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ON THE APPLICATION OF GENERIC NUMERICAL TORNADO MODEL TO EVALUATE TORNADIC WIND LOADS ON STRUCTURES

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Abstract: Realizing the importance of understanding the nature of tornadic loading on structures, several experimental and numerical studies have been conducted to evaluate wind loads due to tornadoes. However, it is a common practice to use geometric dimensions and configuration of physical elements (like guide vane angle, ceiling height, etc.) of an experimental simulator to extract the parameters needed to characterize a tornado-like vortex. This often makes wind load evaluation results very specific to an individual experimental facility (lacking common interpretation) and hinders experimental validation of numerical studies. In this paper, it is aimed to demonstrate the application of a generic numerical tornado model, that the authors previously developed, to evaluate tornadic wind loads. To validate the numerical tornado model, Large Eddy Simulation (LES) results were compared with two independently conducted experiments; (i) interaction of a low swirl ratio tornado-like vortex and high-rise building model, reported in Yang et al. (2011) during an experiment conducted in the Tornado Simulator at Iowa State University, and (ii) interaction of a mid-range swirl ratio tornado-like vortex and mid-rise building model, conducted in an experimental test at WindEEE Dome at Western University. First, numerically obtained results using the generic tornado model were qualitatively compared with the Particle Image Velocimetry (PIV) results reported in Yang et al. (2011). The numerically predicted streamlines and velocity contours around the high-rise building model were observed to agree with PIV measurements from the experimental study. Further, numerically computed force and moment coefficients were compared with experimentally reported values. Next, the generic numerical tornado model was used to compute surface pressure coefficients on a 1:200 scale mid-rise building model for various cases of stationary tornado-like vortex. Subsequently, the obtained results were compared with a similar experimental test conducted at the WindEEE Dome. The comparison indicates the significance of vortex wandering in interpreting building surface pressure distribution due to tornado-like vortices and the nature of resulting wind loads. Overall, the study demonstrates the potential of proposed generic numerical tornado model in preliminary wind load estimation and elucidating the underlying aerodynamic interaction between tornado wind field and buildings.

1 INTRODUCTION

A tornado is a violently rotating column of air with high wind speeds that often leaves behind a destruction trail. Based on damage total and number of fatalities due to natural hazards, tornadoes are ranked third, after floods and hurricanes, in the United States (Cutter 2002). With an estimation of around 1200 tornadoes per year on an average, the United States ranks first in terms of annual tornado occurrences. Further, from a statistical perspective, the year 2011 stands out in terms of maximum annual tornado damage in the United States since the 1950s. According US National Oceanic and Atmospheric Administration (NOAA), tornadoes caused 550 deaths and 28 billion dollars in damage that year alone. While most tornadoes in

United States occur in the south-central region (termed as ‘tornado alley), significant tornadoes have also been witnessed in other areas outside of that region. In fact, it has been commonly observed that tornadoes outside of tornado alley often cause more damage than anticipated merely because they are relatively less expected to occur outside of the tornado alley.

Traditionally, wind engineering researchers have extensively studied the effects of synoptic wind systems (commonly referred to as conventional Atmospheric Boundary Layer or straight-line wind) on structures (Davenport 1961 and 1976, Kareem 1982, Tamura et al. 1999, Dagnew and Bitsuamlak 2013 and 2014, Elshaer et al. 2016 and 2017, etc). However, the complex three-dimensional flow-field, and it’s localized, and transient effects make the nature of wind loads arising from non-synoptic systems, like tornadoes, substantially different from their synoptic counterpart (Sabareesh et al. 2009). This has compelled researchers to push boundaries on both, experimental and computational front. While studies like Haan et al. (2008), Thampi et al. (2011), Sabareesh et al. (2012, 2013 and 2013) utilized experimental tornado simulators (which are different from conventional Atmospheric Boundary Layer wind tunnels) to study the effects of tornadic wind field near the ground, studies like Lewellen and Lewellen (1997, 2000 and 2006), Haan et al. (2006), Natarajan and Hangan (2012), Nasir and Bitsuamlak (2016), achieved the same using computational fluid dynamics (CFD) solvers.

