An experimental study of a high-rise building model in tornado-like winds

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A R T I C L E   I N F O

Article history:
Received 15 July 2009
Accepted 25 February 2011
Available online 3 April 2011

Keywords:
Tornado-like winds
Vortex flows
Flow–structure interaction
Aerodynamics of high-rise building
PIV measurements

A B S T R A C T

An experimental study was conducted to quantify the characteristics of wake vortex and flow structures around a high-rise building model as well as the resultant wind loads (both forces and moments) acting on the test model in tornado-like winds. In addition to measuring wind loads acting on the tested high-rise building model using a high-sensitivity load cell, a digital Particle Image Velocimetry (PIV) system was used to conduct detailed flow field measurements to quantify the evolution of the unsteady vortex and turbulent flow structures around the test model in tornado-like winds. The measurement results revealed clearly that the evolution of the wake vortex and turbulent flow structures around the test model as well as the resultant wind loads induced by tornado-like winds were significantly different from those in conventional straight-line winds. The detailed flow field measurements were correlated with the wind load measurement data to elucidate the underlying physics to gain further insight into the flow–structure interactions between the tested high-rise building model and tornado-like vortex. The new findings derived from the present study could be used to provide more accurate prediction of wind damage potential to built environment with the ultimate goal of reducing life loss, injury casualty, and economic loss that results from tornados.

1. Introduction

Tornadoes are violently rotating columns of air extending from thunderstorms to the ground. Although mostly associated with the regions east of Rocky Mountains in the central states, often referred to as “tornado alley”, tornadoes have been found to occur in all fifty states, and also occur in coastal regions as hurricanes make landfall. According to Wind Hazard Reduction Coalition statistics, an average of 800–1000 tornados each year would occur in the United States alone, and cause about 80 deaths (on average), 1500 injuries, and $850 million worth of damage. Statistics also show that almost 90% of all recorded tornados are rated F2 or less on the Fujita Scale (Bluestein and Golden, 1993), i.e., they involve wind speeds less than 160 mph. It has been suggested that it is economically feasible to design built structures such as commercial buildings, bridges, hospitals, power plants and airports to resist F2 or even stronger tornados. Any such design work, however, requires a good understanding about the nature of tornados and accurate information about the tornado-induced wind loads and wind field information around the civil structures due to the presence of tornados.

With the consideration of buildings as surface-mounted obstacles, numerous experimental and numerical studies have been carried out to investigate wind loads and flow structures around surface-mounted obstacles (Tieleman and Akins, 1996;
Hajj et al., 1998; Tamura et al., 1999; Gu et al., 2010). Castro and Robins (1977) and Hunt et al. (1978) investigated the vortex structure and topology of the flow around cuboids for a boundary-layer-type of approaching flow. Martinuzzi and Tropea (1993) investigated the turbulence characteristics of the flows around prismatic obstacles mounted in a plane channel. Schofield and Logan (1990) aimed their research to the characterization of the recovery of the turbulent boundary layer downstream of prismatic obstacles, whereas the effect of flow angle of attack was contemplated in the investigations conducted by Natarajan and Chyu (1994). Shah and Fierziger (1997) conducted a numerical study to investigate the flow passing a cubic obstacle by using Large Eddy Simulation (LES) method. Yakhot et al. (2006) conducted a direct numerical simulation of the turbulent flow around a wall-mounted cube to investigate the spatial and temporal evolution of large-scale vortex structures around the cube. Besides the researches on general prismatic obstacles, several studies have also been conducted recently to consider more realistic high-rise building models (Cermak, 1975; Tamura et al., 1998; Tamura and Miyagi, 1999; Hu et al., 2006; Mendis et al., 2007; Kikitsu et al., 2008; Gu et al., 2010).

While those experimental and numerical efforts have revealed a great deal about the wind loads and flow structures around building models in swirling, tornado-like winds. Jischke and Light (1983) and Bienkiewicz and Dudhia (1993) conducted comparative studies to measure wind loads and surface pressure on small building models in swirling, tornado-like winds and straight-line winds. They found that the wind loads acting on the tested models are significantly higher (3–5 times) in swirling, tornado-like winds, and surface pressure distributions on the tested building models are also quite different compared to those in straight-line winds. This suggests that it is incorrect, at least incomplete, to use a conventional straight-line wind tunnel running with maximum tornado wind speed to estimate tornado-induced wind loads on built structures. It should also be noted that almost all the previous work on building models in tornado-like winds were conducted by measuring wind loads and surface pressure distributions only (Nolan and Farrell, 1999; Sengupta et al., 2008; Mishra et al., 2008a,b; Haan et al., 2010). No study has ever been conducted so far to provide detailed flow field measurements to investigate the characteristics of wake vortex and turbulent flow structures around surface-mounted obstacles (i.e., buildings) in tornado-like winds would be quite different from that in straight-line boundary-layer flows (Chang, 1971; Ward, 1972; Markowski et al., 2002).

