Numerical study of tornado-induced aerodynamic forces for a gable-roof building by using LES model

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Abstract

Tornado-induced aerodynamic forces for a gable-roof building have been numerically calculated. Simulated aerodynamic forces acting on building model showed satisfactory agreement with those in experiment. Some discrepancies between numerical and laboratory simulations may results from the differences of building geometry and the different tornado status. Another gable-roof building model one and half times as large as the original one was built. The aerodynamic forces on the enlarged building were calculated and compared with those on the building model without enlargement to examine the building size effects. No large difference for force coefficients was observed, indicating that the force coefficients are insensitive to the building size. In order to examine the influence from tornado translation, we applied dynamic mesh method to calculate the aerodynamic forces induced by the tornado at a translation speed. Favourable agreement was found between the force coefficients in the situation with tornado translation and those without, which means the influence from tornado translation is not significant.

Keywords: Tornado-like vortex, gable-roof building, aerodynamic forces, LES, CFD simulation.

1 Introduction

Tornados, as the most extreme storm in the atmosphere, are not studied as extensively as the straight line winds. In recent decades tornado occurrence increases and significant amounts of damages as well as fatalities are caused. There were 1,897 tornadoes reported in the US in 2011, due to which at least 577 people were perished. On May 7th this year a tornado tore through Ibaraki in Japan, killing one person, injuring dozens of others and destroying scores of houses. Therefore, clarifying the interaction between tornado-like vortex and structure is very meaningful. Laboratory simulation is currently the main approach studying the tornado-structure interaction. A.r. Mishra et al. (2008) used a tornado vortex simulator to generate a single-celled tornado-like vortex and studied the wind loadings on a cubical model. F.L. Haan et al.(2010) presented wind loads on a one-story, gable-roofed building in a laboratory-simulated tornado and compared them with provisions ASCE 7-05. Hui Hu et al. (2011) carried out an experimental study to examine the effects of several important parameters. Jeremy Michael Case(2011) studied the effects of variations in building geometry on tornado-induced wind loads in a laboratory-simulated tornado. However, numerical studies about the interaction between tornado and building are still very few.

In this study, by using LES turbulent model, we numerically calculated the forces acting on a gable-roof building induced by a tornado and examined the effects of building size as well as translation of tornado. The remainder of this paper is organized as follows: in section 2, the details of the numerical model are described. Section 3 presents the results of numerical simulation, including the tornado like vortex flow fields, the wind forces on the building and the effects from both building size and tornado translation.

2 Numerical model

In respect that momentum and mass are mostly transported by large eddies, and considering the current computing capability, large eddy simulation (LES) is adopted to simulate the tornado-like vortex. In LES, large eddies are computed directly, while the influence of eddies smaller than grid spacing are modeled. Even though LES is computationally expensive, it can provide detailed and accurate information. Boussinesq hypothesis is employed and standard Smagorinsky-Lilly model is used to calculate the subgrid-scale (SGS) stresses.

2.1 Governing equations

The governing equations applied in LES model are obtained by filtering the time-dependent Navier-Stokes equations in Cartesian coordinates (*x*, *y*, *z*) and expressed in the form of tensor as follows:

$$\frac{\partial \rho \widetilde{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\frac{\partial \widetilde{u}_i}{t} + \rho\frac{\partial \widetilde{u}_i \widetilde{u}_j}{x_j} = \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \widetilde{u}_i}{\partial x_j}\right) - \frac{\widetilde{p}}{\partial x_i} - \frac{\tau_{ij}}{\partial x_j} \tag{2}$$

where, the symbol "$\widetilde{\ }$" indicates space filtering, so $\widetilde{u}_i$ and $\widetilde{p}$ are filtered velocities and pressure respectively, μ is the dynamic viscosity, ρ is density, τ_{ij} is SGS stress and is modeled as follows:

$$\tau_{ij} = -2\mu_t \widetilde{S}_{ij} + \frac{1}{3}\tau_{kk}\delta_{ij}; \qquad \widetilde{S}_{ij} = \frac{1}{2}\left(\frac{\partial \widetilde{u}_i}{\partial x_j} + \frac{\partial \widetilde{u}_j}{\partial x_i}\right) \tag{3}$$

