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## Visualization of flow structures around a gable-roofed building model in tornado-like winds

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### 1 Introduction

Tornadoes are violently rotating columns of air extending from thunder storms to the ground. While extensive studies have been conducted to assess wind loads and flow structures around building models in strong winds, most of the previous investigations were conducted with straight-line winds. Bienkiewicz and Dudhia (1993) found that the wind loads acting on building models in tornado-like winds would be significantly higher (3–5 times) compared to those in straight-line winds with the same wind speed. This suggests that it is incorrect, or at least incomplete, to use a conventional straight-line wind tunnel running at maximum tornado wind speed to investigate wake flow features as well as the resultant wind loads acting on buildings in tornado-like winds. While several studies on building models in tornado-like winds have been conducted recently by measuring wind loads and/or surface pressure distributions (Sengupta et al. 2008; Mishra et al. 2008a, b), very little in the literature can be found to provide detailed flow field measurements to elucidate the flow–structure interactions of building models with tornado-like winds. In this communication, we report an experimental study to quantify the characteristics of the wake vortex and turbulent flow structures around a gable-roofed building model in tornado-like winds using a high-resolution particle image velocimetry (PIV) system. The objective of the present study is to elucidate underlying physics for a more accurate prediction of damage potentials of tornado-like winds to buildings.

### 2 Experimental setup

The experimental study was conducted using a large-scale tornado simulator located at Iowa State University (ISU). As shown in Fig. 1, the ISU tornado simulator can generate a tornado-like vortex with a maximum diameter of 1.2 m, maximum tangential velocity of 14.5 m/s, and maximum swirl ratio of 1.2. The vortex height can vary from 1.2 to 2.4 m by adjusting the ground plane upward or downward. Further information about the design, construction and performance of the ISU tornado simulator as well as the quantitative comparisons of the tornado-like vortex generated using the ISU tornado simulator with the tornados found in nature is available at Haan et al. (2008). In the present study, the gable-roofed building model has a base of 90 mm × 90 mm in cross section, an eave height of 30 mm and gable-roof angle of 35°. The radius of the tornado-like vortex core,  $R_O$ , measured at the 30 mm above the ground plate (i.e., the horizontal plane passing the eave of the gable-roof building model) was found to be about 0.16 m (i.e.,  $R_O \approx 0.16$  m), at where the maximum tangential speed ( $V_O \approx 10.0$  m/s) was observed. The corresponding (radial) Reynolds number of the tornado-like vortex is about 100,000. The swirl ratio of the tornado-like vortex, which was calculated according to the expression of  $S = \pi V_O R_O^2 / Q$  with  $Q$  being the

flow rate through the fan, was about 0.1 (Haan et al. 2008). The aspect ratio, which is defined as the ratio between the height and the radius of the tornado-like vortex, was about 4.0. In addition to measuring the wind loads (both forces and moments) acting on the test model using a high-sensitivity load cell, a digital PIV system was used in the present study to conduct detailed flow field measurements to quantify the unsteady vortex and turbulent flow structures around the gable-roofed building model in tornado-like winds. Further information about the experimental setup, digital PIV system and image processing procedures, temporal and spatial resolution of the PIV measurements and the estimation of the measurement uncertainty is available in Yang (2009).

### 3 Results and discussions

According to Haan et al. (2008), with the parameter setting described above, the vortex generated by ISU tornado simulator would be a single cell typed tornado-like vortex, which is confirmed quantitatively from the PIV measurements shown in Fig. 2. The tornado-like vortex in each horizontal plane was found to have a well-defined flow pattern, which can be divided into two regions: an inner core region with air streams rotating concentrically and radial velocity components being almost zero; and an outer region with air streams having significant radial velocity components to generate a strong spiral motion to suck surrounding air flowing towards the center core of the tornado-like vortex. A strong upward flow in the outer region and downdraft jet flow in the vortex core region can also be seen clearly in the vertical plane, which makes the tornado-like vortex a very complex, turbulent three-dimensional vortex flow.

