPS′s data, the resonant and background responses of the super-tall building as well as their contributions to the total displacements are presented and discussed. Finally, damping ratios of the building are evaluated by the random decrement technique, which demonstrate amplitude-dependent characteristics. The outcomes of this study are expected to be of interest and practical use to engineers and researchers who are involved in the wind-resistant design or structural health monitoring of super-tall buildings.

1. Introduction

The development of new 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 (2011) shows that 37 tall buildings over 300 m have been built throughout the world since 2000. Due to fast urban developments in some countries, more super-tall structures will be built. For these high-rise structures, wind loads usually control their 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.

Although significant advances have been made for evaluation of the wind effects on tall buildings by wind tunnel testing and numerical simulation, many critical phenomena can only be investigated by full-scale experiments on prototype structures. Field measurement is still regarded as the most reliable way for investigation of the wind effects on buildings and structures. Numerous studies on wind effects on tall buildings have been carried out by field measurements over the past three decades (Jeary, 1986; Ohkuma et al., 1991; Littler and Ellis, 1992; Tamura and Suganuma, 1996; Campbell et al., 2007; Pirnia et al., 2007). In particular, several full-scale measurement studies on the wind effects on super-tall buildings are being conducted, including the programs on four Chicago super-tall buildings by Notre Dame University and the University of Western Ontario (Kijewski-Correa, 2003) and on ten super-tall buildings in Hong Kong, Taiwan and mainland China by City University of Hong Kong (Li et al., 1998, 2003, 2004a, 2004b, 2005, 2006, 2011). However, opportunities to conduct full-scale measurements are still quite rare, and thus the data obtained are of significant value. Furthermore, it has been recognized the importance of full-scale testing as a benchmark for both wind tunnel and CFD modeling. Literature review reveals that comprehensive full-scale measurements of wind effects on super-tall buildings (buildings with a height > 400 m) have rarely been conducted under typhoon or hurricane conditions. Thus, such a database needs to be created.

A super-tall building with 420 m high and 88 floors, is located in Central, Hong Kong Island. The sitting of the building is very close to the seashore. As typhoons occur frequently in Hong Kong, this super-tall building may be subjected to extreme horizontal wind forces under typhoon conditions. Hence, a wind and movement monitoring system has been installed in the building since 2007 to monitor the wind effects on the high-rise structure.

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Monitoring the performance of the super-tall building under harsh typhoon conditions and the subsequent analysis of the data can provide reliable information on the wind loading and the responses of the super-tall building, which will be useful in gaining a better understanding of the wind-resistant design and habitability of modern tall buildings. Meanwhile, the measurement results can also be used to improve wind tunnel test techniques and numerical simulation methods.

This paper focuses on the investigation of the dynamic characteristics (natural frequencies and damping ratios) and wind-induced responses (acceleration and displacement) of the super-tall building based on the field measurements from the wind and movement monitoring system during typhoons. Accelerometers have been widely used for measurements of structural vibration, which are regarded as an effective tool to measure the resonant responses of structures. However, the low frequency displacement responses are difficult to be reconstructed by using in-situ measured accelerations (Tamura et al., 2002; Kijewski-Correa and Kochly, 2007). For this reason, Global Positioning System (GPS)-based techniques have been used to measure the mean and low frequency deflections of civil structures in the past two decades (Lovse et al., 1995; Ashkenazi and Roberts, 1997; Brown et al., 1999; Fujino et al., 2000; Nakamura 2000; Wong et al., 2001; Tamura et al., 2002; Kijewski-Correa and Kochly, 2007; Li and Wu, 2007). It has been widely accepted that the combination of these two types of measurements can provide comprehensive information on these response components of structures. Hence, both accelerometers and GPS were adopted in the monitoring system installed in the super-tall building.

The aim of this study is to further the understanding of the wind effects on the super-tall building during typhoons in order to apply that knowledge to design similar high-rise structures in the future. Meanwhile, it provides useful information for structural health monitoring of super-tall buildings.

2. Introductions of the field measurement program

The monitored super-tall building is located in central, on the north shore of Hong Kong Island. There are a great amount of buildings including some tall buildings with heights of 70–150 m on the north of the building in Kowloon where it is 1.5 km away from the building location across the Harbor. In a sector spanning from east clockwise to west, the building is surrounded by a large number of tall buildings with heights of more than 150 m. The northwest of the building corresponds to open-sea fetch.