where, μ_t denotes SGS turbulent viscosity, and $\widetilde{S}_{ij}$ is the rate-of-strain tensor for the resolved scale, δ_{ij} is the Kronecker delta. Smagorinsky-Lilly model is used for the SGS turbulent viscosity:

$$\mu_t = \rho L_s^2 |\widetilde{S}| = \rho L_s \sqrt{2\widetilde{S}_{ij}\widetilde{S}_{ij}}; \qquad L_s = \min(\kappa d, C_s V^{\frac{1}{3}}) \tag{4}$$

in which, L_s denotes the mixing length for subgrid-scales, κ is the von Kármán constant, 0.42, d is the distance to the closest wall and V is the volume of a computational cell. In this study, C_s is Smagorinsky constant and is determined as 0.032 based on Oka and Ishihara (2009).

For the wall-adjacent cells, when they are in the laminar sublayer, the wall shear stresses are obtained from the laminar stress-strain relationship:

$$\frac{\widetilde{u}}{u_\tau} = \frac{\rho u_\tau y}{\mu} \tag{5}$$

If the mesh cannot resolve the laminar sublayer, it is assumed that the centroid of the wall-adjacent cells falls within the logarithmic region of the boundary layer, and the law-of-the-wall is employed, which is expressed as:

$$\frac{\widetilde{u}}{u_\tau} = \frac{1}{\kappa}\ln E\left(\frac{\rho u_\tau y}{\mu}\right) \tag{6}$$

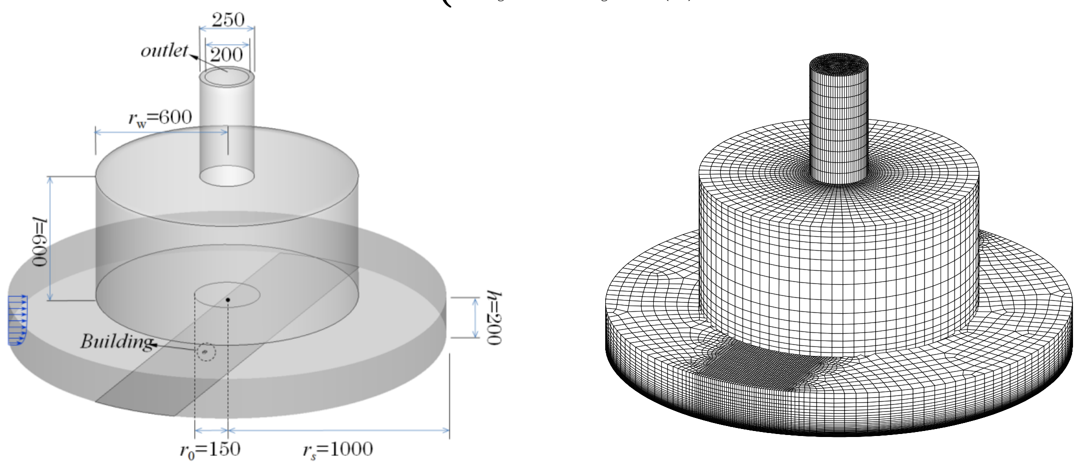
where, $\widetilde{u}$ is the filtered velocity tangential to wall, y is the distance between the center of the cell and the wall, u_τ is the friction velocity, and the constant E is 9.793.

Finite volume method is used for the present simulations. The second order central difference scheme is used for the convective and viscosity term, and the second order implicit scheme for the unsteady term. SIMPLE (semi-implicit pressure linked equations) algorithm is employed for solving the discretized equations (Ferziger and Peric, 2002).

