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Large eddy simulation of the tornado-structure interaction to determine structural loadings

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Abstract. A tornado changes its wind speed and direction rapidly; therefore, it is difficult to study the effects of a tornado on buildings in a wind tunnel. The status of the tornado-structure interaction and various models of the tornado wind field found in literature are surveyed. Three dimensional computer modeling work using the turbulence model based on large eddy simulation is presented. The effect of a tornado on a cubic building is considered for this study. The Navier-Stokes (NS) equations are approximated by finite difference method, and solved by an semi-implicit procedure. The force coefficients are plotted in time to study the effect of the Rankine combined vortex model. The tornado is made to translate at a 0^o and 45^o angle, and the grid resolution is refined. Some flow visualizations are also reported to understand the flow behavior around the cube.

Keywords: CFD; tornado; forces; building; cube; wind engineering.

1 Introduction

Tornadoes cause millions of dollars in property damage every year in the USA. In order to mitigate this damage, it is necessary to design buildings that are more resistant to tornadoes. The first requirement for accomplishing this goal is a better knowledge of the tornado-structure interaction and tornado-induced loads on buildings. Since the winds in a tornado change their speed and direction rapidly, depending on location, it is difficult to study the effects of a tornado on a building in a wind tunnel. Mehta, *et al*. (1976) calculated tornado forces on buildings from post storm damage investigations. The maximum wind speed in the tornadic wind field was determined from the calculation of equivalent straight-line wind capable of such building failure. A drawback to this procedure is that the force coefficients are considered to be constant in time, whereas in the case of a tornado, the force coefficients change in time.

In recent years, computational wind engineering has been developed to such an extent that wind flows around buildings are computed considering the effects of viscosity and turbulence. The results from computation compare reasonably well with experimental results for straight boundary layer (SBL) wind (Selvam 1992 and Millett 2003). In this work, the current status of the forces on buildings due to tornadoes is reviewed. Research conducted in the wind tunnel as well as with the use of computer models is reported. Different tornado wind field models that can be used for

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tornado-structure interaction study are surveyed. The recent numerical simulations conducted in our computational mechanics laboratory investigating the tornado loadings on a building are reported herein.

1.1. Objective

The specific objectives of this study are as follows:

- To survey the tornado-structure interaction research up to date.
- To survey tornado-wind field models that can be used in computer models.
- To model the tornado-structure interaction using the large-eddy simulation turbulence model in a three-dimensional environment.
- To visualize the flow around a cube and to report the time dependent force coefficients.

1.2. Literature review on tornado forces on building

The amount of research aimed at determining exactly how tornadoes affect buildings has been incredibly meager over the past few decades. Although there have been numerous attempts to heighten this knowledge by a variety of different avenues (theoretical and experimental), a widely agreeable and conclusive solution has not yet been achieved. Because of the rotational and translational interaction with a building, the wind speed and direction are ever-changing while the building is in the vicinity of a tornado wind field (Selvam and Millett 2003, Millett 2003). As a result, inertial forces are present and perhaps even dominant, unlike quasi-static wind conditions (Wen and Chu 1973). Wen, using Kuo's (1971) tornado model, calculated the time-dependant forces on a building using a semi-emperical equation including drag and inertia. Dutta, *et al*. (2002) conducted similar theoretical calculations with an actual tornado record and used the FEM to determine structural response. Although this work is useful in determining the dynamic effect, no attention is given to the flow-structure interaction. Much work has been devoted to surveying the resulting structural damage produced by tornadoes (Mehta, *et al*. 1976) in an attempt to calculate tornado loadings by determining the straight winds capable of such damage. Studies have been conducted using laboratory models of vortex wind to determine the loadings on rectangular models (Jischke and Light 1983, Bienkiewicz and Dudhia 1993). These studies do investigate flow-structure interaction; however, since they are unable to simulate a translating vortex, the wind loadings are static and again the dynamic effects are not included. Numerical simulations promise to be beneficial due to their ability to capture both the flow-structure interaction and the time-dependant dynamic effects. Wilson (1977), using inviscid theory, carried out a preliminary study. The work conducted by our group are: McDonald and Selvam (1985), Selvam (1993), (2002a), Selvam, *et al*. (2002b), Selvam and Millett (2003), and Millett (2003). In McDonald and Selvam (1985), an Euler code was used to calculate the force coefficients on a 2D building with comparisons with Wen (Wilson 1977). In Selvam (1993), the model was expanded 3D with turbulence (k-ε model) and drag included; however, difficulties were encountered with boundary conditions for k values. The turbulence model was changed to Direct Simulation and the forces were computed on a 2D cylinder (due to availability in literature for comparison of flow past cylinder) (Selvam 1993). In Selvam and Millett (2003), the model was once again expanded to 3D with a course grid (61×61×37 points). In addition to the force coefficients, the mean pressure coefficients on the building envelope were calculated and plotted. In Selvam and Millett (2003), areas of recirculating flow near the building were observed in simulations while the tornado engulfed the building. A comparison with SBL wind was made, with the realization that the V_{ref} needed to be the maximum velocity in the tornado wind field for an appropriate comparison. For this paper, the grid was greatly refined adjacent to the building and on the building envelope in order to better capture the recirculating flow regions created by the building corners (as seen in Selvam and Millett 2003). This resolution has enabled us to perform a more detailed study of the contrasting forces due to SBL wind and the RCVM model wind.