Surprisingly, very few studies can be found in the literature that specifically address the wind loads and flow structures around building models in swirling, tornado-like winds. While tornado-induced damages are commonly seen in low-rise buildings, tornado-induced damages in high-rise buildings were also occurred in the past years. One of the examples is the tornado outbreak happened on March 14–15, 2008, which caused widespread damages to several high-rise buildings in the downtown of Atlanta, Georgia. In the present study, we reported an experimental investigation to quantify the characteristics of the wake vortex and turbulent flow structures around a high-rise building model as well as the resultant wind loads (both forces and moments) acting on the test model in tornado-like winds. The experimental work was conducted by using a large-scale tornado simulator located in the Aerospace Engineering Department of Iowa State University (ISU). The effects of important parameters, such as the distance between the centers of the tornado-like vortex and the test model and the orientation angles of the test model related to the tornado-like vortex, on the wake vortex and flow structures around the test model as well as the wind loads induced by the tornado-like vortex were assessed quantitatively. In addition to measuring the wind loads (forces and moments) acting on the test model using a high-sensitivity load cell, a digital Particle Image Velocimetry (PIV) system was used to conduct detailed flow field measurements to quantify the evolution of the unsteady vortex and turbulent flow structures around the tested building model in tornado-like winds. To our best knowledge, this is the first effort of its kind. The detailed flow field measurements were correlated with the wind load measurements to elucidate the underlying physics to gain further insight into flow–structure interactions between the building model and tornado-like winds in order to provide more accurate prediction of wind damage potential to built environment with the ultimate goal of reducing life loss, injury and economic loss that results from violent tornado-like winds. It should be noted that a preliminary version of the work reported at here was presented on 47th AIAA Aerospace Science Meeting (Yang et al., 2009), considerable new measurement results and extensive discussions have been added in the present study to elucidate underlying physics to gain further insight into flow–structure interactions between the test building model and tornado-like winds.

2. Experimental setup and tested building models

Fig. 1 shows the schematic and picture depicting the flow circuit and dimensions of the ISU tornado simulator used in the present study. A circular duct of 5.49 m in diameter and 3.35 m in height is suspended from a heavy duty overhead crane. A 1.83 m diameter fan (maximum flow rate is 59.0 m$^3$/s, 125,000 cfm) is mounted concentrically inside the circular duct to generate a strong updraft. The flow from the fan is redirected downward in a 0.30 m wide annular duct to simulate the rear flank downdraft (RFD) encirclement found in natural tornadoes (Chang, 1971). Swirling is imparted to the airflow in the duct by adjusting the angle of the vanes at the top of the tornado simulator. The downdraft air diverges upon hitting the ground with most of the flow moving inward toward the fan. The fan updraft stretches the low-level vorticity into a tornado-like vortex. A unique feature of the ISU tornado simulator is that the tornado-like vortex can travel along the
ground plane as the entire fan/downdraft-producing mechanism translates. This translation, along with the fact that there is a good clearance between the translating duct and the ground plane, allows a wide range of building models to be placed in the path of the tornado-like vortex for testing. The ISU tornado simulator can generate a tornado-like vortex with a maximum diameter of 1.2 m and maximum tangential velocity of 14.5 m/s. The maximum swirl ratio (Church et al., 1979) achieved is 1.14, and the translation speed of the tornado-like vortex can reach up to 0.8 m/s. The vortex height can vary from 1.2 to 2.4 m by adjusting the ground plane upward or downward. Further information about the design, construction and performance of the ISU tornado simulator as well as the quantitative comparisons of the tornado-like vortex generated by using the ISU tornado simulator with the tornados found in nature can be found at Haan et al. (2008).

