Effects of Shape on Wind Forces of High Rise Buildings Using Gust Factor Approach

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Abstract— **The rapid increase of the urban population in developing countries such as India, has forced the reevaluation of the importance of high rise buildings. The structural systems of high rise buildings are usually sensitive to the effects of wind. Gust is the most critical effect of the wind. The gust effectiveness factor method takes into account the dynamic properties of the structure , the wind-structure interactions and then determines the wind loads as equivalent static loads.**

In this paper, different shapes of building of height 150 m having equal plan area, equal stiffness of column are considered for wind load analysis. Wind loads are determined based on gust effectiveness factor method. The critical gust loads for design are determined. After the application of calculated wind loads to the building models prepared in finite element software package ETAB's 13.1.1v. having different shapes are compared in various aspects such as storey displacements, storey drifts, storey shear, axial forces in column etc.

Based on the results, conclusions are drawn showing the effectiveness of different shapes of the structure under the effect of wind loads.

Index Terms— **Storey displacement, Storey drift, storey shear Gust, Wind load**

I. INTRODUCTION

Wind is air in motion relative to the surface of the earth. It varies with time and space. Due to the unpredictable nature of wind, it is necessary to design the tall structures by considering the critical effects of wind on the structure. Wind force depends upon exposed area of the structure. The wind force depends upon terrain and topography of location as well as the nature of wind, size and shape of structure and dynamic properties of building. It is very important to consider fluctuating component of wind pressure while designing. Wind gusts cause fluctuating force on the structure which induced large dynamic motions and oscillations. The performance of a structure can be improved when a wind acts by improving the shape of the structure by providing curved edges so that the wind load will be less. The evaluation of along wind load can be done by using gust factor method. The gust factor method uses the statistical concepts of a stationary time series to calculate the response of structure to a gusty wind. Hence it is important for the estimation of wind loads on the flexible structures.

It is important to evaluate the characteristics of fluctuating wind forces and the dynamic characteristics of the building. The wind induced building response of tall buildings can be reduced by means of aerodynamic based design and modifications that change the flow pattern around the building or break up the wind affecting the building face.

II. METHODOLOGY

In this study, the gust response factors for various along wind response components at different shape of building as per I.S 875(part3)-1987 are calculated and analyzed with the help of ETAB's 13.1.1v.

Table -1: Parameters considered for the study

No. of Storey	50
Bottom storey height	3m
Storey height	3m
Soil type	Medium
Wind zone	I
Terrain category	II
Shape of buildings	Rectangular, square, circular and elliptical
Plan area	2500 m^2
Grid size	5 m x 5m
Thickness of slab	0.125m
Beam size	0.3m x 0.6 m
Column size	1m x 1m
Material Properties	
Grade of concrete	M40
Grade of steel	Fe500
Dead load intensities	
FF on floors	1.75 kN/m^2
FF on roof	2 kN/m^2
Live load intensities	
LL on floors	2 kN/m^2
LL on roof	1 kN/m^2

2.1 DESIGN WIND SPEED

The basic wind speed (V_z) for any site shall be obtained from Fig.1 IS: (875(Part 3)-1987) and shall be modified to include the following effects to get design wind velocity at any height (V_z) for the chosen structure:

a) Risk level
b) Terrain roughness, height and size of structure; and
c) Local topography

$V_z = V_b.k_1.k_2.k_3$

V_z= hourly mean wind speed in m/s, at height z

V_b = regional basic wind speed in m/s

k_1 = probability factor (risk coefficient) (Clause 5.3.1 of IS: 875(Part 3)-1987)

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k_2 = Terrain and height factor (Clause 5.3.2 of IS: 875(Part 3)-1987)

k_3 = topography factor (Clause 5.3.3 of IS: 875(Part 3)-1987)

2.2 DESIGN WIND PRESSURE

The design wind pressure at any height above mean level shall be obtained by the Following relationship between wind pressure and wind velocity:

P_z=0.6 V_z^2

Where, P_z= Design wind pressure in N/m2 at height 'z' m

V_z= design wind velocity in r

2.3 BUILDING MODELS

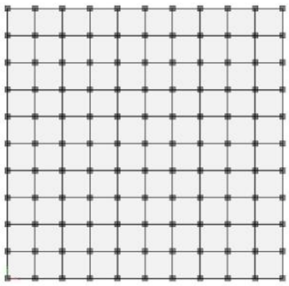
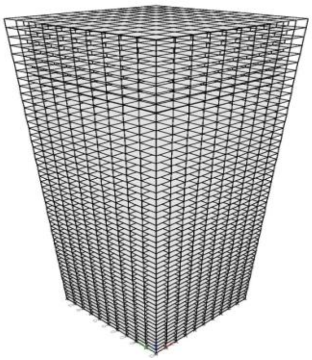



