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NON-STATIONARY TORNADO-INDUCED WIND LOADS COMPARED WITH TRADITIONAL BOUNDARY LAYER WIND LOADS ON LOW-RISE BUILDINGS

Fred L. Haan, Jr.*, Partha P. Sarkar*, Vasanth K. Balaramudu* and Wei Zhang*

*Department of Aerospace Engineering
Iowa State University, Ames, Iowa, 50111, U.S.A.
e-mail: haan@iastate.edu, ppsarkar@iastate.edu, vasanth@iastate.edu, weizhang@iastate.edu

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1 INTRODUCTION

The effects of wind loading on buildings due to straight line boundary layer type winds have been studied extensively in the past. Building code provisions are based primarily on studies of this sort. Comparatively little research has been done, however, to study how buildings and other structures are affected by transient, non-stationary, three-dimensional flow phenomena such as gust fronts, microbursts and tornadoes. This paper summarizes data resulting from an investigation of the effects of tornado-induced wind loading on low-rise buildings. Extensive testing was performed on a host of scaled, low-rise building models (1:100) to compare the loading patterns resulting from the tornado-like vortex of a large laboratory tornado simulator to the turbulent incident flow of an atmospheric boundary layer wind tunnel and to ASCE 7-05 provisions.

2 EXPERIMENTAL APPROACH

The boundary layer wind tunnel and tornado simulator at Iowa State University were used for these experiments. The boundary layer wind tunnel has a test section with dimensions 2.44 m by 2.21 m and a maximum speed of 53m/s. The tornado simulator consists of a circular duct 5.49 m in diameter and 3.35 m high is suspended from a 4500 kg overhead crane so that it can translate along a 10.36m long ground plane. A 1.83m diameter fan is mounted in the center of this duct to act as an updraft. The maximum translation speed of the crane is 0.61 m/s. More details on the design and validation of this system can be found in Ref. [1]. By adjusting the amount of inflow rotation, a range of vortex diameters and vortex flow patterns were generated (with swirl ratios ranging from 0.08 to 1.14, see Ref. [1]). Using an 18-hole pressure probe, the tornado flow fields were measured and found to agree well with Doppler radar data from the Spencer, South Dakota tornado of 1998 and the Mulhall, Oklahoma tornado of 1999 (from Ref. [2]). Contours of the largest swirl ratio vortex are shown in Fig. 1(a) while comparisons between laboratory and radar tangential profiles are shown in Fig. 1(b).

A single-story, gable roof building model (nominally 1:100 scale with a 91mm by 91mm plan, an eave height of 36mm, gable roof angle of 35° and maximum height of 66 mm) was subjected to the facility's full range of tornado sizes, types and translation speeds. Additional tests were performed on similarly-scaled buildings to observe effects of building height and roof geometry. The roofs that were tested included: a flat roof, a hip roof with 15° degree angle and gable roofs with 13° and 26° angles. Pressure and force measurements were conducted using a Scanivalve electronic pressure scanner and a 6-component load cell, respectively. All tornado tests were repeated 10 times to reduce statistical uncertainty.

3 DISCUSSION OF RESULTS

Fig. 2(a) shows the building model orientation for the tornado experiments (the vortex translates in the +*x*-direction). Figure 2(b) plots instantaneous force coefficients to summarize the character of the tornado-induced loading as the tornado translates past. The C_{F_x} signal shows that as the tornado traverses the model, the model is pulled first in the negative direction and then in the positive direction. The C_{F_y} signal follows the pattern of the tangential velocity component of the vortex. The tangential velocity of the vortex exerts a positive *y*-direction force as the vortex core first encounters the model and a negative force as the opposite side of the core passes the model. The peaks for C_{F_x} and C_{F_y} occur very close to x/D ~ 0.5 (is the radius of the vortex). The character of C_{F_z} is primarily due to the suction caused by the vortex core. This can be inferred from the fact that maximum C_{F_z} occurs at $x/D = 0$.

Peak side force coefficient values from plots such as those in Fig. 2(b) were then obtained from tests of all the tornado and building combinations and plotted in Fig. (3). Peak magnitudes were found to decrease with vortex translation speed, and larger building incidence angles resulted in larger magnitudes. Compared to ASCE 7-05, the tornado-induced coefficients were observed to be as much as twice as high for some cases. Similar plots were constructed for the other force coefficients as well but are not shown here for the sake of brevity.

A host of different building model types was also tested to identify the effects of building roof and building height (see Fig. (4)). Peak magnitudes did not depend significantly on roof geometry but did increase for taller buildings (2-story models experienced higher peaks).

