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Monitoring Wind Characteristics and Structural Performance of a Skyscraper during a Landfall Typhoon

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ABSTRACT

Wind characteristics in the atmospheric boundary layer (ABL) and structural performance under extreme wind conditions are of major concern in the design of tall buildings in tropical cyclone-prone regions. On 22nd August 2008, Typhoon Nuri (0812) made landfall over Hong Kong and then passed over its city center directly. This paper presents analyzed results of the observations collected at two offshore meteorological stations and by a structural health monitoring system installed in a downtown 420 m high super-tall building in Hong Kong, during the entire passage of Typhoon Nuri. The wind characteristics over open (sea) and urban (city) terrains at different stages of the typhoon are presented and discussed. Moreover, the wind-induced responses of the super-tall building during the typhoon are investigated. The structural dynamics properties and serviceability of the super-tall building under typhoon condition are evaluated. This study aims to investigate the wind characteristics in the ABL during a landfall typhoon and its impact on high-rise buildings in a metropolis so as to provide useful information for the wind-resistant design of super-tall buildings in tropical cyclone-prone regions.

1. INTRODUCTION

Mature tropical cyclones, including typhoons and hurricanes, cause severe casualties, financial losses and building damages almost every year. Records show that a number of tropical cyclones made landfall over coastal cities, such as Hong Kong and Taiwan, and passed over their urban areas directly. Knowledge of landfall tropical cyclones is therefore of great importance for the wind-resistant design of civil structures in these tropical cyclone-prone regions. Although meteorological observations of tropical cyclones and structural health monitoring programs have been conducted extensively over the past few decades, measurements of wind-induced structural responses during landfall tropical cyclones are still insufficient. In consideration of the boom in high-rise buildings in coastal areas where landfall tropical cyclones may

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frequently attack, and the lagged development of existing wind load codes or standards, there is an urgent necessity to update the knowledge of landfall typhoon to wind-resistant designs, especially for wind-sensitive structures such as super-tall buildings.
Field measurement is regarded as the most reliable approach to investigate the wind effects on structures. In the past three decades, numerous field measurements of structural performance and wind loads of tall buildings have been conducted (e.g. Jeary, 1986). In particular, several full-scale measurement studies on the wind effects on super-tall buildings have been conducted, including the programs on three Chicago super-tall buildings by University of Notre Dame and the University of Western Ontario (Kijewski-Correa, 2003) and on more than ten super-tall buildings in Hong Kong, mainland China and Taiwan by City University of Hong Kong (e.g. Li et al., 2014; He and Li, 2014; Li and Wu, 2007; Yi and Li, 2015). Nevertheless, the opportunities to conduct full-scale measurements are still quite rare, especially for those measurements on super-tall buildings (with height over 300 m) under extreme wind conditions such as tropical cyclones. Given the lack of information on structural performance during windstorms, it is required to conduct more field measurements on super-tall buildings during tropical cyclones so as to further the understanding of the wind effects on high-rise buildings.

2. INSTRUMENTAL AND METEOROLOGICAL INFORMATION

2.1 Offshore meteorological stations

This paper adopts the observations collected at two offshore meteorological stations in Hong Kong during Typhoon Nuri. One is located at the zenith (71.9 m above Mean Sea Level (AMSL)) of Cheung Chau Island as indicated in Fig. 1. This station that is abbreviated as the CCH station hereafter is equipped with both ground-based devices for surface weather measurements (i.e., air pressure, temperature and wind) and a remote sensing facility. The surface wind records were collected by a cup anemometer, and profile records were collected by a boundary layer type Doppler radar profiler system. The other meteorological station is situated on the top of Waglan Island which is a small island with area less than 0.1 km^2. This station, which is called as the WGL station hereafter, is equipped with a cup anemometer to measure horizontal surface wind components.