2.2 Numerical tornado simulator and building

The configurations of the numerical tornado simulator are shown in Fig.1(a). Two significant geometry parameters are the height of the inlet layer, h, and the radius of the updraft hole, r_0, which are 200mm and 150mm respectively. Reynolds number, $\mathrm{Re} = W_0 d/\nu$, is calculated as 1.6×10^5, where W_0 is the updraft wind velocity at the outlet, 9.55m/s, and d is the diameter of the updraft hole. In this study, we specified the wind profile at the inlet instead of using guide-vanes to provide angular momentum, which have been studied and proved by Liu(2013) as an effective way to generate different types of tornados through changing the inflow angle. The velocity profiles at the inlet are specified as below:

$$\begin{cases} U_{r_s} = U_1 \frac{z}{z_1}^{\frac{1}{n}} \\ V_{r_s} = -U_{r_s}\tan(\gamma) \end{cases} \tag{7}$$



(a) Geometry of tornado simulator (b) Grid of tornado simulator

Figure.1 Geometry (a) and grid system (b) for tornado simulator.

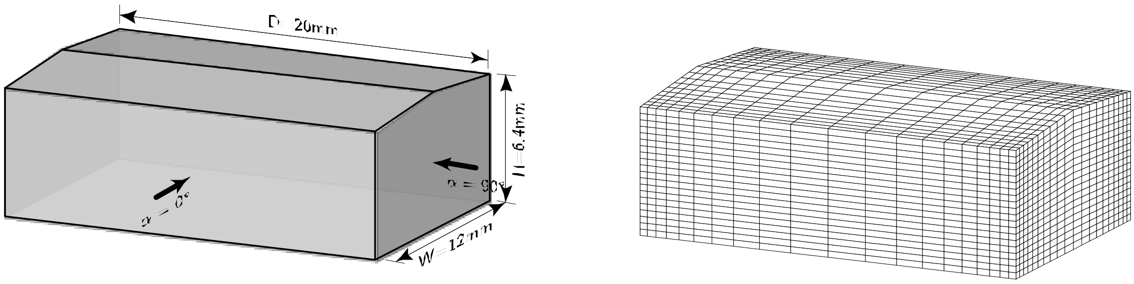
where, U_{r_s} and V_{r_s} are radial and tangential velocities at $r = r_s$, n equals to 7, the reference velocity U_1 and the reference height z_1 are set to 0.24m/s and 0.01m respectively , γ is the degree of the inflow angle specified as 84.4^o corresponding to the tornado at multi-vortex stage. The building model is mounted on the bottom of the convergence region.

Fig.1(b) shows the mesh system of the numerical tornado simulator. In order to accurately capture the flow fields of tornado-like vortices and quantitatively investigate the wind loading on the building, in the central part of convergent zone and the vicinity near the ground, very fine mesh is considered. The minimum grid size is 0.1mm in vertical direction and 0.15mm in horizontal direction. The growing ratios in the two directions are less than 1.2 in order to avoid a sudden change of the grid size. The total mesh number is about 8×10^5. Table.1 illustrates the computational parameters for the tornado simulator.

Table.1 Parameters for numerical tornado simulator

Mesh number	8×10^5
Non-dimensional time step size	$\Delta t W_0/r_0 = 0.032$
Reynolds Number	$\mathrm{Re} = W_0 d/\nu = 1.6\times10^5$
Inflow angle	$\gamma = 84.4^\circ$
Convergence criteria	5×10^{-4}

A gable roofed model with a 24m×38m plan, eave height of 12.2m and roof slope of 1:12 in full scale is applied in the present study. As discussed later, the length scale of the simulated tornado is calculated as 1:1900 by matching the size of numerical tornado with that of Spencer, South Dakota F4 tornado(2005), thus the gable-roofed building model simulated here is also scaled with 1:1900. The scaled dimension and the orientation of the building are illustrated in Fig.2(a), where D and W are the length and width respectively. Details of the grid distribution on the surface of the building are shown in Fig.2 (b). For clarity, only half of real grids are plotted.



(a) Geometry of building model.

(b) Grid of building model, plotted with half of real grids density for clarity.

Figure.2 Geometry (a) and grid (b) of building model.