Boundary layer wind tunnel tests were conducted for a range of building orientations. Table 1 compares the peak uplift coefficients for tornado simulator tests, straight-line boundary layer tests and ASCE 7-05 provisions. Tornado-induced wind loads were observed with peak magnitudes 1.5 to 3.7 times larger than building code provisions. More complete comparisons will be included in the full paper.

	Tornado	Straight-Line	ASCE 7-05
$C_{\hat{F}_z}$	1.12	0.3-0.8	0.3

Table 1 Peak uplift coefficients, $C_{\hat{F}_z}$, from tornado, straight-line wind and ASCE 7-05 provisions.

4 CONCLUSIONS

Peak coefficients of tornado-induced side loading and uplift on low-rise buildings was found to be between 1.5 and 4 times greater than coefficients derived from straight-line boundary layer flows or from ASCE 7-05 provisions. More specific detailed comparisons between tornado-induced loading characteristics and those of straight-line boundary layer wind will be included in the full paper.

ACKNOWLEDGEMENTS

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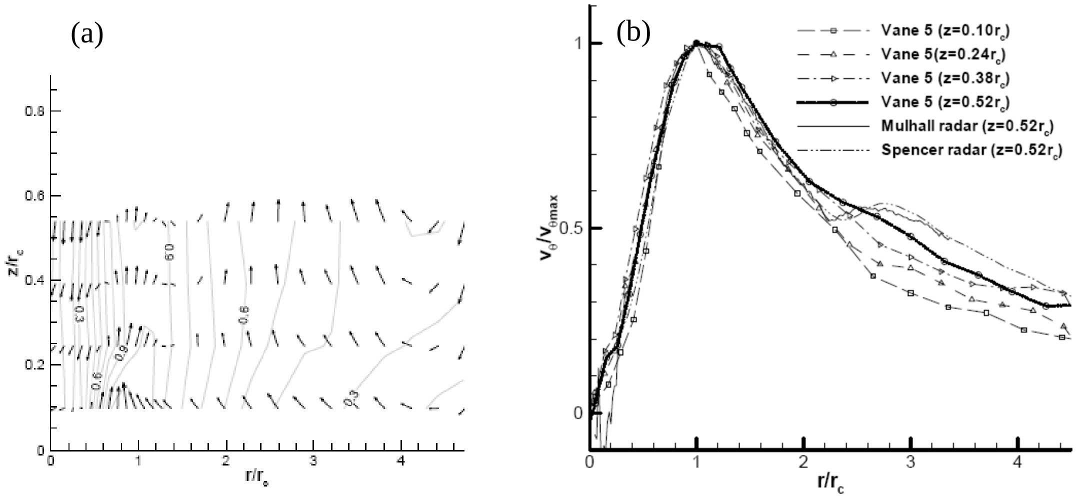

Figure 1(a) Contour and vector plots to show laboratory simulator tornado corner flow structure for a swirl ratio of 1.14. The contour labels denote tangential velocity (normalized with $V\theta_{max}$) while the vectors show radial and vertical velocity. The large swirl ratio case exhibits the structure of a drowned vortex jump well on its way to a two-celled structure. (b) Scaled tangential velocity profiles for the same laboratory tornado case at different elevations along with radar data from Mulhall and Spencer tornadoes (Wurman, 2004).

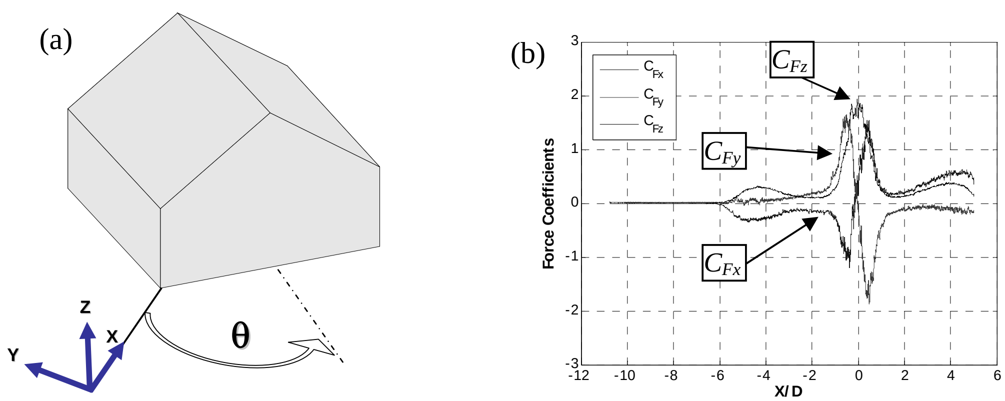

Figure 2 (a) Building orientation with respect to the vortex translation direction. The vortex translates along the *x*-axis in the positive direction. (b) Example time histories of force coefficients showing relative magnitudes for *x*, *y* and *z* components. *X/D* is the position of the tornado relative to the center of the building (where *D* is the diameter of the tornado vortex).