2. Tornado wind field modeling

The simplest model that can satisfy the NS equations for tornado wind field model is the Rankine-Combined vortex model (RCVM) as reported in Lewellen (1976). In the RCVM, the tangential velocity varies linearly up to radius r_{max}, i.e., $V_\theta = \alpha r$, where r is the radius from the center of tornado and a is a constant (Fig. 1). At radii larger than r_{max}, V_θ varies as $\alpha r^2_{max}/r$. In this computational simulation, a translational velocity, V_t, with respect to the building is superimposed onto the RCVM wind field, in addition to a vertical logarithmic variation to account for the boundary layer, as reported by Selvam (1993). Considering that the origin of the x- and y-axis is at the center of the building and the z axis on the ground, and time, t, is zero when the center of the tornado coincides with the center of the building, the velocity components in the x and y directions (which are calculated at boundary points) are expressed as:

For any approach angle of tornado translation:

$$
\begin{aligned}
V_x &= [V_{tx} + (V_{ty}t - y)\alpha]*Z_f \text{ for } r \le r_{max} \\
V_x &= [V_{tx} + (V_{ty}t - y)C]*Z_f \text{ for } r > r_{max} \\
V_y &= [V_{ty} + (x - V_{tx}t)\alpha]*Z_f \text{ for } r \le r_{max} \\
V_y &= [V_{ty} + (x - V_{tx}t)C]*Z_f \text{ for } r \le r_{max}
\end{aligned} \tag{1}
$$

Where: $V_{tx} = x-$component of Vt;
$V_{ty} = y-$component of Vt;
$C = \alpha r^2_{max} / r^2$;
$r^2 = (x - V_t t)^2 + y^2$;
$Z_f = u*\ln((z+z0)/z0)/\kappa$

