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Dynamic Response of Plane Frame Buildings Subjected to Tornado Loads

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ABSTRACT : *Study of tornadoes is fairly old, however, the dynamic response of structures subjected to tornadoes has not been studied by many. Some of the studies are based on experimental approaches. A few investigators have followed analytical methods. To our knowledge, no study has been reported so far on dynamic analysis of structures subjected to tornadoes using STAAD Pro software. Here, we report the dynamic response of R C framed buildings under the tornadic wind loads. The response of two, eight and twelve (2 bay), twenty and forty (2 and 3 bay both) storied RC plane frame have been investigated using the scaled tornado velocity time history of Fujita's record. The Fujita record has been converted to horizontal and vertical forces at each floor level for analysis. Displacement response under tornodic forces has been found fifty times more than the response obtained using basic wind speed (50m/ s) as per IS code.*

Keywords – *Tornado Time History, R C framed building, Plane frame, Dynamic response, Fujita's record.*

1. INTRODUCTION

A tornado is defined as a violently rotating column of air extending from a thunderstorm to the ground. The most violent tornadoes are capable of tremendous destruction with wind speeds of 250 mph or more. The rapidly increasing threat of disasters from tornado demands concerning approaches in designing of tall buildings for safety in these storms. The earliest work on tornadoes had been reported in 1884 by Finley [1] on the characteristics of 600 tornadoes. Only a few studies on tornadoes from a structural engineering point of view have been reported. It was started in 1966 with the first man made tornado in the laboratory by Chang [2]. Chang [3 - 5] later reported the details of simulation of tornadoes, measurement of different velocities and their nature of variations. Chang [4] proposed that the structures be designed for dynamic pressures, which may vary from 20% to 70% more than the mean. Buildings may oscillate violently during tornadoes. To account for designs for tornadoes, dynamic pressures for some types of buildings have been suggested. Subsequently, Jischke and Light [6] studied some rectangular structural models using the modified version of Ward's [7] tornado cell. Mcdonald et al. [8] carried out a response study of a 20-storeyed building subjected to Lubbock tornado. Wen [9] and Wen and Ang [10] presented a detailed dynamic study of a 24-storeyed steel building subjected to a modelled tornado. The structure of the wind field of a tornado has been a subject of research among meteorologists for quite some time. A great number of theoretical and experimental works have been carried out including, among others, the laboratorial study by Ying and Chang [11] and field observations by Hoecker [12] and Fujita [13]. The wind field of a tornado resembles that of a Rankine combined vortex,

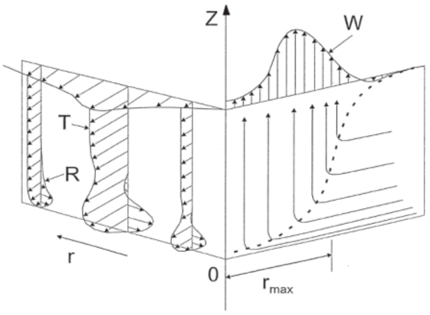


Fig.1 Basic wind field structure of the modelled tornado (*R*=radial velocity component, *T*=tangential velocity component, *W*=vertical velocity component).

the detailed behaviour of a tornado vortex and the physics involved are much more complex. Kuo [14] presented a theoretical model of the 3-D flow in the boundary layer of a tornado-like vortex where wind velocityprofiles as functions of radial distance and height were obtained. A schematic representation of Kuo's solution is shown in Fig.1, where the origin of the coordinate is at the centre of the vortex and the dashed lines represent limit of the boundary layer. It compared quite favorably with both Hoecker's observation and Ying and Chang's tests. Dutta et al. [15] has performed the dynamic analysis of structures subjected to tornadoes using FEM. In the present work an attempt has been made to analyse the response of the structures subjected to tornadic loads using STAAD Pro. Time histories of tornadic wind velocities have either been generated using Kuo's mathematical model of tornado or scaled from the Fujita's field observations.