For the measurement results given in the present study, the ground floor was fixed at 0.457 m below the exit of the outer duct, and the fan speed was fixed at 20 Hz (1/3 of the full speed). The radius of the tornado-like vortex core, $R_0$, measured at the 70 mm above the ground plate (i.e., $Z=70$ mm horizontal plane) was found to be 0.165 m (i.e., $R_0=0.165$ m), at where the maximum tangential speed ($V_T=7.0$ m/s) was observed. The corresponding (radial) Reynolds number of the tornado-like vortex is about 80,000 for the present study. In the present study, the swirl ratio of the tornado-like vortex, which was calculated according to the expression of $S = \pi V_T R_0^2 / Q$ with $Q$ being the flow rate through the fan, was about 0.1. The aspect ratio, which is defined as the ratio between the height and the radius of the tornado-like vortex, was about 3.6 for the present study. According to Haan et al. (2008), with the parameter setting described above, the vortex generated by ISU tornado simulator would be a single cell typed tornado-like vortex.

Two high-rise building models were made to conduct the present study. The test models had the same dimensions (a square cross section of 34.4 mm × 34.4 mm (i.e., $A=34.4$ mm × 34.4 mm) and a height of 140 mm, i.e., $H=0.14$ m) as shown in Fig. 2(a). The first one was made of wood for wind load (both force and moment) measurements. The second one was made of transparent Plexiglas, which was used for PIV measurements of flow fields around the tested building model. Fig. 2(b) shows the relative positions of the tornado-like vortex center with respect to the center of building model and the building orientation angle (OA), where $R$ is the distance between the centers of the tornado-like vortex and the test building model.

During the experiments, the aerodynamic force coefficients ($C_{FX} = F_X / (1/2) \rho V_T^2 A$, $C_{FY} = F_Y / (1/2) \rho V_T^2 A$ and $C_{FZ} = F_Z / (1/2) \rho V_T^2 A$, where $\rho$ is the air density) and moment coefficients ($CM_X = M_X / (1/2) \rho V_T^2 AH$, $CM_Y = M_Y / (1/2) \rho V_T^2 AH$ and $CM_Z = M_Z / (1/2) \rho V_T^2 AH$) corresponding to the forces ($F_X$, $F_Y$, $F_Z$ ) and moments ($M_X$, $M_Y$, $M_Z$) acting on the building model...
were measured by using a high-sensitivity force–moment sensor (JR3, model 30E12A-I40). The JR3 load cell is composed of foil strain gage bridges, which are capable of measuring the forces on three orthogonal axes, and the moment (torque) about each axis. The precision of the force–moment sensor cell for force measurements is $\pm 0.25\%$ of the full range (40 N).

As shown in Fig. 2(c), a digital Particle Image Velocimetry (PIV) system was used to conduct detailed flow field measurements to quantify the evolution of the unsteady vortex and turbulent flow structures around the transparent test model. The flow was seeded with $\sim 1 \mu m$ oil droplets by using a droplet generator. Illumination was provided by a double-pulsed Nd:YAG laser (NewWave Gemini 200) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm with a repetition rate of 10 Hz. The laser beam was shaped to a sheet by a set of mirrors with spherical and cylindrical lenses. The thickness of the laser sheet in the measurement region was about 1.0 mm. A high resolution 12-bit CCD camera (Pixelfly, CookeCorp) was used for PIV image acquisition with the axis of the camera perpendicular to the laser sheet. The CCD camera and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a Digital Delay Generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition. Instantaneous PIV velocity vectors were obtained by a frame to frame cross-correlation technique involving successive frames of patterns of particle images in an interrogation window of 32 pixels $\times$ 32 pixels. An effective overlap of 50% of the interrogation windows was employed in PIV image processing. The time-averaged velocity ($U$, $V$) distributions were obtained from a cinema sequence of 300 frames of measured instantaneous velocity fields. The measurement uncertainty level for the velocity vectors was estimated to be within 2.0%.
3. Experimental results and discussions