Table 1
Three groups of sensors installed in three levels at the top part of the building.

Sensors	Height level
Anemometers: including one Gill Wind MasterPro ultrasonic anemometer and two Young 05103 propellers	Installed on a mast at height of 420.55 mPD, the highest level of the building. The diameter of the mast at the location of anemometer is 0.2 m and the anemometer are installed away from the master by about 1.5 m through a steel cantilever (Gill on one side and two propellers on the other side), at about 14 m height above the roof of the building.
One GPS antenna: AX 1202 smart track antenna	Installed on the roof with the installation height of 414.55 mPD
Four accelerometers (A1, A2, A3, A4)	Fixed at the 88th floor (the top floor) at height of 400.10 mPD

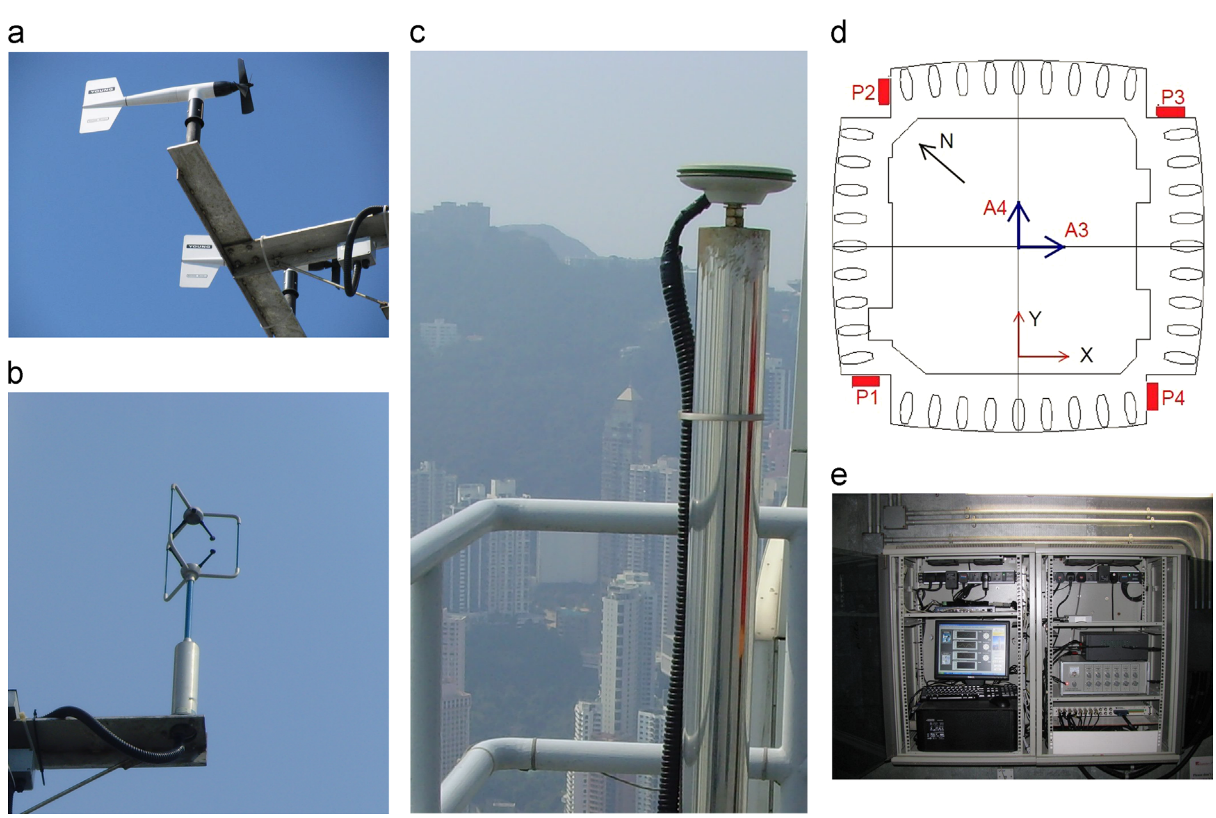

Fig. 1. Sensors installed atop the tall building: (a) propeller anemometers; (b) ultrasonic anemometer; (c) antenna of GPS; (d) locations of the accelerometers; and (e) control system.