3 Numerical results

In this section, firstly the flow fields of tornado like vortex are presented, secondly we calculate the aerodynamic forces on the building model and compare them with those in experiment by J.M.Case(2011), then the effects of building size are checked, finally whether or not the translation of tornado influences the aerodynamic forces on the building model is clarified.

3.1 Tornado flow fields

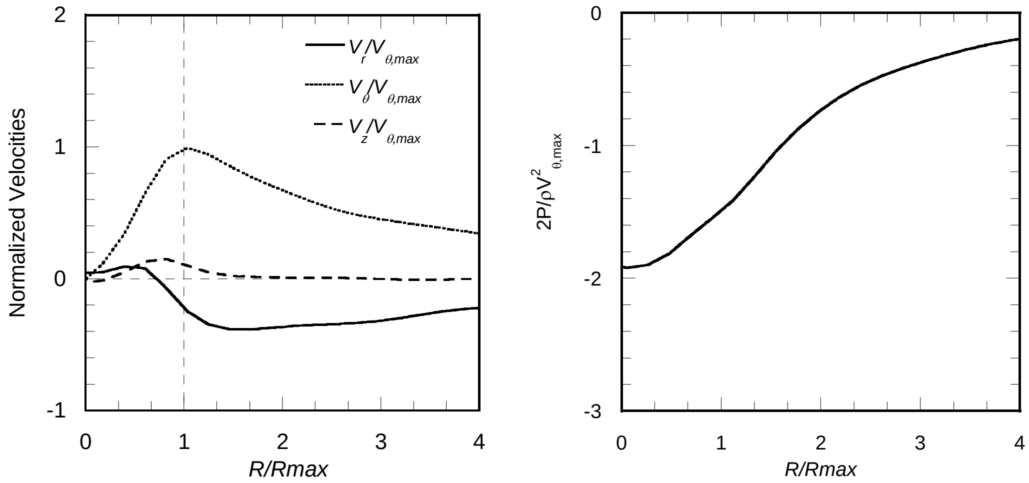
In the present study, the flow fields of tornado like vortex were quantified before the gable-roof building model was mounted. The largest time-averaged tangential velocity, $V_{\theta,\max}$, at the mean roof height, H, was measured as 22.8m/s. The radius, $R_{\max}$, at which $V_{\theta,\max}$ occurs, is 0.06m. Using a length scale of λ_l= 1:1900, the scaled up radius of the vortex core was found to be 110m. This matches well with the radius of the core at low elevation in Spencer, South Dakota F4 tornado (2011).

Based on the calculation of the flow fields in the tornado vortex, the swirl ratio can be calculated as:

$$S = \frac{\pi r_c^2 V_c}{Q} \tag{8}$$

where, r_c is radius at which the maximum tangential velocity, V_c, in the quasi-cylindrical region occurs, and Q is the flow rate. The parameters r_c, V_c and Q are measured as 0.112m, 18.62m/s and 0.3m^3/s respectively, thereby the swirl ratio is 2.44 in this study.

Time-averaged radial, tangential and vertical velocities at mean roof height were normalized by $V_{\theta,\max}$ and shown in Fig.3(a). The radial velocity V_r experiences negative value in most regions of the tornado-like flow fields indicating an effect drawing the building toward tornado itself. The magnitude of tangential velocity, V_θ, is much larger in comparison with V_r and exhibits maximum value at the location $R = R_{\max}$. Compared with the horizontal components, the magnitudes of the vertical component velocity, V_z, show very small values. Tornado induced pressure on the ground is illustrated in Fig.3(b), where great pressure drop can be clearly found at the center. Therefore, we can imagine that at the center the vertical force acting on the gable-roof building will be very large. The pressure on the ground recovers gradually as the distance to the simulator center increases.