3.1. Flow characteristics of tornado-like vortex generated by the ISU tornado simulator

During the experiments, PIV measurements were conducted to quantify the characteristics of the tornado-like vortex generated by the ISU tornado simulator before the high-rise building models were mounted on the ground plane. While the cinema sequence of instantaneous PIV measurement results revealed clearly that the tornado-like vortex are highly turbulent with varying vortex sizes and vortex center from one frame to another, only the time-averaged PIV measurement results were presented in the present study to characterize the time-averaged behavior of the tornado-like vortex. Fig. 3 shows the time-averaged PIV measurement results (i.e., velocity distributions and the corresponding streamlines) to reveal the 3-D flow structures of the tornado-like vortex. Axisymmetric flow pattern in the form of a well-defined single counter-clockwise vortex structure can be seen clearly in the horizontal planes. The streamlines in the vertical plane passing the center of the time-averaged vortex reveal clearly that air streams near the ground far away from the vortex center would flow towards the vortex core and turn upward abruptly before reaching the vortex core. It indicates a radial and upward vertical flow appearing in the region outside the vortex core, as it is expected. An interesting flow feature is seen in the vortex core region, where flow is found to be a downdraft jet impacting the ground. As the downdraft jet approaching the ground in the vortex core, it would move outwards radially and contact with the radial inflow from outside, both branches will join and move upward. As shown clearly in Fig. 3, a “circulation bubble” structure was found to form near the ground in the interface between the upward outside flow stream and the downdraft jet in the core of the tornado-like vortex. The downdraft jet flow in the tornado-like vortex core revealed from the present PIV measurements was found to be well consistent to the findings of Wurman and Gill (2000), who conducted Doppler Radar measurements of the Dimmitt, Texas tornado of 2 June 1995 and found the downdraft jet flow in the tornado-like vortex core penetrating up to 400 m above the ground level.

In order to reveal the mean flow features of the tornado-like vortex in horizontal planes more clearly, Fig. 4 shows the time-averaged PIV measurement results with the center of the tornado-like vortex moving away from the center of the measurement window (i.e., the position where the building models would be mounted). For the PIV measurements given in Fig. 4, the measurement plane was selected in the horizontal plane (i.e., \(X-Y\) plane) at 70 mm above the ground plane (i.e., \(Z/R_0=0.42\) horizontal plane), which is also the middle plane of the high-rise building model if mounted on the test plate.

Fig. 4(a)–(c) show the measurement results in the core region of the tornado-like vortex with the measurement window centered at \(R/R_0 \approx 0.0, 0.5\) and 1.0, respectively. As visualized clearly in the plots, the streamlines of the flow field in the core region of the tornado-like vortex were found to be a group of concentric circles. While the magnitude of the flow velocity was found to increase almost linearly with the increasing radial distance away from the vortex center, the radial components of the flow velocity vectors in the core region of the tornado-like vortex were found to be almost zero. Such measurement results indicate that the flow in the core region of the tornado-like vortex would be very much like that of a potential vortex with the flow velocity vectors being mainly tangential and the radial components of the flow velocity almost negligible.

While the streamlines of the flow field in the inner region of the tornado-like vortex core (i.e., region with \(R/R_0 < 1.0\)) were found to be concentric circles, the streamlines in the outside region of the tornado-like vortex core (i.e., the region with \(R/R_0 > 1.0\)) revealed an interesting flow feature of the tornado-like vortex, i.e., a spiral motion. As shown clearly in Fig. 4(d)–(f), the flow velocity vectors in the outside region of the tornado-like vortex were found to have significant radial components \((V_r)\) in addition to tangential components \((V_\theta)\) as the center of the tornado-like vortex moving farther away from that of the PIV measurement window (i.e., \(R/R_0 \approx 2.3, 4.5\) and 6.2, respectively). The strong radial flow in the outside

![Fig. 3. The perspective view of the tornado-like vortex.](image)
Fig. 4. The flow characteristics of the tornado-like vortex.
region of the tornado-like vortex can also be seen from the PIV measurement results in the vertical plane shown in Fig. 3. Such PIV measurements suggest a strong spiral flow would be generated in the outside region of the tornado-like vortex core, which made the surrounding air streams flow towards the core of the tornado-like vortex.

Fig. 5 shows the measured velocity profiles of the tornado-like vortex in the terms of radial velocity \(V_R\) and tangential velocity \(V_\theta\) components compared to those of the field measurement data of two tornados found in nature to demonstrate the similarity between the tornado-like vortex generated by using the ISU tornado simulator and the tornados found in nature. The field measurement data of the tornados used for the comparison were made available to ISU researchers by Mr. J. Wurman under a subcontract of a NSF-sponsored project, which were also published in Wurman and Alexander (2005). The field data were acquired using Doppler Radar on Wheels observations from the Spencer, South Dakota tornado of May 30, 1998 and the Mulhall, Oklahoma tornado of May 3, 1999. It can be seen clearly that, even though the tornado-like vortex generated by the ISU tornado simulator and the two tornados found in nature have significantly differences in their core diameters (0.33 m for the tornado-like vortex generated by the ISU tornado simulator vs. approximately 400 and 800 m for Spencer and Mulhall tornados, respectively), the overall flow structures scale with each other reasonably well.

