

Field measurements of wind loads on an instrumented low-rise building during typhoons and comparison with wind tunnel test results

Q. S. Li ^{a, b}, S. Y. Hu ^b, Y. M. Dai ^b

^a *Department of Civil and Architectural Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong*

^b *Key Laboratory of Building Safety and Energy Efficiency of Ministry of Education, College of Civil Engineering, Hunan University, Changsha 410082, P.R. China*

ABSTRACT: A full-scale moveable instrumented low-rise building has been constructed and implemented to monitor wind velocity field and associated building surface pressures during typhoons. The major objective of the field study is to further understand typhoon-generated wind characteristics and wind effects on the low-rise building under extreme wind conditions during typhoon landfalls. This paper presents a combined study of field measurements and wind tunnel tests. Detailed analysis of the mean, standard deviation and negative peak pressures measured on a roof corner zone of this building is conducted to investigate the pressure distribution characteristics in conical vortex region under oblique approaching wind directions. The field measurement results reveal that the windward leading edges on the corner area are consistently subjected to the most severe suction pressures for quartering winds. The measured extreme peak pressures are compared with those stipulated by ASCE 7-10 Standard. It is found that the measured extreme peak pressures at the windward leading edge area on the corner are significantly larger in absolute value than those determined by ASCE 7-10. Moreover, the effect of spatial and time average on the peak pressures on the corner zone is discussed. On the other hand, wind tunnel tests are performed to assess the wind effects on the experimental building. Comparison of the full-scale measurements and the model test results of negative peak and fluctuating pressure coefficients near the roof corner, roof ridges and leading edges shows distinct discrepancies. In general, the wind tunnel tests underestimate the real negative peak and fluctuating pressure coefficients on the roof corner zone for quartering winds. The outputs of this comprehensive study are expected to provide useful information for the wind-resistant design of low-rise buildings in typhoon-prone regions.

KEYWORDS: low rise building, typhoon, field measurement, wind tunnel test, wind-induced pressure, flat roof.

1 INTRODUCTION

Full-scale measurement is considered to be the most reliable method for evaluating wind effects on buildings and structures. There have been a number of field studies of wind effects on low-rise buildings conducted in the past several decades, including Aylesbury building field experiment (Eaton and Mayne, 1975), the Silsoe structure building field experiment (Richardson et al. 1990) and the Texas Tech University (TTU) Building field experiment (Levitan and Mehta 1992a, 1992b). The collected wind pressures on full-scale low-rise buildings were also used to validate the accuracy of wind tunnel test results, as reviewed by Uematsu and Isyumov (1999).

For example, the Aylesbury building measurement program provided wind pressure data for validation of wind tunnel experimental results (IAWE Aylesbury comparative experiment) using 1:100 models at 17 laboratories worldwide (Sill et al., 1992). The Silsoe structure building experiment provided the wind loads on a steel, gable-roof, and portal framed structure for verifying model test data (Richardson et al., 1994, 1995, 1997). In particular, several wind tunnel studies (e.g., Cocharan and Cermak, 1992; Okada and Ha, 1992; Endo et al., 2006) for the TTU Building have been conducted, and detailed comparisons with the full-scale measurements have been made. However, there are distinct discrepancies between the full-scale measurements and the wind tunnel test results of negative peak and fluctuating pressure coefficients near roof corners and roof leading edges.

More recently, field measurements on the Kern P. Pitts Centre provided valuable information of external pressure distributions and characteristics recorded during the passage of three cyclones in the proximity of the building (Caracoglia and Jones, 2009). In particular, the extensive Florida Coastal Monitoring Program currently being undertaken by three institutions in the USA focuses on monitoring of near-surface hurricane wind characteristics and wind pressures on residential low-rise buildings (Aponte, 2006). However, full-scale measurements of wind loads on low-rise buildings have rarely been conducted under strong windstorm conditions such as in eye-walls of hurricanes or typhoons. Consequently, there is lack of wind-induced pressure data on low-rise buildings under extreme wind conditions during typhoon landfalls. Obviously, there is an urgent need to enhance our understanding of turbulence structure of typhoons and the mechanisms for generations of extreme suctions in the region of flow separation or conical vortex. In this connection, a full-scale moveable instrumented low-rise building has been constructed and implemented to monitor wind velocity field and associated building surface pressures during typhoons. The major objective of the field study is to further understand typhoon-generated wind characteristics and wind effects on the low-rise building under extreme wind conditions during typhoon landfalls.

