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Computer Modeling of Tornado Forces on a Cubic Building Using Large Eddy Simulation

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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 the finite difference method and solved by an implicit procedure. The force coefficients are plotted in time to study the effect of Rankine combined vortex model. The tornado is made to translate at a 0° and 45° angle, and the grid resolution is refined. Some flow visualizations are also reported to enhance understanding of the flow behavior around the cube.

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 tornado changes its wind speed and direction rapidly, 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 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, which produces more damage comparatively.

In recent years, computational wind engineering has been developed to such an extent that wind flows around buildings can be 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). 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 the use of computer models is reported. Different tornado wind field models that can be used for tornado-structure interaction study are surveyed. Some of the recent work conducted in our laboratory investigating the tornado effects on a building is also reported.

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.

Literature Review.—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 a tornado's rotational and translational interaction with a building, the wind speed and direction are ever-changing with respect to the building while in the vicinity of the tornado wind field (Selvam and Millett, 2002). As a result, inertial forces are present and perhaps even dominant, unlike in 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-empirical equation which includes drag and inertia. Dutta et al. (2002) conducted similar theoretical calculations with an actual tornado record and the Finite Element Method. 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

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calculate tornado loadings by calculating 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. A preliminary study was carried out by Wilson (1977), and ongoing reports have been issued by our group: (McDonald and Selvam, 1985; Selvam, 1993, 2002; Selvam et al., 2002; Selvam and Millett, 2002; Millett, 2003).

Methods

Tornado wind field modeling.--The simplest model that can satisfy the Navier-Stokes 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 α is a constant (Fig. 1). At radii larger than r_{max} , V_{θ} varies as $\alpha r_{max}^2/r$. 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 both 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 center of the building, the velocity components in the x and y directions are expressed as follows:

For any approach angle of tornado translation:

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

where $V_{tx} = x$ -component of V_t ; $V_{ty} = y$ -component of V_t ; $C = \alpha r_{max}^2/r^2$; $r^2 = (x - V_{tx}t)^2 + y^2$; $Z_f = u^* \ln((z+z_0)/z_0)/\kappa$.

Here u^* is the frictional velocity, which is determined from the known velocities at the known height, $\kappa = 0.4$, z_0 is the roughness length of the ground, and z is the height from the ground. In this work, z_0 has been set equal to 0.00375, and Z_f is considered to be one at the top of the cube.

Fluid-structure interaction modeling.--Turbulence in fluid flow can be considered in computational fluid dynamics (CFD) by direct simulation (DS), large eddy simulation (LES), and Reynolds averaged equations as

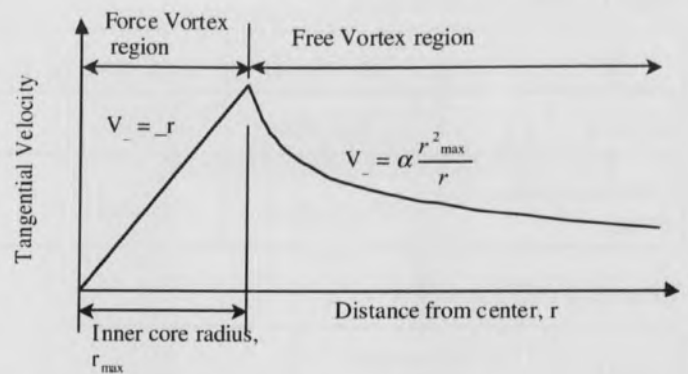


Fig. 1. Tangential Velocity (V_{θ}) for RCVM

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 problems for low Reynolds number flow (Selvam and Qu, 2000). The turbulence for this work is modeled using the large eddy simulation. The Navier-Stokes equations using LES used with this CFD simulation program can be obtained by referencing Selvam (1998) and Selvam et al. (2002)

Problem geometry and boundary conditions.--A plan view of the relative position of the tornado with respect to the building is shown in Figure 2. The tornado translates across in the x-direction. The width of the cube is assumed

