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Computer modeling of tornado forces on buildings

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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. In this work, the status of the tornado-structure interaction is surveyed by numerical simulation. 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 tornado on a cubic building is considered for this study. The Navier-Stokes (NS) equations are approximated by finite difference method, and solved by a semi-implicit procedure. The force coefficients are plotted in time to study the effect of the Rankine-Combined Vortex Model. Some flow visualizations are also reported to understand the flow behavior around the cube.

Key words: tornado; building; tornado-structure interaction; computational fluid dynamics; 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 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. In this procedure, failure loads for damaged or destroyed buildings due to tornadic winds are calculated. A drawback to this procedure is that the forces were calculated assuming straight-line wind conditions, despite the fact that tornadoes have rotational wind.

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). 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 cubic structure is presented.

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2. 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 employed as 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.

3. Literature review on tornado forces on building

The effects of a tornado on a building are much different from straight boundary layer (SBL) wind because of the rotational and translational interaction on a building. Hence, the wind speed of a tornado changes in time with respect to the center of a building producing inertial forces in addition to drag forces. Wen (1975) recognized and included the effect of inertial forces in addition to drag forces using a simple semi-empirical equation without having any experimental or theoretical verification. This equation calculates the forces for the given wind speed at the center of a building, at any instant, assuming that the tornado wind is like a SBL wind. McDonald and Selvam (1985) verified and suggested modifications for the application of the inertial effect suggested by Wen (1975) by using computer simulation based on the principles of fluid dynamics. The main drawback of Wen's procedure is that the equation calculates the effect of drag and inertia separately. The inertial effect is considered as if the wind flow is inviscid. In reality, wind is viscous and highly turbulent.

3.1. Experimental studies

Jischke and Light (1983) studied the effect of a tornado-like vortex on a rectangular building in a wind tunnel using a Ward simulator. The vortex is simulated in the wind tunnel without any translational velocity, i.e., the tornado is like a freestanding vortex. Bienkiewicz and Dudhia (1993) also simulated a standing vortex (very similar to Jischke and Light) and reported the pressure coefficients on the roof of a cubic building. The limitations in both of these studies are that there is no translational velocity for the tornado.

3.2. Computer modeling studies

Wilson (1977) conducted computer modeling of tornadic effects on square and rectangular buildings using a two-dimensional Euler code and a Rankine-combined vortex model for the tornado simulation. However, because the effects of viscosity and turbulence were neglected, and the grid produced was very course, the value of the computed force coefficients may not bear any practical application and the accuracy is quite questionable.

In recent years, computational wind engineering has been developed to such an extent that wind flows around buildings are computed considering the viscous and turbulence effect of wind. The results from computation compare reasonably well with experimental results for SBL wind (Selvam 1992). Using these experiences Selvam (1993) conducted further computer modeling of tornado effects on building in three dimensions. In this work, the effect of viscosity and turbulence is considered. The turbulence model (k-ε) and the boundary conditions used in that study were not satisfactory. Due to computer storage and CPU time limitations, more detailed work could not be conducted at that time.

In Selvam *et al.* (2002), the interaction of a tornado on a two-dimensional circular cylinder at Reynolds number of 1000 is reported in detail. The computation is considered to be direct simulation. The flow visualization showed the development of the tornado vortex in the computational field. Results show that when the tornado is far away from the cylinder, the computed C_D and C_L are the same as for free stream flow. The computed mean C_D of 1.4 and S_t of 0.235 for free stream flow are in comparison with Selvam and Qu (2000) for a Reynolds number (R_e) of 1000. Hence, the results of the tornado interaction can be considered with confidence. Also reported, the tornado forces were about 5 times less than those from the semi-empirical equations of Wen (1975), because Wen computed the forces using the instantaneous velocity at the center of the building. This principle is not valid because in a tornado, at each instant in time, the velocity varies. This is also illustrated using CFD work.

4. Computer modeling

The tornado-structure interaction is a complex phenomenon. For instance, the details of tornado wind speed and turbulence from ground level up to 100 meters are needed. Most of the work done by meteorologists has been concerned with wind flow 100 meters or more above the ground. They predict the maximum wind speed generated by a tornado near the ground using a stationary vortex. In tornado-structure interaction modeling, the tornado is moving with respect to the building and hence the details of the tornado wind speed at every instant of time are essential to impose the proper boundary conditions.

