CWE-8
June 7-11, 2026
London, ON, Canada

Comparison of pressure coefficient between tornado-like vortex and boundary layer wind

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SUMMARY

Tornadoes rank among the most destructive windstorms worldwide, and post-event damage assessments consistently report severe roof failures. These failures are often attributed to elevated uplift demands induced by the strong vertical velocity components present in tornadic flows. To incorporate the influence of these vertical velocity components into design practice, ASCE 7-22 introduced a tornado pressure-coefficient adjustment factor for vertical winds ($\underline{K_{vT}}$). This study presents results from a comprehensive series of experiments conducted in both the VorTECH tornado simulator and an Atmospheric Boundary Layer (ABL) wind tunnel, in which surface pressures were measured on building models with a range of geometric configurations. Pressure coefficients obtained under tornado-like loading are compared with those derived from ABL testing to assess the adequacy of the current K_{vT} values in ASCE 7-22 and to inform proposed revisions for ASCE 7-28.

Keywords: *Tornado Adjustment Factor, Vertical Winds, Tornado Simulator, Boundary Layer Wind, ASCE 7-22*

1. INTRODUCTION

Tornadoes rank among the most destructive wind hazards, inflicting substantial damage on the built environment. Between 1996 and 2024, they accounted for nearly \$1.5 billion in annual property losses (NOAA, 2025). The 2011 EF-5 Joplin tornado alone damaged more than 8,000 structures and resulted in approximately \$3 billion in property losses (Kuligowski et al., 2014). Following this event, the National Institute of Standards and Technology (NIST) conducted a technical investigation and released a comprehensive report detailing major findings and recommendations. A central conclusion of the report was that tornado-induced loads greatly exceeded the design provisions that had been established for straight-line wind events.

Several studies have employed laboratory tornado simulators to measure building surface pressures and investigate the effects of tornadic loading. These studies consistently report load demands that exceed those specified in ASCE 7 for straight-line winds. For example, Haan et al. (2010) tested a 1:100-scale model of a low-rise residential building with a gable roof subjected to a translating vortex. Their results indicated that the resulting vertical force coefficients were two to three times larger than the values prescribed in ASCE 7-05 for open-terrain straight-line wind conditions. Similarly, Wang et al. (2018) examined a 1:300-scale cubic building (15 × 15 × 15 m) under a stationary tornado and found that the external pressure coefficients on the roof exceeded those in ASCE 7-10 by a factor of two to five, largely due to the contribution of Atmospheric Pressure Change (APC) within the vortex.

In response to growing evidence of the distinct nature of tornadic loading, the American Society of Civil Engineers (ASCE) introduced a dedicated tornado design chapter (Chapter 32) in the ASCE 7-22 Standard for Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE, 2022). This chapter provides tornado hazard maps and establishes a framework for evaluating tornado-induced loads. Tornado loads fundamentally differ from straight-line wind loads due to three primary factors: (1) APC associated with the tornado's core pressure deficit, (2) rapid spatial and temporal variations in wind speed and direction, and (3) the presence of significant vertical wind components.

Vertical winds are especially pronounced near the tornado's corner-flow region, where strong updrafts generate substantial uplift forces that contribute to roof failures. To account for these effects, Chapter 32 of ASCE 7-22 introduces an adjustment factor (K_{vT}), which modifies the straight-line wind external pressure coefficient (C_p), to incorporate tornado-induced vertical wind influences, as expressed in Eq. (1).

$$p_T = qG_T K_{dT} K_{vT} C_p - q_i(GC_{piT}) \tag{1}$$

where p_T is the resultant pressure due to tornado; q and q_i are the external and internal pressure, respectively; G_T is the tornado gust-effect factor, K_{dT} is the tornado directionality factor; GC_{piT} is the tornado internal pressure coefficient. Using the experimental dataset of Haan et al. (2010), Haan (2017) separated static and dynamic pressure components to isolate the vortex-only induced loading. The study demonstrated that vortex-only loading coefficients increase by as much as 89 % in certain regions of the building. Each test configuration was repeated only ten times. Unlike the stationary vortex, however, the loadings due to translating tornado-like vortex are highly nonstationary and non-Gaussian. The associated uncertainty can be substantial, and a limited number of repetitions may not adequately capture the true loading characteristics. Addressing this limitation, Chen et al. (2023) performed as many as 1,700 repeated tests under a tornado-like vortex and concluded that at least 200 realizations are necessary to reliably estimate peak loads.

In the present study, multiple building models were tested in both the VorTECH tornado simulator (TS) and the Atmospheric Boundary Layer (ABL) wind tunnel at Texas Tech University (TTU), measuring the wind-induced pressure. Using these pressure measurements, the primary objective of this paper is to evaluate the vertical uplift pressure coefficients induced by tornadoes and to compare them with the K_{vT} adjustment factors specified in ASCE 7-22. The K_{vT} factor is computed as the ratio of the maximum tornado-induced external wind pressure from the TS to that from the ABL. The resulting values from the experiment tests will be used to propose updated K_{vT} adjustment factors for use in ASCE 7-28.

2. EXPERIMENTAL TESTS

2.1. Tornado-like Vortex Flow

Three types of tornado-like vortices were generated in the VorTech tornado simulator, in which the characteristics (i.e., swirl ratio [S], Reynolds number [R_{er}], maximum mean tangential velocity [$\overline{V}_{\theta,max}$], core radius [$r_c$], height at which r_c occurs [z_c]) of the simulated vortices are summarized in Table 1. Building models were translated back and forth (± translation direction) through each of three vortices at different translational path (y/r_c = 0, 0.5, 1.0) with various orientations (β = 0°, 45°, 90°) and translation speeds (U = 0.25 m/s, 0.75 m/s, 1.25 m/s). A schematic drawing of the test configuration is shown in Figure 1.