This paper is organized into four sections. Section 2 briefly describes the full-scale and wind tunnel measurement program for obtaining wind pressures on the instrumented low-rise building. Section 3 presents the measurement results from the instrumented building during the passage of several typhoons. Detailed analysis of the mean, standard deviation and negative peak pressures measured on a roof corner zone are conducted to investigate the pressure distribution characteristics in conical vortex region under oblique approaching wind directions. The measured extreme peak pressures are compared with those stipulated by ASCE 7-05 Standard. Furthermore, the effect of spatial and time average on the peak pressures on the corner zone is discussed. Moreover, wind tunnel tests are performed to assess the wind pressure distributions on the experimental building. The model test results are then compared with the field measurements to evaluate the accuracy of the model test results. Section 4 summarizes the major findings and conclusions from this combined full-scale measurement and wind tunnel test study.

2 FULL-SCALE AND WIND TUNNEL MEASUREMENT PROGRAMS

2.1 Full scale measurement

The monitoring station of the moveable instrumented building consists of a 6.0×4.0×4.0m flat-roof low-rise building and a 10m high meteorological tower located seven meters away from the building, as shown in Figure 1. Eighty differential pressure transducers (Setra model 264 or 265) with three types of measurement ranges of ± 1250 Pa, ± 2500 Pa and ± 6250 Pa were used to measure the surface pressures on the building. A CR-5 PC based central recording monitoring

system which can simultaneously record data from 60 channels was used to measure wind speed, wind direction and pressure data. The pressure transducers and anemometers were sampled at 20 Hz. A more detailed description of the measurement system can be found in Li et al. (2009). The field measurements of wind speeds and wind pressures on the buildings were conducted under strong windstorm conditions such as in the eye-walls of Typhoons Hagupit and Chanthu. The information on the tracks of these typhoons and the building site is shown in Figure 2. This paper presents the selected results of the pressure data measured from nine taps on a roof corner and six taps at mid span of the experimental building, as shown in Figure 3. These corner taps are distributed in grids of 3 columns and 3 rows in two orthogonal directions. The tap locations nearest the roof edges are 0.12m from the edges. Tap12 indicates a tap located at row 1 and column 2 on the corner, as illustrated in Figure 3. Pressure coefficient is defined as follows:

$$C_p(t) = \frac{p(t) - p_s}{1/2 \rho U_{ref}^2} \quad (1)$$

where $p(t)$ is the external pressure at a point of interest, p_s is the free stream static pressure or reference static pressure, ρ and U_{ref} are the air density and 10-minute mean wind speed at 10m height (reference height), respectively. The mean, standard deviation and peak pressure coefficients were calculated based on the measured pressure data. The pressure data presented in this paper were measured when the 10-min average wind speed at 10m height was larger than 8m/s (i.e., for dynamic pressure >40.2Pa).



Figure 1. The moveable instrumented building

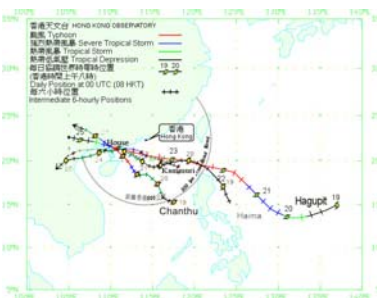


Figure 2. Track of typhoons and location of the instrumented building

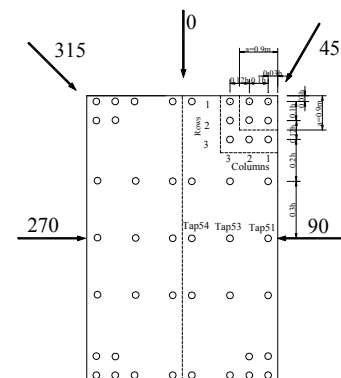


Figure 3. The locations of pressure taps and definition of incident wind direction

2.2 Wind tunnel test

The wind tunnel test was conducted at the Wind Tunnel Laboratory of Building and Environment of Hunan University. The wind tunnel is an open circuit tunnel with a working section of 3 meters wide and 2.5 meters high. With consideration of the size of the full-scale building, a geometric scale of 1:20 of the low-rise building was selected for the wind tunnel study.