4.1. Tornado wind field modeling

The simplest model that can satisfy the NS equations for tornado simulation is the Rankine-Combined Vortex Model (RCVM) as reported in Lewellen (1976). In RCVM, the tangential velocity varies linearly out 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 (see Fig. 1). Here, r_{max} is the maximum radius of the forced vortex region as well as the location of the peak tangential velocity. At radii larger than r_{max}, V_θ decreases by $\alpha r_{max}^2/r$. This region is commonly called the free vortex region. In addition, the tornado moves with a translational velocity, V_t, with respect to the building. This model does not include vertical velocity; however, in the actual tornado, vertical velocity does occur inside the vortex core. To consider the effect of the boundary layer, a logarithmic variation from the ground is considered, as reported by Selvam (1993). As an initial study in this work, this is the model that is employed. 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 center of the building, the velocity components in the x and y directions are expressed as:

$$
\begin{aligned}
&\text{if } r \le r_{max} \quad Vx=(V_t-y\alpha)Zf \quad Vy=(x-V_t t)\alpha Zf\\
&\text{if } r > r_{max} \quad Vx=(Vt-Cy)Zf \quad Vy=(x-V_t t)CZf
\end{aligned}
\tag{1}
$$

Where: $C=\alpha r_{max}^2/r^2 \qquad r^2=(x-V_t t)^2+y^2 \qquad Zf=u^*\ln((z+z0)/z0)/\kappa$

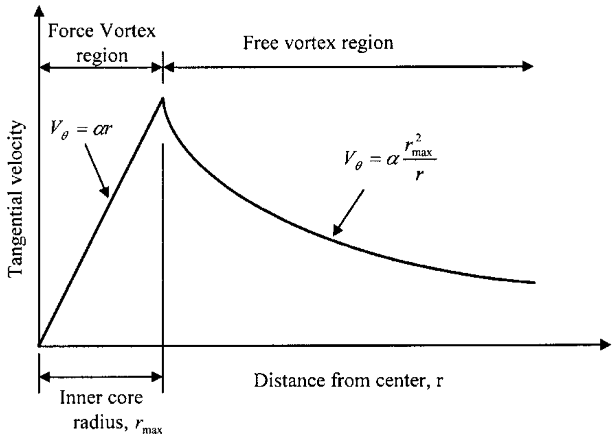


Fig. 1 Tangential velocity (V_θ) for Rankine-combined vortex tornado model

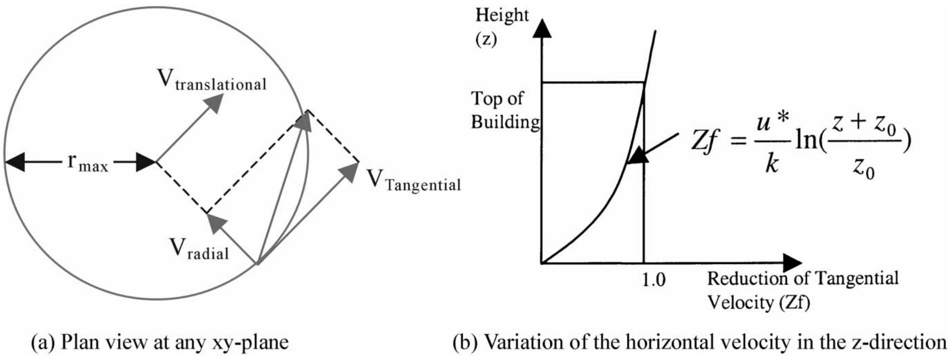


Fig. 2 Illustrations of the boundary layer effects in the tornado model

Here r is the distance from vortex center to boundary point, 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 considered to be one at the top of the cube (see Fig. 2b).