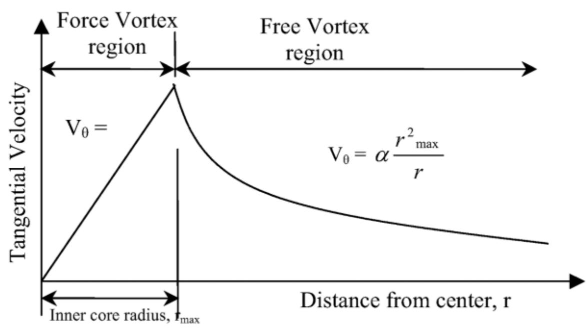


Fig. 1 Tangential velocity (V_θ) for

The Z_f function is used to taper the tangential velocity components in the z-direction to represent the boundary layer. Here u^* is the frictional velocity which is determined from the known velocities at the known height, $\kappa = 0.4$, $z0$ is the roughness length of the ground and z is the height from the ground. In this work, $z0$ has been set equal to 0.00375, and Zf is fitted to be one at the top of the cube. The κ is von Karaman's constant and the roughness coefficient $z0$ for terrain category B (high grass) is in the range of 0.075 m as reported in Simu and Scanlan (1978). To use nondimensional calculations for numerical convenience, we consider height of the building $H = 20$ m and the velocity at the roof height to be the reference values. When $z0$ is converted to a nondimensional number, it becomes 0.00375(0.075 m/20 m). Similarly the reference velocity is nondimensionalized at the roof height to be one and hence $Zf = 1.0$.

2.1. Fluid-structure interaction modeling

Turbulence in fluid flow can be considered in CFD by direct simulation(DS), large eddy simulation (LES) and Reynolds averaged equations as surveyed by Selvam (1998). Reynolds averaged equations are applied in many fields of engineering and science. These equations solve for Reynolds averaged stresses using transport equations or simple equations. One form of Reynolds averaged equation is the k-ε model. Selvam (1993) in his earlier work on tornado effects on buildings used this turbulence model. The large eddy simulation turbulence model is based on the filtered Navier-Stokes equations. Direct simulation requires a large number of grid points and hence it is possible to apply to wind engineering problem for low Reynolds number flow, as reported by Selvam and Qu (2000). The turbulence for this work is modeled using the large eddy simulation. The solution procedure to solve the Navier-Stokes equations using LES turbulence model is identical to that reported in Selvam (1993, 2002a, 2002b).

2.2. Problem geometry and boundary conditions

The boundary of the computational domain is located at a reasonable distance away from the cube, to not inhibit the flow-structure interaction. The domain has a size of 30 unit×30 unit×10 units as shown in Fig. 2. The dimensions of the grids that were generated for this study are presented in Table 1. Five grids were used for a convergence study. On the surface of the cube, the

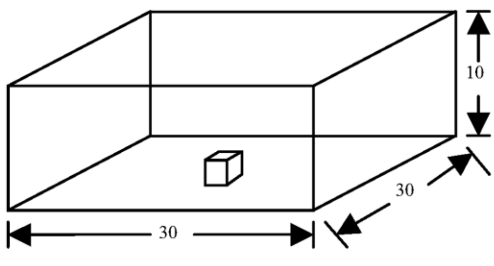


Fig. 2 Isometric view of computational domain

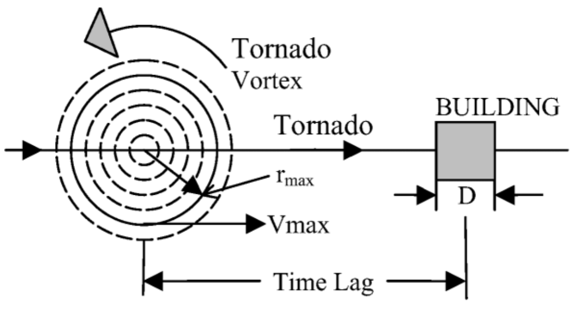


Fig. 3 Schematic of plan view of dynamics of flow field for 3D program

Table 1 Grid properties

GRID	Computational Region	Points on bldg. face	Min. Spacing next to bldg.	Total # of points
A	45×45×25	10×10×10	0.1000 H	50,625
B	61×61×37	10×10×10	0.0720 H	137,677
C	103×103×56	20×20×10	0.0104 H	594,104
D	131×131×69	30×30×20	0.0078 H	1,184,109
E	155×155×69	40×40×20	0.0055 H	1,657,725

Table 2 Tornado parameters

	α (see Fig. 1)	$r_{\max}$ (see Fig. 1)	V_t (trans. vel.)	V_θ (tang. vel.) $= \alpha \times r_{\max}$	$V_{\max}$ $= V_t + V_\theta$
SI units	1.5 (constant)	60 m	72 km/h	324 km/h	396 km/h
Non-dimensional units	1.5 (constant)	3.0 units	1 unit/sec	4.5 units/sec	5.5 units/sec