For the critical wind directions (0°-90°) where the building roof was subjected to the most severe suctions, the terrain exposures at the building site can be categorized as coastal terrain and open land terrain, respectively. Therefore, the boundary layer wind flows for coastal terrain and open land terrain in the wind tunnel test were simulated based on the recorded profiles during typhoons and the terrain conditions around the instrument building site. The mean longitudinal wind speed and turbulence intensity profiles for the coastal terrain and the open land terrain, including the field measured profiles and those simulated for the wind tunnel test, are shown in

Figure 4 and Figure 5, respectively, for comparison purposes. The model scale mean wind speed profile was normalized by the mean wind speed at 0.5 meter height which corresponds to 10 meter full-scale height in order to compare the profile with the field measured profile. It can be seen from these figures that the mean wind speed profiles simulated for the model test are in good agreement with the field measured profiles. The mean wind speed profiles for the coastal terrain are well matched by a simple logarithmic profile with a roughness length z_0 ranged from 0.0027-0.0033m. A power-law exponent (α) 0.12 represents a mean value for the profiles over the coastal terrain. The simulated turbulence intensities for the coastal terrain were slightly larger than the measured ones. The mean value of the surface roughness length for the wind tunnel test was 0.03m which was close to the field measured mean value of 0.02m for the open land terrain. The power law exponent (α) was found to be 0.16 for this terrain. The model scale Jensen Number ranged from 133 to 1200 which was in accordance with the full-scale Jensen Number. The Reynolds Number based on the full-scale building height is 10^6 while it is 10^5 in the wind tunnel test.

Model and full-scale normalized longitudinal velocity spectra at 10m height are presented in Figure 6 for comparison purposes. Figure 6 shows that the full-scale velocity spectrum measured within the eye-wall region of Typhoon Chanthu follows a Karman-type spectrum in the main frequency range. Meanwhile, the model scale spectra are in good agreement with the full-scale spectrum in the main frequency range, implying that the spectral characteristics of a strong typhoon can be reproduced in the wind tunnel test. There are three interdependent scaling factors; length, velocity and time. The length scaling was fixed by the 1:20 scale model. The mean longitudinal mean wind speed at the reference height of the model test for the coastal terrain and the open land terrain were 7.93m/s and 8.45m/s, respectively. The mean longitudinal wind speed at the reference height of 10m in full-scale was typically between 10 and 40m/s during the typhoons. Thus, the velocity scaling is about 1:5. This means that the sampling period of 6s in the model test is equivalent to a 10min period recording in full-scale.

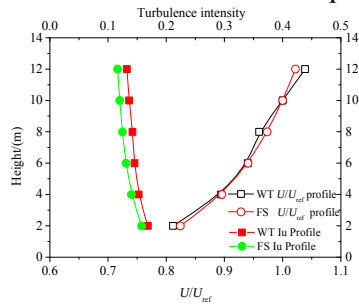


Figure 4. Mean wind speed and turbulence intensity profiles for the coastal terrain

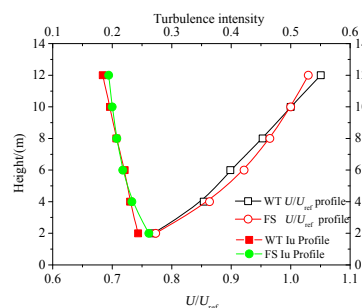


Figure 5. Mean wind speed and turbulence intensity profiles for the open land terrain

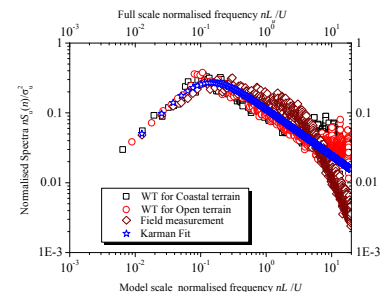


Figure 6. Comparison of the field measured spectra to those simulated in the wind tunnel test at 10m height

3 PRESSURE RESULTS AND DISCUSSIONS

3.1 Wind pressures in conical vortex region

Variations of the mean, negative peak and rms pressure coefficients at the windward leading edge on the corner (Tap12, Tap13 and Tap21, Tap31) with the mean incident wind direction are presented in Figure 7(a) through 7(c), respectively. The mean pressure coefficient distributions for all the taps were similar. The negative peak pressure coefficients and rms pressure

coefficients at Tap12 and Tap21 were consistently subjected to the most severe suction pressures around 20° - 60° . The minimum negative peak pressure coefficient at Tap21 was found to be -13.5. Conical vortices were believed to form on the roof corner region, which produced the worst severe suctions on the corner for quartering winds. This observation is consistent with those obtained from other low-rise buildings (Tieleman et al. 1994; Kawai and Nishimura, 1996; Zhao, 1997; Banks et al., 2000; Wu et al., 2001; Blessing et al., 2009). Such extreme suctions occurring on roof corner zones and roof edges are the primary causes of roof damages of low-rise buildings during hurricanes and typhoons (Holmes, 2001).

