Indian Journal of Engineering & Materials Sciences
Vol. 29, June 2022, pp. 323-330

Evaluation of wind pressure on the low-rise buildings and surrounding terrain under the influence of tornadolike vortex induced aerodynamic loads

Mohammed Moizuddin[a], Rajesh Goyal[b], Nakul Gupta[c*], & Masahiro Matsui[d]

[a]Civil Engineering Department, RIMT University, Punjab 147 301, India
[b]National Institute of Construction Management and Research, Delhi NCR Campus, New Delhi 110 037, India
[c]Department of Civil Engineering, GLA University, Mathura, Uttar Pradesh 281 406, India
[d]Wind Engineering Research Centre, Polytechnic University, Tokyo 164-8678, Japan

Received: 25 January 2022; Accepted: 16 February 2022

Wind loading on buildings caused by straight line boundary layer winds has been thoroughly investigated in the past. The effects of vortex loading on structural projections will induce crosswind loads and torsional loads on low rise building which has severe dynamic resonant effect not only on the structural projections but also on over all structural elements of a building. These structural projections can be in the form of cantilever balconies, canopies, sunshades, overhangs, aesthetically projected elements. The purpose of each of these projections is different and designed to suit the convenience of habitats. During the tornado, the damage of projections becomes flying debris due to the fatigue effect of fluctuating pressure. In the present study,a model of low-rise buildings is tested under the influence of tornado-induced vortexes. Models were tested for F3 – F4 tornado for the wind speed 60m/s to 90m/s. Tornadoes of vortex core diameter 0.46 m to 1.06 m in a smooth open terrain, simulations were carried out.A prototype of model of building in a scale of 1:400, actual dimensions of building is 20m x 20m x 10 m; the prototype model is prepared using flexi glass. An arrangement is made to study the effect of building on the ground terrain in surrounding region of building. Model was provided with pressure tapping to measure the surface pressure on all the walls and roof.

Keywords: Tornado Simulator, Low rise building, Attached canopy, Surface pressure

1 Introduction

Tornado events have caused insurance losses and as many as life's. Despite the high expense and destruction caused by tornadoes the body of information about tornadoes has evolved steadily. This is since tornadoes are short-lived, it is difficult to forecast where and where they will strike, and it is difficult to obtain real-time wind speed and pressure data in tornadoes[1].

Much of the analysis of tornado vortices has been reduced to experimental simulators and numerical models. Tornadoes -like vortices simulated in labs have been attempted to measure tornado characteristics based on experiments, but there have been little attempts at quantifying the load caused by swirling tornado winds in low-control buildings as force and pressure coefficients. The tornadoes flow structure depends on the relation between the tangential and the radial flows in the vortex[2]. The ratio of angular momentum of the swirling flow to radial inflow into the vortex, which is known as the swirl ratio, is defined at a given radial distance. In the past, the swirl ratio (S) has been the most often used parameter to classify simulated tornadoes flow structure. The effects of vortex loading on structural projections will induce crosswind loads and torsional loads on low rise building which has severe dynamic resonant effect not only on the structural projections but also on over all structural elements of a building. These structural projections can be in the form of cantilever balconies, canopies, sunshades, overhangs, aesthetically projected elements. The purpose of each of these projections is different and designed to suit the convenience of habitats[3]. Various codes of standards such as IS: 875 (Part-3)-2015[4], BS 6399-2:1997[5], ASCE-7-2010[6] is being used for the wind resistant design of buildings with attachment and in Japan AIJ recommends parallel information for design of buildings. The available information in these wind design codes is very limited and based on researches carried out in wind tunnels without the consideration of tornado attacks. In the situation of

---

*Corresponding author (E-mail:nakul030588@gmail.com) tornadoes, the suggested design parameters may not be sufficient for safe design of such projections[7]. Therefore, it is necessary to carry out study on buildings with structural projections under the effect of vortex aerodynamic loading generated using tornado simulator.

2 Materials and Methods

The building model was tested under the simulated tornado like wind flow of tornado simulator of Tokyo Polytechnic University, Japan. Before the placement of the model on the ground, pressure is measured on the ground for 80 m x 80m area. This study was carried out to understand the behavior of tornado like flow on the bare ground. For this measurement of pressure on bare ground, tornado position was also changed in longitudinal and later direction by 10 m, 20 m and 30 mlaterally, model of building was fixed on the ground and pressure on building as well as ground was measured. The measurement of pressures was also carried out with the different position of tornado flow[8]. Figure 1 shows the different measurement of model and bare ground with different position of tornado flow.

2.1 Model Dimensions

It was proposed to conduct surface pressure measurement on the models of flat roof building under the influence of tornado vortex. The prototype was small industrial building with flat roof having dimensions L = 20 m, B= 20 m and height H= 10 m. To understand the behavior of tornado like flow induced pressure on the ground and the surrounding to the building, a square area of 80 m x 80 m with pressure tapping points is considered Fig. 2 depicts this.