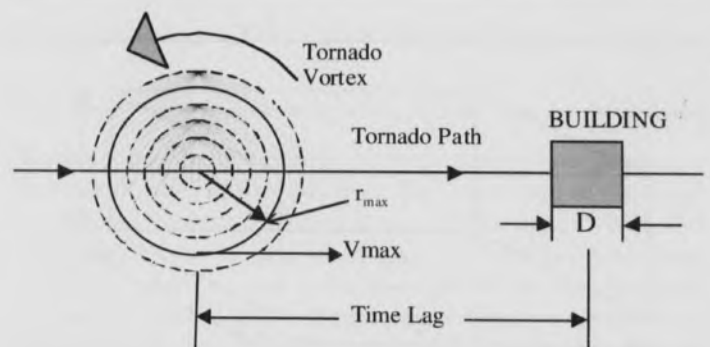


Fig. 2. Schematic of plan view of dynamics of flow field for 3D program.

Table 1. Tornado parameters

	r_{in} (see Fig. 1)	r_{max} (see Fig. 1)	V_1 (trans. vel.)	V (tang. vel.)	$V_{max} = V_1 + V_{in}$
SI units	1.5 (constant)	61 meters	45.4 mph	$r_{max} = 204$ mph	250 mph
Non-Dimensional units	1.5 (constant)	3.0 units	1 unit/sec	4.5 units/sec	5.5 units/sec

Table 2. Grid Properties

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

to be 20.3 m. To nondimensionalize the problem, the width 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 1.

The boundary of the computational domain is located at a reasonable distance away from the cube. The domain has a size of 30 units x 30 units x 10 units as shown in Figure 3. The dimensions of the grids that were generated for this study are presented in Table 2. On the surface of the cube, the 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.

Nomenclature.--The nomenclature used in this study is given below:

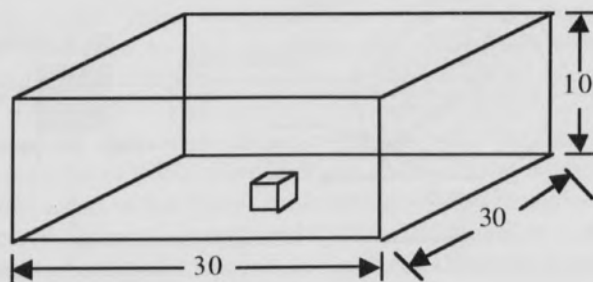


Fig. 3. Isometric view of computational domain.

$$\begin{aligned} C_x &= F_x/[0.5\rho V^2 A] & C_y &= F_y/[0.5\rho V^2 A] \\ C_z &= F_z/[0.5\rho V^2 A] & C_p &= \Delta P/[0.5\rho V^2 A] \end{aligned} \quad (4)$$

Here, C_x , C_y and C_z are the computed force coefficients in the x, y, and z directions, respectively, and C_p 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, $P - P(\text{ref})$ [$P(\text{ref})$ is equal to 0.0]. The reference velocity is the maximum velocity in the tornado wind field, which is equal to $V_\theta + V_t$. The forces are computed by integrating the pressures on the wall in each direction.

Results and Discussion

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. Figure 4 below displays the interaction of the tornadic wind (45° approach) and a cubic building (at the 90% of building height) at various instances in time ($t = 7$ sec, 10 sec, 13 sec) for a time lag of 10 sec. The time lag is the amount of time from beginning of simulation until when the center of the tornado coincides with the center of the building.

Figures 4b,c above illustrate the flow separation near the building due to the multiple sharp corners of the cubic building. The resulting vortex shedding produces highly localized negative pressure regions on the walls of the