From wind engineering perspective, there are two major challenges in studying tornadoes, (i) linking simulated vortices to real tornadoes, and (ii) linking numerical simulations to experimental simulations. Unlike straight-line wind, extremely violent, localized and transient nature of tornadoes create a lack of availability of good quality field data. This further prevents experimental and numerical simulations from being realistic representatives of real tornadoes. In other words, it is extremely challenging to establish a link between real tornadoes and simulated vortices. To this end, scaling techniques like the one developed by Refan et al. (2014) have been developed that provide a framework to link simulated vortices to real tornadoes.

Further, (ii) arises because most numerical tornado models like Haan et al. (2008), Hangan and Natarajan (2012) and Nasir and Bitsuamlak (2016) are inspired by experimental simulators. The experimental simulators are simplified into a numerical model by typically modelling the convergent and convection regions, and the effect of guide vanes was created by providing radial and tangential velocity vector components at the inlet (curved surface surrounding the convergent area). However, the common practice of using geometric dimensions of experimental simulators and configuration of physical elements (like guide vane angle, ceiling height, etc) to extract the parameters needed to characterize tornado-like vortices makes such flow field characterization ad-hoc in nature and very specific to an individual facility. This creates a challenge for numerical models, that rely on vortex characterizing obtained directly from experimental simulators for computational domain size and inflow boundary conditions. The ad-hoc nature of vortex characterization also hinders common interpretation of wind load evaluation results between various experimental studies as well as numerical studies.

The authors previously developed a generic numerical tornado model to overcome this challenge. In this study, the utility of the same generic numerical tornado model to evaluate wind loads and to understand the nature of aerodynamic interaction between tornado wind-field and buildings is demonstrated. To achieve this, numerically obtained results of interaction of tornado-like vortices with bluff bodies were validated with two independently conducted experiments, (i) interaction of a low swirl ratio tornado-like vortex and high-rise building model, reported in Yang et al. (2011) during an experiment conducted in the Tornado Simulator at Iowa State University (will be referred to as high-rise building case) and (ii) interaction of a mid-range swirl ratio tornado-like vortex and mid-rise building model, conducted in an experimental test at WindEEE Dome at Western University (well be referred to as mid-rise building case).

2 DESCRIPTION OF EXPERIMENTAL SET-UP

This section presents a brief description of the experimental set-ups and configurations used to assess the performance of the previously developed generic numerical model for its application to wind load evaluation.

2.1 High-rise Building Case

Yang et al. (2011) tested the effect of tornado-like winds on a typical high-rise building model of plan area 34.4 mm x 34.4 mm and height 140 mm. The building was subject to tornado-like wind field achieved by vane 1 setting of the ISU Tornado Simulator. The building position was altered with respect to the centre of a stationary vortex and the resulting force and moments coefficients were computed. The force and moment coefficients were computed as following.

$$CF_x = \frac{F_x}{\frac{1}{2}\rho V_{ref}^2 A};\ CF_y = \frac{F_y}{\frac{1}{2}\rho V_{ref}^2 A};\ CM_z = \frac{M_z}{\frac{1}{2}\rho V_{ref}^2 AH}$$

Here F_x is the component of force in the x direction, F_y is the component of force in y direction and M_z is the component of moment of force in z direction (torsion) (shown in Figure 1), A is the projected area, H is the building height, ρ is air density and V_{ref} =7m/s (maximum mean tangential velocity at 70 mm height).

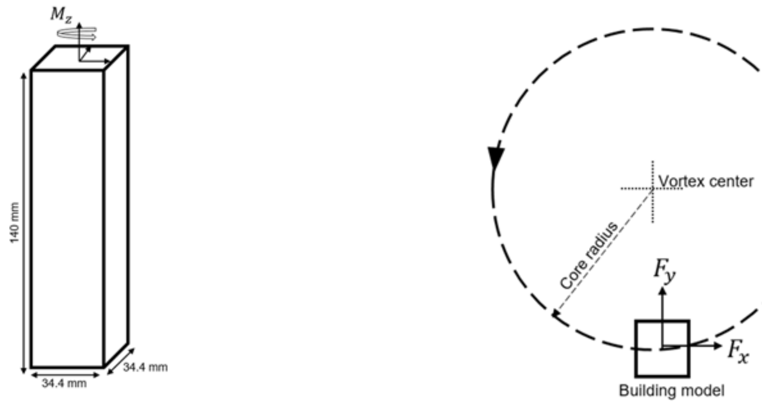


Figure 1: Experiment test configuration (high-rise building case).