Recently a large laboratory tornado simulator has been designed, constructed and tested at IOWA State University Wind Tunnel Lab [16] to generate tornado-like vortices for the purpose of quantifying tornado induced aerodynamic loads on engineering structures. This simulator (Fig.3) generates a vortex that can translate along a ground plane to interact with models of structures on the ground.

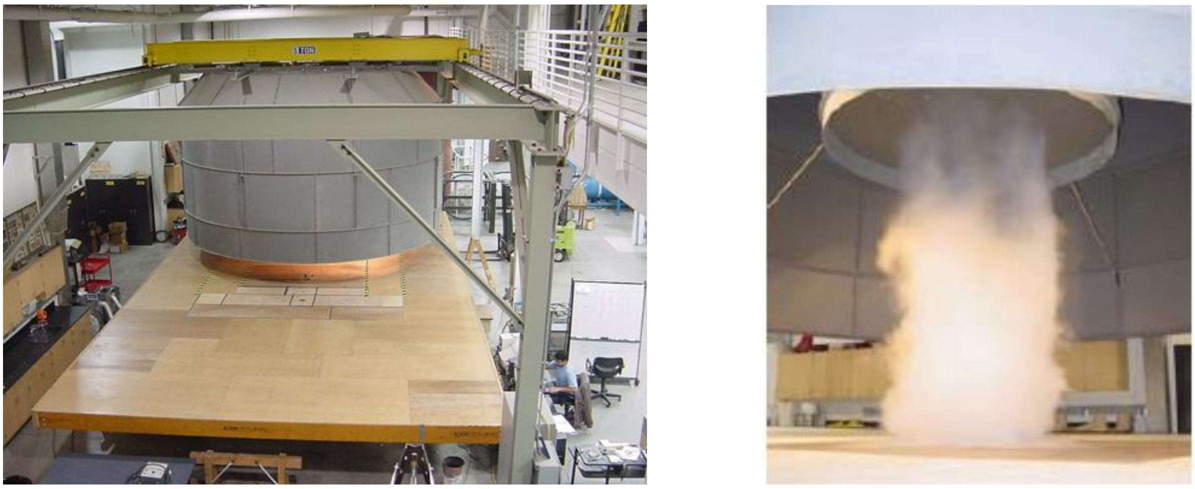
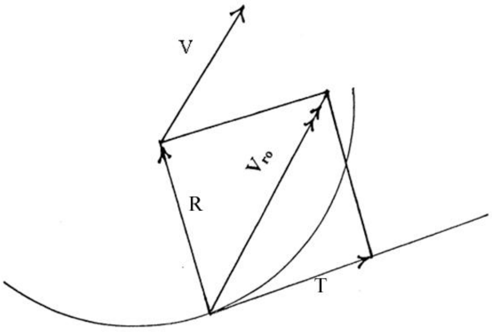


Fig.3 Photo of tornado simulator (circular duct) (designed in IOWA State University Wind Tunnel Lab) mounted on an overhead crane to move above the ground plane.

2. NUMERICAL STUDY

This paper discusses the dynamic analysis of two dimensional multi-storeyed reinforced concrete building due to tornado loading with the help of Finite element software STAAD Pro. The dynamic responses of Two, Eight, Twelve, Twenty and Forty storeyed building have been studied. All the calculations were made for a maximum tornadic wind speed of 360 Km/hr. Maximum velocity (V_m) used, is the resultant of three velocity components viz. radial (R), tangential (T), and translational (V) (Fig. 4). As suggested by Mehta et al. [17], the vertical component can be approximated as



$W = T/3$ to $2T/3$ and $R = T/2$

$$V_{ro}^2 = T^2 + R^2$$

Maximum Velocity: $V_m = V_{ro} + V$

Now substituting the above,

$$V_{ro}^2 = T^2 + {T^2}/_4 = 5T^2/4.$$

The maximum wind velocity, V_m can be given as

$$V_m = \sqrt{V_{ro}^2} + V \quad \text{or,} \quad V_m = 1.12T + V$$

Fig.4 Velocity components of wind in a tornado

The past records suggest that the translational speed can be anything between 0 and 104 km/h [17]. However, on an average V can be taken as 1/8th of the maximum wind velocity or equivalently as 1/6th of tangential velocity.