2.2 Model Scale

Models were prepared as geometric similar model of prototype on a scale of 1:400 by flexi-glass sheet to conduct the tests. No. of pressure tapping were provided at all the walls and roof surface of model

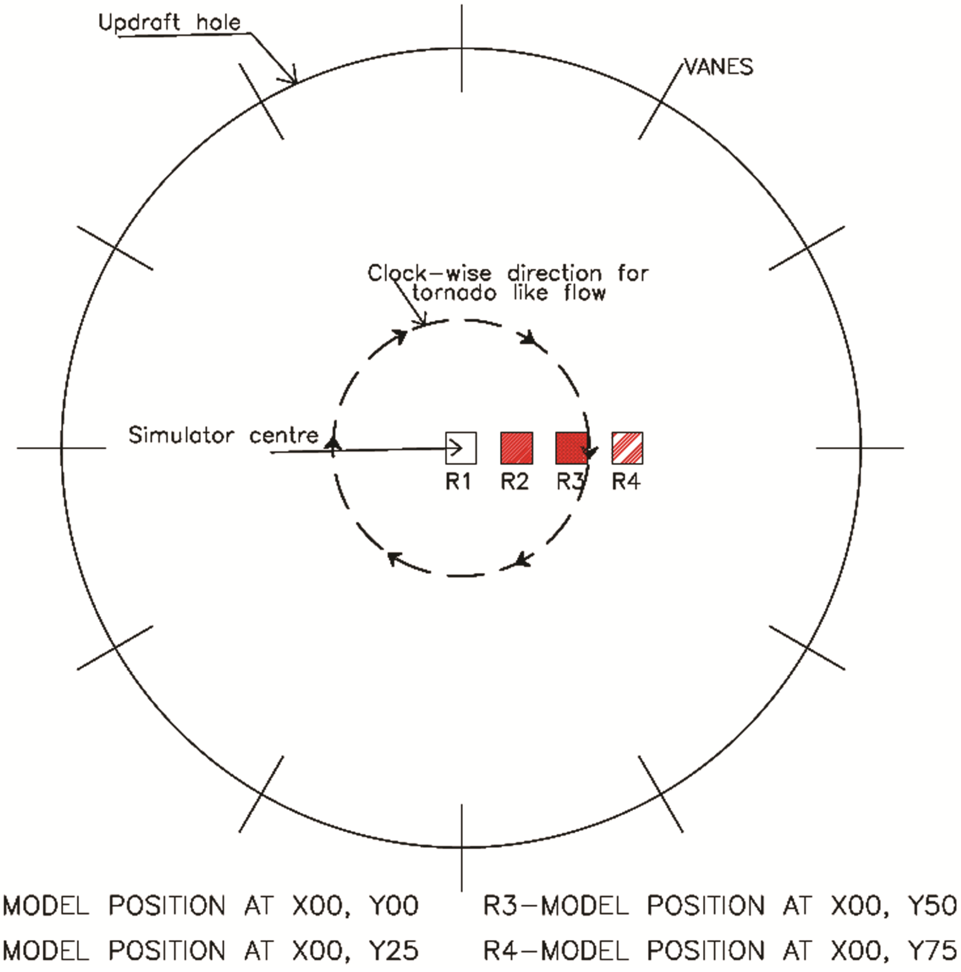

Fig. 1 — Building Model position on simulator floor

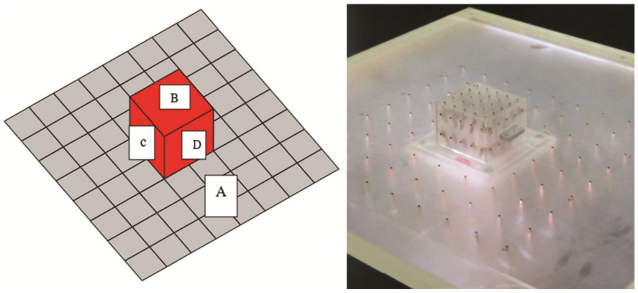

Fig. 2 — Graphical representation of building prototype and its surroundings.

Table 1 — Number of pressure points provided on different surfaces

Structural Element	Number of pressure points	Remarks
Base plate	81	
Flat roof	25	
Sides (4 sides)	40	10 points on each side

for measuring the pressures[9]. Similarly, surrounding ground model was prepared with the same material and number of pressure tapping was provided. The measured pressures were presented in the form of external pressure coefficients and compared with available data in wind design codes or presented by other researchers.

2.3 Detail of Pressure Points

The pressure on building and surrounding ground was measured with the help of pressure tapping provided on the surfaces. Pressure taping was provided with a copper tube of internal diameter 1 mm and external diameter as 1.4 mm. These copper tubes were further connected to PVC tubing of 1 m length which was further connected to pressure measuring instrument.