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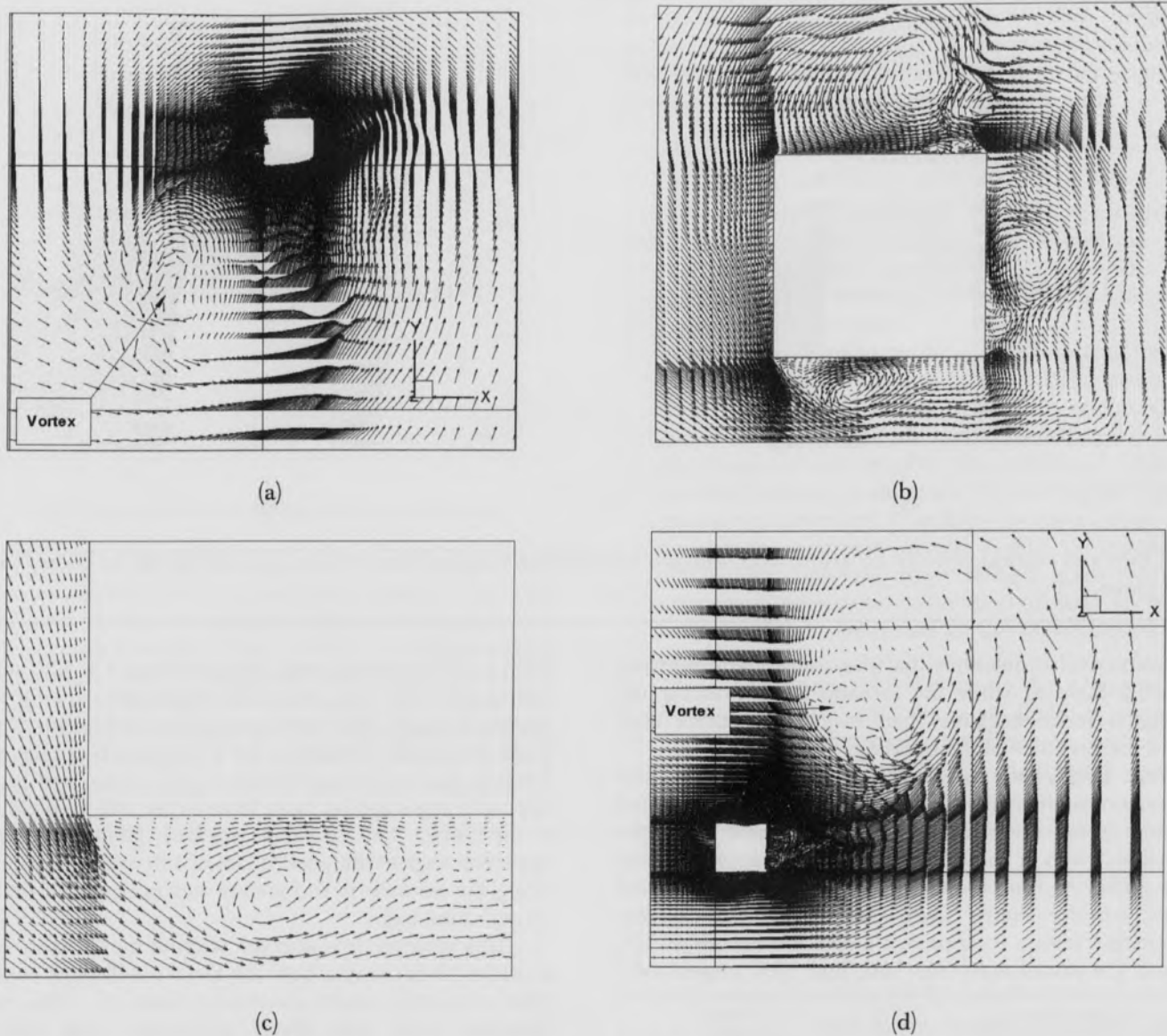


Fig. 4. XY-plane view of tornado velocities (45° approach angle, Grid C, time lag = 10 sec.) at (a) 7 sec.; (b) 10 sec.; (c) 10 sec, close-up of SW corner flow separation; (d) 13 sec.

building (see Fig. 5), which is in agreement with experimental results (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 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. 7a). The numerical simulations performed in this work may perhaps shed some light on why this occurs. It is shown in

Figure 5 that large amounts of vertical wind are produced around all sides of the building. This is a result of the wind converging 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 Fig. 5a). It has been observed in laboratory simulations (Bienkiewicz and Dudhia, 1993) and

