ABSTRACT

Extreme local weather disturbances like tornadoes involve very complex interaction between wind and structure, making real time evaluation difficult. A tornado simulator was developed in the Wind Engineering Research Centre at Tokyo Polytechnic University and wind speeds and pressure distributions on a cubic model in tornado-like flow were measured. The present investigation focuses on fluctuations of pressure on the cube faces and the neighboring floor under a tornado-like flow. The pressure on the floor was distributed cylindrically and the curve best fitted to Rankine-type showed its core size to be of the same size as one from the wind speed distributions. The pressure was expressed as a wind pressure coefficient based on the central pressure depth. The wind pressures around the cube also showed the effect of swirl flow. A statistical analysis of the pressure coefficients was carried out and the results show the distribution of pressures on the faces of the cube and on the simulator floor. The results are compared with those obtained from a boundary-layer flow for the same cube over a range of incidence angles.

1. INTRODUCTION

Many past studies have contributed to the simulation of tornado-like flow regimes for a cube. These studies have reported that there are large differences between the mean pressures obtained in boundary-layer and tornado-like flow fields. This necessitates analysis of wind loadings on structures in such extreme flow situations.

Mehta et.al (1976) calculated tornado forces on buildings from post-storm damage investigations and discussed failure loads for damaged or destroyed buildings. However, these forces were calculated assuming straight-line wind flow, neglecting rotational wind. Chang (1971) and Wan and Chang (1972) developed a laboratory simulator for generating tornado-like vortices. They determined the tangential and radial velocity profiles inside the vortex. They also explained the
influence of parameter ‘ε’, which is later called swirl ratio in tornado field modeling, and performed pressure measurements for two cases at two locations assuming a single-celled vortex. Ward (1971) improved upon Chang’s simulator by providing a flow straightening honeycomb at the top of the chamber that removed vertically oriented vorticity from the generated tornado vortex. Jischke and Light (1983) recognized the importance of location and orientation of structure to tornado vortex in addition to maximum wind speeds as factors influencing a tornado’s capacity to inflict damage. The limitation was that the tornado was assumed to have no translational velocity, but was considered as a free standing vortex. Lewellen & Lewellen (1997) performed large eddy simulation of a tornado's interaction with the surface and investigated the sensitivity of flow to physical variations in boundary conditions, surface roughness, etc. Dutta et al. (2002) investigated the dynamic response of structures subjected to tornado loads by FEM. They contributed to understanding of the importance of translational wind speed over lateral wind in governing the effects of resonance. Computer modeling of tornado forces on buildings was carried out by Selvam and Millet (2003) They found that force coefficients are less than those of straight boundary layer wind in the x direction, but higher for tornado-like flow in the z-direction. However, they neglected vertical velocity in their study. Mishra et.al (2008) subjected a cube model to a tornado-like vortex having characteristic velocity and surface pressure profiles matching Manchester and Spencer tornadoes. They evaluated pressure and force coefficients to determine the wind loading on a building model assuming a permeable structure. However, the reference dynamic pressure was calculated by taking the reference velocity as the resultant horizontal velocity at the eaves height. Sarkar et.al (2008) designed and tested a tornado simulator with a rotating forced downdraft that resembled the rear flank downdraft emphasized as important to tornado genesis. This was a new addition to conventional simulators.

In the present work, an attempt is made to statistically analyze the pressure coefficients for a cubic model placed in the centre of a tornado simulator, Figure 1(a), and the neighboring floor in the absence of the model. The tornado simulator was developed by the Wind Engineering Research Centre at Tokyo Polytechnic University. This is compared with the behavior of the same cube when subjected to an approaching boundary layer flow having angles of incidence varying from 0~45deg, as shown in Figure 1(b). The method of defining pressure coefficients in a tornado-like flow is different from those of earlier related studies.