Table 1 shows number of pressure points provided on different surfaces. Figure 3 shows the location of pressure points with their dimensions.

2.4 Tornado Simulator

A translating tornado-like flow simulator, as shown in Fig. 4, was used for the current analysis. It depicts an updraft system fitted with an axial flow fan, which converts surrounding air into the confluence area, where it converges collectively at the vortex's center before ascending. There is a honeycomb structure in the convection zone.

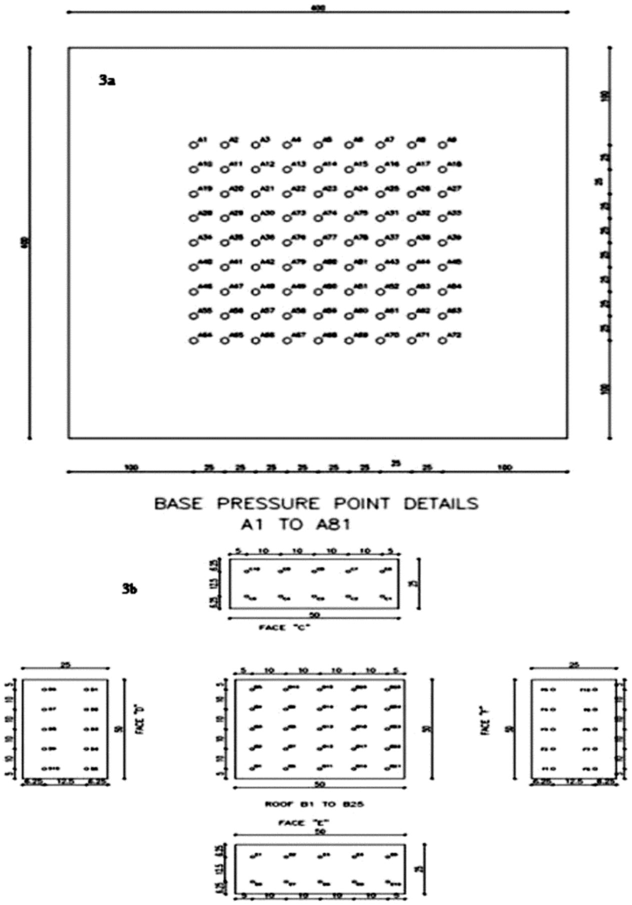

Fig. 3 — Exploded view of the pressure points of base plate and model surface.

The updraft stimulator has a 1,580 mm outer diameter. The guide vanes on the updraft system's periphery are used to apply the necessary angular momentum for the inflow. Equation-1 is used to determine the swirl ratio, the swirl ratio is basically a measure of the tornado-scale helicity it is defined as a ratio of tangential to updraft flow rate which measures the intensity of the induced vortices. Frequency of 50 Hz.

$$Swirl\ Ratio\ (S) = \frac{R}{2h} tan\theta \qquad \dots (1)$$

θ = 60 degrees, R= 206mm, h= 500mm, S= 0.36 for the actual tornado conditions, Radius of tornado = 1 to 3km, Height of tornado 0.5km to 2kmHere, "θ" corresponds to the guide vane angle and

Aspect Ratio (a): the ratio of height confluence region (h) to the radius of updraft hole (R) Aspect ratio 2.42.

2.5 Velocity Measurement System

Particle image velocimetry (PIV) is a measurement technique is used to measure the velocity of tornado, this method enables the determination of planar velocity fields. PIV can be used for qualitative flow visualization as well as for quantitative analysis of the velocity distribution of a flow. Introduced in the late