Table 1: Summary of simulated vortex characteristics

Vortex type	S	R_{er}	$\bar{V}_{\theta,max}$ (m/s)	r_c (cm)	z_c (cm)
Single-celled	0.17	6.5×10^5	11.2	8	5
Multi-celled	0.83	5.7×10^5	11.5	46	6
Multi-celled	1.88	5.2×10^5	12.5	87	9

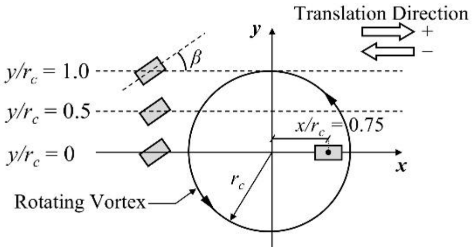

Figure 1: Schematic drawing of test configuration under VorTech simulator.

2.2. Boundary Layer Flow

To directly compare the tornado-like and ABL wind loading, the same building models were tested under the boundary layer flow in the ABL wind tunnel using the same tubing and data acquisition system. The mean along wind speed was 11.6 m/s at mean eave height and mean wind directions ranged from 0° to 180° with 15° increments.

2.3. Building Models

A total of four building models were used in this study, a: (1) 1:100 scale of the TTU Wind Engineering Research Field Laboratory (WERFL) with flat roof, (2) 1:100 scale of the TTU Wind Engineering Research Field Laboratory (WERFL) with gable roof at 4/12 roof pitch, (3) 1:200 scale of rectangular building (representative of a school building), and (4) 1:200 scale of mid-rise building (representative of medical office building). The dimensions of the building models are shown in Figure 2.

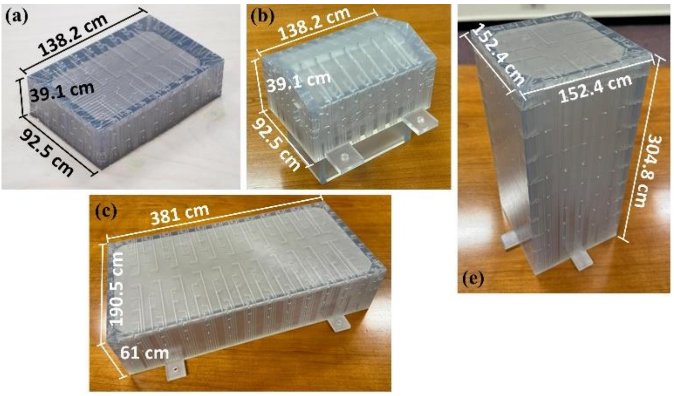

Figure 2: Building models with dimensions.

As discussed in Section 1, the tornado-like vortex produces non-stationary and non-gaussian flow and loading characteristics, and thus the TS testing of each configuration was repeated at least 100 times, providing more reliable ensemble loading statistics. More detailed descriptions of the experimental tests in the VorTECH can be found in Chen et al. (2023) and Tang et al. (2018).

3. PRELIMINARY RESULT

Figure 3 presents a comparison of the pressure coefficients obtained under (a) tornado-like vortex loading and (b) ABL wind tunnel testing. The tornado pressure coefficient ($\langle C_{p,T} \rangle$) shown in Figure 3(a) represents the ensemble-averaged instantaneous pressure coefficient from 100 realizations for the WERLF building under the test configuration $S = 0.83$, $y/r_c = 0$, $\beta = 0°$, and $U = 1.25$ m/s with the building positioned at $x/r_c = 0.75$ (see Figure 1) and subjected to a mean horizontal vortex wind direction of 75°. Figure 3(b) shows the corresponding mean pressure coefficients from the ABL wind tunnel ($\bar{C}_{p,A}$) at the same 75° wind direction. The comparison reveals a higher pressure magnitudes under tornado-like loading, despite the matched incident wind direction, indicating that the current ASCE 7-22 K_{vT} values may underestimate the additional uplift demands induced by tornadic vertical velocities. Notably, the tornado tests also show substantial increases in pressures on windward walls, even though no pressure adjustments for walls (i.e., $K_{vT} = 1.0$) are included in ASCE 7-22 code provisions. Comprehensive analyses across all building models are ongoing to further evaluate the adequacy of the K_{vT} factors specified in ASCE 7-22.

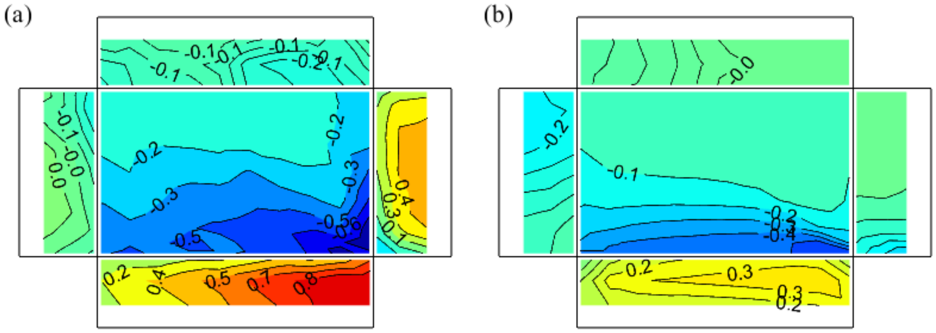

Figure 3: Contour plots of the (a) $\langle C_{p,T} \rangle$ and b) $\bar{C}_{p,A}$ of the flat roof WERLF building.

ACKNOWLEDGEMENTS

The VorTech tornado simulator experimental tests were supported under the NSF-funded Wind Hazard and Infrastructure Performance Center (WHIP-C) project.

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