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Numerical simulation of wind effects on a skyscraper and validation against wind tunnel test and field measurement during a super typhoon

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SUMMARY:
Comprehensive validations of computational fluid dynamics (CFD) in predicting the wind effects on high-rise buildings are necessary to examine the reliability of CFD in wind-resistant design of structures. To promote the application of CFD in wind-resistant design, this study evaluates the accuracy of large eddy simulation (LES) in predicting the wind pressures on a 600-m-high supertall building in Shenzhen, China, by comparison with a wind tunnel test and a field measurement during a super typhoon. The wind speed and turbulence intensity profiles obtained from a 356-m-high meteorological tower in Shenzhen and the wind profiles specified in the local design load code are used to set the inflow conditions in the LES. The comparison shows that the mean, maximum, and minimum pressure coefficients predicted by the LES highly correlate to those obtained from the wind tunnel test and field measurement. However, these pressure coefficients predicted by the LES show a systematic bias toward underestimation compared with the field measurement results.

Keywords: Supertall building; Tropical cyclone; Wind load assessment

1. INTRODUCTION

The damages of claddings of high-rise buildings were frequently reported in the post-disaster assessments after intense tropical cyclones (TCs). Numerous wind tunnel tests and several field measurement studies have been conducted over the past few decades to investigate the wind pressures on the claddings of high-rise buildings. However, the wind pressure information provided by wind tunnel test and field measurement is still insufficient due to a limited number of pressure taps or pressure transducers distributed on building surfaces. In particular, very few field measurement studies were performed under extreme wind conditions such as severe TCs.

Comparatively, computational fluid dynamics (CFD) simulations can provide more comprehensive information about wind pressures on building claddings. Nonetheless, CFD has not been widely applied in practical wind-resistant design of structures due to the lack of reliability. To promote the application of CFD as a design tool in wind-resistant design of structures, comprehensive validations of CFD in predicting the wind loads on buildings are necessary, particularly for high-rise buildings with unconventional shapes. Therefore, this study evaluates the accuracy of CFD in predicting the wind pressures on a real supertall building in an urban environment by large eddy simulation (LES). The target supertall building is 600 m high named Ping An Finance Center, the fourth tallest building in the world located in a central business district in Shenzhen, Guangdong Province, China. The wind pressures on the surfaces of the supertall building predicted by the LES are compared with those obtained from a wind tunnel test and a field measurement during Super Typhoon Mangkhut. The LES are performed by a transient solver pisoFoam in the open-source software OpenFOAM (version 7) based on the supercomputer at City University of Hong Kong. The parameters related to CFD settings and inlet wind profiles are carefully determined.

2. WIND TUNNEL TEST AND REDUCED-SCALE LES

In the wind tunnel test, the target supertall building model is fitted with 440 pressure taps at 22 different heights, and 20 pressure taps are distributed at each height. The surrounding buildings within a radius of 750 m in full scale around the target building are included in the experiment, as shown in Figure 1. The geometric scale of the building models and wind tunnel flow is 1/500. The approaching mean wind speed and turbulence intensity profiles in the wind tunnel test follow those for the terrain type D (densely populated city) specified in China National Standard – Load code for the design of building structures (GB50009-2012, 2012). For comparison, a reduced-scaled LES is performed, in which the geometries and geometric scale of the building models and inflow conditions are the same as those in the wind tunnel test.