Figure 1: (a) Cube in tornado-like flow (b) Cube in boundary-layer flow
2. DEFINING PRESSURE COEFFICIENT IN TORNADO-LIKE FLOW

The pressure coefficient ($C_{pj}$) at the measuring point ‘j’ is defined by:

$$Cp_j = \frac{P_j - P_\infty}{q_r}$$

$$q_r = \frac{1}{2} (P_\infty - P_o) \sim \frac{1}{2} \rho V_{RM}^2$$

![Figure 2: Location of Reference Pressure.](image)

In the tornado-like flow regime, $(P_j - P_\infty)$ represents the wind pressure acting at the pressure tap location. The reference dynamic pressure $q_r$, is estimated as half the centre pressure depth. Assuming Rankine-Vortex behavior, this value is equal to $\frac{1}{2} \rho V_{RM}^2$ at the radius of the maximum tangential velocity ($R_M$), as shown in Figure 2. This mode of defining pressure coefficient is different from those of earlier studies made by Jischke & Light (1983) and Mishra et al. (2008).

3. EXPERIMENTAL SETUP

Figure 3 shows the arrangement for tornado-like flow simulation. The convection chamber comprised a cylindrical piece of acrylic material 480mm high. The updraft hole had a diameter of 250mm, and the height of the confluence region was 200mm. Air was caused to flow in from the surroundings by generating a vertical updraft in the upper part of the convection region using a variable speed fan. A honeycomb structure was used as a flow-straightening device. A cubic model with 100mm side dimension was positioned in the simulator centre, resulting in a very complex flow field. Pressure taps were distributed uniformly across all five faces of the cube and also on the simulator floor. Contour plots of the mean and standard deviation of pressure coefficients were obtained on all faces of the cube and the simulator floor.
4. COMPARISON OF PARAMETERS GOVERNING FLOW

Based on dimensional analysis, some important parameters that govern the tornado vortex are swirl ratio ($S$), aspect ratio ($a$) and radial Reynolds number ($Re_r$). The updraft hole radius ($r_o$), the confluence region radius ($r_s$) and the convection region radius ($r_w$) also combine to form a set of non-dimensional parameters that define the tornado-like flow qualitatively.

<table>
<thead>
<tr>
<th>Non-dimensional parameters</th>
<th>Characteristics of actual tornado systems (Church et al. (1979))</th>
<th>Characteristics attainable in laboratory model vortex flows (Church et al. (1979))</th>
<th>Present Investigation Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_s/r_o$</td>
<td>2~5</td>
<td>1.9~7.5</td>
<td>7.2</td>
</tr>
<tr>
<td>$r_w/r_o$</td>
<td>1.5~4</td>
<td>1.8~7</td>
<td>4.8</td>
</tr>
<tr>
<td>$a$</td>
<td>0.2~1</td>
<td>0.2~3</td>
<td>1.6</td>
</tr>
<tr>
<td>$S$</td>
<td>0.05~2</td>
<td>0.01~27.5</td>
<td>0.18, 0.54</td>
</tr>
<tr>
<td>$Re_r$</td>
<td>$10^5$~$10^{11}$</td>
<td>$4.1 \times 10^2$~$1.2 \times 10^5$</td>
<td>$3.3 \times 10^4$</td>
</tr>
</tbody>
</table>

Table 1: Comparison of Present Investigation Values with the proposed values by Church et al (1979)

These parameters that govern the tornado like flow obtained in the present study showed good agreement with those proposed by Church et al. (1979), as attainable in laboratory model vortex flows. Table 1 compares the present investigation values with the values proposed by Church et al (1979).
5. RESULTS AND DISCUSSIONS

5.1 Tornado-like flow case

Tornado-like flow was investigated for two swirl ratios $S=0.18$ corresponding to the 30deg vane angle case and $S=0.54$ corresponding to the 60deg vane angle case.