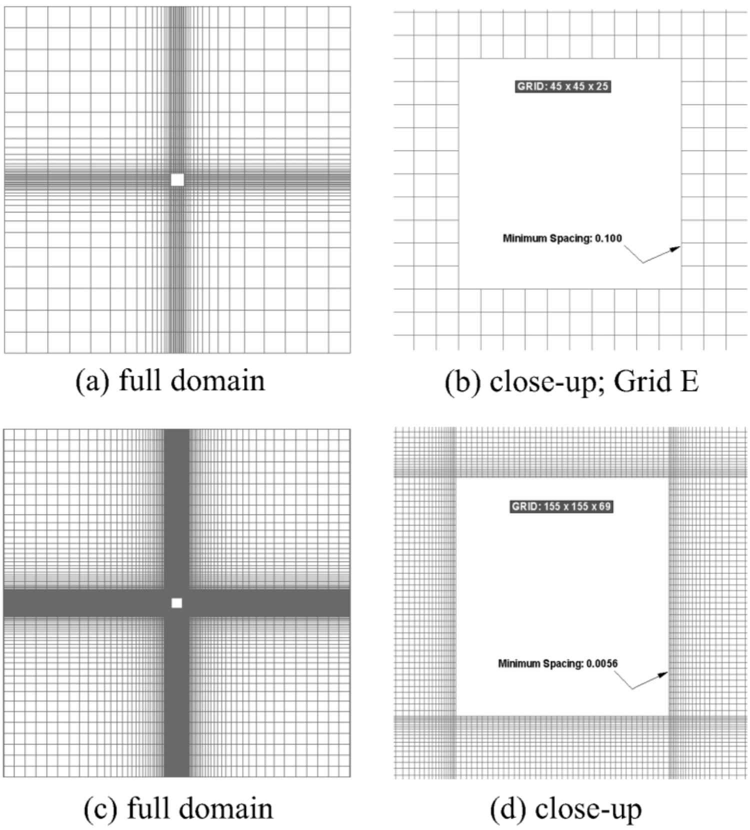


Fig. 4 Grid A, (a) full domain, (b) close-up; Grid E (c) full domain, (d) close-up

velocities are considered to be zero, i.e., no-slip condition. At each time step, the interior velocities and pressures are computed by solving the NS equations.

A plan view of the relative position of the tornado with respect to the building is shown in Fig. 3. In this study, the tornado is made to translate across the domain in the *x*-direction or at a 45^o angle to that. To nondimensionalize the problem, the heigth of the cube (H), the translational velocity, and the density of air are set at 1 nondimensional (ND) unit. With that assumption, the parameters of the tornado are assigned the values presented in Table 2. Fig. 4 below displays the features of grids *A* and *E*.

2.3. Nomenclature

The nomenclature used in this study is given below:

$$Cx = \frac{Fx}{\frac{1}{2}\rho V^2 A}, \quad Cy = \frac{Fy}{\frac{1}{2}\rho V^2 A}, \quad Cz = \frac{Fz}{\frac{1}{2}\rho V^2 A}, \quad Cp = \frac{\Delta P}{\frac{1}{2}\rho V^2 A} \tag{4}$$

Here, *Cx*, *Cy* and *Cz* are the computed force coefficients in the *x*, *y*, and *z* directions, respectively, and *Cp* is the mean pressure coefficient. F_x, F_y, and F_z are the respective forces in the *x*-, *y*- and *z*-directions, *V* is the reference velocity, ρ is the density of air, ν is the kinematic viscosity of air, and ΔP is the pressure difference, $P-P$(ref) [P(ref) is equal to 0.0]. The reference velocity is the maximum velocity in the tornado wind field at the height of the building, which is equal to $V_\theta + V_t$. This is done because the velocities are continuously changing in space and time, and one reference velocity needs to be assumed. Common classification of tornadoes, such as the Fujita scale, is based on maximum wind speed, therefore V_{max} was chosen. The forces are computed by integrating the pressures on the wall in each respective direction.