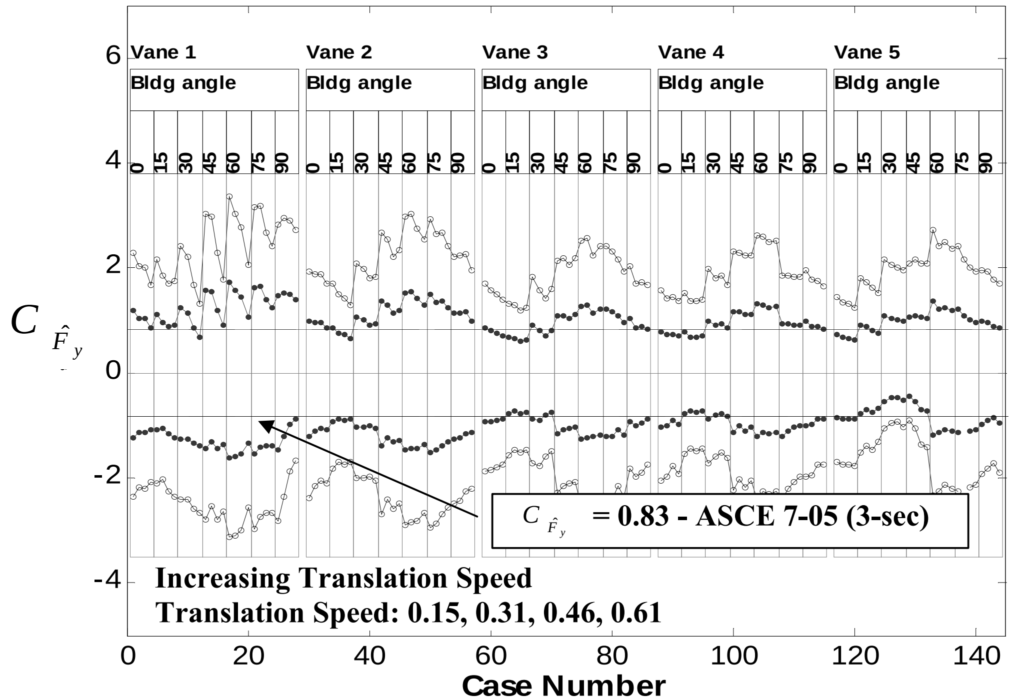

Figure 3 Maximum and minimum peak side force coefficients for gable roof building compared with ASCE 7-05 provisions. Open symbols represent model-scale coefficients; filled symbols represent full-scale coefficients. Vane1 through Vane5 represent tornado vortices ranging in diameter from 0.23m to 0.53m. Each building orientation was tested for 4 different tornado translation speeds.

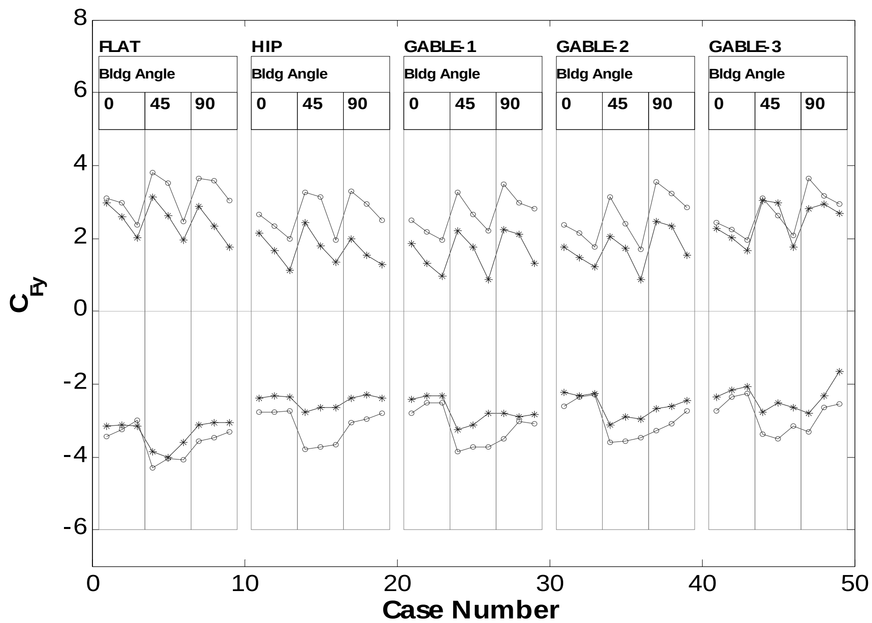

Figure 4 Maximum and minimum peak side force coefficients for different building roof configurations and building heights. "*" denotes 1-story building models and "o" denotes 2-story building models.