

Comparison of Wind Tunnel Tests of Peak Pressures over the TTU WERFL Building with Full-scale Measurements

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Summary

Boundary-layer wind-tunnel tests have advanced the building wind load design in the past few decades and will continue to do so in the foreseeable future. However, it is well known that peak pressure coefficients measured in traditional wind tunnels with scaled building models are underestimated compared to those of full-scale tests. Recent efforts have been put in large-scale testing by using a much larger building model and in an open-jet type of wind tunnel with a large test section. This work aims to evaluate rooftop surface pressure distributions over a 1:6 Texas Tech University (TTU) Wind Engineering Research Field Laboratory (WERFL) building model subjected to a cornering wind of 45°, measured at the FIU WOW experimental facility, and compared against the full-scale test data archived at TTU. Results of this careful comparison of both inflow characteristics and rooftop peak pressures will shed light on strategies for improving wind-tunnel simulation and interpretation of full-scale field data.

Keywords: *ASCE wind load provision, full-scale field measurements, large-scale wind tunnel test, peak pressure coefficient*

1 INTRODUCTION

Wind-induced pressures are a critical factor contributing to the failure of low-rise buildings. In particular, strong suction pressures developing on roof edges and roof corners can trigger severe roof damage. The Wind Engineering Research Field Laboratory (WERFL) building at Texas Tech University (TTU) is a unique experimental facility for acquiring full-scale wind pressure data along with monitoring incoming wind conditions (Levitan and Mehta, 1992; Pruitt, 2000; Smith et al., 2018). Prior wind-tunnel studies have reported mean pressure coefficients similar to the full-scale test values; however, reproducing full-scale peak pressure coefficients has been challenging, particularly at the roof corners/edges for cornering wind directions. Recent studies using large-scale building models in open-jet wind facilities aim to reduce the scaling issue and achieve near-full-scale Reynolds numbers to address the discrepancies of peak pressures in wind tunnel tests compared to those of the full-scale tests (Moravej et al., 2024). In this study, a specific case under cornering wind (45°) is examined to assess the mean pressure coefficient, the standard deviation of the pressure coefficient, and the peak pressure coefficient on the rooftop of the TTU WERFL building in large-scale wind tunnel tests and full-scale measurements.

2 EXPERIMENTAL SETUP AND DATA ANALYSIS METHODS

2.1 ABL Flow Simulation at the Wall of Wind Experimental Facility

The NHERI 12-fan Wall of Wind (WoW) Experimental Facility (EF) at Florida International University (FIU) was used to simulate the ABL inflow over open terrain. The WOW EF can generate an ABL wind reaching the maximum speed of 71.5 m/s (160 mph) in the large test section of 6.10 m (wide) \times 4.27 m (high). Incoming wind velocities were measured using a vertical rake of three TFI cobra probes at the turntable center at 2000 Hz . At the roof height, the “High Speed” wind condition generates $U_H = 22.12 \text{ ms}^{-1}$, $Re_H = 0.92 \times 10^6$, and a turbulence intensity $I_u = 13\%$. An angle of attack (AOA) of 45° is considered for the comparison study.

2.2 TTU WERFL Building Model and Pressure Measurements

A 1:6-scale model of the TTU WERFL building was constructed with dimensions of $L = 2.286 \text{ m}$, $W = 1.524 \text{ m}$, and ridge height $H = 0.648 \text{ m}$. In contrast to the 1:100 or 1:200 scaled building models, the 1:6 TTU building model allows for achieving near full-scale Re_H given sufficiently high incoming wind speed. The wind pressure distribution on the roof surface was measured using a Scanivalve DSM4000 and ZOC33 pressure scanning system. Figure 1 illustrates the pressure taps on the WERFL building roof for the field tests and WOW wind tunnel tests. A total of 228 pressure taps were installed on the building model’s roof, with a higher tap density near the windward corner than in the full-scale field test. Thus, the wind-tunnel data capture higher-resolution pressure statistics near the roof corner and windward roof edges.