The availability of the field measurements of wind pressure results from this experimental building provides an excellent opportunity for comparisons with the provisions of wind codes and standards to assess the suitability of the codes of practice. Comparisons between the measured pressures and those derived from ASCE 7-10 Standard (2010) are presented in Figure 7 (b). It should be noted that the pressure coefficients stipulated in the ASCE were determined based on 3 sec gust wind speed. Hence, appropriate transformations are necessary in order to make meaningful comparison with the field results which were determined based on 10 min mean wind speed data. The value determined from ASCE 7-10 Standard is -9.25 for the corner zone, which was converted from -2.8 stipulated in the Standard by consideration of a gust pressure factor of $1.51^2=2.28$ (converting 3s gust speed to 10min mean wind speed) and the associated adjustment factor was 1.45 for the reference height and terrain exposure. The pressure coefficients measured at Tap12 and Tap21 on the corner are significantly larger in absolute value than that stipulated in ASCE 7-10 for the corner zone.

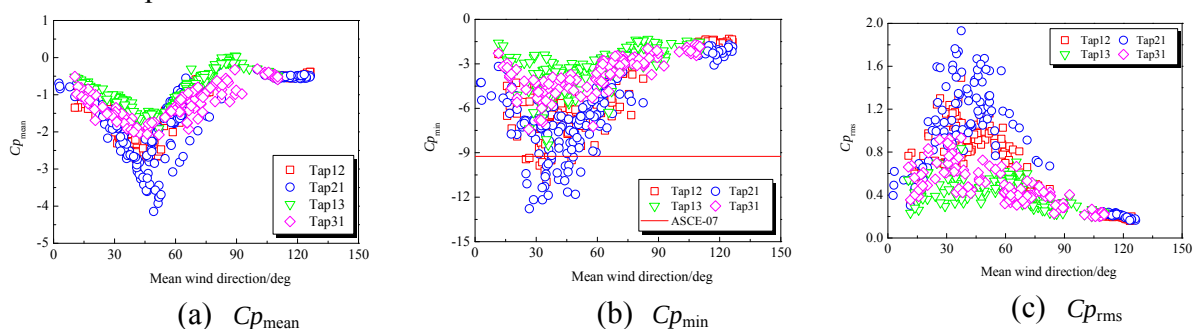


Figure 7 Variations of pressure coefficients with mean wind direction for the taps on the roof corner

3.2 Area-averaged pressure coefficients

The design wind loads on roof member and cladding stipulated in current codes or standards are made up of the most critical area averaged pressure coefficients specified as functions of tributary area. Area-averaged pressure coefficients and the duration for determination of peak wind loads are key factors for evaluation of wind loads on roof members and claddings.

Firstly, the correlations of pressure coefficient in the corner zone were investigated. The correlations of pressure coefficient indicate how well the pressures are related in space under the conical vortex flow. The correlations between Tap 11, Tap 13, on the short-span leading edge of the roof, and Tap 31, on the long-span leading edge, with the other corner taps are shown in Figure 8. It can be seen from the figure that the pressures at Tap 11 are reasonably correlated with other taps in row 1 (above 0.85 for Taps 12, 13) and are also related to those in column 1 on the diagonally opposite edge (above 0.75 for Taps 21 and 31). In general, it appears that there are higher correlations at most locations in the corner area. These results indicate that both edges are affected by the generation of delta wing vortices. Therefore, the area-averaged pressures on the corner area can be obtained by adding up the pressures measured at all the taps, weighted by the respective tributary areas involved the taps. As an example, corner leading edge area I includes

Tap11, Tap 21 and Tap 31 and corner area II covers the cross-area of row 2 and column 2, while corner area III with 1.44m^2 includes the nine taps marked as the dotted square, as shown in Figure 3.

The variations of the negative peak pressure coefficient at the corner leading edge area I, corner area II and corner area III with the mean wind direction are presented in Figure 9. As expected, the largest peak coefficients in absolute value occurred at the windward leading edge on the corner area zone for wind attacking angles around 20° - 45° . The minimum peak negative pressure coefficient on the corner leading edge area I was found to be -9.9 which was slightly larger in absolute value than that stipulated in ASCE 7-10 Standard (2010) for corner zones.

For investigation of the area and time averaged effects on peak pressures, the pressure data on the roof corner zone with 1h record duration under a quartering wind around 45° with mean wind speed 18.3m/s were selected herein as a case study. The effects of time and area average on the negative peak pressure coefficients on the corner zone are presented in Figure 10. The minimum peak pressure coefficients decreased generally with an increase in time average (T). But, the peak pressure coefficients stabilized around 3s average time. As expected, the area averaged peak negative pressure decreased considerably when the area increased.