5.1.1 Swirl ratio 0.18

The contour lines are indicators of constant pressure coefficient. The mean pressure coefficients were calculated assuming a stationery vortex and translational effects were not considered for the tornado-like flow. From Figure 4(a), it is observed that the mean pressure coefficient for all faces of the cube except the roof face registered values in the range of -0.05 to -0.2, whereas the roof face registered a value of -0.3. The reason for such a large suction value on the roof face of the cube can be due to the rotational component of wind produced by the tornado-like flow. It is also observed that for the anticlockwise tornado-like flow, the leading edges of the cube show smaller values of mean pressure coefficient in the range of -0.2 to -0.1, whereas for the trailing edge the value falls to the order of -0.05. This observation is similar to that of Chang (1971). The side negative pressure areas occurring upstream in the circulation direction indicate the existence of a large separation zone at the leading edge of each side of the flow. The distribution of these statistical values of pressure coefficients was anti-symmetrical for the opposite faces of the cube. When the simulator floor was analyzed without the cube, as shown in Figure 4(b), the mean pressure coefficients increased steadily from -1.8 at the centre of the simulator to -0.01 at the periphery. This justifies the very low pressure at the centre of the tornado-like flow. It is also observed that the floor experienced only negative pressures without the cube.
It is observed from Figure 5(a) that the standard deviations are higher, of the order of 0.03 at the leading edge of the cube facing the anti-clockwise tornado-like flow, compared to those at the trailing edge, where the value is of the order of 0.01. The faces of the cube in tornado-like flow experienced significant pressure fluctuations as observed from the considerable differences in values of the standard deviation of pressure coefficients.

When analyzing the floor without the cube Figure 5(b), it was observed that the magnitude was in the range of 0.2~0.6 at the centre of the simulator. At the periphery it was in the range of 0.008~0.009. These results indicate that there are significant fluctuations at the centre of the simulator and no significant fluctuations at the periphery without the cube in a tornado-like flow regime.

### 5.1.2 Swirl ratio 0.54

When analyzing the mean pressure coefficient for the swirl ratio of 0.54 as shown in Figure 6(a), it can be observed that there is a larger suction value ($C_{p\text{mean}}=-1.1$) on the roof face of the cube compared to that for a swirl ratio of 0.18. For anticlockwise tornado-like flow, the leading edges of the cube experience mean pressure coefficients in the range of -0.7 to -0.2, whereas for the trailing edge the value falls to the order of -0.2. The magnitude is higher than that in the $S=0.18$ case. When the simulator floor was analyzed without the cube as shown in Figure 6(b), mean pressure coefficients increased steadily from -1.8 at the centre of the simulator to -0.05 at the periphery, exhibiting a similar distribution to that in the $S=0.18$ case.
From Figure 7(a), showing fluctuating components of pressure coefficients, it can be observed that there are significant deviations at the leading edge bottom corners. The magnitudes were in the range of 0.09–0.18 at these corners of the cube facing the anti-clockwise tornado-like flow, whereas at the trailing edge it was of the order of 0.03. The roof face of the cube in tornado-like flow experienced significant pressure fluctuations. The simulator floor without the model showed a magnitude in the range of 0.2–0.3. The fluctuations decreased from the centre of the simulator to the periphery.
5.2 Boundary layer flow case

The same cube was subjected to boundary layer flow for a range of incident angles from 0deg to 45 deg and the mean pressure coefficient was evaluated. Figure 8 shows the contour plots of mean pressure coefficients on exploded cube faces under straight-line flow. In each exploded view, the central square represents the roof face, the upper and bottom squares are the leeward and windward faces, respectively, and the left and right squares represent the corresponding side faces. The pressure distribution showed good agreement with the results of Sakamoto et al. (1982). It is observed that the windward face experiences positive pressures, whereas the side faces, roof and leeward faces to the flow experience negative pressures for a normal 0deg angle of incidence, as shown in Figure 8(a). As the wind direction changed from 0~20deg, Figures 8(a)-(d), the windward face continued to experience mean pressure coefficients in the range of 0.4~0.6 and the right face started experiencing lesser negative values in the range of -0.6~0.1. The right face experienced a mean pressure coefficient of around 0.1, corresponding to a 30deg incident angle, as shown in Figure 8(e). These positive pressures on the windward and right faces may be due to the fact that, at a 30deg angle of attack, these two regions may be exposed to the approaching flow.
Figure 8 Mean pressure coefficients in boundary-layer flow (a) 0 deg (b) 10deg (c) 15deg (d) 20deg (e) 30deg (f) 35deg (g) 40deg (h) 45deg

