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# Tornado-induced wind loads on a low-rise building: Influence of swirl ratio, translation speed and building parameters

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ABSTRACT

Significant parameters that influence tornado-induced wind loads on low-rise buildings are yet to be fully explored. In the current study, the influence of tornado parameters such as swirl ratio and translation speed and building's spatial parameters such as its distance from the tornado mean path and its orientation with respect to the tornado's translation direction on tornado-induced wind loads are investigated. A low-rise gable roof building with a roof angle of 35 degrees and a square plan area is chosen for this study. Laboratory simulated tornadoes with two swirl ratios with different ground-surface pressure characteristics, and three translation speeds were used. The 1:200-scaled building model that was used for this study was located on both sides of the simulated tornado's mean path at several locations up to the distance of several tornado-core radii. At locations where maximum loadings occurred, orientation of the building was changed to explore its effect on peak loads. Results show significantly larger peak load coefficients for the tornado with lower swirl ratio which were comparable to its peak ground surface pressure drop. Peak roof uplift on the building located at the tornado's mean path is smaller by 6–19% for the lower-swirl tornado case and up to 16% for the higher-swirl tornado case, compared to the other locations, for the three translation speeds investigated. For simulated tornado with lower swirl ratio, measurements showed that peak roof uplift increases with increase in translation speed when building is located on tornado mean path, whereas peak roof uplift decreases with increase in translation speed at locations other than tornado mean path. For tornado with higher swirl ratio, increase in translation speed does not change the maximum peak uplift load. Building experiences maximum horizontal and uplift loads at building orientation angle of $-45^{\circ}$ and $0^{\circ}$ for lower swirl tornado case and $-45^{\circ}$ and $-30^{\circ}$ for higher swirl tornado case, respectively, with respect to the translation direction of the tornado.

## 1. Introduction

Significant parameters such as swirl ratio, tornado translation speed, building orientation, building distance to the tornado mean path and many others that govern tornado-induced wind loads on low-rise buildings need further investigation to find the worst-case loading for the purpose of their design. This type of investigation is important to fully understand the cause of the immense property loss in tornadoes, particularly the recently occurring catastrophic ones at Joplin, MO in 2011, Tuscaloosa, AL in 2011 and Moore, OK in 2013 (http://www.spc.noaa.gov/faq/tornado/damage$.htm), with the goal of developing wind load design provisions that will help to prevent such losses in the future. Significant parameters that influence tornado-induced wind loads are either related to flow field characteristics of tornadoes, including but not limited to swirl ratio [1,2], translation speed [2–6], ground roughness [2,4,7–9] and topography [10–12] or building's geometry [13], relative distance of the building to tornado mean path [14–17] and building orientation [16,18–20]. Jischke and Light [14] studied tornado induced loading on a rectangular building in a Ward-type-simulator where they found the peak tornado loads to be more severe than those caused by the tornado winds only. According to their study, tornado wind load analysis from straight-line atmospheric boundary layer (ABL) wind tunnel tests with the same wind speeds is unreliable. They found that building orientation and its location with respect to the center of tornado are important factors in tornado loading. Mishra et al. [15] examined pressure distribution of a stationary tornado on a cubic building and found that pressure distribution on building walls and roof in tornado events is different from the pressure distribution resulted from straight-line ABL winds. This difference is not only magnitude-wise but also in number and location of walls with positive or negative pressures. Building's distance from the center of the tornado was found to be an important factor in external pressure distribution and resultant load. They also found that permeability of the building, which influences the internal pressure, is an

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important factor in producing net loads. Sengupta et al. [19] found peak loads and peak moments of translating tornado to exceed that of straight-line winds with the same wind speed, by a factor of 1.5 or more. Hu et al. [16] investigated the effects of the distance of the building to the tornado center as well as building orientation of the same building as considered in this study. In their study, a stationary tornado with constant swirl ratio was considered. Sharp ground-surface pressure drop around the center of the simulated tornado was observed. They found peak tornado loads of at least 3 times that of straight-line ABL winds considering all building orientations. Cao et al. [21] studied effects of tornado loading for a stationary tornado on a cooling tower and observed that peak pressure and peak load occur at the tornado center and core radius-location where maximum tangential velocity occurs, respectively. Among all the investigations on tornado wind loads, only few have considered loading effects of translating tornadoes [13,19,20,22], where the building model is located on the tornado mean path or at a fixed location with a constant distance to the tornado mean path. These past studies have motivated the current study on the effect of building distance to the tornado mean path on tornado loads. Due to asymmetry in flow field of translating tornadoes, the effect of distance to the tornado mean path on tornado loading should be examined on both sides of the tornado mean path. After finding the locations where maximum loads occur, effect of another important parameter which is the orientation of the building on peak loads should be studied. Orientation effect was previously examined at specific locations only [14,16,19,20]. It does not guarantee finding the worst tornado loading case. In this study, the worst orientation angle of the building was found after finding the distance of the building to tornado mean path that gave the worst-case load components. Since tornado direction is generally from southwest to northeast with some variation while building's geographical orientation is fixed, results from this section can be used to decide the worst loading case for design. Another effect to be studied is the effect of swirl ratio on peak tornado loads. All previous studies have only considered one swirl ratio [14–16] except the study by Sengupta et al. [19] and Haan et al. [20]. In their study, tornado-induced wind loads as a function of swirl ratio was examined only when the building is located on tornado mean path.