It should also be noted that the measured radial velocity profile given in Fig. 5 reveal quantitatively that the radial components of flow velocity vectors in the core region of the tornado-like vortex (i.e., \(R/R_0 < 1.0\)) are very small, which is almost negligible with respect to the reminder components. However, in the outside region of the tornado-like vortex \((R/R_0 > 1.0)\), the radial component of flow velocity was found to increase rapidly with the increasing radial distance away from the center of the tornado-like vortex.

Based on the PIV measurements described above, the flow structures of the tornado-like vortex in horizontal planes was reconstructed, which is shown schematically in Fig. 6. As revealed in the figure, the tornado-like vortex in each

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**Fig. 5.** The tornado-like vortex vs. Mulhall and Spencer tornados found in nature (Doppler Radar Data were taken from Wurman and Alexander, 2005).

**Fig. 6.** A planar view of a tornado-like vortex in each horizontal plane.
horizontal plane can be divided into two regions: an inner core region and an outer region. In the inner core region, air streams rotate concentrically with the wind speed increasing linearly with the increasing radial distance away from the rotation center. The flow inside the tornado-like vortex core rotates like a rigid column. The flow velocity vectors in the vortex core region were found to be almost tangential with the radial components being almost negligible (i.e., \( V_R \approx 0 \)). After reaching its peak value at the outer boundary of the tornado-like vortex core, wind speed was found to decrease gradually with the increasing distance away from the center of the tornado-like vortex in the outer region. The flow velocity vectors in the outer region of the tornado-like vortex have significant radial components flowing towards the core of the tornado-like vortex. While the interesting flow features of the tornado-like vortex shown in Fig. 6 were deduced based on the time-averaged measurement results of the flow field, similar flow features can also be seen clearly from the time sequences of the instantaneous PIV measurement results. The instantaneous PIV measurement results also revealed clearly that the instantaneous center of the tornado-like vortex would move around its time-averaged center randomly due to the turbulence nature of the tornado-like vortex. It should be noted, as revealed clearly from the PIV measurement results in the vertical plane shown in Fig. 3, there also exists a strong upward flow in the outer region and downdraft jet flow in the vortex core, which makes the tornado-like vortex being a very complex, turbulent three-dimensional vortex flow.

3.2. Flow structures around the test model and resultant wind loads in tornado-like winds

3.2.1. Effects of distance between the tornado-like vortex and the building model

Fig. 7 shows the profiles of the measured wind loads (both force and moment coefficients) acting on the tested high-rise building model as a function of the distance between the centers of the tornado-like vortex and the test model. During the experiments, the orientation angle (OA) of the building model related to the tornado-like vortex was set to 0.0° (i.e., OA=0.0°). As revealed in Fig. 7, since the X, Y and Z components of the measured aerodynamic forces are positive, it indicates that the tornado-like wind would try to push the test model tangentially; pull the test model towards the vortex core; and lift the model up from the test ground, which are the most common damage patterns to the damaged buildings observed in the aftermath of tornado attacks in nature (Bluestein and Golden, 1993).

The force measurement results given in Fig. 7 also revealed that all three components of the aerodynamic force acting on the building model would increase with the distance between the centers of the test model and the tornado-like vortex at first, and reach their peak values at the location of \( R/R_0 \approx 1.0 \). This indicates that the building model would experience maximum aerodynamic forces if it is mounted at the outer boundary of the core of the tornado-like vortex, where the velocity of the flow approaching the building model was found to be the maximum. Since the tangential components of the flow velocity vectors was dominant in the inner core region of the tornado-like vortex, the X-component of the aerodynamic force, which is along the tangential direction of the flow streams approaching the test model, was found to be much significant compared with other two components. The maximum value of the X-component of the aerodynamic force was found to be about 4.0 times greater than those of the other two components (Y and Z components) at \( R/R_0 \approx 1.0 \). The roof uplift force (i.e., Z-component) was found to be slightly bigger than the inward pushing force (i.e., Y-component) in the region close to the core region of the tornado-like vortex (\( R/R_0 < 3.5 \)).

As the building model was mounted in the outer region of the tornado-like vortex core (i.e., \( R/R_0 > 1.0 \)), all three components of the aerodynamic force acting on the test model were found to decrease with the increasing distance...
between the centers of the test model and the vortex. It should be noted that, the Y-component of the aerodynamic force 
(i.e., the component pushing the test model towards the vortex core) was found to increase slightly with increasing 
distance when \( R/RO > 2.5 \). The slightly increase of the inward pushing force is believed to be closely related to the spiral 
motion of the flow field in the outer region of the tornado-like vortex, as revealed from the PIV measurements shown in 
Figs. 4 and 5.