2.2 Mid-rise Building Case

A typical mid-rise building model was subject to tornado-like flow field generated at WindEEE Dome and a High Frequency Pressure Integration (HFPI) test was conducted. To achieve this, WindEEE was operated in the second mode (non-functional peripheral fans) and the 15-degree guide vane configuration was used. The generated vortex was reported to have a swirl ratio of around 0.5 with a core radius and maximum mean tangential velocity at 0.17 m (building height) to be around 0.5 m and 15m/s, respectively. Both, stationary and translating vortex tests were conducted. For the stationary vortex case, the building was place at two locations i.e. core center and core radius. The test cases have been schematically depicted in Figure 2.

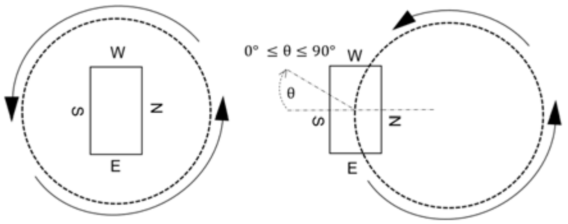


Figure 2: Experimental test configurations (mid-rise building case).

Surface pressure and force coefficients acting on the building model were then computed as shown below.

[1] $Cp = \frac{P-P_0}{\frac{1}{2}\rho\, U_{ref}^2}$

Here, P_0 is the reference static pressure (atmospheric pressure in this case, measured outside the test chamber) and U_{ref} is the reference velocity (mean maximum tangential velocity measured at building height, in the absence of building).

3 DESCRIPTION OF NUMERICAL SET-UP

The parameters for the simplified generic numerical tornado model (previously developed) corresponding to vane 1 setting of ISU Tornado Simulator and 15-degree vane angle setting of WindEEE have been summarized in Table 1.

	h_0 (m)	r_0 (m)	h_u (m)	r_u (m)	v_t (m/s)	v_r (m/s)
ISU Tornado Simulator	0.27	2.05	1.45	0.915	0.83	3.74
WindEEE Dome	0.8	6	4	1.8	1.52	2.85

Table1: Summary of parameters for the generic numerical model.

The dimensions and inlet velocities (uniform) for the simplified model were obtained from the table above. The obtained computational domain (double concentric cylinder) was then discretized using polyhedral mesh cells with 2-layered prism layers near the wall, as shown in Figure 3. Large Eddy Simulations were carried to simulate the interaction of a tornado-like vortex and bluff body. LES was initialized with RSM (RANS) solution and the time step was chosen while satisfying the Courant–Friedrichs–Lewy (CFL) condition as shown.

[2] $C = \frac{U\Delta t}{\Delta x} < 1$

Here C is the Courant number, Δx is the mesh size, U is the local velocity and Δt is the time step.

Using this, 15 seconds of physical time was simulated. Furthermore, a grid independence test was also carried to check for the convergence of mean flow properties in an empty computational domain.