The Burgers-Rott vortex model has vertical and radial velocity in addition to tangential velocity (Lewellen 1976). This model satisfies the NS equations and accounts for the vertical velocity inside the tornado vortex core. The tangential velocity distribution is almost the same as the RCVM. The Sullivan vortex is similar to the Burgers-Rott model but it is a two-celled vortex. This also satisfies the NS equations. It has an inner cell in which air flow descends from above and flows outward to meet a separate air flow that is converging radially. This is the simplest vortex that can describe the flow in an intense tornado with a central downdraft as reported in Lewellen (1976). There are several other models reported in meteorological literature. To choose one that suits the boundary layer for tornado-structure interaction is a difficult task. The RCVM model is considered as a start for this preliminary investigation.

4.2. 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 the Reynolds averaged stresses using transport equations or simple equations. One form of Reynolds averaged equation is the k-ε model and it is widely used in engineering applications. Selvam (1993) in his earlier work on tornado effects on buildings used this turbulence model. Because the turbulence statistics are not available in literature, proper values could not be given on the boundary. The large eddy simulation turbulence model is based on the filtered Navier-Stokes equations. Direct simulation requires a large number of grid points, hence it is possible to apply to wind engineering problems with low Reynolds number flow (Selvam and Qu 2000). The turbulence in the flow is modeled using the large eddy simulation, which requires less number of points than DS, and more accurate than the RANS equations. The two and three-dimensional equations for an incompressible fluid using the LES turbulence model in general tensor notation are as follows:

Continuity Equation: $U_{i,i}=0$ (2)

Momentum Equation: $U_{i,t}+(U_j-V_j)U_{i,j}=-(p/\rho+2k/3)_{,i}+[(\nu+\nu_t)(U_{i,j}+U_{j,i})]_{,j}$ (3)

where: $\nu_t=(C_s h)^2(S_{ij}^2/2)^{0.5}$ $\quad Sij=U_{i,j}+U_{j,i}$ $\quad h=(h_1h_2h_3)^{0.333}$ $\quad k=(\nu_t/(C_k h))^2$

Empirical Constants: $C_s=0.15$ for 2D & 0.1 for 3D $\quad C_k=0.094$

Where U_i, and p are the mean velocity and pressure respectively, V_i is the grid velocity, k is the turbulent kinetic energy, ν_t is the turbulent eddy viscosity, h_1, h_2, and h_3 are control volume spacing in the x, y, and z directions, respectively, and ρ is the fluid density. Here the area or volume of the element is used for the computation of h. A comma represents differentiation, t represents time, and $i=1$, 2 and 3 refers to variables in the x, y and z directions. For further details, one can refer to Selvam (1998).

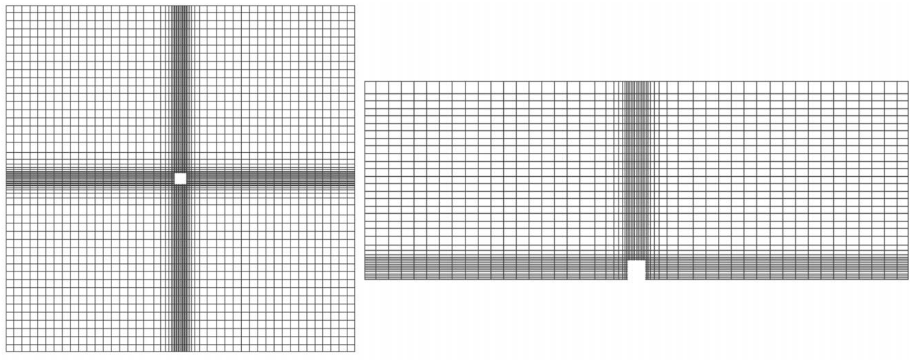
4.3. Problem geometry and boundary conditions

A plan view of the relative position of the tornado with respect to the building is shown in Fig. 4. The tornado translates across in the x-direction. The width of the cube is assumed to be 20.3 m. To nondimensionalize the problem, the width of the cube and the density of air are made to be unity. With that assumption, the parameters of the tornado are assigned the following values:

- $\alpha=1.5$ (see Fig. 1)
- inner core radius (r_{max})=61 m=3.0 units
- translational velocity (V_t)=**45.4 mph**=20.3 m/s=1 units/s