3. Results and discussion

3.1. Tornado-structure interaction

The primary advantage of CFD modeling of the tornado-structure interaction is the capability to investigate the wind characteristics from any angle at any instant in time. Fig. 5 below displays the interaction of the tornadic wind (45^o approach) and a cubic building (*xy*-plane at 90% of the building height) at various instances in time (t = 7 sec, 10 sec, 13 sec) for a time lag of 10 sec. using grid *D*. The time lag is the amount of time from the beginning of simulation until when the center of the tornado coincides with the center of the building.

The figures (Fig. 5(b),(c)) below illustrate recirculating flow areas near the building due to the multiple sharp corners of the cubic building. The resulting vorticity produces highly localized suction pressure regions on the walls of the building (see Fig. 9(b)), which has been observed with experimental results in a stationary vortex chamber (Jischke and Light 1983). Typically the walls of a building, unlike the roof, are not designed to withstand such high suction forces.

The rotational wind created by a tornado also produces large suction forces on the roof of a cubic building. When the vortex core is completely surrounding the cubic building, the vertical force coefficient is the highest (see Fig. 9(a)). The numerical simulations performed in this work may perhaps shed some light on why this occurs. It is shown in Fig. 6 that around all sides of the building are produced large amounts of vertical wind. This is a result of the wind converging

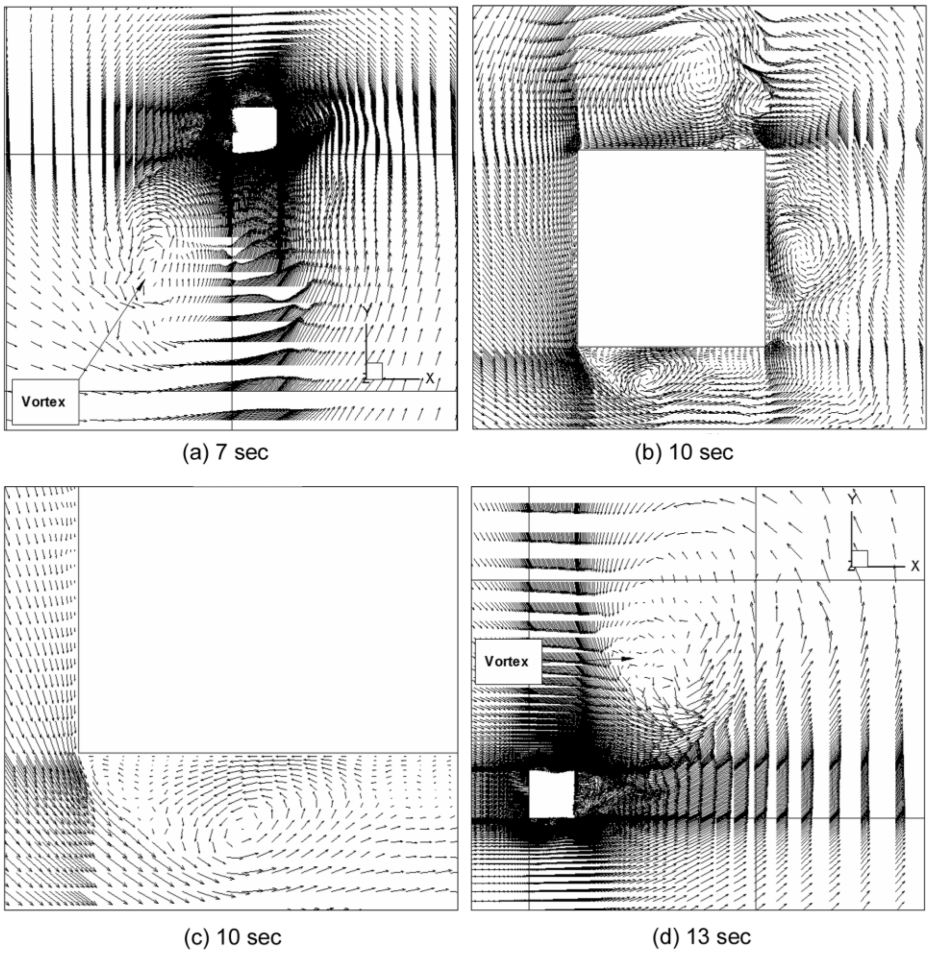


Fig. 5 XY-plane view of tornado velocities (45^{o} approach angle, Grid D, time lag = 10 sec.) at (a) 7 sec.; (b) 10 sec.; (c) 10 sec, close-up of SW corner flow separation; (d) 13 sec