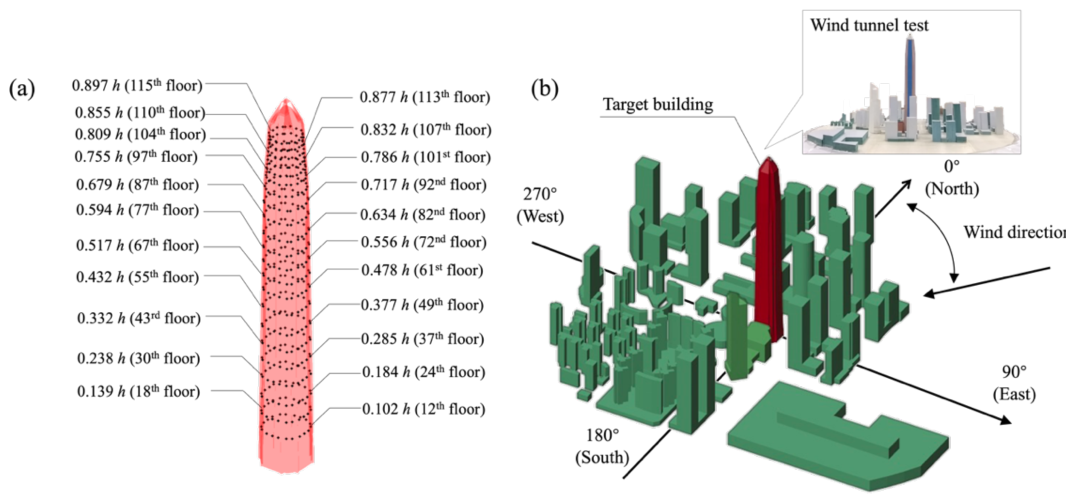

Figure 1. (a) Locations of the pressure taps on the target building and (b) geometry of the building models in the wind tunnel test.

2. FIELD MEASUREMENT AND FULL-SCALE LES

In the field measurement, there are 48 pressure transducers installed at five different heights to measure the wind pressures on the claddings of the target building during Mangkhut, as shown in Figure 2 (a). The details about the field measurement program on the target building can be found in Han et al. (2021). The LES used for comparison with the field measurement is performed in full scale size. The surrounding buildings within a radius of 5 km from the target building are constructed in the LES, as shown in Figure 2 (b). Two inflow conditions are considered in the LES. The first inflow condition uses the wind profiles specified in GB50009-2012 for the terrain type D. The second inflow condition employs the wind profiles obtained from the wind records from the 356-m-high Shenzhen Meteorological Gradient Tower (SZMGT) during Mangkhut. The LES using the first and second inflow conditions are labelled GB case and SZMGT case, respectively.

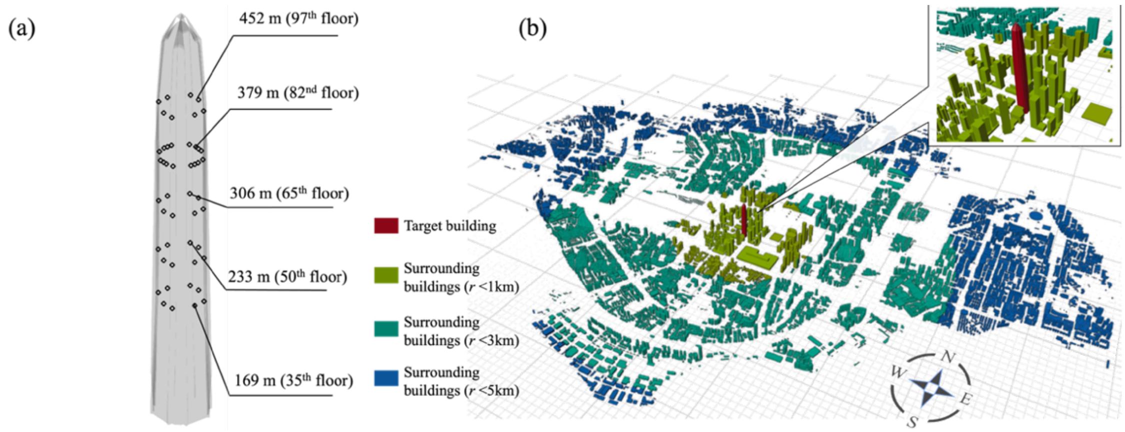

Figure 2. (a) Locations of the pressure transducers on the target building in the field measurement and (b) geometry of the building models in the full-scale LES.

3. RESULTS AND DISCUSSION

The wind pressures on the target building are described by time series of pressure coefficient $C_p(t)$:

$$C_p(t) = \frac{p(t) - p_{\text{static}}}{\frac{1}{2}\rho U_h^2} \tag{1}$$

where $p(t)$ is the time series of the wind pressures extracted at the locations of the pressure taps or pressure transducers on the building surfaces. ρ is the air density. p_{static} is the reference static pressure. U_h is the mean wind speed at the target building height. In the field measurement, p_{static} was taken to be the mean internal pressure of the target building, and U_h is measured based on an anemometer installed atop the target building. The mean, root mean square, maximum, and minimum values of $C_p(t)$ are represented by $\bar{C}_p$, C_p', $\hat{C}_p$, and $\check{C}_p$, respectively. The selected wind direction for comparing the pressure coefficients is 90° (wind direction is defined in Figure 1b). This wind direction corresponds to the 10-min mean wind direction of the approaching wind from 13:40 to 13:50 on September 16, 2018, measured by the anemometer at the target building during Mangkhut in the field measurement.