The mean pressure coefficient, $\overline{C_p}$, and its standard deviation, C_p' , at each measurement location are defined as

$$\overline{C_p} = \frac{1}{N} \sum_{i=1}^N C_{p_i} \quad (1)$$

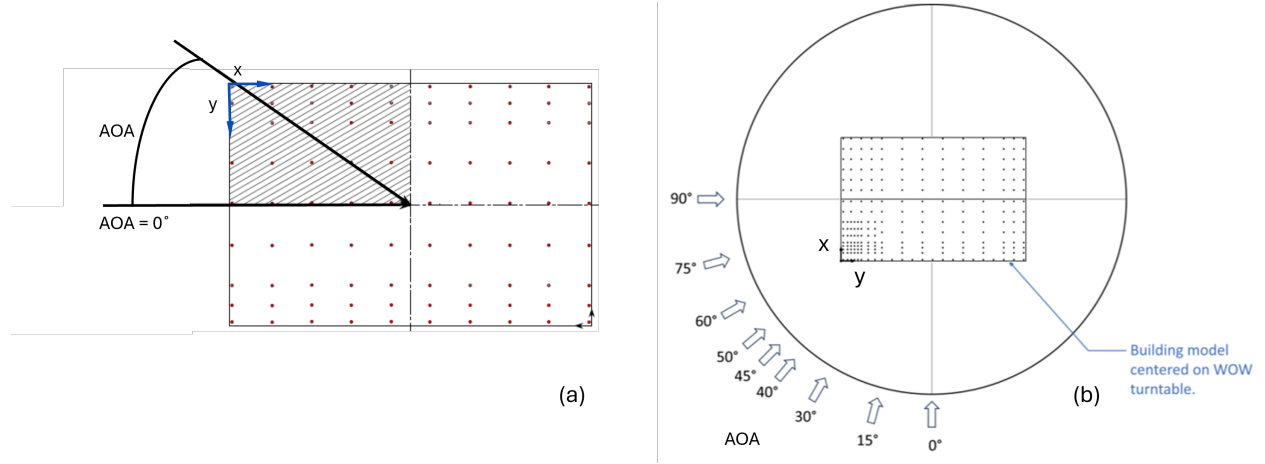


Figure 1: Schematic diagram of surface pressure taps on the WERFL building roof: (a) full-scale case and (b) model-scale case.

$$C_p' = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (C_{p_i} - \overline{C_p})^2} \quad (2)$$

where N denotes the total number of samples in the pressure coefficient time history, and C_{p_i} represents the i^{th} sample.

Since pressure fluctuations are only recorded over a finite duration of the wind tunnel experiment, estimation of full-scale peak pressures requires a statistical treatment of extreme values. Following the methodology of Gavanski et al. (2016), peak values extracted from segmented time series are fitted to a Gumbel distribution using the Lieblein best linear unbiased estimator (BLUE). This approach yields an estimate of the peak pressure coefficient, $C_{p,\text{peak}}$, given by

$$C_{p,\text{peak}} = \frac{P_i - P_{ref}}{\frac{1}{2} \rho U_{3s}^2} \quad (3)$$

where P_i is the measured surface pressure, P_{ref} is the reference pressure from the scanner, and the denominator represents the dynamic pressure computed using the air density, ρ , and the peak 3-second wind speed at the model eave height, U_{3s} .

2.3 Full-scale Field Data

The field test facility is situated at TTU in Lubbock, Texas, and it comprises a test building and an adjacent meteorological tower. The WERFL building is a prefabricated metal building with a plan dimension of $9.1 \text{ m} \times 13.7 \text{ m}$ and height of 4.0 m (Levitan and Mehta, 1992). A total of 90 pressure taps were installed on the roof to measure the differential pressure, which is later converted to the pressure coefficient (Levitan et al., 1991). The pressure coefficients and corresponding incoming wind data for different wind speeds and AOAs are available on the DesignSafeCI website. This study focuses on the roof pressure distribution for a 45° cornering wind. A run of wind measurement is determined when the wind is relatively constant in both direction and speed, and the mean wind speed at the roof height is larger than 6.7 m s^{-1} (or 15 mph), see Smith et al. (2018)