toward the vertical axis of the vortex. With the building interaction, the wind is converted from horizontal to highly concentrated vertical wind all around the roof corners of the building. As the high-velocity vertical wind flows past the corners of the building, flow separation occurs just above the entire roof surface (as seen by the turbulent wake above the building in Figs. 6(a),(b)). It has been observed in laboratory simulations (Bienkiewicz and Dudhia 1993) and these numerical simulations that the pressure above the building while the tornado is surrounding the building is more negative than inside the vortex core without the presence of the building. With no building in the vortex, the maximum *Cp* value inside the vortex was -1.71. While the vortex surrounded the building, the maximum *Cp* above the building was -2.31.

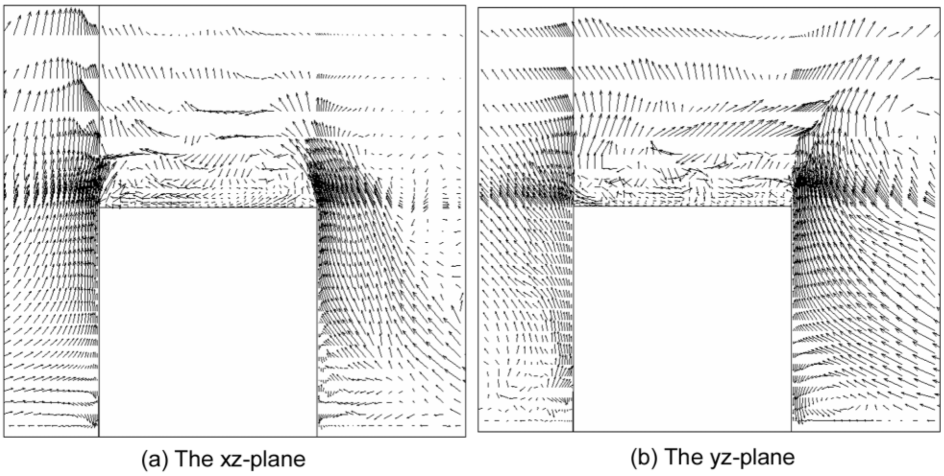


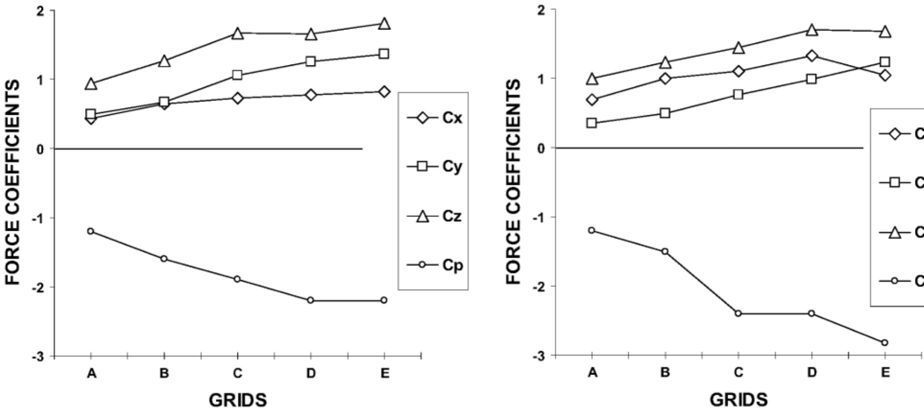
Fig. 6 Views of vertical velocity for grid *D* with tornado surrounding building (time = time lag) with (a) the *xz*-plane and (b) the *yz*-plane