Figure 3 shows the scatter plots of the pressure coefficients obtained from the wind tunnel test and reduced-scale LES, and Figure 4 is for the comparison between the field measurement and full-scale LES. In both figures, the Pearson correlation coefficient (R) of $\bar{C}_p$, C_p' and $\check{C}_p$ are high with R > 0.9, while C_p' shows a wider dispersion with R < 0.8. The comparison between the wind tunnel test and reduced-scale LES results shows that 71.8%, 49.3%, 42.2%, and 68.9% data of $\bar{C}_p$, C_p' ,$\hat{C}_p$ and $\check{C}_p$, respectively, have errors less than 30%. The comparison between the field measurement and full-scale LES shows that the simulated $\bar{C}_p$, $\hat{C}_p$, and $\check{C}_p$ have a systematic bias toward underestimation. By comparing normalised mean square error (NMSE), the performances of the GB case and SZMGT case are generally similar.

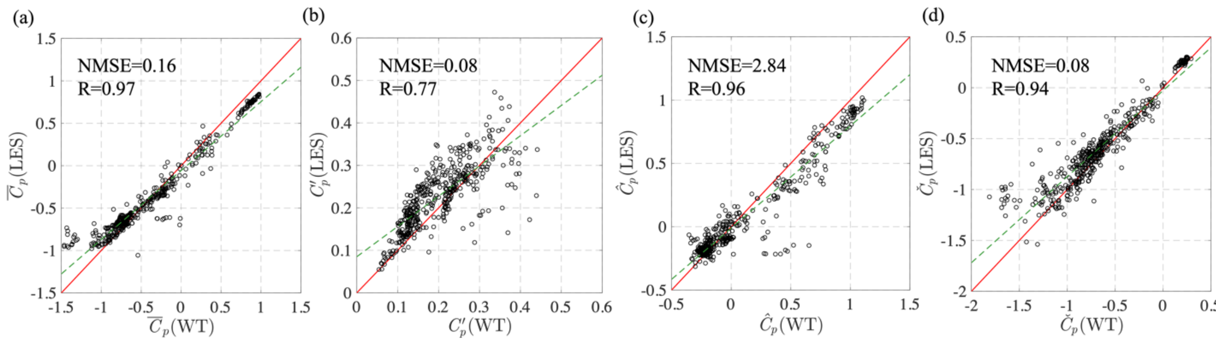

Figure 3. Scatter plots of (a) $\bar{C}_p$, (b) C'_p, (c) $\hat{C}_p$, and (d) $\check{C}_p$ between the wind tunnel test and reduced-scale LES. Dash lines denote linear regressions.

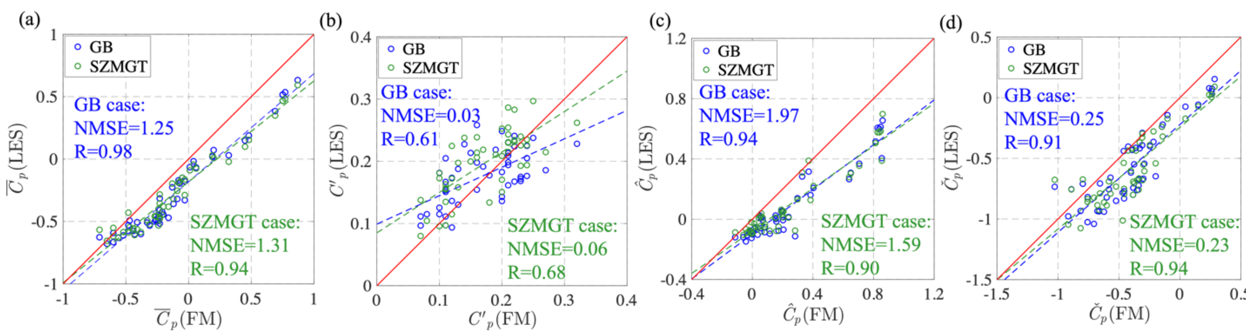

Figure 4. As in Figure 3 but for comparing the field measurement and full-scale LES.

5. CONCLUSION

The wind pressures on the world's fourth tallest supertall building (600 m) in a highly developed coastal city were simulated by large eddy simulation (LES). The aerodynamic characteristics of the target building simulated by LES were compared with those obtained from the wind tunnel test and the field measurement during the passage of Super Typhoon Mangkhut. The objective of this combined study of LES, wind tunnel test, and field measurement is to evaluate the reliability and quantify the errors of CFD in the wind-resistant design of high-rise buildings.

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