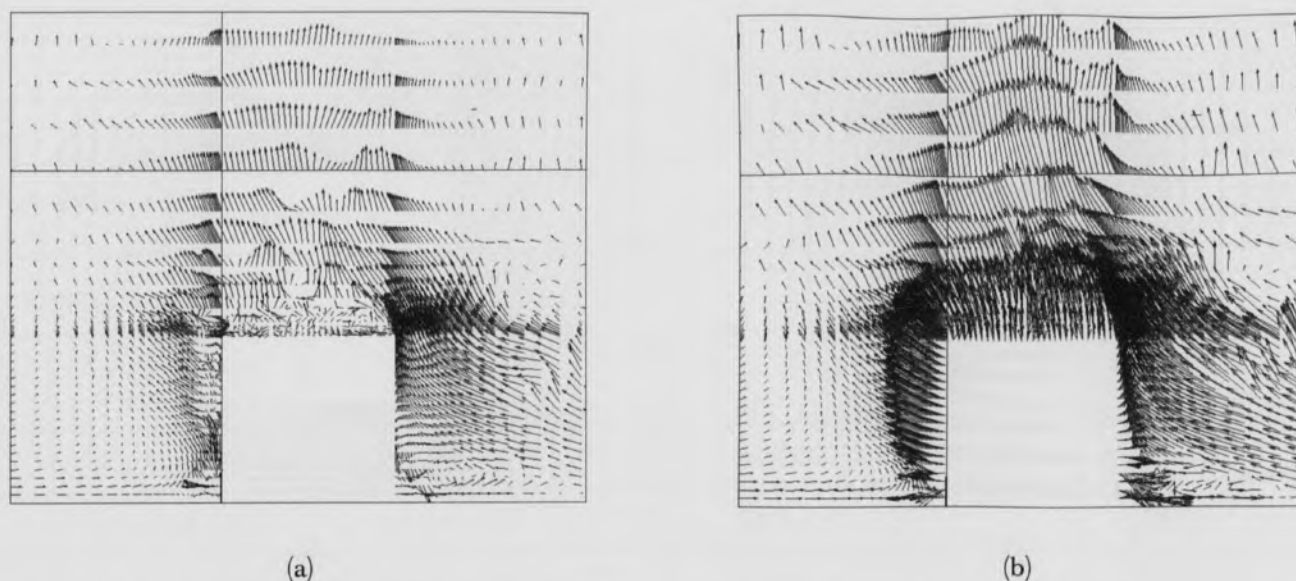


Fig. 5. Views of vertical velocity for grid C with tornado surrounding building (time = time lag) with (a) the xz-plane, and (b) the yz-plane.

these numerical simulations that the atmospheric 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.

Force Coefficients on Building.--The computed force and pressure coefficients, C_x , C_y , C_z , and C_p , are presented in Table 3 for the proposed RCVM model with the dimensions given in Table 1 for a 0° and 45° approach with all the grids. As can be seen in Figure 6, the more refined meshes produce higher force coefficients and pressure coefficients. With a 0° approach angle, the maximum C_x , C_y , and C_z values are 0.82, 1.36, and 1.81, respectively.

Table 3. Force and pressure coefficients

GRID	TORN. APPR.	C_x	C_y	C_z	C_p
A	0°	0.65	0.67	1.27	-1.60
B	0°	0.73	1.06	1.67	-1.90
C	0°	0.78	1.26	1.66	-2.20
D	0°	0.82	1.36	1.81	-2.20
A	45°	1.00	0.49	1.23	-1.50
B	45°	1.11	0.77	1.45	-2.40
C	45°	1.33	0.99	1.71	-2.40
D	45°	1.05	1.24	1.68	-2.82
SBL	0°	0.76	0.00	0.87	-1.20
SBL	45°	0.94	0.90	0.89	-2.00

With a 45° approach angle, the maximum C_x , C_y , and C_z 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° approach applies more force to the wall perpendicular to the y-axis, and the 45° approach angle applies more force to the wall perpendicular to the x-axis. The C_z 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 calculated with full-scale measurements, wind tunnels, and CFD. The C_x , C_y , C_z , and C_p values for the 0° angle of approach (aoa) are 0.76, 0.00, 0.87, and -1.20; and for the 45° aoa they 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 Selvam et al. (2002). In addition, a dynamic factor also needs to be included because of the rapid change in the applied direction of the forces (C_x and C_y) during a short period of time (Fig. 7a).