With the value of $\alpha=1.5$, the largest tangential velocity, $V_{tangential}$ as shown in Fig. 1, is equal to:

- $V_{tangential}=\alpha* r_{max}$=4.5 units/sec=91.35 m/s=**204 mph**
- $V_{max}=V_{tangential}+V_{translational}$=4.5 units/sec+1.0 units/sec=**250 mph**



(a) (b)

Fig. 3 Three-dimensional grid (61×61×37 points) viewed in the (a) *xy*-plane, (b) *xz*- and *yz*-plane

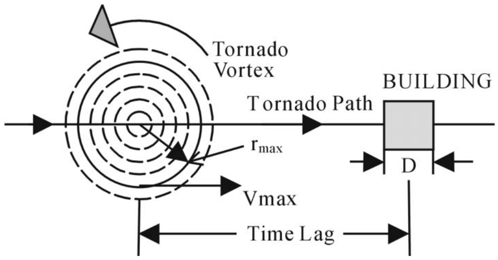


Fig. 4 Schematic of plan view of dynamics of flow field for 3D program

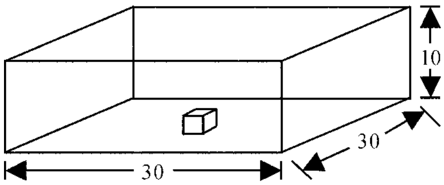


Fig. 5 Isometric view of computational domain

Table 1 Grid properties

	Points on bldg. face	Min. Spacing next to bldg.	Max. Spacing in domain	Total # of points
61×61×37	10×10	0.072	0.75	137,677

The boundary of the computational domain is located at a reasonable distance away from the cube. The domain has a size of 30 unit×30 unit×10 units as shown in Fig. 5. The dimensions of the grid that was generated for this study are presented in Table 1. The velocities are specified at the far-away boundaries of the three-dimensional domain as shown in Fig. 5. On the surface of the cube, the velocities are considered to be zero, i.e., no-slip condition. From these boundary conditions, at each time step the interior velocities and pressures are computed by solving the NS equations.

4.4. Numerical procedure

The three-dimensional incompressible, unsteady NS equations are integrated using control volume procedure. The resulting equations are solved on an orthogonal grid system. The velocities and pressures are stored on a nonstaggered grid system. The equations are integrated in time by a semi-implicit form as reported by Selvam (1997). In this work, line iteration and modified incomplete conjugate gradient procedure are used to solve the momentum and the pressure equations, respectively.

4.5. Nomenclature

The nomenclature used in this study is given below:

$$Cx = F_x/(0.5\rho V^2 A) \quad Cy = F_y/(0.5\rho V^2 A) \qquad Cz = F_z/(0.5\rho V^2 A) \qquad R_e = VD/\nu \tag{4}$$

Here, Cx, Cy and Cz are the computed force coefficients in the x, y, and z directions, respectively. F_x, F_y, and F_z are the respective forces in the x, y and z directions, A is the area of the respective building face, V is the reference velocity, ρ is the density of air, and ν is the kinematic viscosity of air. The reference velocity is the free stream velocity with the absence of the tornado vortex, which is equal to the translational velocity, V_t. R_e represents the Reynolds number. The forces are computed by integrating the pressures on the wall in each direction.

5. Results and discussion

5.1. Tornado-structure interaction

The primary advantage of CFD modeling of the tornado-structure interaction is the capability to investigate the wind flow from any angle at any instant in time. With adequate grid refinement, it is possible to capture even very small vortices that form around the corners and roof of the building. Fig. 6 below displays the tornado translation across the domain in the x-direction, and the interaction of the wind and cubic building at various instances in time (t=7 sec, 10 sec, 13 sec) for a time lag of 10 sec. The time lag refers to the amount of time from the beginning of computational simulation to when the axis of the tornado is aligned with the vertical axis of the building. The flooded contour in the isometric view (left pictures) represents the variance in pressure. There exists a drastic drop of pressure inside the tornado core. When the structure is fully surrounded by the tornado vortex, there occurs vortex shedding from every corner of the building in the direction of the wind rotation. This is illustrated in Fig. 7.

