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Local effects induced by tornadic flows on a low-rise structure for different building orientations

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SUMMARY:
The transient aerodynamics of a pressure model of a low-rise structure subjected to the action of a travelling tornado is investigated by mean of an extensive wind tunnel test campaign conducted at the WindEEE Dome. In particular, different orientations between the translating tornado and the structure are tested, aiming at unveiling the presence of local effects. Specific conditions, based on the similitude between measurements from single-point wind angle of attack, are studied. The data are analyzed through ensemble-averaging procedures based on the tornado location. The outcomes point out the presence of fundamental differences in a localized portion of the roof, as reflected by the different values of the mean and fluctuating pressure coefficients, as well as of higher order statistical moments. The combination between experimental data and the analytical fitting of wind measurements indicates that the differences are due to a different local wind field and flow curvature. Such induced local effects may well be of interest for the design of cladding elements of low-rise structures to withstand tornadic flows.

Keywords: Tornado-induced aerodynamic loading, Cladding pressure, Transient aerodynamics.

1. INTRODUCTION

Tornadoes are catastrophic events which are known to be linked with significant economic losses, especially in the United States and Canada (Kopp and Wu, 2020). They differ from the synoptic case because of several properties, including (but not restricted to) genesis, spatial extent, time duration, and intensity of the generated speeds. As a matter of fact, tornado-induced wind speeds are the highest amongst the ones generated by Aeolian events (Solari, 2019). Knowledge about wind fields in tornadoes is still limited, and this is reflected on the challenging definition of the relevant aerodynamic loading induced on structure. In fact, there is a persistent lack of knowledge concerning the effects associated with the translational and rotational wind speeds relative to the tornado cell, as well as the different flow properties. To improve their knowledge, in the last decade several tornado simulators have been designed and built (such as the WindEEE Dome at the University of Western Ontario, e.g., Refan and Hangan, 2018), and the relevant lines of research produced as a general outcome that the peculiarities of tornadic flows are likely to result in significantly different design criteria than those adopted for 'straight-line' atmospheric boundary layer winds. In fact, their features may alter the building aerodynamics, if compared with the classical framework relevant to synoptic winds (e.g., Tieleman, 2003). Flow field curvature and local directionality effects may well change the nature of flow separation and reattachments, generating different vorticity fields and hence affecting the pressure distributions on the building.

This paper focuses on this aspect, deeply investigating the bluff-body aerodynamics of a low-rise structure subjected to the aerodynamic loading induced by a translating tornado. Specifically, the building is installed along two different orientations with respect the travelling tornado. Besides comparing the two configurations in terms of overall loading, two specific cases are particularly selected based on the similitude based on a local single-point wind measurement, and further scrutinized.

2. WIND TUNNEL TEST CAMPAIGN AND METHODOLOGY

The WindEEE Dome is a relatively large-scale testing facility whose plan shape is hexagonal. Its inner test has a diameter of 25 m. Six fans are installed on top of the test chamber, producing the updraft flow typical of a tornado, while the rotational component of the inlet flow is controlled by adjusting the angles of the guide vanes that are distributed along the peripheral walls of the test chamber. The simulated tornadoes object of this research have a nominal swirl ratio,

$$S = \frac{r_0 \Gamma_{max}}{2Qh} = 0.76, \qquad (1)$$

being r_0 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.

Figs. 1a and 1b display the tested configurations. They both show that the origin of the Cartesian coordinate system (x,y) is located at the center of a circular ground plate. The z-axis is vertical and coincides with the nominal axis of vortex rotation. In both cases, the tornado travels along the y-axis. Its nominal core location is represented by the position $\mathbf{x}_{TC}$. This translates across the center for a distance close to 4 m at a speed of 57 mm/s by the movement of the bell-mouth, whose instantaneous locations were recorded through a laser transducer mounted on the roof of the test chamber. The ambient ground pressure is measured through a total of 173 pressure taps radial-symmetrically distributed on a plywood circular plate whose radius is 1118 mm.