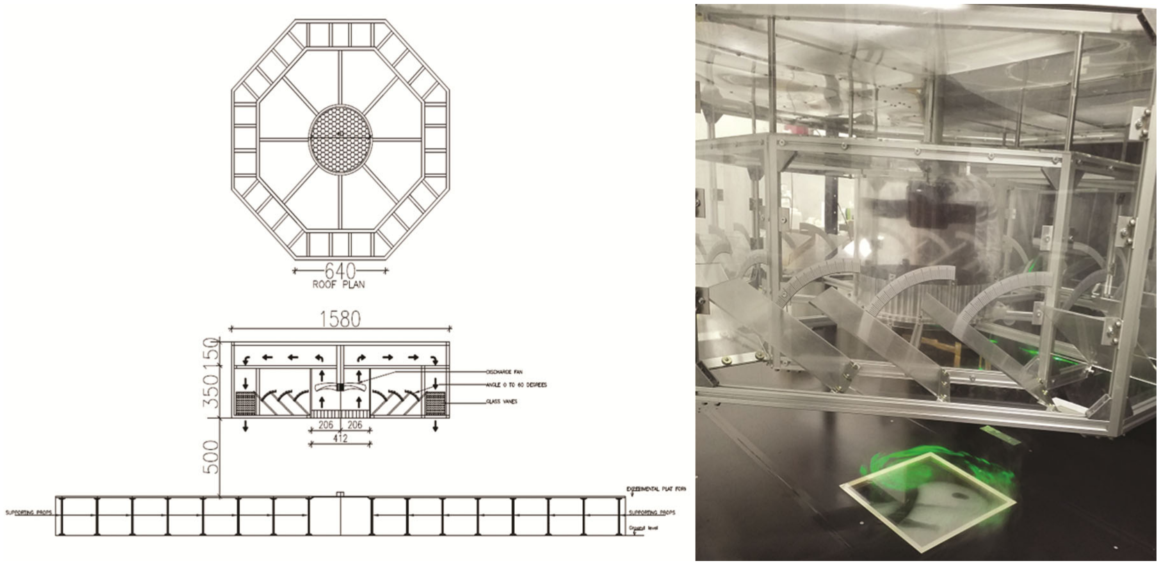

Fig. 4 — At Tokyo Polytechnic University, a tornado-like flow simulator is being translated, and a diagram showing the dimensions is being developed.

Table 2 — Average operating Frequency of 50Hz

Distance from Centre (M)	Wind speed (m/s)	Flow rate Q (m3/s)	Average upward flow velocity W (m/s)	Flow ratio
0	2.22	0.0007	6.49531	0.3148
0.02	2.34	0.00588		0.3603
0.04	3.34	0.01679		0.5142
0.06	3.95	0.02978		0.6081
0.08	5.73	0.0576		0.8822
0.1	6.65	0.08357		1.0238
0.12	6.7	0.10103		1.0315
0.14	6.43	0.11312		0.9899
0.16	6.75	0.13572		1.0392
0.18	7.36	0.16648		1.1331
0.2	7.8	0.15526		1.2009

1970s, it since has become established as a standard measurement technique in fluid mechanics. This technique is based on the visualization of small tracer particles that in most cases need to be added to the flow. These tracer particles should be homogeneously distributed within the measurement region[10].

In order to quantify the vortex properties such as a tornado generated by the tornado simulator, PIV tests are taken before models are put on the ground level. While instantaneous PIV measurements indicate that, a tornado-like vortex is more turbulent as vortex size increases, a sequence of instantaneous PIV measurements in the cinema show that a tornado-like vortex is more turbulent as vortex size increases. - The study portrays vortex activity, such as general tornadoes, based on time-to-average results of PIV measurements from one system to the next. PIV results of time-averaged data are used to demonstrate the three-dimensional mechanisms of vortex flow, such as tornadoes.

In the horizontal planes an Axisymmetric flow pattern is easily evident in the form of a well-defined single anti-clockwise vortex configuration. The streamlines in the vertical plane, which travel through the middle of the time, demonstrate that air streams in close proximity to the ground, some distance from the center of the vortex, go in the direction of the vortex [and unexpectedly turn upside down much sooner as the vortex core is achieved. It shows that the flow acts beyond the vortex center in the region, as expected, is radial and vertically upwards[11].

In the vortex core area, floats are seen as a downdraft jet that influences the ground, a fascinating drift phenomenon. As the down drawn jet processes the earth in the vortex center, it moves radially outwards and from above, and each branch joins and rises upwards.

See Table 2 and Table 3 for wind speed varying distance from center for 50Hz and 10Hz.

Table 3 — Average operating Frequency of 10Hz

Distance from Centre (M)	Wind speed (m/s	Flow rate Q (m3/s)	Average upward flow velocity W (m/s)	Flow ratio
0	0.43	0.00014		0.4063
0.02	0.41	0.00103		0.3874
0.04	0.8	0.00402		0.755
0.06	0.91	0.00686		0.8599
0.08	0.99	0.00995		0.9355
0.1	1.02	0.01282	1.05822	0.9639
0.12	0.99	0.01493		0.9355
0.14	0.95	0.01671		0.8977
0.16	1.04	0.02091		0.9828
0.18	1.16	0.02624		1.0962
0.2	1.38	0.02747		1.3041

Um= 1.26m/s at height 15mm Vm = 7.735m/s

3 Results and Discussion

In order to understand the outcome of the building in a tornado near the horizon, it is useful to think about the motion of the tornados on flat ground and to provide a base for distinguishing the consequences of the tornado flow on harder topographies. In order to achieve so, the emphasis must be on tornado flow movements.

Highest horizontal wind speed radius -Rmwcan also be found around the tornado center as shown in Fig. 5. It is not constant. The horizontal extreme wind velocities are similar to the tornado core, leading edge shows smaller Rmw and Notice that helically up to the extreme left side of the origin of the tornado, from the point on the center edge of the clockwise direction Rmw increases.