The rotational wind created by a tornado, not unlike high-speed SBL wind, 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). The numerical simulations performed in this work may perhaps shed some light on why this occurs. It is shown in Fig. 8 that around all sides of the building are produced large amounts of vertical wind. 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.

5.2. Force coefficients on building

The computed force coefficients Cx, Cy, and Cz are plotted in Fig. 9 for the proposed RCVM model with the dimensions given in the previous section. As shown in Fig. 9, the absolute maximum values of Cx, Cy, and Cz with vortex, are 13, 15, and 28, respectively. However, the calculation of these force coefficients raises a questionable subject in determining what value shall

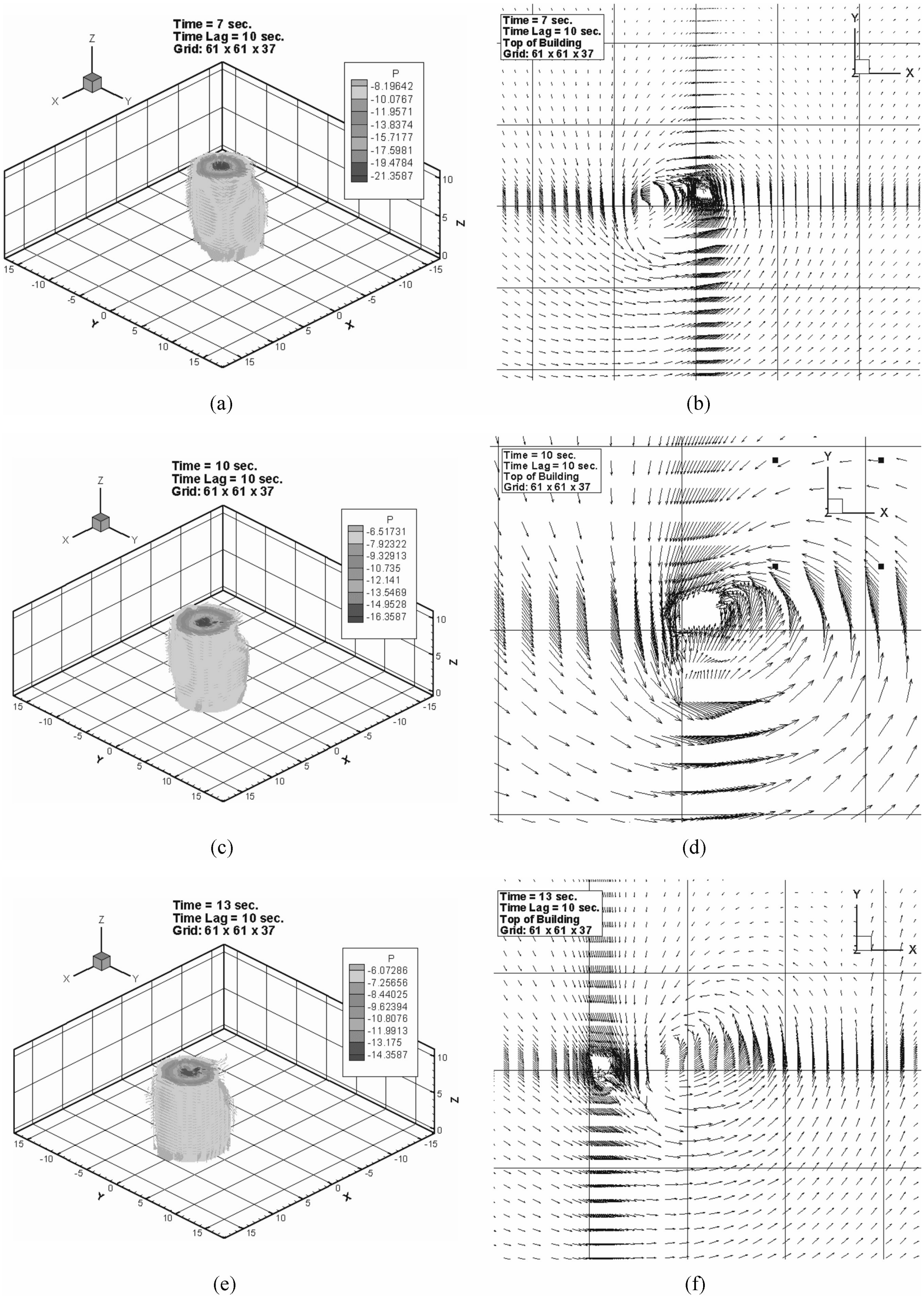


Fig. 6 Isometric and *xy*-plane view of tornado velocities and pressures (Grid: 61×61×37) at (a) and (b) 7 sec.; (c) and (d) 10 sec.; (e) and (f) 13 sec.

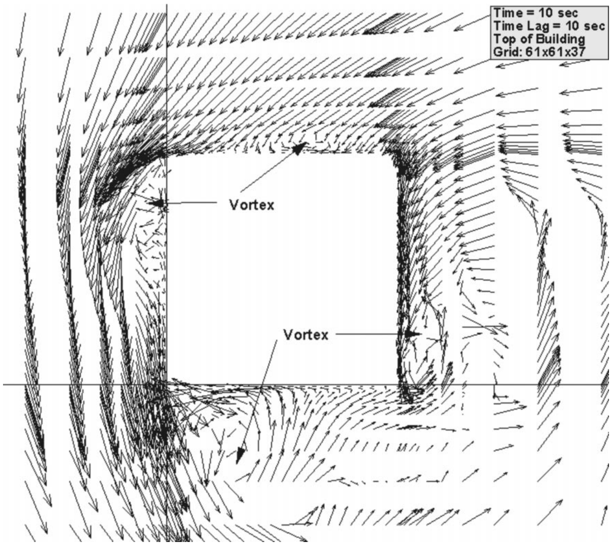
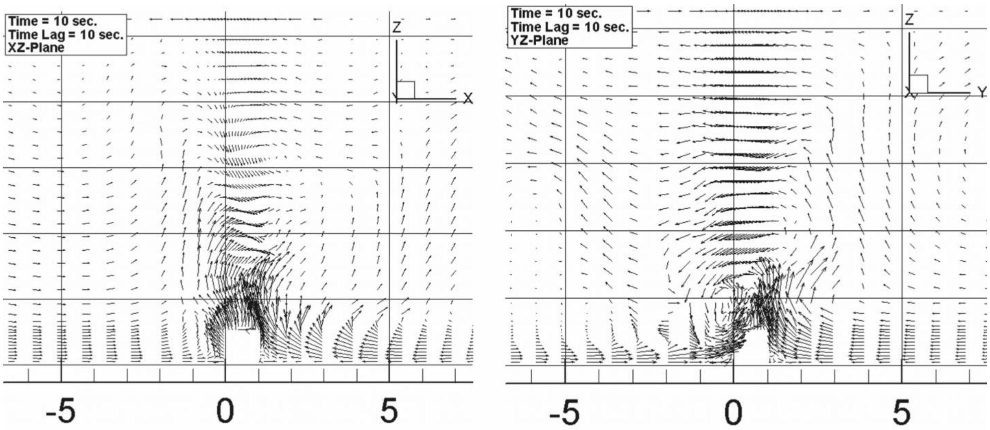


Fig. 7 Illustration of vortex-shedding behind every corner of building



(a) (b)

Fig. 8 Views of vertical velocity for the 61×61×37 grid with tornado surrounding building with (a) the *xz*-plane, and (b) the *yz*-plane

be assigned to the reference velocity: vortex translational velocity or the maximum velocity in the wind field domain? The values presented in Fig. 9 are calculated using Eq. (4) with the reference velocity equal to the translational velocity of the tornado vortex: 1.0 units/sec. However, much of the tornado forensic studies are concerned with determining the maximum wind speed of a tornado; furthermore, all tornadoes are categorized on Fujita's scale by their maximum velocities. Therefore, perhaps the maximum velocity in the computational domain is appropriate to use for comparison with SBL wind. It is also worth noting that the maximum velocity in the tornado wind field only occurs in a narrow width of the computational domain (at the core radius on one side of the vortex; see Fig. 4) as opposed to throughout the region as in SBL wind. Table 2 above shows the force