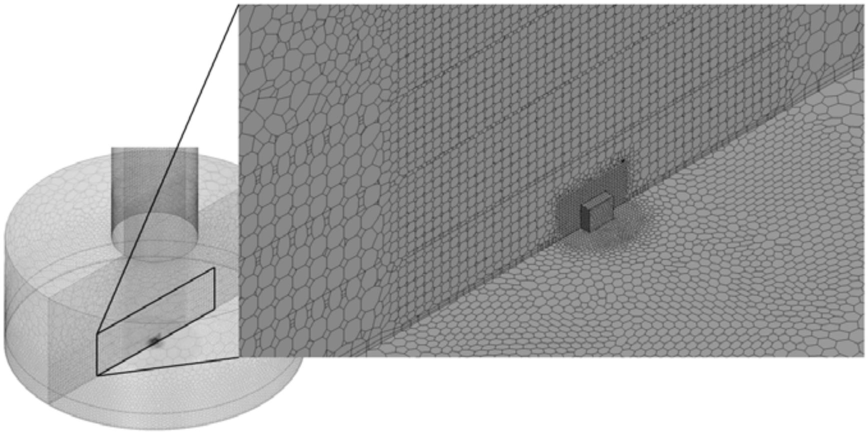


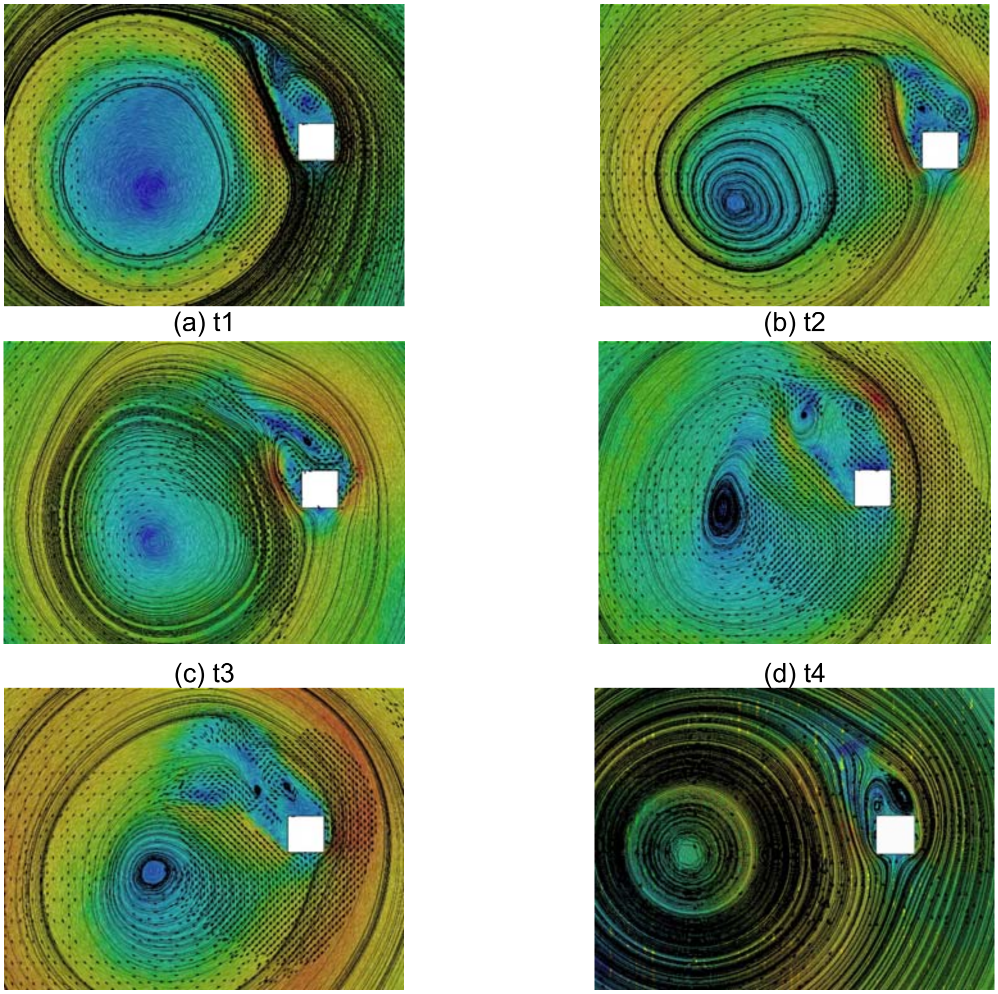
Figure 3: Numerical set-up showing discretization.

4 RESULTS AND DISCUSSION

Results of numerical simulations and their comparison with experimental studies for both, high-rise and mid-rise building cases have been presented in this section.

4.1 High-rise Building Case

Figure 4 shows the velocity field plotted at 70 mm height (half height) for the core radius location of the building at five-time instances as well as the time averaged streamlines. It can be seen from Figure 4 (a) through (e) that the system is very dynamic due to wandering of the vortex and vortex moves significantly, completely altering the wake around the building model as it does so. This observation is also consistent with Yang et al. (2011), who reported movement in the vortex centre, based on PIV measurements. At time instant t1, the vortex is close to the geometric centre of the simulator. The flow hits the building and separates; however, it can be seen from Figure 4 (a) that on the side of the building away from the vortex centre, the separation is not very prominent. In fact, even the wake behind building is asymmetric and is skewed towards the vortex centre. This indicates that while aerodynamic phenomenon associated with bluff-bodies, like flow separation and formation of wake, do occur locally, the overall structure of wake is influenced (and dominated by suction inside the vortex). Time instant t2 is right before the vortex centre overlaps with the building and time instant t3 is right after it crosses the building. It can be observed that the wake around the building significantly changes between these two instances. At time instant t4, the vortex is at a location such that the flow strikes the building model near the corner edge and this results in a large wake behind the model.



