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Estimation of aerodynamic loads induced by tornado-like flows on a low-rise structure for various levels of translation speed

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SUMMARY
The transient aerodynamics of a low-rise building subjected to tornado-like flows are investigated through an extensive wind tunnel campaign conducted at the WindEEE Dome. Multiple translation speed tests were reproduced, encompassing both quasi-stationary and full-scale tornado scenarios, by means of a moving floor system driven by a rapid traversing mechanism. Simultaneous measurements of wind velocity and pressure are acquired on both the building model and the underlying floor over multiple nominally identical repeats. The primary objective of this study is to quantify the aerodynamic loading as a function of translation speed. Preliminary results reveal the presence of distinct loading mechanisms that vary with the translation velocity, highlighting the role of transient aerodynamic effects in shaping the structural response.

Keywords: Tornado-induced aerodynamic loading, Experimental techniques, Transient aerodynamics.

1. INTRODUCTION

Tornadoes are catastrophic wind events associated with significant economic losses, particularly in the United States and Canada. They differ fundamentally from synoptic-scale winds in several aspects, including their genesis, spatial extent, duration, and the intensity of the generated flow. Despite their importance, the characterization of tornado wind fields remains limited, which is reflected in the difficulty of defining the corresponding aerodynamic loads on structures. In particular, there is a persistent lack of understanding regarding the combined effects of translational and rotational wind components within the tornado, as well as their associated flow features.

To address these gaps, significant experimental efforts have been undertaken over the past decade, leading to the development of advanced tornado simulators, such as WindEEE Dome at Western University (e.g., Refan and Hangan, 2018). These studies have consistently shown that the unique characteristics of tornadic flows can lead to structural loading conditions that differ markedly from those associated with conventional straight-line atmospheric boundary layer winds. Indeed, such features may substantially alter building aerodynamics when compared to the classical framework established for synoptic winds (e.g., Tieleman, 2003). Among the distinctive aspects of tornadoes, the translation speed of the vortex emerges as one of the most complex, as it modifies local flow properties and accelerations, breaks axial symmetry, and introduces inherently transient effects.

This paper focuses on this aspect, investigating the bluff-body aerodynamics of a low-rise structure subjected to the action of translating tornado-like flows for different translational speed. The experimental set-up, which was documented by Brusco et al. (2026), is briefly summarized in

Section 2, while Section 3 includes preliminary results relevant to the aerodynamic loading and conclusions.

2. EXPERIMENTAL METHODOLOGY

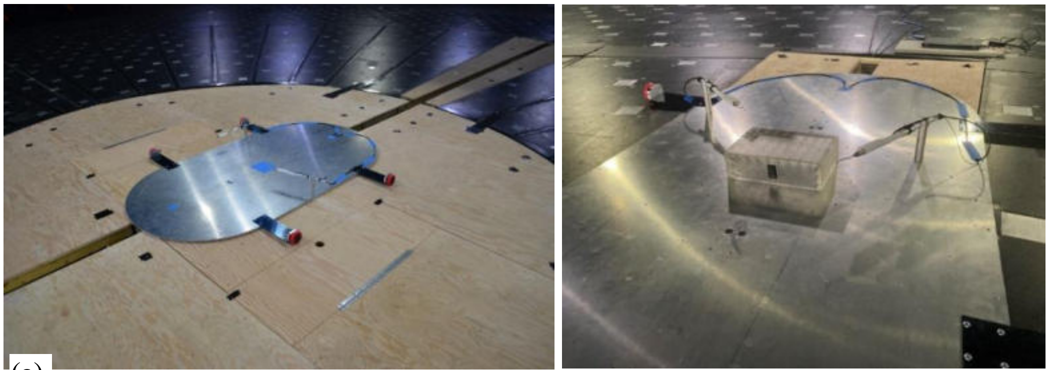
WindEEE Dome is a large-scale experimental facility characterized by a hexagonal plan configuration and an inner test chamber with a diameter of 25 m. The facility is equipped with six fans mounted above the test chamber, which generate the updraft flow representative of tornado-like vortices. The rotational component of the inflow is controlled by adjusting the angles of guide vanes distributed along the peripheral walls of the chamber. The simulated tornadoes investigated in this study are characterized by a nominal swirl ratio,

$$S = r_0 \Gamma_{max} / 2Qh \ = 0.76 \quad (1)$$

where r_0 is the updraft radius, Γ_{max} is the maximum circulation in the flow, Q is the flow rate per unit axial length, and h the inflow depth. The core radius of the tornado is about 400 mm near ground level and the simulated tornadoes are characterized by multiple sub-vortices.

The translating nature of tornado-like flows in WindEEE Dome can be reproduced by moving the bell-mouth along one of the symmetry axes of the test chamber. Using this configuration, the ratio between the translation speed and the maximum tangential velocity typically reaches values in the range of 0.08–0.11 (Narancio et al., 2024). To extend this range toward higher values, a new rapid traversing system was conceived, designed, and implemented (Brusco et al., 2026). The traversing system consists of seven components which, once assembled, form a 12.8 m track. An aluminum cart moves along this track via a chain-driven mechanism connected to a plate bolted to its underside. A servo motor drives the chain system and is calibrated to achieve a range of prescribed translation velocities. An elliptical aluminum baseplate (2.05 m × 1.10 m, with a thickness of 9.525 mm) is mounted on top of the cart, forming the moving floor. The cart is designed to house and protect the instrumentation required for the measurements. The system was calibrated to reproduce three distinct translation velocities: approximately 53 mm/s (1), 1.50 m/s (2), and 4.21 m/s (3). In particular, (3) enables the simulation of ratio of the translation speed to the maximum tangential speed that are typical of full-scale tornadoes.