The above equation reduces to $V_m = 1.12T + {}^{T}/_{6} = 1.28T$

Then the tornadic forces on each node of the structure have been calculated using following equation $F(t) = \frac{1}{2} C_D \rho V_m{}^2 A6$

Where; A = Effective projected area of the structure for a particular node, normal to the direction of V_m.

The problems have been idealised as two-dimensional (2D) multi-degree freedom systems. The scaled velocity record of Fujita (Fig.5) in order to suit the maximum velocity of 360 km/h (100 m/s) has been used for the present study. The damping has been kept constant in all the cases at 2%, which kept increasing with the modes. Geometry of all building has been taken as Bay width of 6.0 m and 5.0 along width and length respectively with a Bay height of 3.0 m. Other parameters used for analysis are given in Table 1.

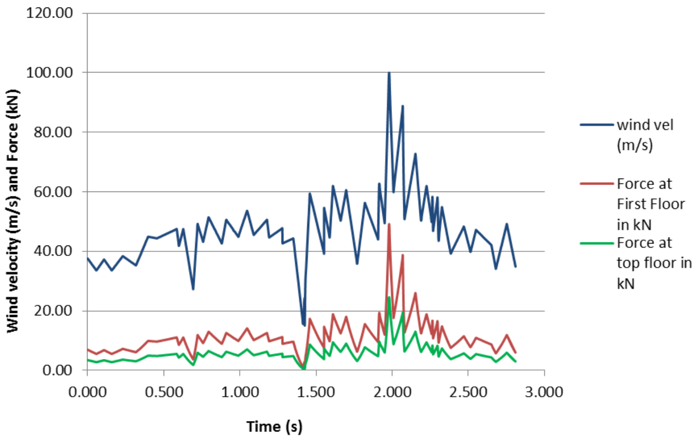
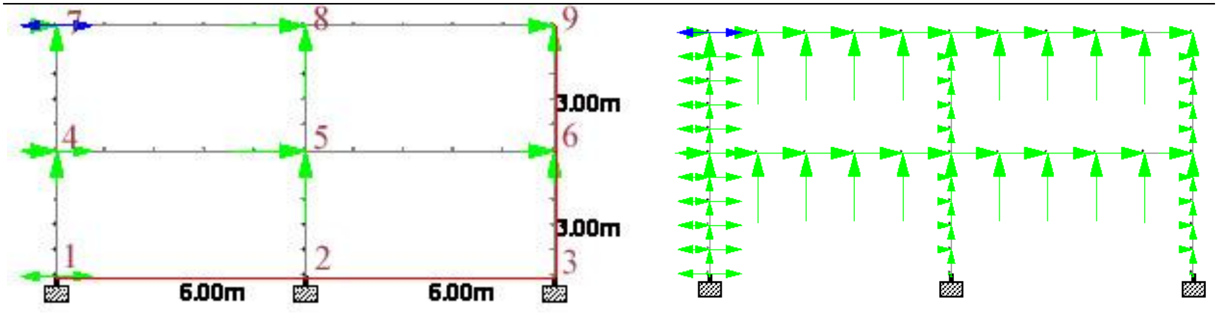


Fig.5 Scaled tornado velocity variation based on Fujita's record and corresponding drag force for the 2-storeyed building

TABLE 1: Values of different parameters used

Parameter	Time step taken	Vertical wind velocity	Drag coefficient	Air density (at 25℃)	Damping
Value	0.005 s	$0.4V_m$	0.7	1.17 kg/m^3	2%