(a) (b)

Figure.3 Profiles of velocity components at mean roof height (a) and pressure coefficient on the ground of simulator (b), calculated with absence of the building

3.2 Tornado-induced forces

The building was tested with thirteen different distances between the center of the building and the center of the tornado simulator from 0mm to 240mm with a step size of 20mm. The tornado induced aerodynamic forces on the building are normalized as:

$$\begin{cases} C_{F_x} = \frac{F_x}{\frac{1}{2}\rho V_{\theta,\max}^2 WH} \\ C_{F_y} = \frac{F_y}{\frac{1}{2}\rho V_{\theta,\max}^2 DH} \\ C_{F_z} = \frac{F_z}{\frac{1}{2}\rho V_{\theta,\max}^2 WD} \end{cases} \quad (9)$$

in which, F_x, F_y and F_z indicate the time averaged forces in *x* and *y* directions respectively. The profiles of the computed force coefficients are shown in Fig.4, where the *x* axis is normalized by $R_{\max}$. The negative sign of the force in *x* direction and the positive sign of the force in *y* direction indicate that the gable-roof building is pulled inward and pushed tangentially by the tornado. Both the profile of C_{F_x} and that of C_{F_y} show peaks at about $R = R_{\max}$, and reach to zero at the center of the simulator. However, different with the horizontal components, the lift force coefficients still exhibit very large value at the center, which is due to the significant atmospheric pressure drop there.

J.M.Case(2011) carried out a research to examine the wind loading on low building models in a laboratory-simulated tornado, in which Model 1 is geometrically similar with the building model used in this study. Fig.4 shows the comparison between the force coefficients of present simulation and those of Model 1 in experiments by J.M.Case(2011). The peak values and where the peak values occur show satisfactory agreements. Some discrepancies are owing to the factor that the geometry of the building model in present research is not exactly same with that of Model 1. In the present study, the geometry parameters of the building, i.e. D/W, H/W and the roof slope, are 1.67, 0.54 and 1:12 respectively, on the other hand, the corresponding values for Model 1 are 1.5, 0.46 and 1:3.5 respectively, as illustrated in Table.2.

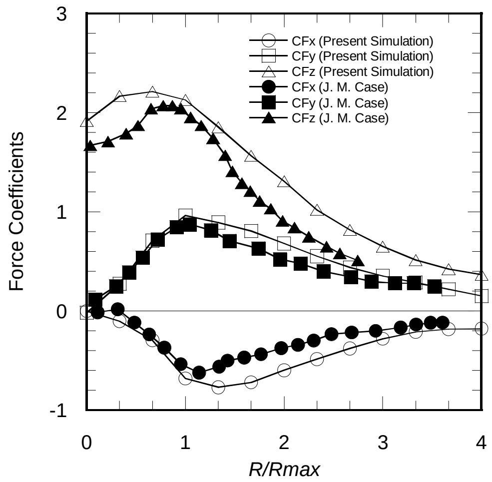


Figure.4 Tornado-induced forces on the building mode compared with the experimental results by J.M. Case.

Table.2 Comparison of representative values used in present study and those in experiments by J.M.Case

	Swirl ratio(S)	Length scale	D/W	H/W	Roof slope
Present study	2.44	1/1900	1.67	0.54	1:12
J.M.Case	2.6	1/100	1.5	0.46	1:3.5

3.3 Building size effects

In order to examine the sensitivity of wind loadings to the size of building model, another group of simulations were carried out. In these simulations, the building was enlarged to one and half times its original size but no change for the shape.

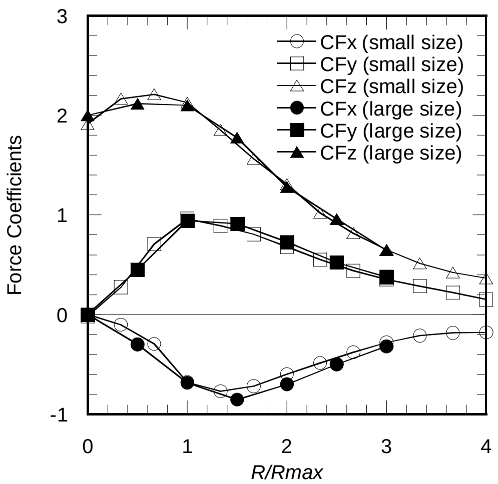


Figure. 5 Examination of size effects on wind forces acting on the building model, plotted are the aerodynamic force coefficients on the model in small size and those in large size.