Table 3 Force and pressure coefficients

GRID	TORN. APPR.	*Cx*	*Cy*	*Cz*	*Cp*
A	0^o	0.44	0.49	0.94	-1.20
B	0^o	0.65	0.67	1.27	-1.60
C	0^o	0.73	1.06	1.67	-1.90
D	0^o	0.78	1.26	1.66	-2.20
E	0^o	0.82	1.36	1.81	-2.20
A	45^o	0.70	0.35	1.00	-1.20
B	45^o	1.00	0.49	1.23	-1.50
C	45^o	1.11	0.77	1.45	-2.40
D	45^o	1.33	0.99	1.71	-2.40
E	45^o	1.05	1.24	1.68	-2.82
SBL	0^o	0.76	0.00	0.87	-1.20
SBL	45^o	0.94	0.90	0.89	-2.00

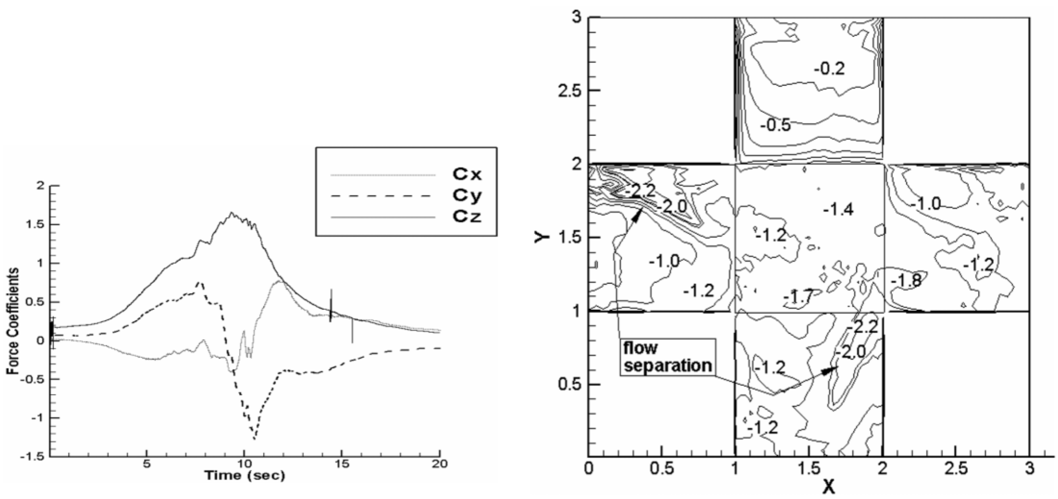
3.2. Force coefficients on building

The computed force and pressure coefficients, *Cx*, *Cy*, *Cz*, and *Cp*, are presented in Table 3 for the proposed RCVM model with the dimensions given in Table 1 for a 0^o and 45^o angle of attack (AOA) with all the grids. As can be seen in Fig. 7, the more refined meshes produce higher force coefficients and pressure coefficients. With a 0^o AOA, the maximum *Cx*, *Cy*, and *Cz* values are 0.82, 1.36, and 1.81, respectively. With a 45^o AOA, the maximum *Cx*, *Cy*, and *Cz* values are 1.33, 1.24, and 1.71, respectively. For the two approach angles, the maximum force coefficients for the walls are similar, however, the 0^o approach applies more force to the wall perpendicular to the *y*-axis, and the 45^o approach angle applies more force to the wall perpendicular to the *x*-axis. The *Cz*



(a) 0° tornado angle (b) 45° tornado angle

Fig. 7 Convergence of force and pressure coefficients for (a) 0^o tornado angle and (b) 45^o tornado angle



(a) Time variation of force coefficients due to RCVM (grid D, approach = 0^o)

(b) Pressure coefficients around cubic building for time = 10 sec (grid D, approach = 0^o)

Fig. 8 (a) Time variation of force coefficients due to RCVM (grid D, approach = 0^o); (b) pressure coefficients around cubic building for time = 10 sec (grid D, approach = 0^o)

values are fairly similar for the two approach angles with peak values of 1.81 and 1.71 occurring while the tornado is completely surrounding the building (time = time lag).