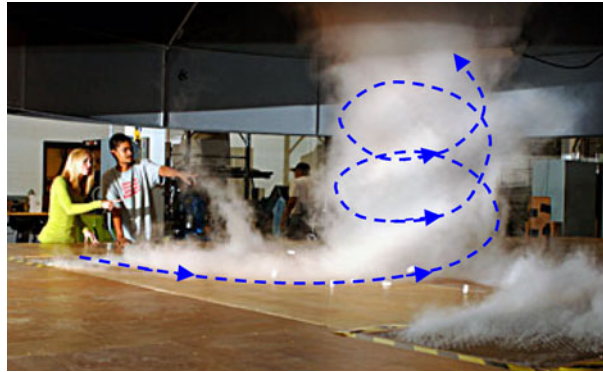


Fig. 1 A photo of the ISU tornado

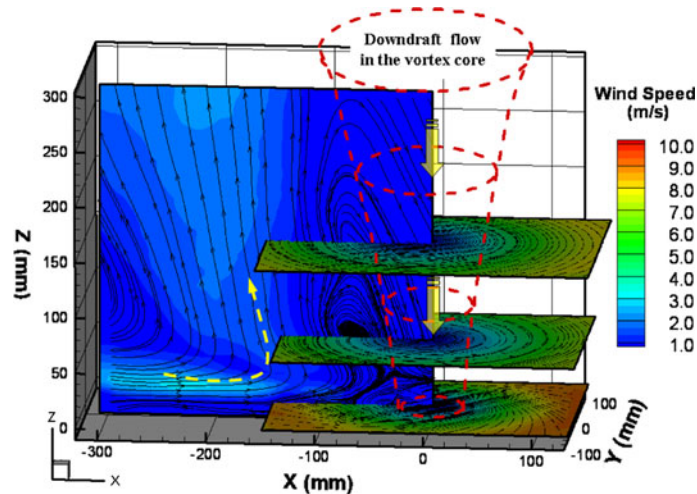


Fig. 2 A tornado-like vortex structure

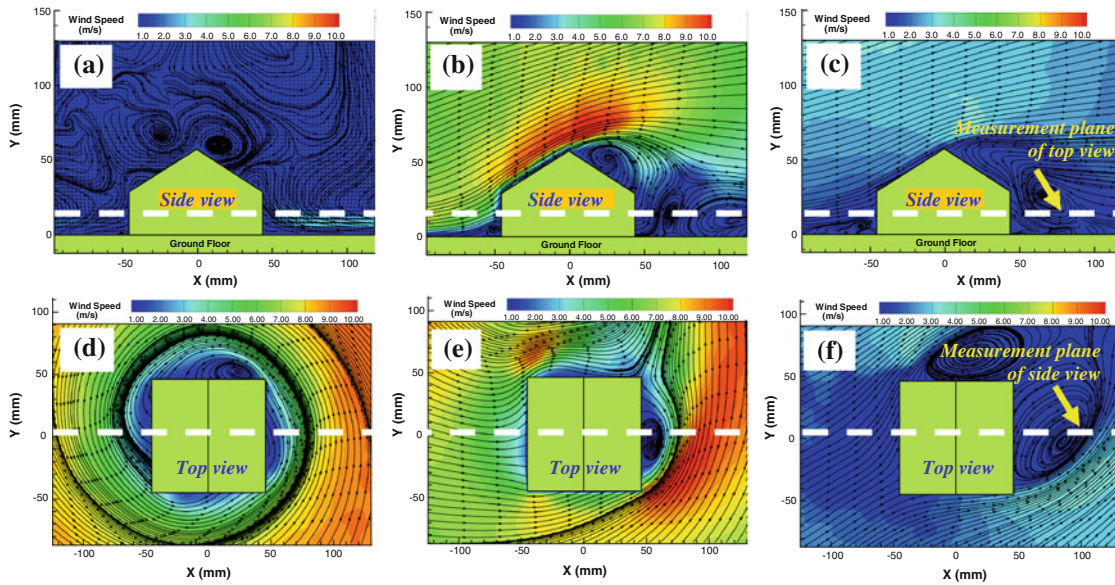


Fig. 3 Flow structures around the gable-roofed building model in tornado-like winds. a–c for side views, d–f for top views