The value of increasing Rmw in the translation direction is that it increases the time of sensitivity to high wind speeds and low pressures for the system over which it translates. Similarly, an increase in rmw as shown in Figs (6-8) in the direction normal to the translation direction (y-direction) increases the harm width so a larger number of buildings are exposed to the maximum wind speeds and low pressures. Figure 9 displays the distribution pressure coefficients across the middle of the stationary tornado in the x- and y-direction.

The tornado simulator parameters are defined in EQn2 and the ground pressure coefficient is calculated[12]

$$C_p = \frac{(P-P_o)}{0.5\rho v^2} \qquad \ldots (2)$$

If Cp is the pressure coefficient and P_o is the pressure deficit, taken as the room pressure in the laboratory, from the distant static pressure. ρ is the air density, and V is the reference speed that is the mean radial speed at the inlet. Figure 9 shows the distribution of pressure on the ground in the two lines (x- and y-direction), which travel through the tornado center. The area outside the tornado center with a maximal pressure deficit. A maximum coefficient of pressure of −1.1 can be seen.

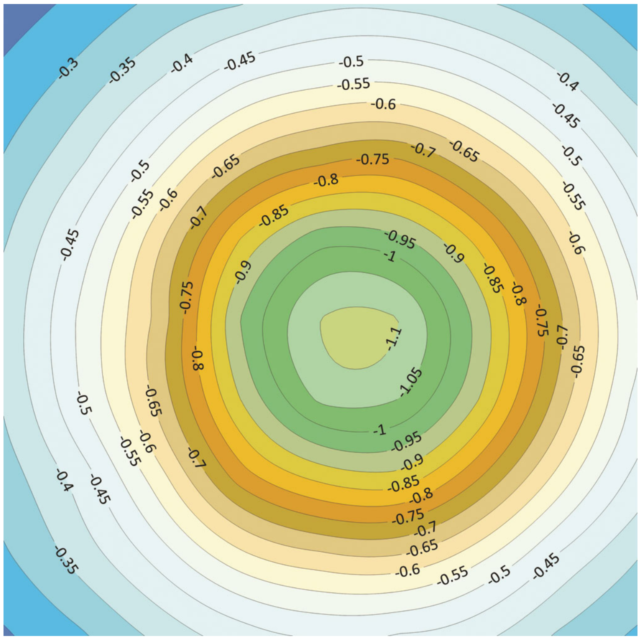

Fig. 5 — Tornado at center.

For the location at the core center, the pressure coefficients do not show significant variation in all terrain surface on outer edges the pressure coefficient varies from -0.4 to -0.9 as it is governed by the high angular momentum primarily, the pressure coefficients on the roof of model varies from -1.125 to -1.195 whereas on pressure coefficient at the center of core without model was -1.1,Cp on the surface “C” varies from -0.55 to -1.05, Cp on the surface “D” varies from -0.68 to -1.14, Cp on the surface “E”

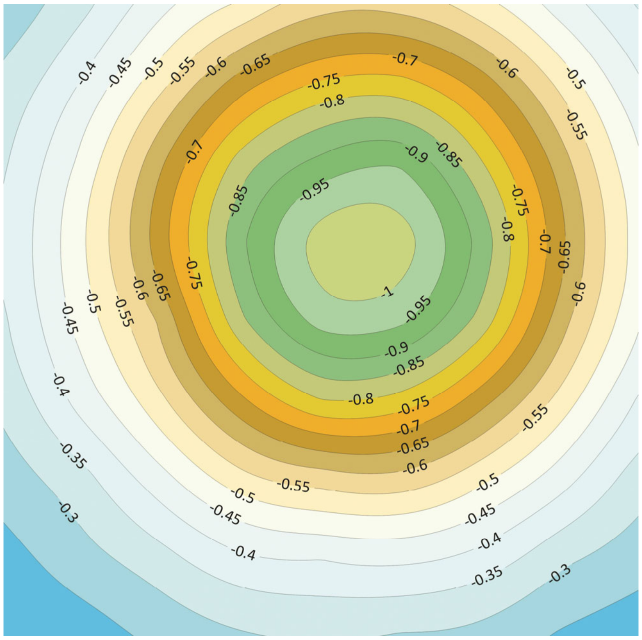

Fig. 6 — Tornado at 10m.

