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Can pressure coefficients obtained from ABL wind tunnel be used for tornadoes?

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SUMMARY:
In this study we attempt to answer the question whether pressure coefficients derived from atmospheric boundary layer wind tunnel tests can be used to evaluate loads induced by tornadoes. Furthermore, if this is the case, under what conditions and if not, how pressure patterns differ. This investigation was performed by analysing the correlation between pressure coefficients obtained from physical simulations in an ABL wind tunnel and the ones obtained from the interaction of tornado like vortices and the same scaled model. The experiments were performed at the WindEEE Dome at the University of Western Ontario. It was found that when the distance from the core to the building is higher than half the radius of maximum wind, pressure coefficient obtained from atmospheric wind tunnel test can be used for tornado. If the distance is lower the pressure patterns are different. The next stage of this research involves the analysis of the relationship between pressure coefficients when the distance is lower than half radius of maximum wind.

Keywords: Tornado-induced loads, pressure coefficients, physical simulation

1. INTRODUCTION

Although tornadoes are a devastating phenomenon which causes extensive damage and loss in many parts of the world, particularly in the central part of North America, they have been explicitly excluded from building codes until the recent addition of a full chapter dedicated to tornado-induced loads calculation in ASCE/SEI 7-22. This addition comes as a response to the fact that "recent research on tornado climatology has shown that tornadoes occur with much greater frequency and intensity than had previously been quantified" (ASCE, 2022). The loads calculation involves the use of pressure coefficients obtained from atmospheric boundary layer (ABL) wind tunnel modified by an "external pressure coefficient adjustment factor for vertical winds", which is obtained from ABL tests changing the vertical angle of attack.

The development of tornado risk assessment models is critical to both generate accurate estimates of damage and loss statistics and to evaluate the suitability of damage mitigation measures. Generally speaking, there are two kinds of models in terms of how they link the wind speed to damage or loss: (1) models that use an empirical vulnerability curve (e.g. Romanic et al., 2016) and (2) engineering based models that use fragility curves for components to build a vulnerability curve (e.g Peng et al., 2016). The first kind of models are suitable to evaluate loss. On the other hand, models like Peng et al., 2016 are more appropriate to evaluate damage and mitigation measures. Implicit in engineering based models is the assumption that pressure coefficients from ABL can be used for tornadoes.

Tornado hazard maps (Hong et al., 2021; Twisdale et al., 2021), provide design wind speeds for a given return period, therefore, there is an underlying assumption that loads can be linked to a wind velocity through ABL pressure coefficients.

In all the previously mentioned applications it is assumed that the external pressure coefficients obtained from ABL wind tunnel tests (C_p^{ABL}) can be used directly or with simple modifications for tornadoes. This hypothesis has not been extensively tested, moreover, the evidence suggest this assumption is not accurate.

This research aims to answer the question of whether C_p^{ABL} can be used to evaluate tornado-induced loads and if this is possible, under what conditions. This is done by analysing the correlation between C_p^{ABL} and pressure coefficients (C_p^{TLV}) obtained from physical simulation of the interaction of tornado like vortices (TLV) and a scaled model of a community comprising eight low-rise residential buildings. Our hypothesis is that a necessary condition to be able to use C_p^{ABL} for tornado loads calculation is that for some direction, C_p^{ABL} and C_p^{TLV} must to have high correlation. Both tests (ABL and TLV) were performed at the WindEEE Dome at the University of Western Ontario.

2. EXPERIMENTAL SETUP

All physical simulations were performed at the Wind Engineering, Energy and Environment (WindEEE) Dome at Western University, Canada. WindEEE is capable of reproducing tornadoes, downbursts, gusts and currents, shear flows, and boundary layer flow at high Reynolds numbers (Hangan et al., 2017).

2.1. Model

The scaled model has eight instrumented residential low-rise buildings that are part of the community of Dunrobin, Ontario, that was hit by an EF3-rated tornado on September 21, 2018 (Fig. 1). In addition, there are 22 non-instrumented surrounding buildings. The length scale used was 1:150. 1152 pressure taps were used distributed on the surface of the buildings and the ground.

2.2. TLV simulations

The physical simulation of the interaction of several TLVs and the scaled model was performed at the WindEEE Dome using mode A, which uses only the upper plenum fans to generate the updraft and peripheral louvres to generate the background circulation. By changing the angle of the louvres, different flow configurations are achieved. 14 different configurations were tested, involving different paths, and swirl ratios. The swirl ratio controls the characteristics of the simulated TLVs. All TLV's translate at $1.0^{m}/_{s}$.