The negative sign of the X-component of the measured moment coefficient, \( CM_X \), indicates that the building model 
would likely bend towards the tornado-like vortex core due to the wind loads induced by tornado-like winds. The positive 
sign of the Y-component of the measured moment coefficient, \( CM_Y \), indicates that the building model would bend towards 
tangential flow direction, as expected. Such collapsed patterns are found to agree with those of the damaged buildings 
observed afterward of tornado attacks in nature. The magnitude of the Z-component of the moment coefficient, \( CM_Z \), 
was found to be much smaller than other two components, which is negligible. Similar to the measured force coefficients, 
the measured moment coefficients were also found to reach their peaks at the location of \( R/RO \approx 1.0 \). Such measurements indicate 
that buildings would most likely to fail when they are located near the outer boundary of the tornado core (i.e., \( R/RO \approx 1.0 \)), 
where the wind reaches its maximum speed.

With the findings derived from the force and moment measurements in mind, PIV measurements were carried out to 
visualize the evolution of the wake vortex and flow structures around the high-rise building model in order to elucidate 
underlying physics to improve our understanding about the characteristics of the wind loads acting on the test model in 
tornado-like winds. Fig. 8 shows the time-averaged results of the PIV measurements (i.e., the velocity distributions and the 
corresponding streamlines around the test model) with the tornado-like vortex positioned at different distances related to 
the center of the test model. For the PIV measurements given in Fig. 8, the measurement plane was selected in an X–Y 
plane at 70 mm above the ground plane (i.e., \( Z/RO=0.42 \) horizontal plane), which is also the middle plane of the high-rise 
building model.

Compared to those in straight-line winds, the wake vortices and flow structures around the building model were found 
to become much asymmetrical and complicated in the tornado-like wind. As visualized in Fig. 8(a), while a large wake 
vortex was found to be formed at leeward side of the building model, the streamlines outside the wake region were still 
found to be concentric circles when the tested building model was mounted near the center of tornado-like vortex core 
(\( R/RO \approx 0.0 \)). Such streamline distribution suggests that the wake structures behind the building model would stay locally 
within the core of the vortex. Corresponding to the low wind speed in the core of the tornado-like vortex, the aerodynamic 
forces and moments acting on the building model were found to be relatively small when the model is placed within the 
core region of the tornado-like vortex, as shown in Fig. 7.

Fig. 8(b) shows the wake vortex and flow structures around the test model when the test model was moved away from 
the center of the tornado-like vortex by a distance of \( R/RO \approx 0.5 \) (i.e., the building model is still within the core region of the 
tornado-like vortex). Two strong vortex structures were found at the leeward side of the test model with the outer vortex 
being stronger than the inner one. The two vortex structures revealed in the horizontal plane were actually the signature 
of the two legs of the complicate 3D wake vortex formed at downstream of the test model, which was shown clearly 
in Fig. 13.

Concentric circular streamlines can still be found in the regions slightly away from the model. Since the local wind 
speed becomes much higher than that at the center of the tornado-like vortex core, aerodynamic forces and moments 
acting on the building model would increase rapidly, which was also confirmed by the measured aerodynamic force and 
moment coefficient data shown in Fig. 7.

Fig. 8(c) shows the streamlines of the flow field around the tested building model when the test model was mounted at 
the outer boundary of the tornado-like vortex core (i.e., \( R/RO \approx 1.0 \)). As described above, this is the position where 
maximum wind speed was observed at the center of the model. It is also the location where maximum wind loads acting 
on the test building model were measured. As visualized by the streamlines, the wake vortex structures at the leeward side 
of the model were found to become much larger and stronger. The wake vortex structures and the streamlines at outer 
side of the test model were found to lean slightly towards the inner core of the tornado-like vortex due to the spiral motion 
in the outer region of the tornado-like vortex.