and Geleta et al. (2024). Surface pressure data were obtained at a sampling rate of 30 Hz for 15 minutes per run. The peak pressure coefficient value was obtained as the single minimum value from the time history at each tap location (Levitan et al., 1991). For this case, the mean wind speed at the roof height is $U_H = 8.01 \text{ m.s}^{-1}$ and the corresponding Reynolds Number $Re_H = 2.2 \times 10^6$. The key parameters used in both cases are summarized in Table 1. The Reynolds numbers of the same order of magnitude are achieved in both cases.

Table 1: Basic parameters of the wind tunnel tests and full-scale measurement

Parameters	Wind Tunnel Test	Field Test
Geometric scale	1:6	1:1
Velocity scale	2.75:1	1:1
Time scale	1:16.5	1:1
Sampling period (seconds)	55	900
Sampling frequency (Hz)	625	30
Number of pressure taps on the roof	228	90
Angle of Attack AOA ($^\circ$)	45	45 ± 14 (mean \pm std)
Reference velocity, U_H (m/s)	22.12	8.01
Reynolds number, Re_H	0.92×10^6	2.2×10^6
Integral Length Scale at roof height, L_u/H	1.4	7.54

3 RESULTS AND DISCUSSION

3.1 Turbulent Inflow Characteristics

Vertical profiles of the mean incoming wind speed normalized by the wind speed at roof height, are depicted for the full-scale and model-scale tests in Figure 2. The along-wind velocity profile of the full-scale case follows a typical atmospheric boundary layer trend, with a power law exponent $\alpha = 0.13$, which represents open terrain conditions (ASCE-7, 2017). The wind tunnel flow profile exhibits a power law exponent $\alpha = 0.17$. Overall, both full-scale and wind tunnel results demonstrate consistent behavior: a dominant along-wind component that increases with height and a negligible vertical component.

The turbulence intensities of both the along-wind and cross-wind velocity components are shown in Figure 3. For the field test, the turbulence intensity of the along-wind component is approximately 0.2 near the ground and roof surface. Above the roof height, it decreases to about 0.17. The vertical turbulence intensity is about 0.05 at roof height and increases to 0.08 at higher levels. In the wind-tunnel test, the along-wind turbulence intensity is about 0.13 at roof height and increases to 0.2 near the ground. The vertical turbulence intensity is 0.1, which is higher than that in the full-scale test. It is noted that, the wind direction AOA shows significant variability in the full-scale measurement while it remains constant in the wind tunnel test (Table 1).

3.2 Rooftop Pressure Coefficients

Figure 4 shows the statistics of surface pressure coefficients over the roof obtained from the FIU WOW tests, which exhibit significantly stronger suction along the windward edges and roof corners induced by conical vortices. The region of dynamic vortices also has a higher standard deviation C'_p , as noted in Shelley et al. (2023). The wind-tunnel test yields a $\overline{C_p}$ range of -4.43 to $-$

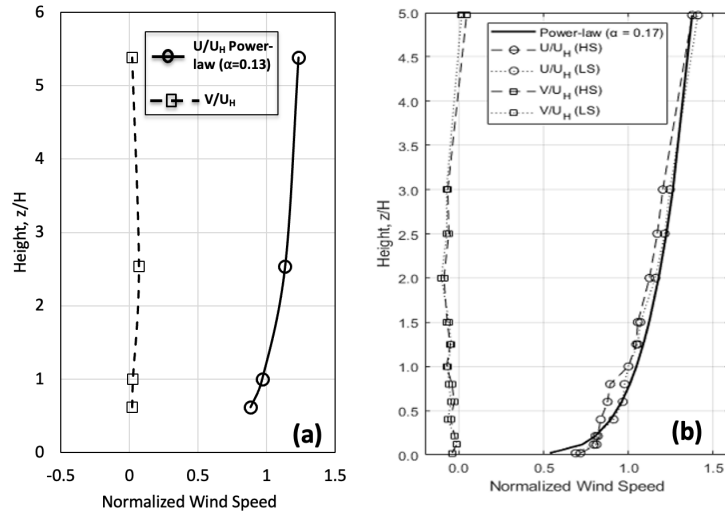


Figure 2: Vertical profiles of mean wind speeds: (a) full-scale case and (b) model-scale case.