(a) t1

(b) t2

(c) t3

(d) t4

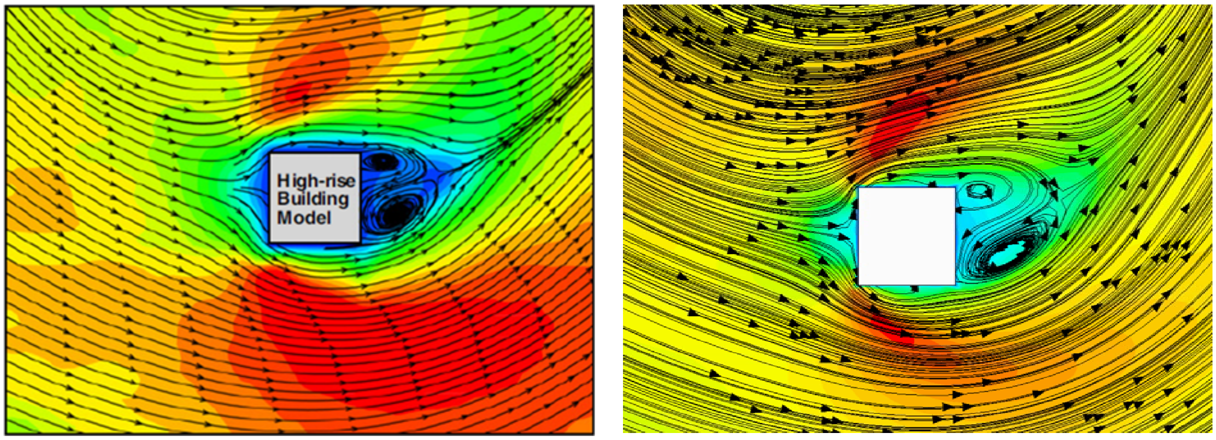
(e) t5

(f) Time-averaged LES

Figure 4: (a) Velocity field at time instant t1, (b) Velocity field at time instant t2, (c) Velocity field at time instant t3, (d) Velocity field at time instant t4, (e) Velocity field at time instant t5, (f) Time-averaged LES.

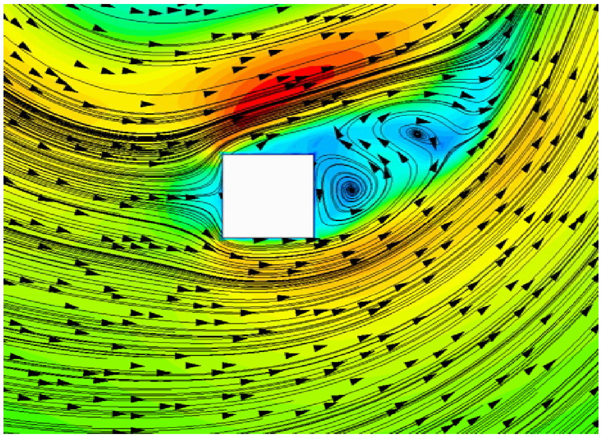
The wandering was observed to have a periodic cycle, i.e. the vortex would return to original position after about every 4-5 seconds. This can also be seen from Figure 4 (e), at time t5, the vortex is almost back to where it was at t1. The discussion above also arises questions about associating mean values with a fixed location of building model with respect to vortex centre of a “stationary” tornado. For example, in this case the location of the building model was intended to be at the core radius of the vortex but from Figure 4 and discussion presented here, it can be concluded that there were several instances when the vortex was over the building (like core centre location) and when the building was at a distance less than the core radius from the vortex centre etc., making mean values relatively less informative and possibly even misleading. Overall, it can be seen from Figure 4 that the wake structure around the building model, even for a stationary vortex case, is highly unsteady which is consistent with what was reported in Yang et al. (2011).

Figure 5 shows a comparison of time averaged velocity field obtained from the numerical model and Yang et al. (2011). A reasonably good agreement between the two can be instantly observed. Slight difference between the average velocity field obtained from steady RANS and time-averaged LES, and the similarity between time-averaged PIV and time-averaged LES can be seen from Figure 5.



(a)Yang et al. (2011)

(b) Time-averaged LES



Steady RANS

Figure 5: Comparison of streamlines.