Fig-1: Plan and 3-D view of square building

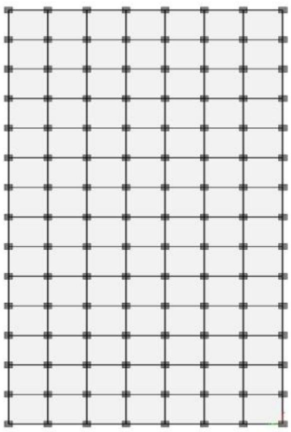
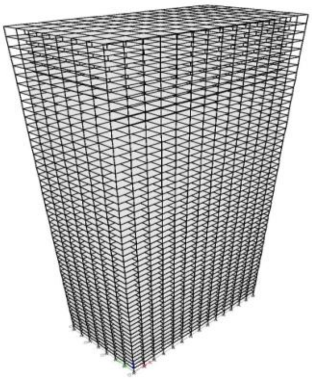
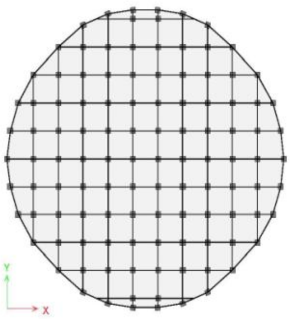



Fig-2: Plan and 3-D view of rectangular building



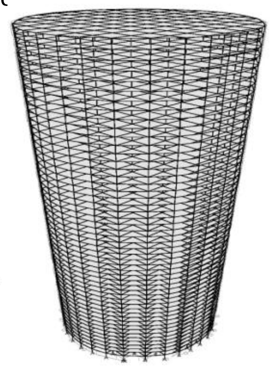


Fig-3: Plan and 3-D view of circular building

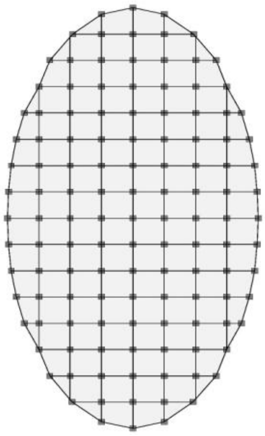
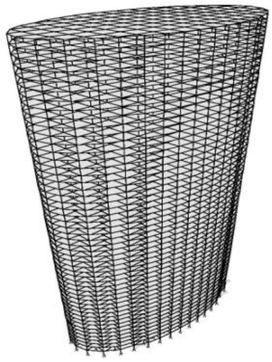



Fig-4: Plan and 3-D view of elliptical building

2.4 GUST FACTOR METHOD

A gust factor, defined as the ratio between a peak wind gust and mean wind speed over a period of time can be used along with other statistics to examine the structure of the wind. Gust factors are heavily dependent on upstream terrain conditions (roughness).

Since early 1960's, when Davenport's (1961) explained statistical concepts of the stationary time series for the determination of the response of simple structures to a turbulent gusty wind, efforts had been made to express peak stresses, accelerations, etc., in terms of the mean wind velocity, the spectrum of the gustiness and the mechanical and aerodynamic properties of the structure. Still today Davenport's (1967) 'gust loading factor approach' forms the most acceptable approach for prediction of mean and fluctuating response of slender structures.

2.5 ANALYSIS

Constants and parameters used for gust factor analysis are:

i. T = Time period (pg.48, IS 875(part-3)-1987)

ii. C_f = Force coefficient for clad building (fig. 4 of IS 875(part-3)-1987)

iii. g_f = Peak Factor and Roughness Factor (fig. 8 of IS 875(part-3)-1987)

iv. B = Background factor (fig. 9 of IS 875(part-3)-1987)

v. S = Size reduction factor (fig. 10 of IS 875(part-3)-1987)

vi. Ø = Constant

vii. E = Gust energy factor (fig. 11 of IS 875(part-3)-1987)

viii. β = (pg.52, IS 875(part-3)-1987)

ix. G = Gust factor

$$G = 1 + gfr\sqrt{\left[B(1+\emptyset)^2 + \frac{SE}{\beta}\right]}$$

x. F_x = Along wind load on the structure on a strip area at any height

$$Fx = Cf.Ae.Pz.G$$

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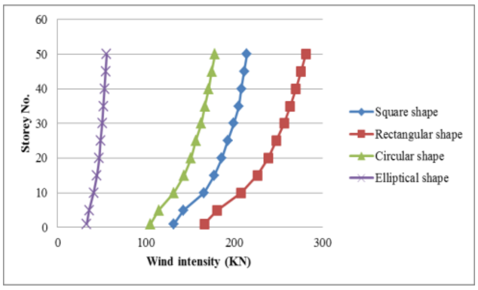
Table -2: Parameters considered for gust factor analysis