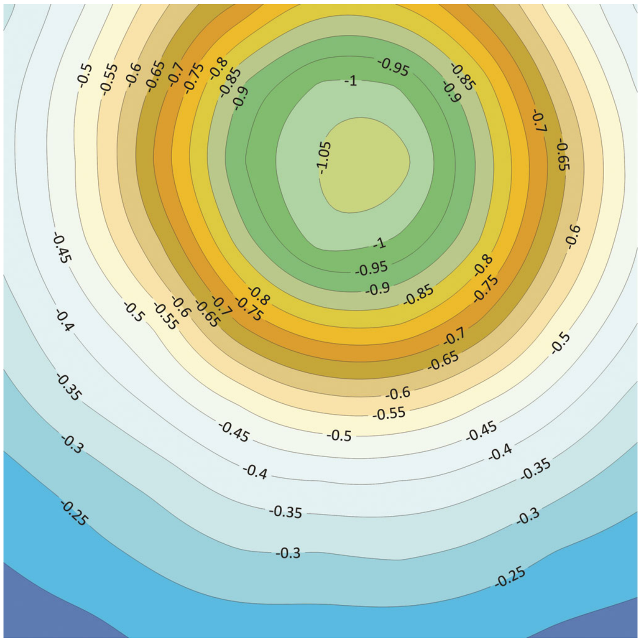

Fig. 7 — Tornado at 20m.

varies from -0. 8 to -1.14, Cp on the surface “F” varies from -0.84 to -1.1, as shown in Fig. 10.

For the location at the core at 10m , the pressure coefficients do not show significant variation in all terrain surface on outer edges the pressure coefficient changes from -0.35 to -0.85 as it is governed by the high angular momentum primarily, the pressure coefficients on the roof of model varies from -1.11 to -1.2 whereas on pressure coefficient at the center of core without model was -1.1,Cp on the surface “C” varies from -0.64 to -1.06, Cp on the surface “D” varies from -0.48 to-0.96, Cp on the surface “E” varies from -0. 6 to -1.06, Cp on the surface “F” varies from -0.86 to -1.1 as shown in Fig. 11.

For the location at the core at 20m , the pressure coefficients do not show significant variation in all terrain surface on outer edges the pressure coefficient changes from -0.25 to -0.95 as it is governed by the high angular momentum primarily, the pressure coefficients on the roof of model varies from -1.02 to -1.32 whereas on pressure coefficient at the center of core without model was -1.1,Cp on the surface “C” varies from -0.88 to -1.15, Cp on the surface “D” varies from -0.24 to-0.6, Cp on the surface “E” varies from -0. 6 to -1.06, Cp on the surface “F” varies from -0.86 to -1.1 as shown in Fig. 12.

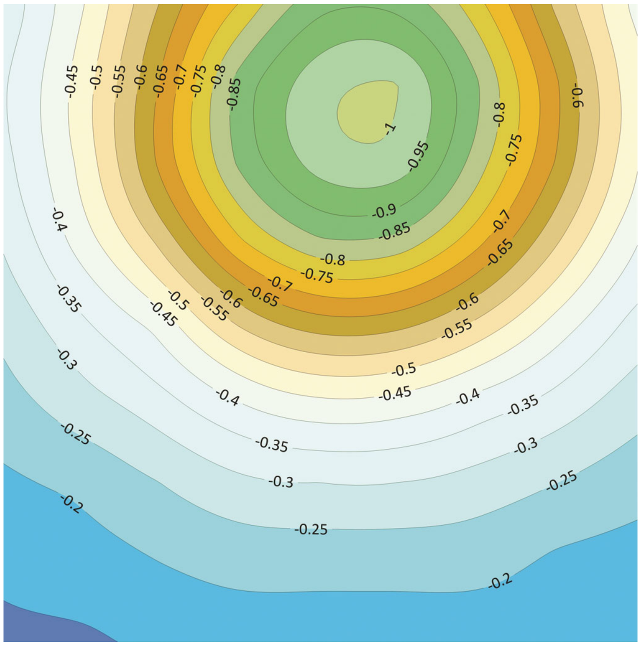

Fig. 8 —Tornado at 30m.

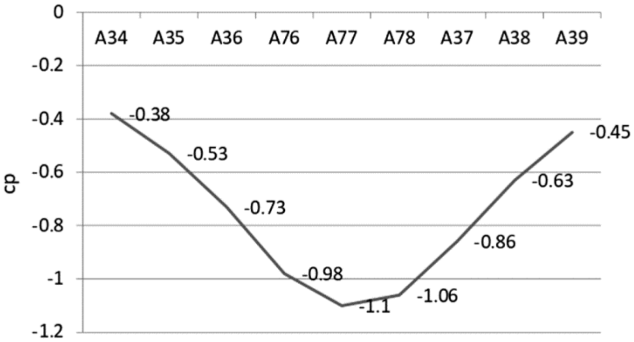

Fig. 9 — In the x- and y-directions of the stationary tornado center, Radial surface pressure coefficient distribution.