The maximum localized pressure coefficient, C_p , 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

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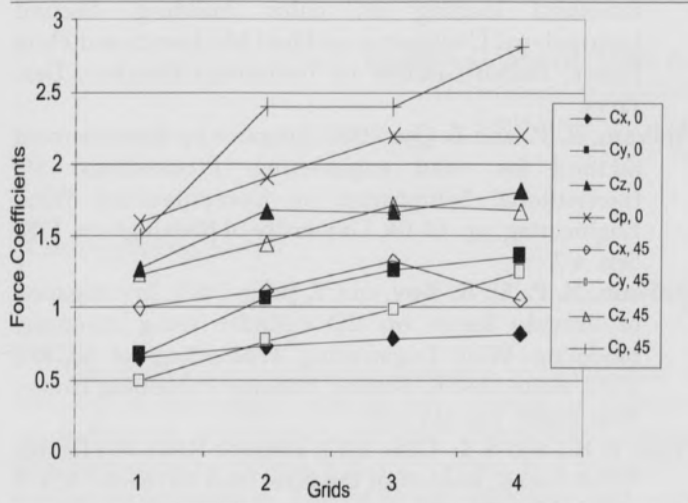


Fig. 6. Convergence of force and pressure coefficients

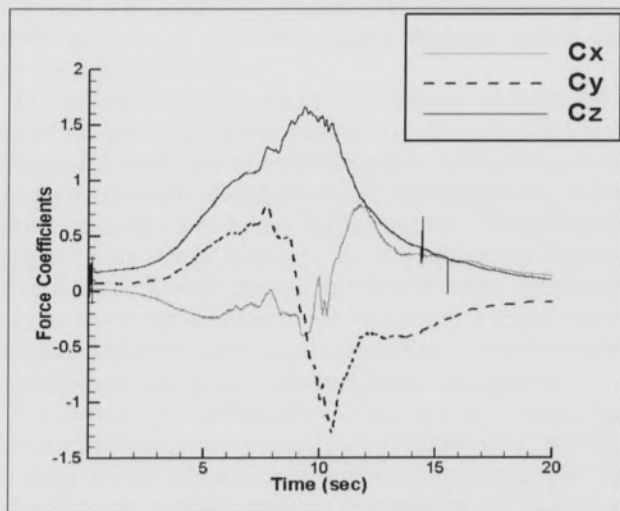
suction pressures occur in multiple locations (Fig. 7b), behind wall corners and along the entire roof section due to flow separation from the sharp corners. It is observed that only the most refined grids show these local gradients in pressure due to the high concentration of grid points near the building that can capture the vortex formations near the building shown in Figure 4. It is necessary to point out that the V_{ref} used in equation (4) is the maximum velocity in the

domain ($V_{\theta} + V_v$). 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.

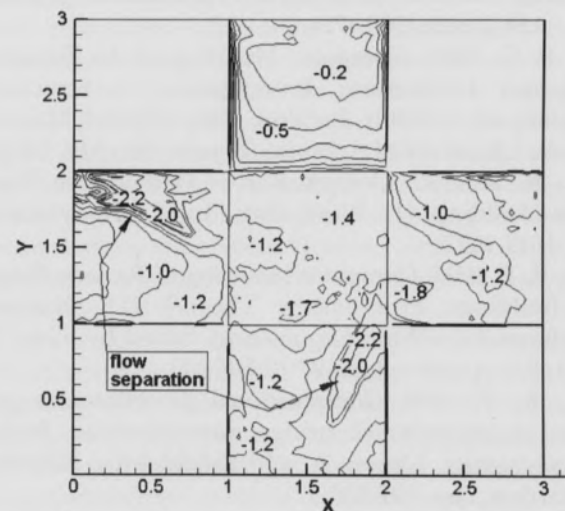
Conclusions

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 generated in multiple locations, unlike those caused by 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.
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



(a)



(b)

Fig. 7. (a) Time variation of force coefficients due to RCVM (grid C, approach = 0o); (b) pressure coefficients around cubic building for time = 10 sec (grid C, approach = 0o).

tornado parameters such as translational velocity, core size, and maximum tangential wind speed. The more data collected with these experiments, the closer we will be to determining exactly how any tornado effects any type of building.

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