Figure 6 presents a comparison of numerically and experimentally obtained force and moment coefficients. The force coefficients (x and y) obtained from numerical simulations show the same trend as experimentally obtained values. However, the numerically obtained force coefficients are seen to be slightly lower in magnitude. During the development of the generic numerical model, all pressures were referenced to the ground static pressure at the updraft radius (commonly observed practice in numerical studies). However, to be consistent with experimentally obtained data, during pressure and load coefficient evaluation, atmospheric pressure was used as reference. It is possible that atmospheric pressure might not be the best choice for reference pressures when comparing results between different facilities and between experimental and numerical studies. This would, however, require more detailed research in the future. Further, it can be observed that both numerical and experimental simulations show negligible torsional moment at every location and are therefore in good agreement.

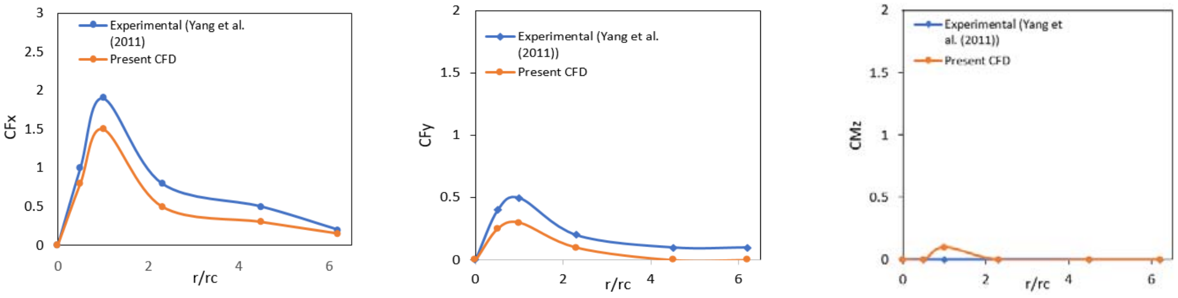
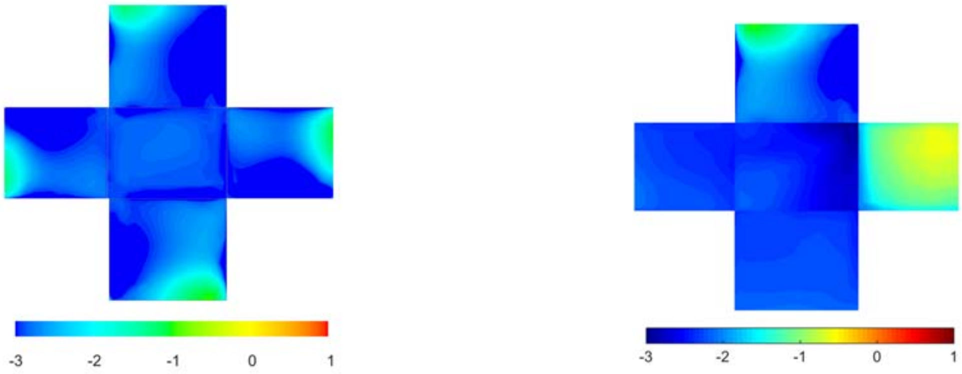


Figure 6: Comparison of variation on force and moment coefficients with radial distance from the center.