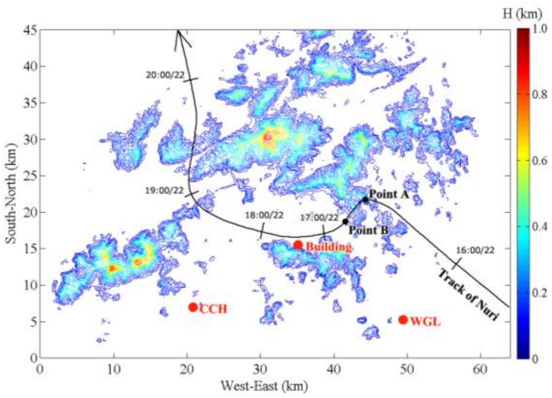


Fig 1. Topographic map of Hong Kong, track of Typhoon Nuri and the locations of measurement sites

2.2 SHM system installed in a super-tall building

This study also analyzes the filed data recorded ny a SHM system installed in a 420 m high super-tall building in Hong Kong during the passage of Typhoon Nuri. The measuring devices of the SHM system that provided data for this study are as follows. A Young 05103 propeller anemometer (Fig. 2(a)) installed approximately 14m above the building's roof, A high-precision Leica GMX902 GG GPS receiver and an AX 1202 SmartTrack GPS antenna (Fig. 2(b)) mounted on the building's roof, and a pair of orthogonally placed accelerometers on the top level of the building. Signals collected by the anemometer and the accelerometers were sampled at 20 Hz while those recorded by the GPS were sampled at 10 Hz, and all these signals were continuously and simultaneously recorded by a data acquisition unit (DAU) during the passage of Typhoon Nuri. Fig. 2(c) shows a photo of the control system of the SHM system, Fig. 2(d) shows the layout of the accelerometers, and Fig. 2 (e) shows a photo of the super-tall building.

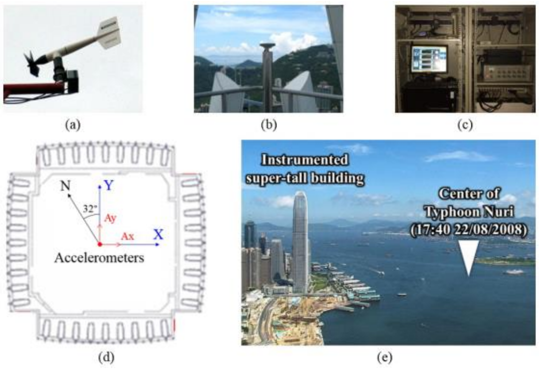


Fig 2. Some sensors of the SHM system installed in a super-tall building: (a) propeller anemometer; (b) GPS antenna; (c) control system; (d) locations of the accelerometers and orthogonal directions X and Y; (e) locations of the instrumented super-tall building and the center of Typhoon Nuri around 17:40 on 22 August, 2008.

3. WIND PROFILES

Fig. 3 illustrates the vertical profiles of 30-min mean horizontal wind speed (U) by filled color contours, which are overlaid by [Ux, Uy] wind vectors indicated by black arrows (downward for north wind, leftward for east wind). It reveals some typical features of a TC: The TC eye located at central area around 18:00/22 was characterized by calm wind indicated by blue color; while the eyewalls surrounding the TC eye, centered at 12:00/22 and at 22:00/22, respectively, contained maximum winds colored by red color. Mean wind directions varied significantly from 0° to 200° after the passage of the TC eye. Within the regions of the two eyewalls, the radius of maximum wind (RMW) is found to tilt outward with height, which is similar to those observed over deep oceans (e.g. Giammanco et al., 2013).

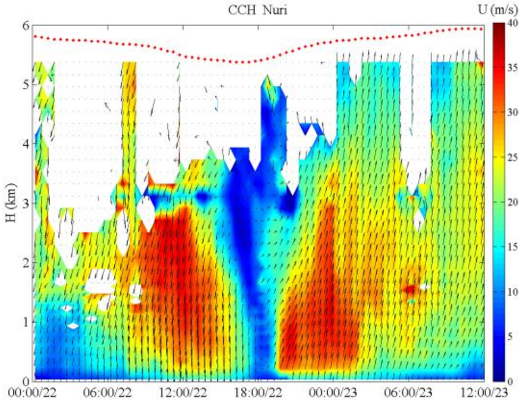
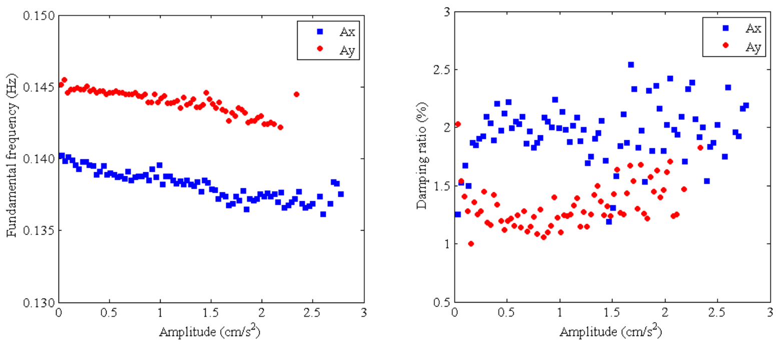