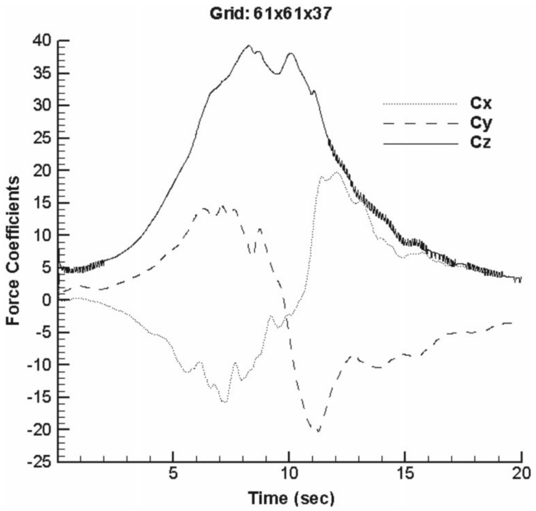


Fig. 9 Time variation of force coefficients due to Rankine combined vortex model for 20 sec

Table 2 Results and comparisons of force coefficients

	Equation (4) (With $V_{ref}=V_t=1.0$ units/sec)	Equation (4) (With $V_{ref}=V_{max}=5.5$ units/sec)	SBL Wind (Velocity of 1.0 units/sec)	Comments
Cx	13	0.43	0.76	Tornado Model produces lower *Cx* than SBL
Cy	15	0.50	0.01	--------------
Cz	28	0.93	0.65	Tornado Model produces higher *Cz* than SBL

coefficients ascertained with both reference velocities. It is shown that by comparing columns 3 and 4 in the table, the drag coefficient produced by the tornado model is less than that for SBL wind, which can be attributed to the fact that the maximum velocity isn't applied along the windward face of the building. The maximum velocity is actually never directly applied to the building due to the fact that the vortex radius is larger than the building. On the roof, however, the force coefficient remains much higher. Hence, the vortex flow on the boundary layer increases the load on the roof. Keep in mind that the RCVM has no vertical velocity. A Burgers-Rott vortex may increase the *Cz*. This trend is similar to that reported in Selvam *et al*. (2002). These results indicate that the procedure suggested by Wen (1975) overestimates the forces.

The force coefficients described above and presented in Fig. 9 are calculated using the integrating pressures on each side of the building. However, it is also important to determine the peak pressure on any wall or roof of the building. An additional output file was created which calculates the pressure coefficient, *Cp*, around the cubic building and plots the data in a two-dimensional spread. The equation used to calculate the pressure coefficient is:

$$Cp=\Delta P/(0.5\rho V^2 A) \tag{5}$$

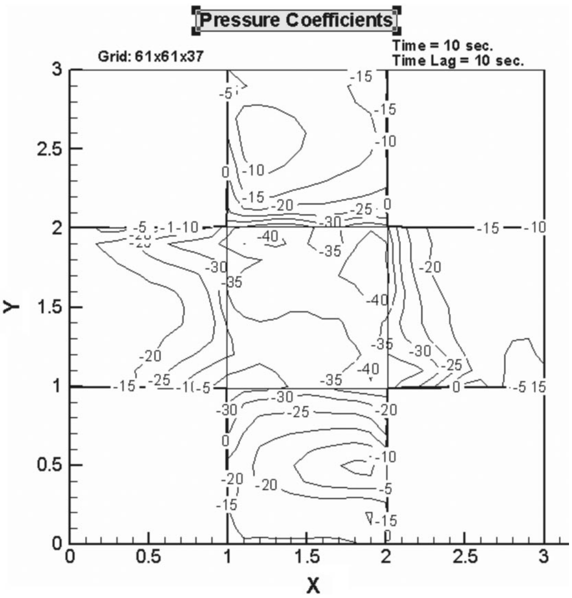


Fig. 10 Pressure coefficient contour plot for cubic building with 100 points on each face

where ΔP is the pressure difference, $P-P(ref)$ [$P(ref)$ is equal to 0.0]. This spread is shown in Fig. 10 with the roof in the middle and the four walls folded up into the same plane. The highest pressure coefficient recorded for the building was -40 on the roof. The reference velocity for equation (5) was set equal to 1.0, the translational velocity of the tornado. As mentioned above, changing the value to the maximum velocity in the wind field will yield more compatible results.