2.3. ABL simulations

As was mentioned before, the ABL simulations were also performed at the WindEE Dome in the multi-fan wind tunnel configuration, in which the 60 fan wall (15 columns x 4 rows) circulates air through the chamber. The boundary layer flow is generated by setting the rotation speed of

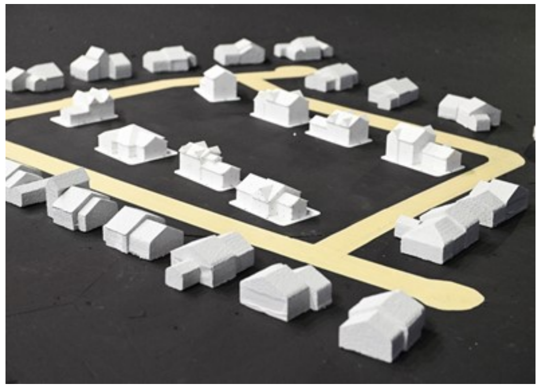


Figure 1. Scaled model of the Dunrobin community

each fan row independently. The roughness is set at 25%, no trips or spires were used. The flow parameters are: roughness length $z_0 = 8.4 \cdot 10^{-6} m$, friction velocity $u_\tau = 0.32 ^m/_s$ and longitudinal turbulence intensity at 10m full scale $I_u \approx 14\%$ which is consistent with an open terrain.

2.4. Measurements

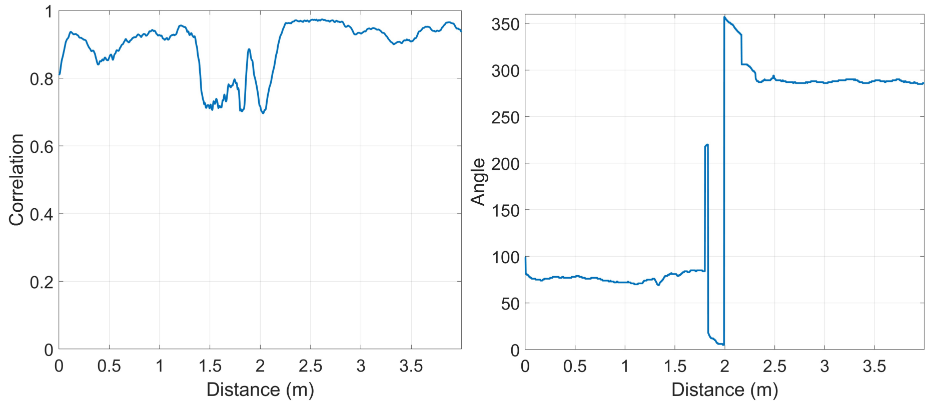
The pressure measurement system consists of miniature Electronic Pressure Scanners (EPS) coupled with Digital Temperature Compensation (DTC) Initiums. The pressure scanners used in this study are ESP-32HD manufactured by Pressure Systems, Inc. (PSI) which have 32 scanning ports each.

3. PROCEDURE

Wind velocity measurements for tornadoes in the near vicinity of the buildings is extremely troublesome since the direction is constantly changing. On top of that is the fact that an undisturbed velocity is needed to build pressure coefficients, which means the measurement probe must be far away from the building, but the three-dimensional nature of tornadic flows dictates the reference velocity must be close to the building to be useful. Both criteria are contradictory. Therefore, here, we decided not to measure a reference velocity for individual buildings and try to find a virtual direction by finding the direction where the correlation of C_p^{ABL} and C_p^{TLV} is maximum. If the correlation is high we can be confident this direction is close to the actual approaching wind direction. If not, nothing can be said. If the correlation is high, the C_p^{TLV} can be inferred from the C_p^{ABL} given a proportionality constant (wind speed) and an offset (reference pressure).

4. RESULTS

Fig. 2 (a) shows the evolution of the maximum correlation between C_p^{ABL} and C_p^{TLV} at House 1 and (b) the direction of the virtual wind speed as a function of the distance of the vortex center to some arbitrary start point. As can be observed, the correlation is very high for most of the trajectory (>0.9) except in the zone where the tornado is close to the house, where the correlation drops to 0.7. This decline in correlation is observed when the core center of the TLV and the model building are within half the radius of maximum wind. The direction changes drastically when the vortex goes over the building.



(a) (b)

Figure 2. (a) Evolution of the correlation as a function of distance. (b) Evolution of the virtual direction.

5. CONCLUSIONS AND FURTHER WORK

This results suggest that when a tornado is further than half the radius of maximum wind, the pressure coefficients obtained from ABL wind tunnel may be used to evaluate tornado-induced loads. On the other hand if the distance is lower than half the radius of maximum wind those pressure coefficients shouldn't be used.

The future work involves analysing the relationship, if any, between C_p^{ABL} and C_p^{TLV} when the core is near the building. Finding such relationship is of great importance to accurately evaluate tornado-induced loads. In addition, we need to analyse the fluctuating part of the pressure.

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