This program was also run without the tornado vortex in order to determine how the force coefficients compare with quasi-static wind conditions (Table 3). The results compare well with those measured in full-scale experiments, wind tunnels, and CFD. The *Cx*, *Cy*, *Cz*, and *Cp* values for the 0^o AOA are 0.76, 0.00, 0.87, and -1.20; and for the 45^o AOA are 0.94, 0.90, 0.89, and -2.00. For comparison, the tornado produces 45% higher overall force on a single wall, and 100% higher overall suction force on the roof than quasi-static wind. This trend is similar to that reported in

Table 4 Comparison of SBL and RCVM force and pressure coefficients

	SBL Wind		RCVM		Difference
	0°	45°	0°	45°	
Wall (*Cx* or *Cy*)	0.76	0.94	1.36	1.24	**50%**
Roof (*Cz*)	0.87	0.89	1.81	1.71	**100%**
Cp	-1.20	-2.00	-2.20	-2.82	**40%**

Selvam and Millett (2003). In addition, a dynamic factor also needs to be included because of the rapid change in the applied direction of the forces (*Cx* and *Cy*) during a short period of time (Fig. 8(a)).

The maximum localized pressure coefficient, *Cp*, is also found to be higher during the tornado event than in quasi-static wind conditions. During straight wind, the largest local suction pressures occur on the roof behind the windward edge (0° and 45°). For a tornado, large local suction pressures occur in multiple locations (Fig. 8(b)), behind wall corners and along the entire roof section due to flow separation from the sharp corners. It is observed that only the most refined grids show these local gradients in pressure due to the high concentration of grid points near the building that can capture the vortex formations near the building shown in Fig. 5. It is necessary to point out that the V_{ref} used in Eq. (4) is the maximum velocity in the domain ($V_\theta + V_t$). This velocity is never actually applied to the building because the $r_{\max}$ is greater than the building length (see Fig. 2). As a result, the coefficients calculated in this study are perhaps underestimated for an appropriate comparison with straight boundary layer wind.

Table 4 below presents numerically a comparison of the force and pressure coefficients calculated by CFD program for SBL wind and the translating RCVM vortex. For the RCVM vortex, the force coefficients are the maximum throughout the simulation, and the pressure coefficient is the maximum on the building envelope at time = time lag.

4. Conclusions

In this paper, the status of the tornado-structure interaction was presented briefly. A three-dimensional study on tornado-structure interaction is conducted using computational fluid dynamics. The following conclusions are arrived from this work:

(1) A translating tornado produces higher overall forces on the walls (45% more) and roof (100% more) of a building than quasi-steady wind. In addition, these forces change magnitude and direction quickly when the tornado core is near the building. Also, the localized suction pressures on the building envelope are greater and occur in multiple locations, unlike straight wind. For computational simulations, only the most refined grids (with high concentration of points near the building) are needed for a convergence of results for this highly unsteady and turbulent flow. For further details one can refer to Millett (2003).

(2) More simulations will be made by changing such variables as size and shape of building (square to various rectangular shapes, low-rise, mid-rise, and high-rise), the number of buildings in the domain, as well as tornado parameters such as translational velocity, core size, and maximum tangential wind speed. With the more data collected with these experiments, the closer we will be to determining exactly how any tornado effects any type of

building.

(3) In addition to Cx, Cy, Cz, it will be interesting to calculate the moment coefficients Cm_x, Cm_y, and Cm_z. These values may offer more details about the differences between SBL wind forces and tornadic forces. Also, although vertical velocity is created in the domain near the building, the current tornado model we use, RCVM, doesn't include vertical velocity. Incorporating vertical velocity into our model will improve the degree of similitude to natural tornadoes. This may prove to be a challenging task for the future because the continuity condition of the Navier-Stokes equations must be satisfied. If vertical wind is exiting at the top of the domain, an equal volume of wind must enter the domain from the sides. We do intend to incorporate this in future modeling. We predict that with more vertical velocity interacting with the building, the roof force, Cz, will increase beyond twice the amount for SBL wind.

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