In the current study, the worst-case loading scenario on a non-porous low-rise building is explored as influenced by translation speed and swirl ratio of a tornado, relative distance of the building to the tornado's mean path and orientation of the building with respect to the tornado's translation direction, simultaneously considering all these factors. As in this study, identifying the magnitudes of the peak tornado loads will help in designing tornado-resistant buildings but more importantly identifying the parameters that influence the peak tornado loads will help in formulating similar studies in the future.

In Section 2, experimental setup along with the procedure to find worst loading scenario is explained. Section 3 includes results and Section 4 includes concluding remarks.

## 2. Methodology

### 2.1. Tornado simulation

First step towards understanding of tornado loading is to simulate a tornado, and this was done in a laboratory by adjusting the control parameters of the ISU Tornado Simulator (Fig. 1). In this simulator, a 1.83 m-diameter fan at its center sucks air upwards that simulates an updraft which passes through a series of screens and a honeycomb that tries to eliminate effects of the fan on the upstream flow, before turning into a horizontal duct comprised of two spaced circular plates, then flowing radially outward at the top of the simulator. The flow gains angular momentum after passing through a series of equally-spaced vanes (hinged flat plates) placed along the outer periphery of the circular plates at a fixed angle. The rotating flow is then guided downward through a vertical duct at the outer section of the simulator, where it

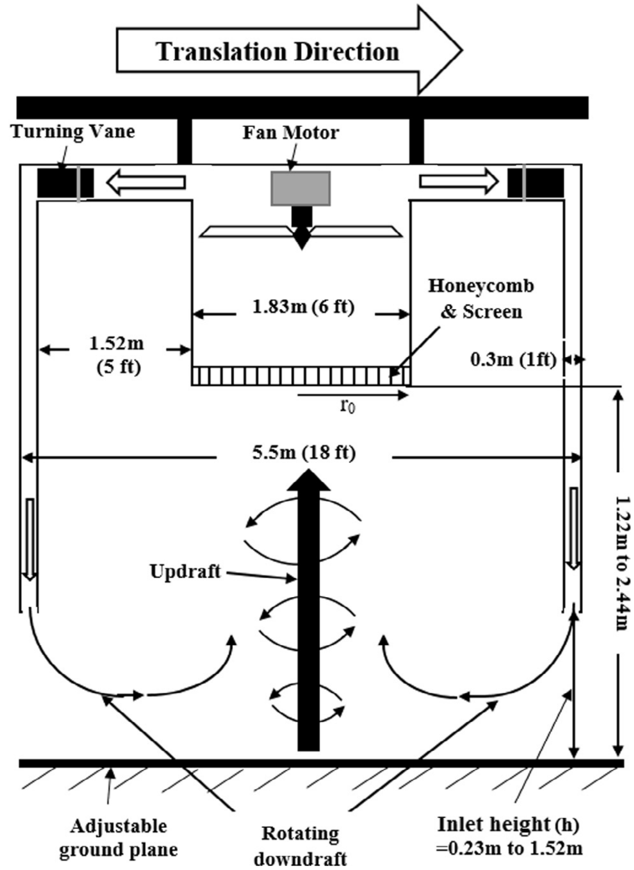


**Fig. 1.** Schematic illustration of ISU Tornado Simulator [10].

resembles the downdraft occurring in tornadoes. The downdraft flows onto the ground plane and inward toward the tornado center before it reaches the updraft region to complete the circuit. To simulate translating tornadoes, simulator is suspended above the ground plane by a 5-ton crane and can be moved on a straight line with a maximum speed of 0.61 m/s [23]. In this study, two vane angles were selected to control the swirl ratio and provide simulation of two tornadoes with different ground-surface pressure characteristics [2,24]. The first type of ground-surface pressure distribution includes a point minima with sharp slopes of pressure reduction on both sides of the minimum pressure region near the tornado center, as in the Manchester tornado of 2003 [16] and the Webb, Iowa tornado of 2004 [24]. In the second type of surface pressure distribution, there is a region of almost constant minimum pressure around the center of the tornado, as in the surface pressure distributions of the Mullinville, Kansas tornado of 2002 and the Tipton, Kansas tornado of 2008 [24]. Table 1 shows the ISU Tornado Simulator control parameters and resultant non-dimensional parameters for *stationary* tornadoes, calculated using Eqs. 14, as in this study. These parameters are:

**Table 1**
Control parameters of ISU Tornado Simulator.

| Controlling parameter | Case 1 | Case 2 |
|---|---|---|
| Vane angle | 15 degrees | 55 degrees |
| Fan power | 33% | 33% |
| Flow rate (Q) | 14.62 $m^3/s$ | 12.03 $m^3/s$ |
| Inflow height (h) | 0.76 m (30 in.) | 0.76 m (30 in.) |
| $S_c$ | 0.05 | 0.22 |
| $S_{vane}$ | 0.16 | 0.85 |
| $Re_r$ | $2.04 \times 10^5$ | $1.68 \times 10^5$ |
| a | 0.84 | 0.84 |