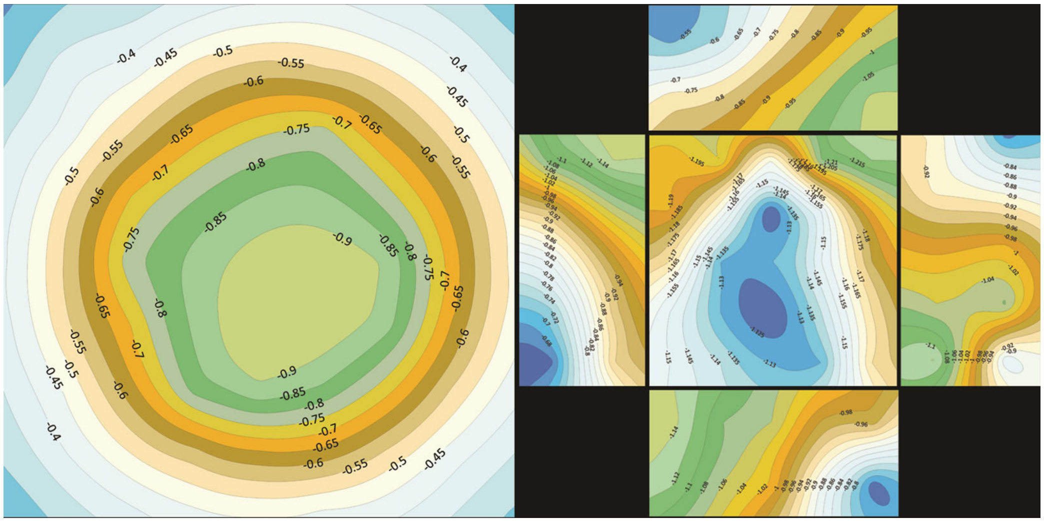

Fig. 10 — Pressure coefficients on terrain, and model surface tornado location at center of model.

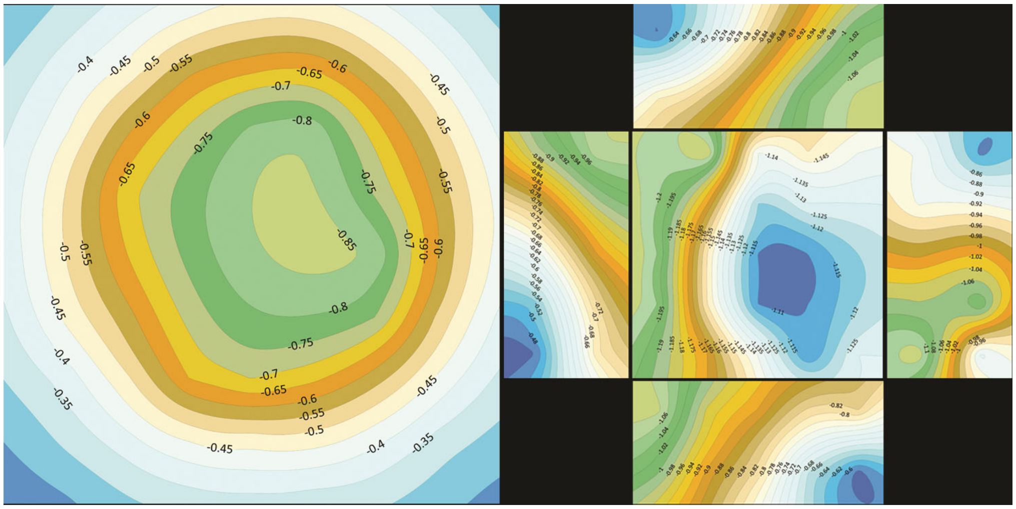

Fig. 11 — Pressure coefficients on terrain, and model surface tornado location at 10m.

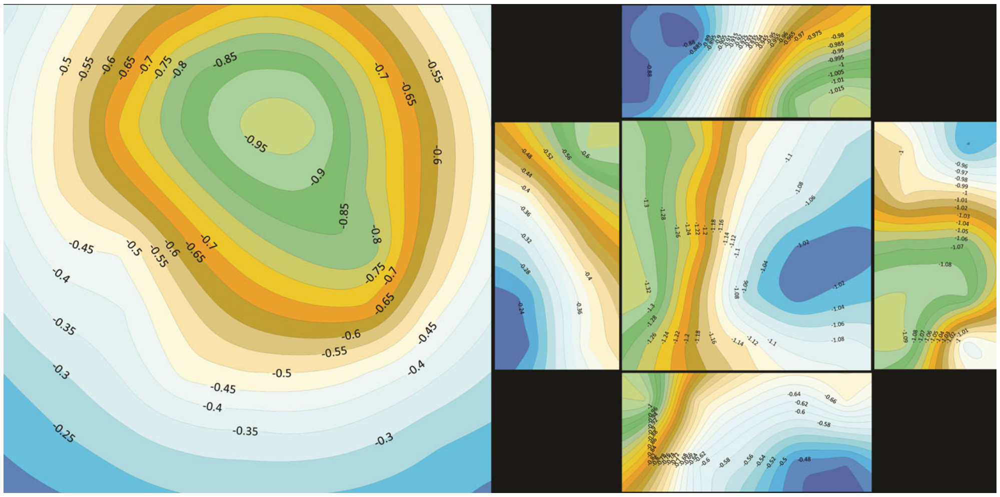

Fig. 12 — Pressure coefficients on terrain, and model surface tornado location at 20m.