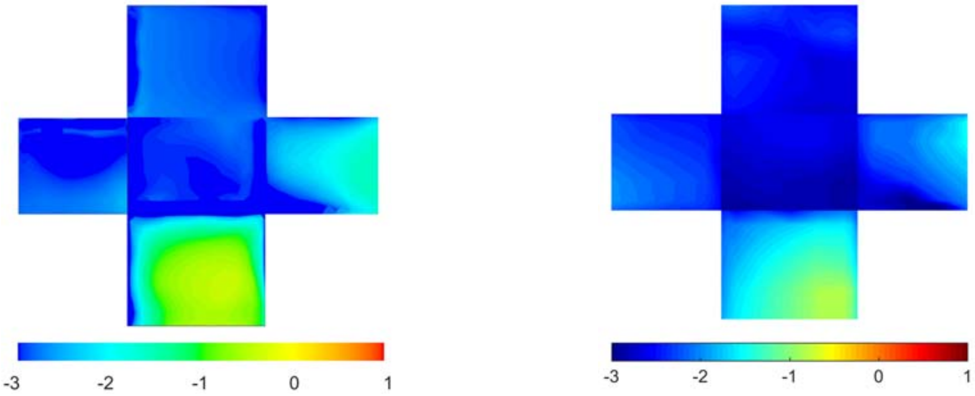
4.2 Mid-rise Building Case

From Figure 7 and Figure 8, a reasonable match (qualitatively) in the surface pressure distribution can be observed between numerical and experimental results. However, an interesting difference is the symmetry displayed for core centre case by numerical simulation, which is absent in experimental results. Although it is not entirely clear at this point as to what could have caused it, one possible explanation is based on the phenomenon of vortex wandering. It was previously observed that while wandering is an inherent property of these vortices, it can be augmented due to unsteadiness arsing from the mechanical system of the wind tunnel. It was seen that the extent of wandering is reduced for the simplified generic model as compared to the full CFD models of the entire system. Further for simplified models, the extent of wandering was higher for lower swirl ratios while it was somewhat mitigated for swirl ratios around 0.5. It is speculated that this is the reason for symmetry in pressure distribution for the simplified numerical results since the vortex simulated for this test had a swirl ratio of around 0.5 and therefore the simplified model showed mitigation in wandering. This has been illustrated in Figure 9.



(a) (b)

Figure 7: Building surface Cp distribution for core center case for (a) numerical (b) experimental.



(a) (b)

Figure 8: Building surface Cp distribution for core radius case for (a) numerical (b) experimental.

The number of up-crossings between ground static pressure time series at the centre and other locations away from the centre has been used to roughly estimate the extent of wandering throughout the study. From Figure 9, it can be observed that wandering for simplified numerical simulations is mitigated (no up-crossing) around 0.5 swirl ratio, however for full WindEEE CFD model, wandering was found to persist. Further, it is anticipated that the extent of wandering in actual WindEEE experimental set up would be even higher than what is predicted by WindEEE CFD model. This is because of the coasting of peripheral fans in WindEEE experimental set-up (that could introduce unwanted turbulence and asymmetry in the flow) that were not modelled in WindEEE CFD simulations (peripheral fans were not modelled in this study that mimics first mode of WindEEE operation). From Figure 8, a reasonable agreement of building surface pressure coefficients between numerical and experimental results for core radius location. Minor differences are attributed to vortex wandering in experimental set-up as previously described.

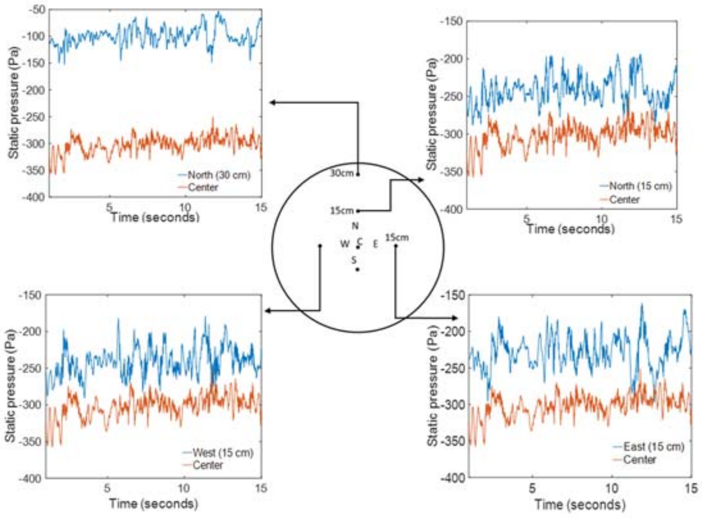


Figure 9: Demonstration of mitigation in vortex wandering for generic numerical model (for S=0.5).

5 CONCLUSION

The previously developed generic numerical tornado model displayed promising results for its application to tornadic wind load evaluation and to understand the aerodynamic interaction between tornadoes and structures. The force coefficients (x and y) obtained from numerical simulations showed the same trend as experimentally obtained values. However, the numerically obtained force coefficients were seen to be slightly lower in magnitude. The dependence of load coefficients on the location of building with respect to a stationary vortex was observed and, in general, highest force coefficients (in the x and y directions) were experienced at the core radius location. Further, turbulent flow structures (wake) around a bluff body were found to be highly unsteady, even for a so called “stationary vortex”, mainly due to wandering. A comparison between numerical and experimental results indicated the significance of vortex wandering in interpreting building surface pressure distribution due to tornado-like vortices and the nature of resulting wind loads.

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