The enlarged building model was placed at seven locations with distances to the center of the simulation ranging from 0mm to 180mm. Any other computational parameters used in this group were set exactly same as the discussion above. Since the size of the building model changes, the largest time-averaged tangential velocity, $V_{\theta,\max}$, at mean roof height and the radius, $R_{\max}$, at which $V_{\theta,\max}$ occurs were again extracted from the tornado flow fields calculated without existence of building model. The values of $V_{\theta,\max}$ and $R_{\max}$ in this group are 22.6m/s and 0.06m respectively. Fig.5 shows the comparison between the aerodynamic force coefficients of the original building model and those of the enlarged one. The results of the two groups almost coincide with each other, which is the indicative that the aerodynamic force coefficients are not sensitive to the building size. However, there should be a limitation for the enlargement, under which the influence of the building size can be neglected, above which the influence should be taken into consideration. Therefore further researches about this issue will be carried out in the future.

3.4 Tornado translation effects

Instead of being stationary, tornadoes observed in the nature usually translate at a speed, thus it is meaningful to examine the effects from the tornado translation. In this study we assume that the time for the full-scale tornado to pass over the full scale building is same as the time the simulated tornado takes to pass over the model-scale building. The translation speed of the tornado in Spencer, South Dakota was reported as 10m/s-30m/s by Wurman(2005) and the length of full scale building used in this examination is 38.1m, therefore the time it takes for the tornado to pass over the building is 2.54s. The length scale is 1:1900 for the numerical tornado simulator, so the scaled translation speed is calculated as 0.008m/s.

In this study sliding dynamic mesh technique was applied to simulate the translation of tornado. The building model is fixed on the ground and the simulator is moved at a speed of 0.008m/s. We run the simulation five times to obtain the ensemble averaged force coefficients. Results are shown in Fig.6, where the ensemble averaged aerodynamic forces are further smoothed using binned averaging method with a bin length of $0.2R_{\max}$. Superimposed on Fig.6 is the wind loading on the same building model induced by the tornado without translation. It can be found clearly that the normalized aerodynamic forces induced by the tornado with translation agree well with those without. A little larger value may result from the nonlinear effects of tornado translation. However, from engineering point of view, we can conclude that the effects from tornado translation are not significant.

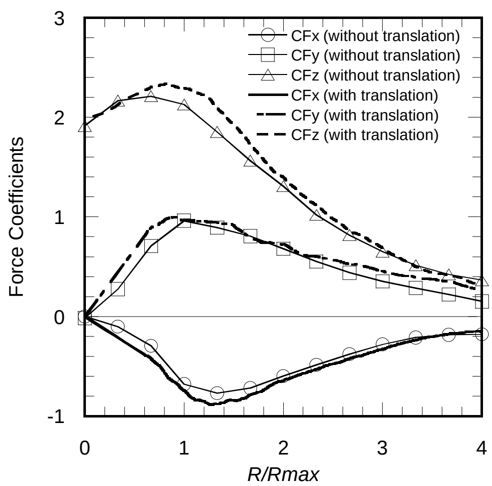


Figure.6 Examination of translation effects on wind forces acting on the building model, plotted are the normalized aerodynamic forces on the model induced by the tornado with translation speed and those without.

4. Conclusions

The aerodynamic forces acting on a gable-roof building model induced by the tornado are studied by using LES model. Following summarized the findings in this study:

1) Numerical simulated aerodynamic forces acting on the building model agree satisfactorily with those in experiment by J.M. Case(2011). Some discrepancies between these two studies are due to the difference of building geometry.

2) The gable-roof building model was enlarged one and half times. Aerodynamic forces on the enlarged building were calculated and compared with those on the building model without enlargement. For the force coefficients no large difference was observed, indicating that the force coefficients are insensitive to the building size.

3) By using dynamic mesh method, the aerodynamic forces induced by the tornado at a translation speed are computed. It is found that the force coefficients in the situation with tornado translation agree well with those without translation, which means the influence from tornado translation is not significant.

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