Fig. 8(d)–(f) show the time-averaged flow field around the test high-rise building model when the model was mounted 
in the outer region of the tornado-like vortex (i.e., \( R/RO \approx 2.3, 4.5 \) and 6.2, respectively). As visualized clearly in the figures, 
the wake vortex structures at the leeward side of the test model were found to become elongated significantly. Because of 
the spiral motion in the outer region of the tornado-like vortex, all the streamlines were found to be tilted towards the 
inner core of tornado-like vortex. As described above, although the magnitude of local wind speed was found to become smaller 
and smaller as the radial distance increased, the Y-components (i.e., inward components) of the velocity vectors were 
found to become more and more significant. As a result, the Y-components of the aerodynamic forces and resultant 
moments were found to increase slightly with the increasing distance away from the tornado-like vortex core, as revealed 
clearly from the wind load measurement results shown in Fig. 7.

3.2.2. The effects of the orientation angle of the test model in tornado-like winds

The effects of the orientation angle of the tested high-rise building model related to the tornado-like vortex on the 
characteristics of the wake vortices and flow structures around the test model as well as the resultant wind loads (force and 
moment) acting on the test model were also investigated in the present study. The definition of the orientation angle (OA)
Fig. 8. Flow field around the test model vs. the distance of between the centers of the test model and the tornado-like vortex in the $Z/R_0=0.42$ horizontal plane.
of the model related to the tornado-like vortex is given schematically in Fig. 2. During the experiments, the tested building model was mounted at the location of $R/R_O = 1.0$.

Fig. 9 shows the measured wind loads (i.e., aerodynamic force and moment coefficients) as the functions of the orientation angle of the test model related to the tornado-like vortex. For a test model with square cross section as the one used in present study, if it was placed in straight-line winds, the maximum wind loads would be reached at the orientation angle OA = 45° due to the maximum blockage of the test model in the flow direction (Fig. 10(a)). However, when the square-shaped test model was mounted in tornado-like winds, the wind load measurement data shown in Fig. 9 revealed that the maximum wind loads (both force and moment) acting on the test model were found to be at OA ≠ 45.0°, instead of OA = 45.0°, as one may expect for the case in straight-line winds.

It is conjectured that the reason why the maximum wind loads acting on the model in tornado-like wind occurring at OA ≠ 45.0° instead of OA = 45.0° is related to the spiral motion of the tornado-like vortex. As shown schematically in Fig. 10(b), with the test model mounted in tornado-like vortex, the velocity vectors of flow streams approaching the test model also have inward radial components besides the tangential velocity components along X-axis direction. As a result, the direction of the resultant flow velocity vector approaching the test model would be tilted slightly inwards to the vortex core center. As it is expected, maximum wind loads (i.e., aerodynamic forces and moments) acting on the test model would be reached when the test model has the maximum blockage related to the approaching flow direction. Therefore, the maximum wind loads (i.e., aerodynamic forces and moments) acting on the test model in tornado-like winds were found to be at OA ≠ 30–45°, instead of OA = 45.0° as it is expected in straight-line winds. Besides the effects of the spiral motion, the curved streamlines with non-uniform incoming wind speed in tornado-like wind may also contribute to the change of the orientation angle for the test model to experience maximum wind loads in tornado-like winds.

The PIV measurement results given in Fig. 11 elucidate more details about the variations of the wake vortex and flow structures around the test model with the orientation angles of the test model related to the tornado-like vortex, which

![Fig. 9. The measured wind loads vs. the orientation angle: (a) force coefficient and (b) moment coefficient.](image)

![Fig. 10. Schematic of the flow streams approaching the test model in straight-line and tornado-like winds: (a) in straight-line wind and (b) in tornado-like wind.](image)
Fig. 11. Flow field around the test model vs. orientation angle.
Fig. 12. Flow field around the test model at different elevation levels.
might be used to explain the characteristics of the wind loads induced by tornado-like winds. The PIV measurements were conducted in $Z/R_0=0.42$ horizontal plane. As visualized clearly from the flow velocity distributions around the test model, as the signature of the two legs of the complicated 3D wake vortex generated at downstream of the test model, a pair of vortex structures were revealed at the leeward side of the test model in the horizontal plane. The size of the wake region at the leeward side of the test model (i.e., the velocity deficits) in the horizontal plane was found to increase with the increasing orientation angle (OA) until it reaches its maximum at $OA \approx 30–45^\circ$. According to Newton’s second law, the more velocity deficits (thereby, less momentum) in the wake downstream the test model would indicate greater aerodynamic forces acting on the test model, which was confirmed by the wind load measurement data shown in Fig. 9.