As the wind direction shifts from 30deg to 45deg, Figures 8(e)-(h), the right side face to which the flow becomes incident experiences higher positive pressures. The extent of the separated region from the windward face diminishes gradually and the approaching flow comes in direct contact with the right face, as for Sakamoto et al. (1982). For the left face, the absolute value of pressure coefficient (0.4) is higher, as seen in Figures 8(a)-(h), due to the influence of the separation vortex generated in the close vicinity of the face. At a 45deg angle of incidence, conical vortices appear at the roof corners facing the incident flow. The largest suctions exist around the roof corners, and are of the order of -1. The reason for this suction may be that these regions (side walls and roof), which are of comparative dimensions for a cubical building, may exist within separation zones. These differences in behavior of the cube in the two flow regimes demand separate analyses of structures in tornado-like flow.
Figures 9(a)-(h) display contour plots of fluctuating components of pressure coefficients when the cube is subjected to straight-line wind flow. When analyzing the contour plots of standard deviation for 0deg angle of incidence, Figure 9(a), it can be observed that the fluctuations are distributed over the complete roof face and are in the range of 0.09~0.12, but the windward face to the flow experiences fluctuations of the order of 0.09. The leeward side experiences fluctuations in the range of 0.06~0.08, less than those on the other faces. As the wind incident angle changes to 10deg, the fluctuations became significant on the right face, exhibiting very significant fluctuations over a wider range: 0.09~0.17. The fluctuations showed a decreasing trend on the windward (0.08~0.09), left (0.06~0.13), and leeward (0.05~0.06) face. As the incident angle is further increased through 15 deg, 20 deg up to 30deg, the trend continues with the right face experiencing significant fluctuations of higher order, and the left, windward and leeward faces continued to experience lesser fluctuations.
At incident angles greater than 30deg, Figures 9(e)-(h), the fluctuations began decreasing on the right face, and the roof face showed greater fluctuations in the range of 0.09–0.18. This trend grew for incident angles through 35–45deg, as shown in Figures 9(f)-(h). At the incident angle of 45deg, Figure 9(h), the region of the corner vortices on the roof face exhibited significant fluctuations. Comparing this behavior with the standard deviation values in tornado-like flow, as shown in Figures 5(a) and 7(a), it can be observed that the fluctuations in the anticlockwise tornado-like flow were less. Only the roof face of cube in tornado-like flow showed significant and comparable fluctuations to a boundary layer flow.

The distribution of pressure contours also varied in both flow regimes. The rotating anticlockwise tornado-like flow induced anti-symmetry in the pressure distribution, whereas a distributed pressure contour distribution was seen in boundary layer flow.
6. CONCLUSION

Based on the results obtained for a cube subjected to two flow regimes, a tornado-like flow, and a straight-line boundary layer flow, the following conclusions can be arrived at:

1. The cube model experienced very high suction pressures on its roof face, the magnitude of which showed an increasing trend with increase in swirl ratio for a tornado-like flow. However, there were no conical vortices on the roof for tornado-like flow even for higher swirl ratios.

2. Significant variations in the fluctuating component of pressure coefficient were observed on the roof core, leading edges to anticlockwise flow and at the centre of the simulator without the cube.

3. The tornado-like flow exhibited very low pressures on the floor of the simulator without the cube.

4. Anti-symmetry in the pressure distribution on opposite faces of the cube model was worth noting for a tornado-like flow, whereas the straight line wind induced a distributed pressure distribution over all the faces of cube, which varied with respect to the incident angle to the flow.

5. The leading edges to anti-clockwise tornado-like flow experienced larger negative pressures, which can be attributed to the encircling flow that engulfs the whole cube model within the tornado-like vortex. This trend was different in a straight-line flow, where the side faces of the cube started experiencing positive pressures when the incident angle increased.

These observations demand the investigations for a tornado-like flow different from a straight line wind as the wind-induced load on structures will be considerably different with these differing flow behaviors.

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REFERENCES