The aluminum baseplate was instrumented with 226 pressure taps. Wind tunnel tests were conducted both over the bare floor (Figure 1a), to characterize the flow at different translation velocities, and with a pressure model installed on the moving surface (Figure 1b). The model is a 1:50 scale representation of the Texas Tech University Wind Engineering Research Field Laboratory (TTU WERFL) building. It has plan dimensions of 183 mm × 275 mm, an eave height of 78 mm, and a ridge height (*H*) of 80 mm. Accordingly, the tornado core diameter is approximately three times the largest plan dimension of the building model. The model is equipped with 204 pressure taps that are nearly uniformly distributed on the building model. The wind field induced by the tornado-like flows is captured by two Cobra Probes, which were installed in proximity to two of the building corners at a height of 114 mm (1.47H) above the ground.



(a) (b)

Figure 1. Experimental set-up at WindEEE Dome: (a) bare floor and Cobra Probes, (b) TTU building installed on the moving floor.

Two different positions of the tornado core relative to the traversing system axis were considered during the experiments, leading to the definition of three distinct configurations, as illustrated in the following. Configurations I and II correspond to bare-floor conditions, with the bell-mouth centre aligned with the long axis of the aluminum baseplate (0 mm offset) and shifted by 320 mm, respectively. Configuration II serves as the reference for Configuration III, which includes the building model while maintaining the same 320 mm offset between the bell-mouth centre and the baseplate axis. The selected offset in Configurations II and III was chosen to replicate the experimental setup adopted by Kopp and Wu (2020) for the same TTU building, where an identical relative position with respect to the translation axis of a slowly translating bell-mouth (57 mm/s) was used.

Table 1 summarizes the test matrix for the moving-floor experiments (MFX), where X denotes the translation speed level (X = 1, 2, 3). The table also reports the number of nominally identical repeats performed for each case.

Table 1. Description of the tests conducted in conditions of moving floor

Configuration	Case	Number of repeats
I	1 – MF2	30
	I – MF3	60
II	II – MF2	15
	II – MF3	30
III	III – MF1	15
	III – MF2	30
	III – MF3	60

The data are processed using conditional averaging techniques based on the instantaneous position of the moving floor. This approach enables the construction of accumulated time histories, in which pressure and velocity measurements from all nominally identical repeats are aligned and aggregated for each position of the moving floor.

3. PRELIMINARY RESULTS AND CONCLUSIONS

The accumulated pressure time histories are used to evaluate the loading induced by tornado-like flows on the structure. These loads comprise both a “static” component, associated with the pressure deficit characteristic of tornado flows, and an aerodynamic component. Following the procedure proposed by Kopp and Wu (2020), the ground pressures obtained under bare-floor conditions are fitted using the static pressure model of Baker and Sterling (2018). Assuming linear superposition of the two contributions, the aerodynamic component is then estimated by subtracting the static contribution from the total measured load.

Figure 2 presents the ensemble-averaged vertical uplift (i.e., force along the z-axis) as a function of the moving floor position, y_{mf}, non-dimensionalized by the radius of maximum tangential velocity, r_c. A value of $y_{mf} / r_c = 0$ corresponds to the alignment of the building center with the bell-mouth center. The building translates from negative values of y_{mf} to positive ones. The results are reported for the three translation speed levels and are distinguished using different grayscale intensities. The figure highlights distinct loading trends as the tornado interacts with the building, reflecting the influence of translation speed. As expected, higher translation speeds generally lead to increased loads. However, the complex three-dimensional structure of tornado-like flows also plays a significant role in shaping the observed response. In fact, for higher translation speeds (III – MF2 and III – MF3), the load does not exhibit a reduction near the tornado center, in contrast with the behavior observed at lower translation speeds (case III–MF1) and in Kopp and Wu (2020).

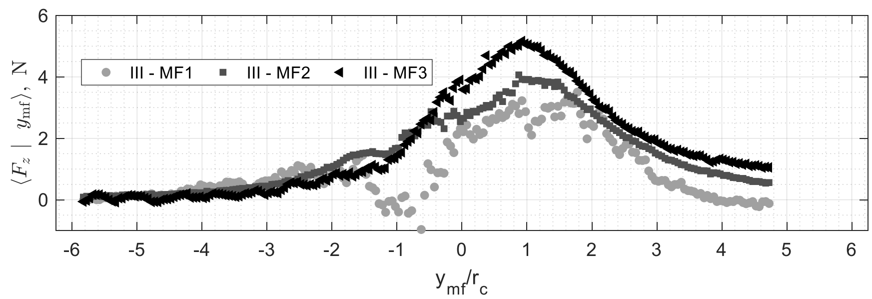


Figure 2. Ensemble mean of the vertical uplift estimated for different positions of the moving floor.

The full paper will further investigate these effects by analyzing both instantaneous and mean pressure distributions, and by comparing the measured loads with those predicted using quasi-steady theory and velocity measurements obtained from the Cobra probes.

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