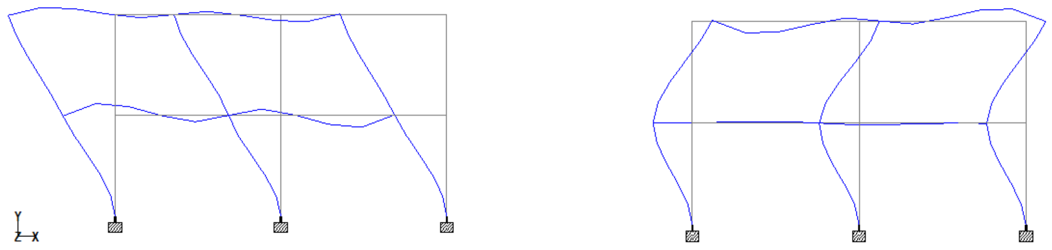
Time histories at different heights are defined. The peak response quantities (for example, member forces, displacements, storey forces, storey shears and base reactions) have been combined as per Complete Quadratic Combination (CQC) method. Each member of the building has been divided into five equal parts and the mass is considered to be lumped in two different manners (i) mass lumped at floor levels (Fig.6a) (ii) mass lumped at each node (Fig.6b)



(a) (b)

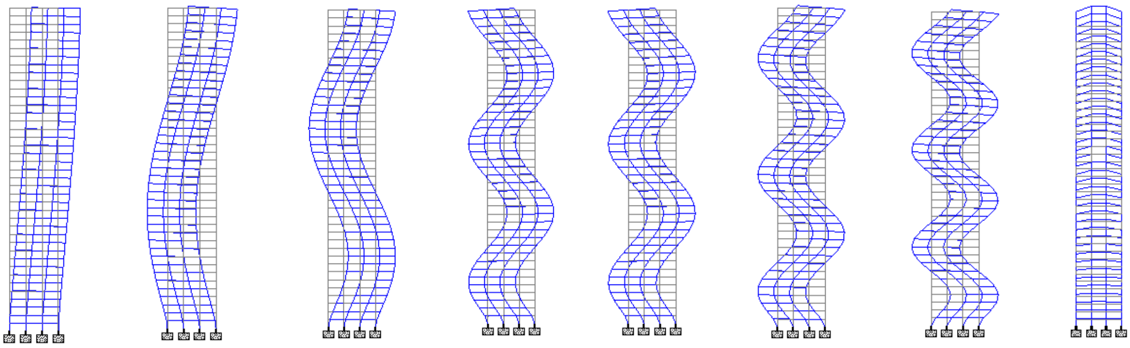
Fig.6: 2-storeyed building (a) mass lumped at floor levels (b) mass lumped at all nodes

The members are divided into parts to facilitate the smooth drawing of mode shapes. The two cases considered for the 2-storeyed building is only to show that it makes hardly a difference in the results when members are divided into parts but still the loads are considered to be lumped at the floor levels. The first two mode shapes for the 2-storeyed building and first eight mode shapes for the 40- storeyed building due to tornado loading are shown in Fig.7 and Fig.8 respectively. Table 2 shows modal frequency and maximum nodal displacement response of different buildings due tornadic load only.