3.2.3. The vortex and flow structures around the test model at different elevation levels

During the experiments, PIV measurements were also conducted at different cross planes parallel to the ground plate at different elevation heights. Fig. 12 shows typical PIV measurement results at different elevation heights with the test model mounted at $R/R_0=1.0$. During the experiments, the orientation angle (OA) of the building model related to the tornado-like vortex was set to $OA=0^\circ$.

As revealed clearly from the PIV measurements results, for the vortex structures in the leeward side of the model, the wake vortex on the inner side (i.e., the one closer to the tornado vortex core) seems to be dominant when the measurement planes were near the bottom of the test model (i.e., closer to the ground plane). As the elevation height increases, the wake vortex structures on the outer side (i.e., the one farther away from the tornado vortex core) were found to grow up rapidly and become dominant. The measurement results also show that the streamlines downstream of the recirculation region in the wake of the test model were tilted towards more to the center of the tornado-like vortex as the elevation height of the measurement plane increase. This may indicate that the strength of the spiral motion of the tornado vortex become stronger and stronger with the increasing elevation height away from the ground floor.

Based on the PIV measurements at different elevation planes, the flow structures around the test model in tornado-like winds were reconstructed. Fig. 13 shows the perspective view of the reconstructed wake vortex and flow structures around the test model in tornado-like winds in the term of iso-surfaces of local swirling strength (Adrian et al., 2000; Sousa, 2002). The 3-D features of the wake vortex and flow structures around the test model in the tornado-like vortex were visualized clearly from the perspective view of the reconstructed flow field.

4. Concluding remarks

An experimental study was conducted to quantify the characteristics of wake vortex and flow structures around a high-rise building model as well as the resultant wind loads acting on the test model induced by tornado-like winds. In addition to measuring wind loads (i.e., aerodynamic forces and moments) acting on the test model using a high-sensitivity force-moment sensor, a digital Particle Image Velocimetry (PIV) system was used to conduct detailed flow field measurements to quantify the evolution of the unsteady wake vortex and flow structures around the test model in tornado-like winds. The detailed flow field measurements were correlated with the wind load measurement data to elucidate underlying
physics to quantify the dynamics of flow–structure interactions between the tested building model and tornado-like vortex in order to provide more accurate prediction of wind damage potential to built environment with the ultimate goal of reducing life loss, injury, casualty and economic loss that results from violent tornado-like winds.

The PIV measurement results revealed clearly that a tornado-like vortex is a very complex, highly turbulent, three-dimensional vortex flow. In addition to a strong upward flow in the outer region and downdraft jet flow in the vortex core along vertical direction, axisymmetric flow pattern in the form of a well-defined vortex structure can be seen clearly in the horizontal planes. Based on the time-averaged flow measurement results, the flow field of a tornado-like vortex in each horizontal plane could be divided into two regions: an inner core region and an outer region. In the inner core region, air streams were found to flow concentrically with the wind speed increasing almost linearly with the increasing radial distance away from the center of the tornado-like vortex. The airflows inside the tornado-like vortex core rotate like a rigid column with the flow velocity vectors being tangential and the radial components being negligible compared with other velocity components. Wind speed was found to reach its maximum value at the outer boundary of the tornado-like vortex core, and then, begins to decrease with increasing distance from the center of the vortex core in the outer region of the tornado-like vortex. The flow velocity vectors in the outer region of the tornado-like vortex were found to have significant radial components to form a strong spiral motion that sucks surrounding air flowing towards the vortex core.

The wind loads (both force and moments) acting on the test model induced by tornado-like wind were found to vary significantly with the position of the test model relative to the center of the tornado-like vortex. The wind loads were found to reach their maximum values when the test model was mounted on the outer boundary of the tornado-like vortex core. Unlike those in straight-line winds, the wake vortex and flow structures around the test model in tornado-like winds were found to become quite unsymmetrical related to the approaching flow. The orientation angle of the test model related to the tornado-like vortex was found to have considerable effects on the wake vortex and flow structures around the test model as well as the resultant wind loads. Interestingly, wind loads acting on the square-shaped model were found to be maximum at orientation angle $\theta = 30^\circ$–$45^\circ$, instead of $\theta = 45.0^\circ$ as one would expect for the same test model placed in straight-line winds.

Acknowledgments

This research was funded by National Oceanic and Atmospheric Administration (NOAA)—Award # NA060AR4600230 with Mr. John Gaynor as the program manager. We also want to thank Dr. Fred Haan, Mr. Bill Rickard and Mr. Anand Gopa Kumar of Iowa State University for their help in conducting the experiments.

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