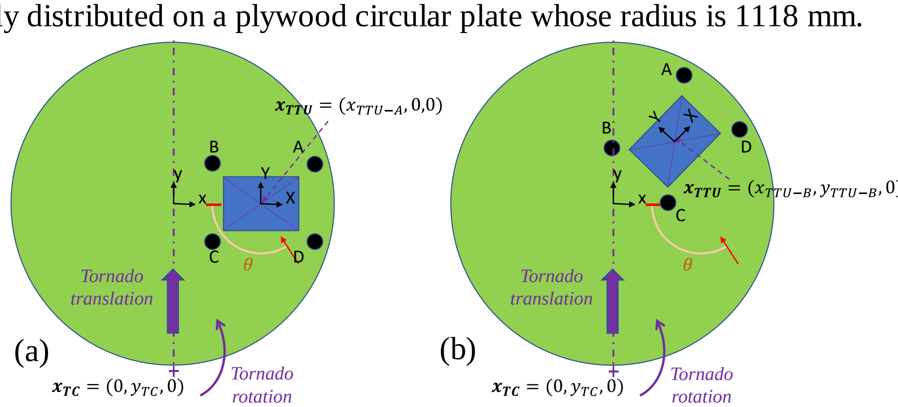


Figure 1. Configurations tested at the WindEEE dome: (a) Case A; (b) Case B.

The wind tunnel model is a 1:50 scale model of the Texas Tech University Wind Engineering Research Field Laboratory (TTU WERFL) building, a classic benchmark for low-rise structures.

It has plan dimensions of 183 mm (along the Y-axis) and 275 mm (along the X-axis), while its eave height is 78 mm and the ridge height (H) is 80 mm. Therefore, the core diameter is about 3 times the largest plan dimension of the building model. Its vertical axis Z coincides with z. It is equipped with 204 pressure taps that are nearly uniformly distributed on the building model. The model is tested in two different positions with respect the travelling tornado. For Case 1 (Fig. 1a), the center of the building model, $\mathbf{x}_{TTU}$ = (320, 0) mm, and the long sides of the building are parallel to the x-axis. On the other hand, the plywood plate and the model are oriented 45 degrees with respect the tornado translation for Case B. The wind field induced by the tornadoes is captured by four cobra probes (A, B, C, D, Figs. 1a and 1b), which are installed in proximity of each building corner (being themselves named A, B, C and D according to the cobra in their proximity) at a height of 98 mm ($1.23H$) above the ground. To overcome the issues associated with the travelling nature of the tornado and the limited range of wind direction ($\pm 40^\circ$) that may be captured by a fixed set of cobra probe orientations, different alignments of the cobra probes have been tested as well. These (evaluated with respect the X-axis of the model) are reported in Table 1, which also indicates the number of repeats that have been conducted.

Table 1. Cobra probe orientation (with respect the X-axis of the model) and number of repeats

Case 1	A	B	C	D	Repeats
I	-30°	-130°	-130°	-30°	30
II	-50°	-130°	-130°	-50°	30
III	-70°	-130°	-130°	-70°	30
Case 2	A	B	C	D	Repeats
I	-65°	-195°	-180°	-95°	30
II	-95°	-180°	-180°	-95°	30
III	-65°	-195°	Not present	Not present	30

Velocity and pressure measurements were synchronized, and their sampling frequency was set at 500 Hz. For pressure acquisition there is no need to distinguish the tests based on the cobra probe orientation, hence the relevant number of nominally identical test runs is 90 for each case. The data (velocity and pressure) are ensemble-averaged based on the tornado location. This is represented by the bell-mouth position y_{TC} which is continuously monitored. The gathered data from the cobra probes allow the definition of the variation of the azimuth angle, of the elevation angle and of the velocity vector with the position of the bell-mouth. The measured generic pressure p at the ground is then referenced to p_{bm}, the static pressure measured at the bell-mouth, which is not affected by the movement of the tornado itself, and therefore represents a suitable reference pressure. These measurements are consequently used to be fitted with the theoretical formulation proposed by Baker and Sterling (2018), allowing the definition of the pressure and force fields that are linked with the aerodynamics induced by the tornadic flow on the structure.