Mode 1 Mode 2

Fig.7 First two Mode shapes for 2-storeyed building



Mode 1 Mode 2 Mode 3 Mode 4 Mode 5 Mode 6 Mode 7 Mode 8

Fig.8 First eight Mode Shapes of 40-storeyed building

TABLE 2: Modal Frequency and Displacement response of different buildings

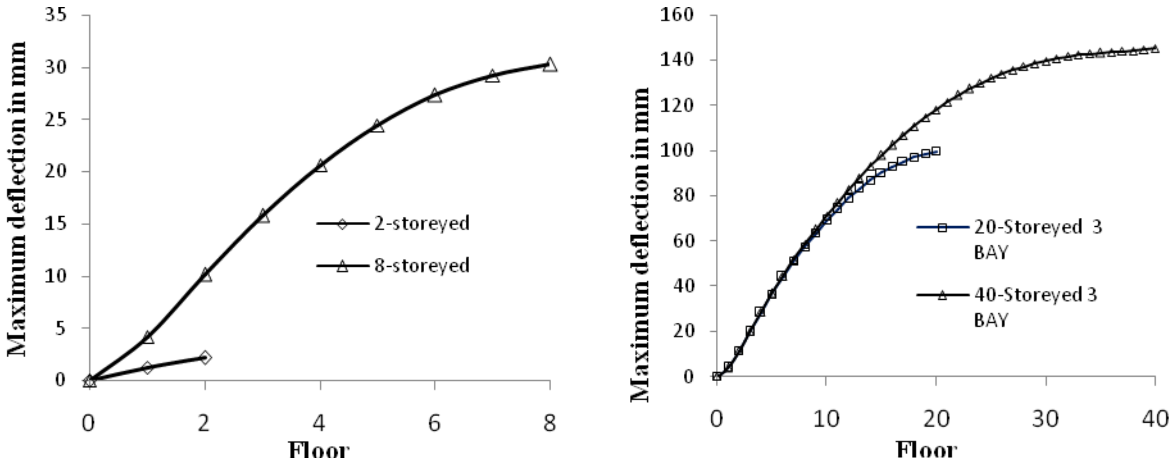
Type of Building		2-storeyed	8-storeyed	12-storeyed	20-storeyed	40-storeyed
Modal Frequency	Mode 1	1.649	0.407	0.32	0.185	0.084
	Mode 2	5.298	1.253	1.011	0.570	0.261
	Mode 3	14.284	2.193	1.847	1.002	0.468
Displacement response for node 4 (mm)	X dir	1.278	4.158	3.123	3.786	3.79
	Y dir	0.008	0.115	0.116	0.221	0.278

Displacement response for node 7 (mm)	X dir	2.159	10.168	9.141	11.249	11.28
	Y dir	0.011	0.208	0.221	0.427	0.541
Roof Displacement response (mm)	X dir	2.159	30.278	48.378	99.648	145.289
	Y dir	0.011	0.392	0.59	1.587	2.478

3. DISCUSSION OF RESULTS

(1) The maximum dynamic deflections for 2-storeyed buildings are 2.159 & 2.067 mm in x-direction and 0.011 & 0.013 mm in y-direction for the two cases respectively. Also the maximum deflections for 8-storeyed buildings are 30.278 & 30.249 mm in x-direction and 0.392 & 0.393 mm in y-direction for the two cases respectively. Hence, either the masses have been lumped at floor levels or also at intermediate points, results of the analysis is almost same.

(2) For the same velocity spectrum and a given maximum velocity, Fig.9 indicates that 20-storeyed building and 40-storyed building suffered equal maximum deflection at lower floors but it is more for the 40-storeyed building at higher floors. At the same time the maximum deflection increases rapidly in the 8-storyed building with compared to the 2-storeyed building as shown in Fig.9. This may be due to its frequency falling in the resonance zone.



(a) (b)

Fig.9 Maximum dynamic deflection at different floors for (a) 2-storeyed & 8-storeyed building; and (b) 20-storeyed & 40-storeyed building

(3) Since the modal frequency for shorter buildings is higher than that of the taller buildings as shown in Fig.10. It may be said that a faster tornado having higher frequency may affect shorter or stiffer building adversely. The slower ones having lower frequency may affect taller or flexible system. This means a stationary tornado may not impart any dynamic effect.