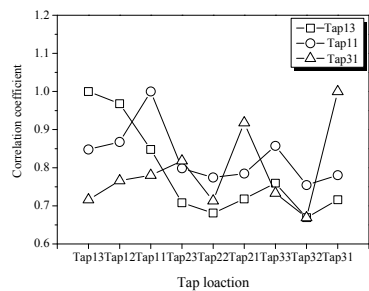


Figure 8. Correlation coefficients between Taps 13, Tap11 and Tap 31 with the other taps in the corner zone

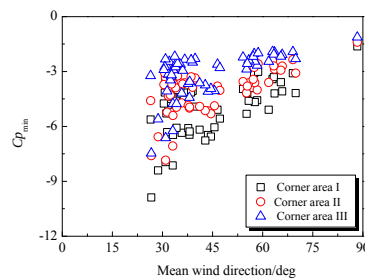


Figure 9. Variation of negative peak pressure coefficients on the corner area with mean wind direction

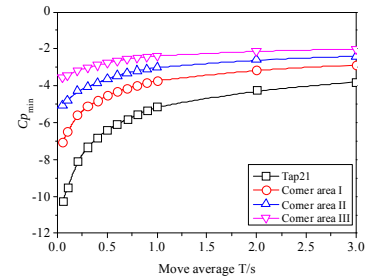


Figure 10. Effects of time and area averaging on negative peak pressure coefficients at Tap21 and in the corner area

3.3 Wind tunnel results and comparison with the full-scale measurements

3.3.1 Wind pressures coefficients on the roof

The comparisons of the mean, negative peak and rms pressure coefficient distributions along the mid-plane section across the roof between the full-scale and model-scale tests for an angle of approaching wind of 90° are shown in Figure.11 (a) through 11 (c), respectively. It can be seen from these figures that the model-scale mean pressure coefficients are in good agreement with the field measured values except for the mean pressures coefficients at the leading edge. Moreover, the field measured negative peak and rms pressure coefficients in magnitude at the leading edge are slightly higher than the wind tunnel results. It was found that the field measured peak suction pressure coefficient of -2.85 was observed near the leading edge area of the roof, while the peak suction pressure coefficients were -2.05 and -2.59 observed for the coastal terrain and the open land terrain, respectively. The discrepancies between the model-scale and full-scale negative peak and rms pressure coefficients at the leading edge of the roof may be caused by several factors, such as non-stationary wind characteristics during typhoons and Reynolds number effects etc. These results indicate that wind tunnel tests may underestimate the fluctuating and negative peak pressures at the leading edge of the flat roof under separation bubble.

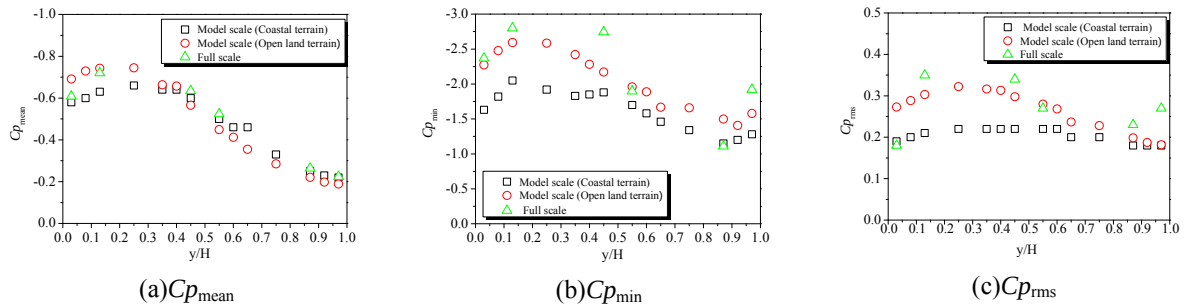


Figure 11. Comparison of pressure coefficients along the centerline on the roof between the field and wind tunnel measurements (at wind direction of 90 degree)

The comparisons between the full-scale and model-scale measurements of the mean, negative peak and rms pressure coefficients at Tap12 are shown in Figure.12 (a) through 12(c). For the mean pressure coefficients, the smoother (coastal) terrain model test results are closer to the full-scale data. High magnitudes of the mean pressure coefficients are observed for angles of attack from 30° to 60° , as shown in Figure 12(a). It is found that the wind tunnel test underestimated the negative peak and rms pressure coefficients in the roof corner region in comparison with the full-scale results for the critical wind angles, as depicted in Figure 12(b) and 12(c). Besides the critical wind direction range (from 0° to 90°), the negative peak and rms pressure coefficients measured in the wind tunnel test for the open terrain are higher in magnitude than the full-scale values. The similar observations were made for Tap21 as shown in Figure13 (a)-13(c). The results displayed in Figures 12 and 13 indicated that the wind tunnel test underestimated the highest fluctuating and peak pressure coefficients near the edges of the roof corner zone under conical vortices. The distinct discrepancies may be attributed that it is difficult to fully simulate the realistic wind characteristics during typhoons in a conventional wind tunnel.