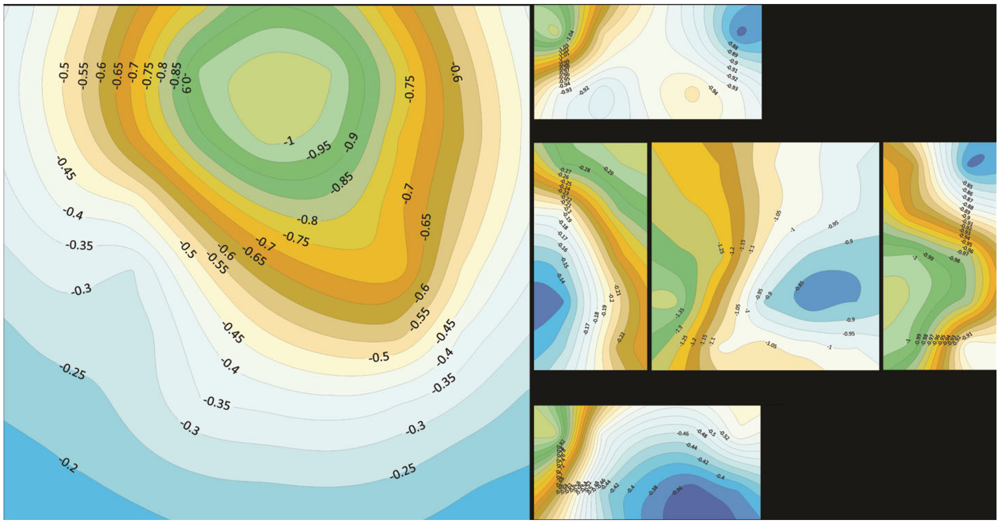

Fig. 13 — Pressure coefficients on terrain, and model surface tornado location at 30m.

For the location at the core at 30m , the pressure coefficients do not show significant variation in all terrain surface on outer edges the pressure coefficient changes from -0.2 to 1 as it is governed by the high angular momentum primarily, the pressure coefficients on the roof of model varies from -0.85 to -1.35 whereas on pressure coefficient at the center of core without model was -1.1,Cp on the surface "C" varies from -0.88 to -1.04, Cp on the surface "D" varies from -0.14 to-0.29, Cp on the surface "E" varies from -0. 36 to -0.82, Cp on the surface "F" varies from -0.85 to -1.0 as shown in Fig. 13.

4 Conclusion

- Pressure on simulator terrain floor captured the nature and distribution of pressure coefficient under tornado like flow, with the central core registering higher pressure suction compared to the periphery of terrain.
- The tornado pressure on terrain is not affected significantly by the presence of the building
- Roof experienced higher pressure coefficient compering with the walls.
- Anti-symmetry was observed in pressure distribution on opposite sides.
- Roof center experience lesser pressure coefficients compared with the roof edges when the tornado is center of model.
- The pressure of the roof core increases as the tornado moves out of the building model core.
- Maximum pressure coefficient on roof experienced when tornado is 30m away from the center of building.

References

1 Chmielewski T, Nowak N, & Walkowiak K J, *Wind Eng Ind Aerodynamics,* 118 (1971) 54.

2 Chang, C C, *In: Proceedings of the 3rd International Conference on Wind Effects on Buildings and Structures*, 54 (1971) 231.

3 Cao S, Wang J, Cao J, Zhao L, & Chen X, *Wind Eng Ind Aerodynamics*, 145 (2015) 75.

4 IS: 875 (Part-3), *Indian Standard code of practice wind loads*, (1987)

5 BS 6399-2, part2,*Code of practice for wind loads* (1997)

6 ASCE/SEI 7-10 *Minimum design loads for building and other structures*, ASCE (2010)

7 Wang M, Cao S, & Cao J *J, Wind Eng Ind Aerodyn,* 205 (2020) 104308.

8 Goyal R, Ahuja A K, & Prasad J, *Asian J Civ Eng*, 8 (2007) 239.

9 Case J, SarkarP, & Sritharan S, *J Wind Eng Ind Aerodynamics*, 133 (2014) 124.

10 Sabareesh G R, Matsui M, & Tamura Y, *Front Built Environ*, 5 (2019) 53.

11 Cao S, Wang J, Cao J, Zhao L, & Chen X, *J Wind Eng Ind Aerodyn,* 145 (2015) 75.

12 ZhangW, &Sarkar P, *The Fifth International Symposium on Computational Wind Engineering (CWE2010) Chapel Hill, North Carolina, USA*(2010).