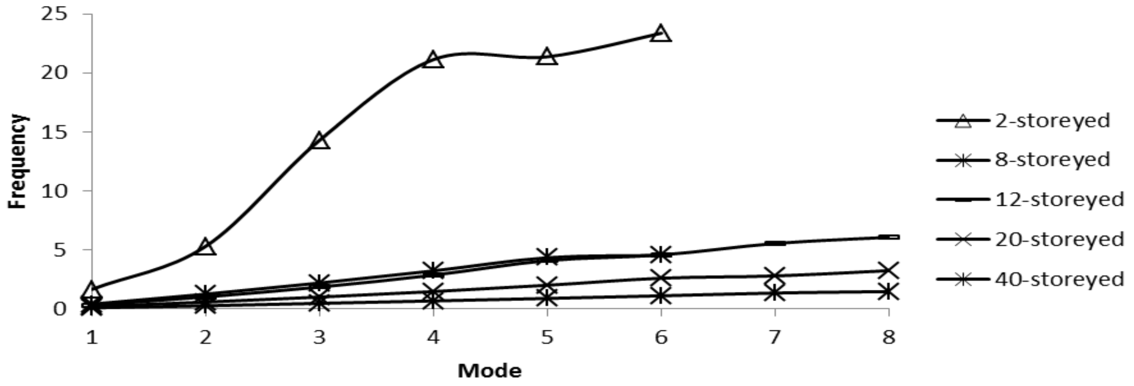
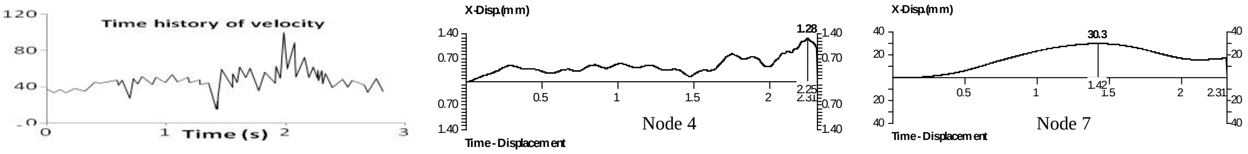


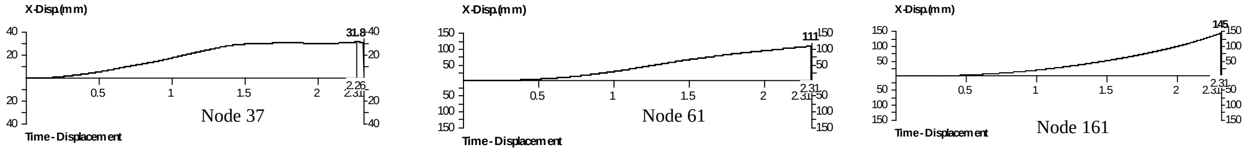
Fig.10 Modal frequency of different buildings

(4) Dynamic response of the buildings at corner node of top storey of each building is shown in Fig.11. The dynamic response of the 2-storyed building reaches its maximum value at 2.25 s (Fig.11). But before reaching this maximum value it has many ridges in the response spectra. This happened due to high frequency of the 2-storeyed (stiffer) building.

(5) Response of the 8-storeyed building (Fig.11) shows that initially the displacement increases with time, reaches its maximum value at 1.42 s, and then decreases with time. The response spectra of 12-storeyed buildings show that initially deflection increases rapidly but after 1.5 s it becomes almost constant with time. While the higher buildings reach at maximum response only once and at the end of the time history. This establishes that resonance has direct dependence even upon the duration of tornadic loading and stiffness of the building. Same trend and response value have been obtained for 2 bay and 3 bay analysis.



Time history of tornado wind 2-storeyed building 8-storeyed building



12-storeyed building 20-storeyed building 40-storeyed building

Fig.11 Dynamic response of the buildings (at corner node of top storey of each building)

4. CONCLUSION

(1) The mode shapes and the ratio of modal frequencies obtained in the present analysis are in great agreement with those obtained by Dutta et al., 2002. This validates our method of analysis.

(2) For the two methods, lumping the masses at floor levels or at intermediate points, results of the analysis are almost same. Also, 2 and 3 bay analysis results are not showing much difference.

(3) Displacement response under tornodic forces has been found fifty times more than the response obtained using basic wind speed as per IS code.

(4) Modal frequencies for 8, 12, 20 and 40 storied buildings follow similar trends whereas two storey building is entirely different showing very stiff.

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