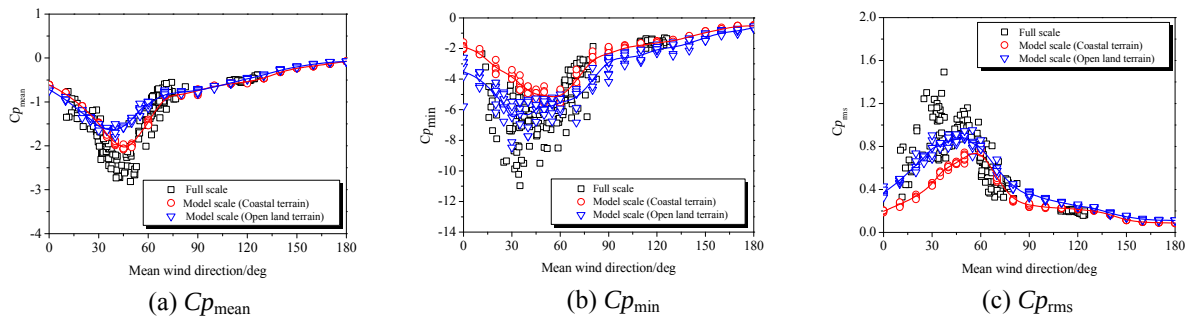


Figure 12. Comparison of the mean, peak and rms pressure coefficients at the roof corner tap12 between the field and wind tunnel measurements

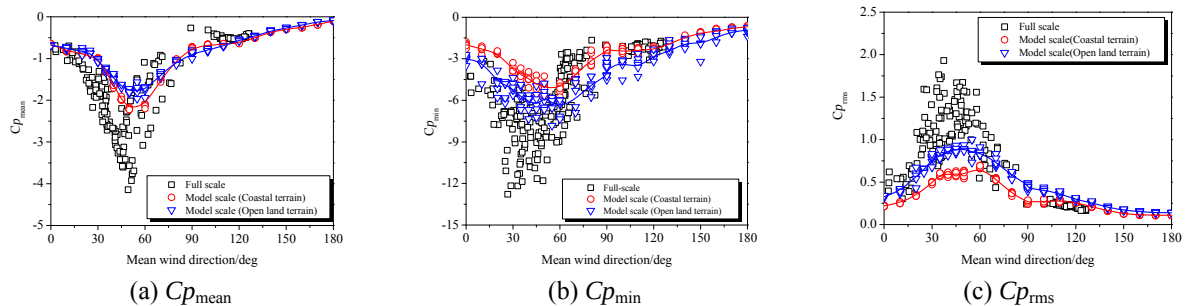


Figure 13. Comparison of the mean, peak and rms pressure coefficients for the roof corner tap21 between the field and wind tunnel measurements

3.3.2 Probability density function

The probability density functions of pressure coefficient for Tap21, corner area I and corner area III obtained from the full-scale measurements and the wind tunnel test for approaching wind direction of 45° were estimated as shown in Figure.14 (a) through 14(c), respectively. It obviously appears that the probability distributions of the field measured pressures at the corner tap and on the corner areas are more highly skew than those of the wind tunnel test, corresponding to skewness to the left. The differences in the tail of the probability density functions indicate that the wind tunnel test underestimate the negative peak pressures. Meanwhile, the probability distributions of the field measured pressures significantly deviate from the Gaussian distribution, demonstrating that the probability distributions of the pressures in a conical vortex flow region are non-Gaussian.