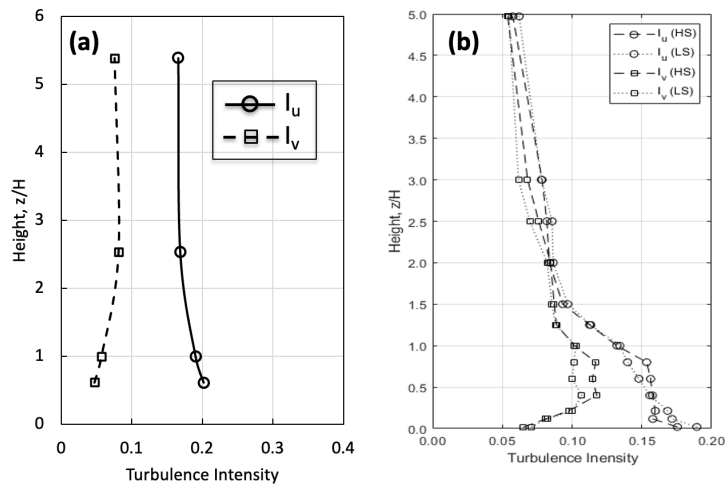


Figure 3: Vertical profiles of turbulence intensities of along wind I_u component and vertical I_v component: (a) full-scale case and (b) model-scale case.

0.14 and C'_p range of 0.03 to 1.48. The peak pressure $C_{p,peak}$ minimum is -8.74, which falls in the range of -4 to -14 in prior studies (Kopp et al., 2005; Moravej et al., 2024). For the full-scale test case (Fig. 5), the average pressure coefficient $\overline{C_p}$ ranges from -2.84 to -0.23 , standard deviations C'_p are of the range 0.098 to 1.54, and the peak values have a range of -15.78 to -0.99 . Both datasets clearly capture the signature of conical vortices developed along the roof edges. The standard deviation C'_p shows a good agreement between wind tunnel data and full-scale field data. However, $\overline{C_p}$ covers a larger range in wind tunnel tests, and the minimum of $C_{p,peak}$ is about 50% of that of the full-scale test case.

The difference in pressure coefficients over the roof from the large-scale wind tunnel tests and the full-scale field test may be due to the following: (1) differences in turbulence intensities and turbulent length scales; (2) significant variability of wind direction in the full-scale field test; (3) the specific procedure to estimate the peak pressure coefficient.