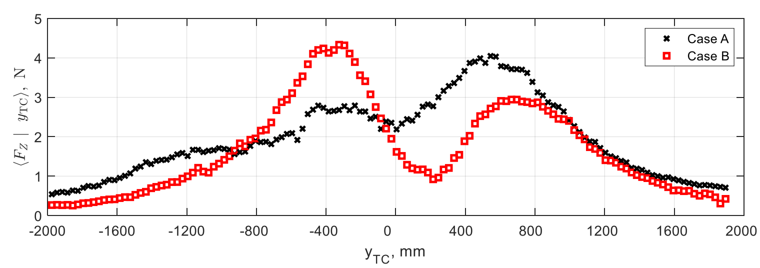
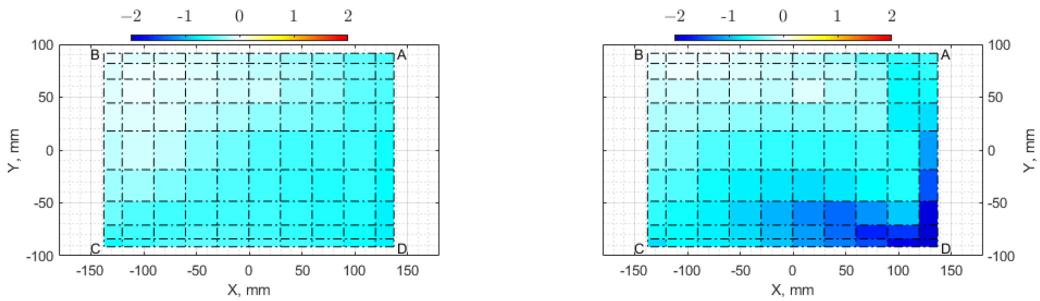


Figure 2. Ensemble mean uplift measured for the two cases.

Great attention is paid to study the effects occurring on the roof of the structure. Fig. 2 shows the comparison between the mean uplift force F_Z (positive if upwards) that is estimated for the two cases. The abscissa reports the position of the bell-mouth along the y-axis (see Figs. 1a and 1b).

3. PRELIMINARY RESULTS AND CONCLUSIONS

Aiming to compare local effects played by tornadic flows on the aerodynamics of the roof, it is possible to find analogies between the two cases according to single-point measurements from one of the cobra probes. In doing so, the situations associated with an angle of attack estimated from Cobra D equal to 90° are selected and deepened. These correspond to y_{TC} = 35.2 mm for Case A and y_{TC} = -215.1 mm for Case B (i.e., the relative position between tornado and structure is different). The mean aerodynamic pressure fields of the roof in these two conditions are converted into mean aerodynamic coefficients by dividing them with the relevant ensemble mean of the dynamic pressure. Fig. 3a reports the roof map for Case A, while Fig. 3b focuses on Case B.



(a) (b)

Figure 3. Map of the ensemble mean of the pressure coefficients in the roof: (a) Case A; (b) Case B.

The comparison between the graphs lets transpire the presence of local effects associated with the different relative position between building and tornado, particularly in correspondence of the edge D. This is confirmed also by further statistical analyses (e.g., fluctuating pressure coefficient, skewness and kurtosis) on the geometry. Despite the same incidence measured by cobra D, the different local wind fields and flow curvature in the two conditions induce local effects that generate different vorticity fields and therefore a different aerodynamic loading on specific regions of the roof. Further considerations will be made by comparing the results with ABL wind tunnel measurement, which will aid in understanding the fundamental differences found in the two cases, as well as in exploring the limits of the strip and quasi-steady theory (e.g., Kawai, 1983).

REFERENCES

Baker, C.J. and Sterling, M., 2018. A conceptual model for wind and debris impact loading of structures due to tornadoes. Journal of Wind Engineering and Industrial Aerodynamics 175, 283–291.

Kawai, H., 1983. Pressure fluctuations on square prisms – Applicability of strip and quasi-steady theories. Journal of Wind Engineering and Industrial Aerodynamics 13: 197-208.

Kopp, G. A. and Wu, C.H., 2020. A framework to compare wind loads on low-rise buildings in tornadoes and atmospheric boundary layers, Journal of Wind Engineering and Industrial Aerodynamics 204, 104269.

Refan, M. and Hangan, H., 2018. Near surface experimental exploration of tornado vortices. Journal of Wind Engineering and Industrial Aerodynamics 175, 120-135.

Solari, G., 2019. Wind Science and Engineering, Springer Nature Switzerland.

Tieleman, H.W., 2003. Wind tunnel simulation of wind loading on low-rise structures: a review. Journal of Wind Engineering and Industrial Aerodynamics 91, 1627–1649.