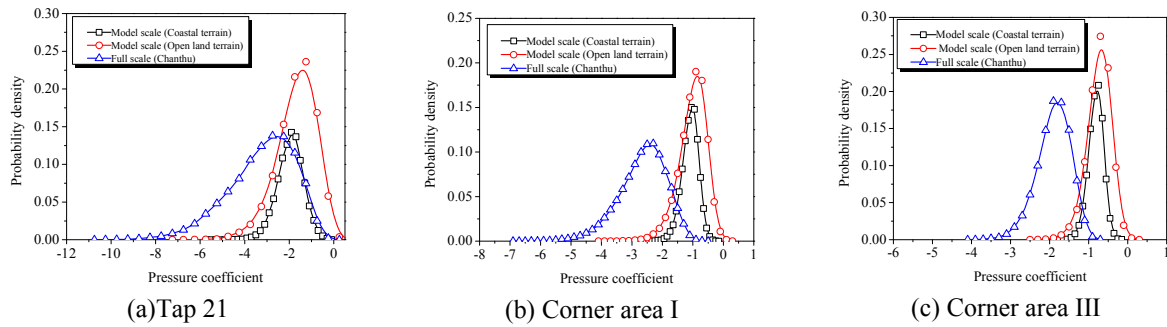


Figure 14. Comparison of probability density of pressure coefficient for Tap21, areas I and II between the full-scale and wind tunnel measurements (for wind direction of 45 degree)

3.3.3 Spectral analysis

The representative spectra of fluctuating pressures for Tap21, corner area I and corner area III, which were obtained from the full-scale measurements and the wind tunnel test, are shown in Figure 15(a) through 15(c), respectively. The comparison shows that the field measured spectral amplitudes are higher than these of the model test results for Tap 21. The spectra measured from the open terrain are closer to the full-scale spectra than those obtained from the coastal terrain, implying that the real wind flows were more turbulent than those from the coastal terrain. The agreement of the spectra is better for corner area III than other two cases. This suggests that as the increase of the considered area for determination of wind loads on it, more accurate area-averaged wind pressures may be obtained.

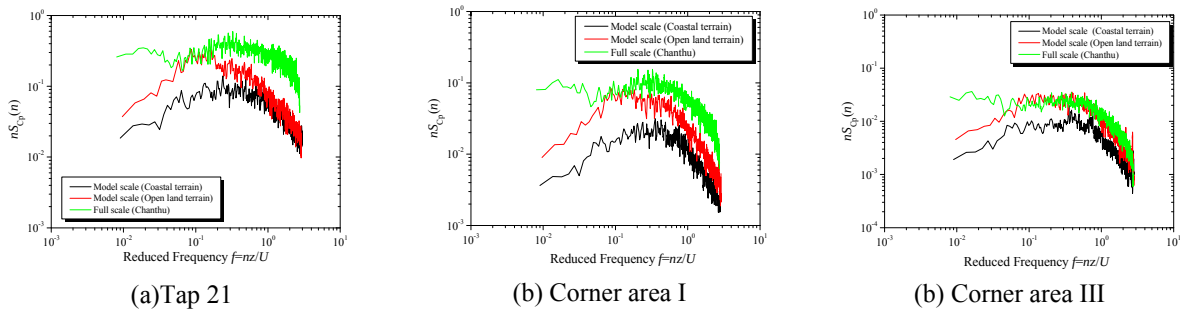


Figure 15. Comparison of spectra of pressure coefficient for corner Tap21 and corner areas between the full-scale and wind tunnel measurements (for wind direction of 45 degree)

4 CONCLUSIONS

A combined study of field measurement and wind tunnel test was conducted to investigate the wind loads on a low-rise building during typhoons. The major conclusions of this study are summarized as follows:

(1) The windward leading edges on the corner area were consistently subjected to the most severe suction pressures for quartering winds. The measured minimum peak pressure coefficient was -13.5 and the associated minimum peak pressure coefficient at the windward corner leading edge area was -9.9. The measured extreme peak pressures at the windward leading edge area on the corner were significantly larger in absolute value than those from ASCE 7-10 Standard. These findings imply that the peak uplift loads prescribed in ASCE 7-10 for components and cladding may be non-conservative for low-rise buildings during typhoons.

(2) Comparison of the full-scale measurements and wind tunnel test results of negative peak and fluctuating pressure coefficients near the roof corner, roof ridges and roof leading edges showed distinct discrepancies. This implied that the conventional wind tunnel techniques cannot reproduce the highest peak and fluctuating pressure coefficients on roof regions under conical vortices or separation bubbles for extreme wind conditions.

5 ACKNOWLEDGEMENTS

The work described in this paper was fully supported by a grant from the “985” Project of Hunan University and grants from City University of Hong Kong (Project No. 7002661 and 7002748).