Fig 3. Variations of 30-min mean wind profiles in form of filled color contour (the dotted line stands for variations in air pressure)

4. BUILDING DYNAMIC PROPERTIES

The random decrement technique (RDT) is used herein to identify the modal parameters of the super-tall building, and detailed discussions on the application of the RDT are presented in He and Li (2014). Based on the accelerations measured by the accelerometers, the amplitude-dependences of fundamental frequencies identified using the RDT in both directions X and Y are shown in Fig. 9(a), in which the plotted points correspond to the RDSs with different initial amplitudes, respectively, indicating that the building's fundamental frequencies lowered approximately 0.003Hz as the amplitude increased from 0 to 2 cm/s^2. Fig. 9(b) plots the variations of damping ratios with the building's vibration amplitude for the two fundamental sway modes in directions X and Y. The damping ratio in direction X increases rapidly and stabilizes around 2% as the amplitude enlarges, and becomes more scattered after the amplitude exceeds 1 cm/s^2. While in direction Y, the damping ratio firstly varies between 1 and 1.5 when the amplitude is lower than 1 cm/s^2, and then gradually increases as the amplitude gets higher. Generally, damping ratios of the super-tall building in the two orthogonal directions ranged from 1% to 2% during the passage of Typhoon Nuri.



(a) (b)

Fig 9. Amplitude dependencies of building modal parameters: (a) natural frequencies; (b) damping ratios

4.5 Serviceability evaluations

With the aim of thoroughly evaluating the serviceability of the super-tall building, this study also employs the building's acceleration responses collected during the passages of four other typhoons besides Nuri (Li *et al*., 2014): Neoguri, Hagupit, Molave and Goni. The maximum hourly mean wind speeds measured at the WGL station during these typhoons, and these wind speeds measured at a height of 83 m were adjusted to those at a height of 200 m using a power law with exponent of 0.11 recommended in the current Hong Kong Wind Code of Practice (Buildings Department, 2004). Based on probability analysis of historic typhoon speed data measured at Waglan Island, Holmes *et al*. (2009) suggested that the maximum hourly mean wind speed at a height of 200 m at Waglan Island is 34.0 m/s for a five-year return period, and 23.7 m/s for a one-year return period. Obviously, all of the measured RMS accelerations of the super-tall building during these five typhoons met the occupant comfort criteria of ISO6897 for one-year period, suggesting that the serviceability of this high-rise building under typhoon condition is a satisfaction.

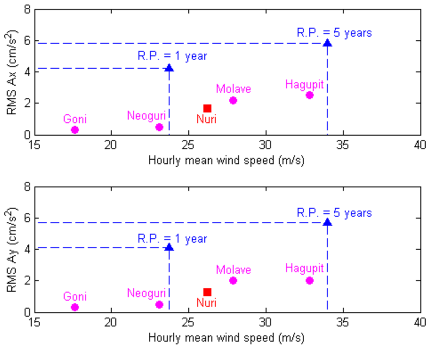


Fig 11. Variation of maximum RMS acceleration responses with hourly mean wind speeds measured at Waglan Island

5. CONCLUDING REMARDS

1. The noticeable phase differences among the mean horizontal wind speeds measured at the two meteorological stations and atop the super-tall building revealed their discrepant storm-relative locations. The dramatic decline of wind strength atop the super-tall building, comparing to those above the offshore meteorological stations, reflected the severe shielding effects caused by the local terrain condition (e.g. hills and buildings).

2. Natural frequencies determined from the field measurements gradually decreased by 0.003 Hz as the building's vibration amplitude increased from 0 to 2 cm/s^2. Damping ratios generally increased with the vibration amplitude, and the measurement results of the fundamental modal damping ratios basically varied between 1% and 2%, which are recommended in the wind-resistant designs of similar super-tall buildings for serviceability consideration.

3. The serviceability of the super-tall building during the entire passage of Nuri met the occupancy comfort criteria suggested by ISO6897 which are dependent on 10-min RMS acceleration responses of a building and its fundamental natural frequencies.

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