6. Conclusions

In this paper, the status of the tornado-structure interaction and tornado wind field models 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) The flow visualization shows the development of the vortex in the flow region in time as it moves. From the flow visualizations, it is found that the grid resolution needs further refinement both on the building face for more accurate pressure contour plots, and surrounding the building to illustrate vortex shedding.
(2) It is found that the force coefficients are less than the straight boundary layer wind in the *x*-direction. In the *z*-direction, the tornado force coefficients are higher. Tornado models with vertical velocity need to be considered for better understanding. The Rankine-combined vortex does not have vertical velocity in the wind field. The computational simulation of the Burgers-Rott vortex will provide a more realistic knowledge of the effects of vertical tornado velocity on a structure, especially the roof.
(3) 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.

References

Bienkiewicz, B. and Dudhia, P. (1993), “Physical modeling of tornado-like flow and tornado effects on building loading”, *Proceedings: The 7th US National Conference on Wind Engineering*, Edited by: Gary C. Hart, Los Angeles, June 27-30, 95-104.

Jischke, M.C. and Light, B.D. (1983), “Laboratory simulation of tornadic wind loads on a rectangular model structure”, *J. Wind Eng. Ind. Aerod.*, **13**, 371-382.

Lewellen, W.S. (1976), “Theoretical models of the tornado vortex”, *Proceedings of the Symposium on Tornadoes*, Edited by: R.E. Peterson, Texas Tech University, Lubbock, June 22-24, 107-143.

McDonald, J.R. and Selvam, R.P. (1985), “Tornado forces on buildings using the boundary element method”, *Proceedings: Fifth U.S. National Conference on Wind Engineering*, Texas Tech University, Lubbock, Texas, 5B41-48, November 6-8.

Mehta, K.C., Minor, J.E. and McDonald, J.R. (1976), “Wind speed analysis of April 3-4 tornadoes”, *J. Struc. Div.*, ASCE, **102**(ST9), 1709-1724.

Selvam, R.P. (1992), “Computation of pressures on Texas tech building”, *J. Wind Eng. Ind. Aerod.*, **43**, 1619-1627.

Selvam, R.P. (1993), “Computer modeling of tornado forces on buildings”, *Proceedings: The 7th US National Conference on Wind Engineering*, Edited by: Gary C. Hart, Los Angeles, June 27-30, 605-613.

Selvam, R.P. (1997), “Computation of pressures on Texas tech building using large eddy simulation”, *J. Wind Eng. Ind. Aerod.*, **67 & 68**, 647-657.

Selvam, R.P. (1998), “Computational procedures in grid based computational bridge aerodynamics”, in *Bridge Aerodynamics*, Larsen, A. and Esdahl (eds), Balkema, Rotterdam, 327-336.

Selvam, R.P. and Qu, Z. (2000), “Adaptive hp-finite element method for wind engineering”, *Proceedings: 3rd International Symposium on Computational Wind Engineering*, pp. 61-64, University of Birmingham, UK, Sep. 4-7.

Selvam, R.P. and Qu, Z. (2002), “Adaptive p-finite element method for wind engineering”, *Wind and Structures*, **5**(2-4), 301-316.

Selvam, R.P., Roy, U.K. and Jung, Y. (2002), “Investigation of tornado forces on 2D cylinder using computer modeling, in Wind Engineering”, *Proceedings of NCWE 2002*, Edited by: K. Kumar, Phoenix Publishing House, New Delhi, 342-353

Wen Y.K. (1975), “Dynamic tornadic wind loads on tall buildings”, *J. Struc. Div.*, ASCE, **101**(ST1), 169-185.

Wilson, T. (1977), “Tornadic structure interaction: A numerical simulation”, Report: UCRL-52207, Lawrence Livermore Laboratory, University of California.

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