6 REFERENCES

- ASCE/SEI 7-10, Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers, Reston, VA, 2010.
- Aponte, L., Measurement hurricane wind pressure on full-scale residential structures: analysis and comparison to wind tunnel studies and ASCE-7. Ph.D. Dissertation. Gainesville, University of Florida. Department of Civil and Coastal Engineering, 2006.
- Banks, D., Meroney, R.N., Sarkar, P. P., Zhao, Z., Wu, F., Flow visualization of conical vortices on flat roofs with simultaneous surface pressure measurement, *J. Wind Eng. Ind. Aerodyn.*, 84(2000) 65-85.
- Blessing, C., Chowdhury, A. G, Lin, J., Huang, P., Full scale validation of vortex suppression techniques for mitigation of roof uplift, *Engineering Structures*, 31 (2009) 2936-2946.
- Caracoglia, L., Jones, N. P., Analysis of full-scale wind and pressure measurements on a low-rise building, *J. Wind Eng. Ind. Aerodyn.*, 97 (2009) 157-173.
- Cochran, L.S., Cermak, J.E., Full-scale and model cladding pressures on the Texas Tech University Experimental Building, *J. Wind Eng. Ind. Aerodyn.*, 44 (1992) 1589-1600.
- Eaton, K.J., Mayne, J.R., The measurement of wind pressures on two storey houses at Aylesbury, *J. Wind Eng. Ind. Aerodyn.*, 1 (1975) 67-109.
- Endo, M., Bienkewicz, B., Ham, H. J., Wind-tunnel investigation off point pressure on TTU test building, *J. Wind Eng. Ind. Aerodyn.*, 94 (2006) 553-578.
- Holmes, J.D., *Wind Loading of Structure*. New York: Spon, 2001.
- Levitan, M.L., Mehta, K.C., Texas tech field experiments for wind loads part I: Building and pressure measuring system, *J. Wind Eng. Ind. Aerodyn.*, 43 (1992) 1565-1576.
- Levitan, M.L., Mehta, K.C., Texas tech field experiments for wind loads part II: Meteorological instrumentation and terrain parameters, *J. Wind Eng. Ind. Aerodyn.*, 43 (1992) 1577-1588.

- Li, Q.S., Hu, S.Y., Da, Y.M., Li, Z.N., Extreme-value analysis for field measured peak pressure coefficients on a low-rise building. In Proc: The seventh Asia-Pacific Conference on Wind Engineering, Taipei, Taiwan, 2009, pp269-276.
- Okada, H., Ha, Y.C., Comparison of wind tunnel and full-scale pressure measurement tests on the Texas tech building, *J. Wind Eng. Ind. Aerodyn.*, 43 (1992) 1601-1612.
- Richardson, G.M., Robertson, A.P., Hoxey, R. P., Surry, D., Full-scale and model investigations of pressures on an industrial/agricultural building, *J. Wind Eng. Ind. Aerodyn.*, 36 (1990) 1053-1062.
- Richardson, G.M., Surry, D., The silsoe structures building: comparison between full-scale and wind-tunnel data, *J. Wind Eng. Ind. Aerodyn.*, 51 (1994) 157-176.
- Richardson, G.M., Blackmore, P.A., Silsoe structures building: comparison of 1:100 model-scale data with full-scale data, *J. Wind Eng. Ind. Aerodyn.*, 57 (1995) 191-201.
- Richardson, G.M., Hoxey, R.P., Robertson, A.P., Short, J.L., The silsoe structures building: comparisons of pressures measured at full scale and in two wind tunnels, *J. Wind Eng. Ind. Aerodyn.*, 72 (1997) 187-197.
- Sill, B.L., Cook, N.J., Fang, C., Aylesbury comparative experiment, A final report, *J. Wind Eng. Ind. Aerodyn.*, 43 (1992) 1553-1564.
- Tieleman, H.W., Surry, D., Lin, J.X., Characteristics of mean and fluctuating pressure coefficients under corner (delta wind), *J. Wind Eng. Ind. Aerodyn.*, 52 (1994) 263-275.
- Okada, H., Ha, Y.C., Comparison of wind tunnel and full-scale pressure measurement tests on the Texas tech building, *J. Wind Eng. Ind. Aerodyn.*, 43 (1992) 1601-1612.
- Uematsu Yasush, Isyumov Nicholas, Wind pressures acting on low rise buildings, *J. Wind Eng. Ind. Aerodyn.*, 82 (1999) 1-25.
- Wu, F., Sarkar, P.P., Mehta, K. C., Zhao, Z., Influence of incident wind turbulence on pressure fluctuations near flat-roof corners, *J. Wind Eng. Ind. Aerodyn.*, 89 (2001) 403-420.
- Zhao, Z., Wind flow characteristics and their effects on low-rise buildings, Ph.D. Dissertation, Lubbock, Texas Tech University, Civil Engineering, 1997.