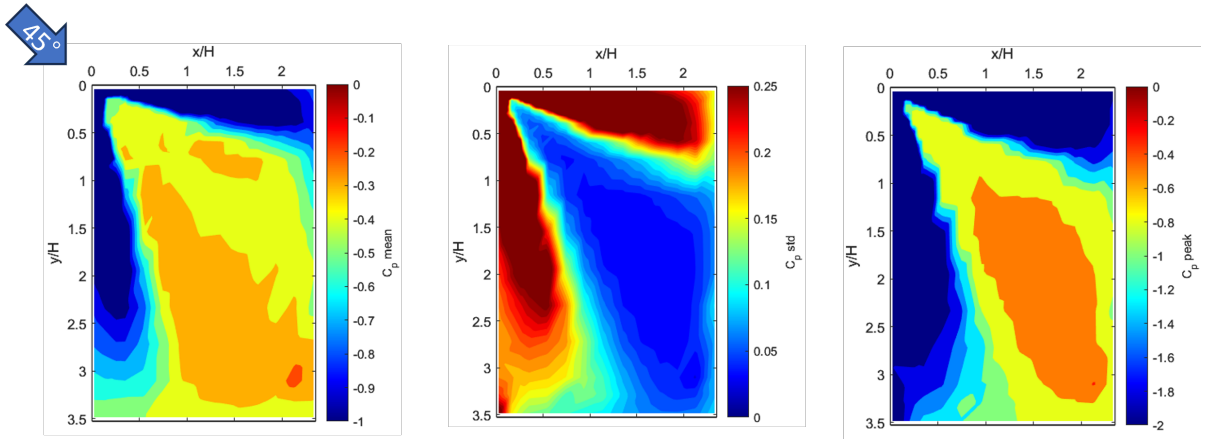


Figure 4: Contours of mean pressure coefficient $\overline{C_p}$ (left), standard deviation C'_p (middle), and peak pressure coefficient $C_{p,peak}$ (right) over the roof at 45° wind and $Re_H = 0.92 \times 10^6$ measured at FIU WOW EF.

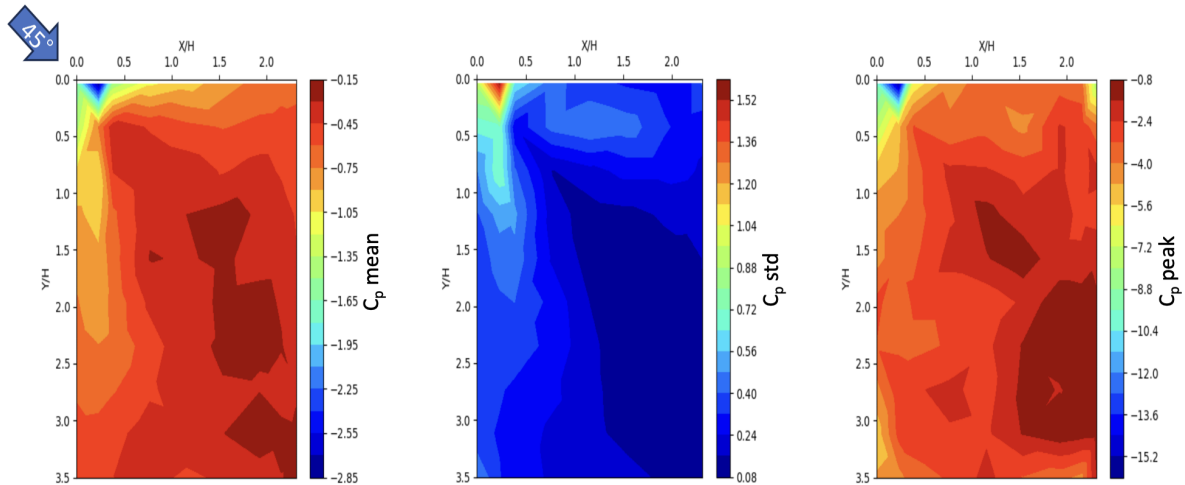


Figure 5: Contour plots of mean pressure coefficient $\overline{C_p}$ (left), standard deviation C'_p (middle), and peak pressure coefficient $C_{p,peak}$ (right) over the roof at 45° wind and $Re_H = 2.2 \times 10^6$ from the full-scale data.

4 CONCLUSIONS

Rooftop pressure coefficients over the 1:6 TTU WERFL building from large-scale wind tunnel tests at FIU WOW facility for a cornering wind condition (45°) are compared with a counterpart full-scale test case. The standard deviation C'_p shows good agreement between wind tunnel data and full-scale field data. The $\overline{C_p}$ covers a larger range in wind tunnel tests, and the minimum of $C_{p,peak}$ is about 50% of that of the full-scale test case. To better clarify the discrepancies in mean and peak pressure coefficients between the two datasets, future work will examine multiple runs of pressure measurements during the field test, options for determining the peak pressure coefficients, and the stationarity of the full-scale wind speed and direction.

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