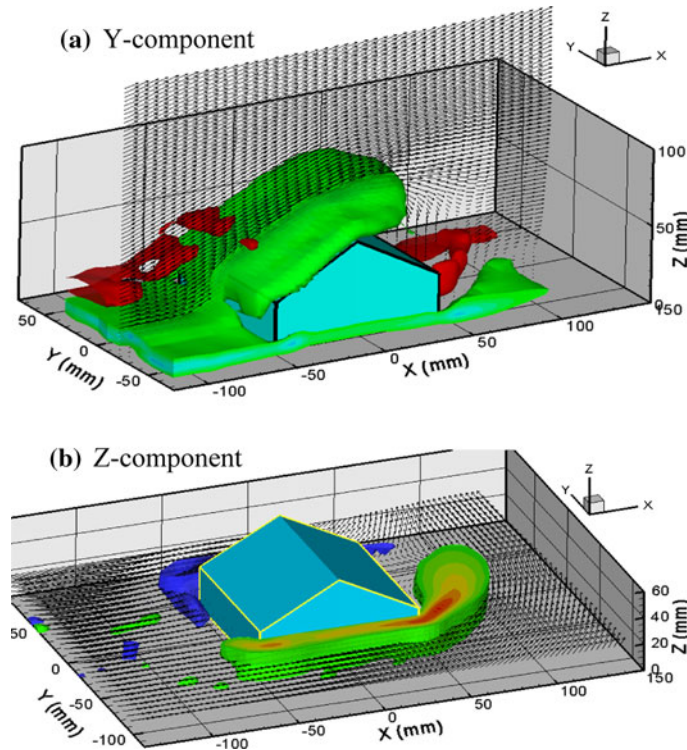


Fig. 4 Iso surfaces of the vorticity field

Figure 3 shows both the side view and top view of the flow structures around the gable-roofed building model as the test model located at the vortex core (Figs. 3a, d), the boundary between the inner core and outer regions of the vortex, i.e. where local wind speed reaches maximum (Fig. 3b, e), and outer region (Fig. 3c, f) far away from the center core of the tornado-like vortex. Compared with those in straight-line winds (Sousa and Pereira 2004), the wake vortices and flow structures around the gable-roofed building model were found to become more involved in tornado-like winds. Due to the strong swirling motion of the tornado-like vortex, the wake vortex structures were found to become highly turbulent and unsymmetrical

inclining towards the vortex center. The corresponding wind load measurements (results not shown at here) also confirmed that the tornado-induced wind loads would be about three times higher compared to those in straight-line winds (Yang, 2009). Based on the PIV measurements at different horizontal and vertical planes, 3-D flow structures around the test model were reconstructed. Figure 4 shows the perspective view of the reconstructed 3-D wake vortex structures around the gable-roofed building model in the term of iso-surfaces of local vorticity as the test model was located at the boundary between the inner core and outer regions of the tornado-like vortex (i.e.,  $R/R_0 \approx 1.0$ ). The 3-D features of the complex vortex structures around the gable-roofed building model in tornado-like winds were visualized clearly from the reconstructed flow field.

In summary, a digital PIV system was used to conduct detailed flow field measurements to quantify the wake vortex and turbulent flow structures around the gable-roofed building model in tornado-like winds. The PIV measurements clearly revealed that the wake flow structures around the test model in tornado-like winds were significantly different from those in conventional straight-line winds. The findings derived from the present study can be used to gain further insight into the flow–structure interactions for a more accurate prediction of damage potentials of tornado-like winds to buildings.

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