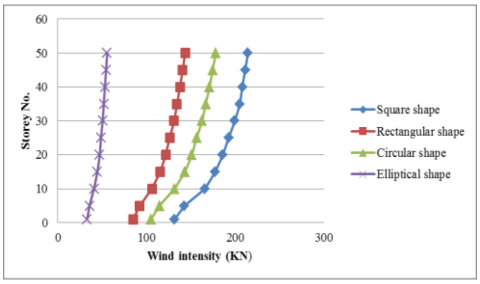
Name of parameter	Square model	Rectangular model	Circular model	Elliptical model
k_1	1	1	1	1
k_3	1	1	1	1
Class	B	C	C	C
T_x	1.9	1.61	2.54	2.18
T_y	1.9	2.25	2.54	2.94
C_f	1.25	1.1	0.7	0.2
g_f	0.85	0.85	0.85	0.85
B	0.85	0.85	0.85	0.85
Ø	0	0	0	0
β	0.016	0.016	0.016	0.016

Table -3: Wind loads with gust factor (kN)

Floor no.	Square	Rectangular		Circular	Elliptical	
		X	Y		X	Y
1	96.46	116.57	67.26	94.77	30.17	29.22
5	111.76	134.82	78.52	109.81	35.17	33.85
10	136.45	162.67	95.85	132.90	42.91	40.80
15	153.23	181.94	107.96	149.22	48.41	45.84
20	165.27	194.96	116.17	160.49	52.06	49.17
25	175.29	204.68	122.30	168.74	54.74	51.67
30	183.98	214.61	128.60	177.10	57.98	54.23
35	191.70	223.33	134.15	184.53	60.85	56.44
40	197.03	229.23	137.91	189.55	62.69	57.96
45	203.04	235.21	141.72	194.60	64.47	59.52
50	209.79	241.27	145.57	200.41	66.31	61.10



Graph -1: Wind intensity in X-direction



Graph -2: Wind intensity in Y-direction

III RESULTS AND DISCUSSION

This section contains behavior of various buildings of different shapes.

3.1 LATERAL DISPLACEMENT

It is displacement caused by the lateral force on the each storey level of structure.

Table -4: Comparison of storey displacement with gust factor (X-direction) (kN)

Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Storey displacement (mm)	Storey displacement (mm)	% Decrease	Storey displacement (mm)	% Decrease	Storey displacement (mm)	% Decrease
0	0	0.7	0.6	14.286	0.8	-14.286	0.2	71.429
10	30	25.2	21.7	13.889	26	-3.175	7.4	70.635
20	60	48.7	37.6	22.793	50.4	-3.491	14.2	70.842
30	90	67.5	49.9	26.074	69.7	-3.259	19.5	71.111
40	120	80.5	58.1	27.826	83	-3.106	23.1	71.304
50	150	87.4	62.1	28.947	90.1	-3.089	24.9	71.510

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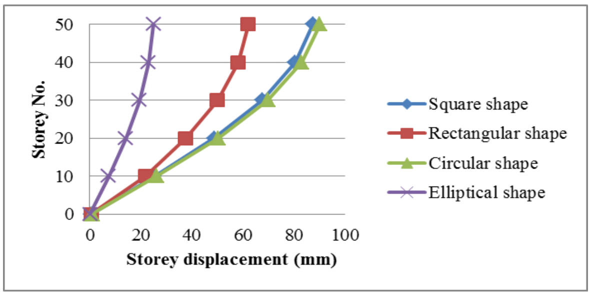
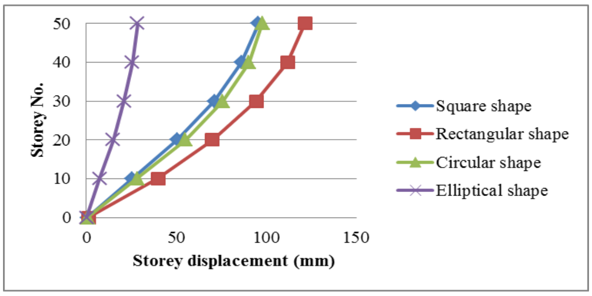
Table -5: Comparison of storey displacement with gust factor (Y-direction) (kN)

Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Storey displacement (mm)	Storey displacement (mm)	% Decrease	Storey displacement (mm)	% Decrease	Storey displacement (mm)	% Decrease
0	0	0.7	1.2	-71.429	0.8	-14.286	0.2	71.429
10	30	25.7	39.8	-54.864	28.3	-10.117	7.5	70.817
20	60	50.6	70	-38.340	55	-8.696	14.9	70.553
30	90	71.2	94.5	-32.725	76	-6.742	21.1	70.365
40	120	86.3	111.8	-29.548	90.4	-4.751	25.7	70.220
50	150	95.6	121.5	-27.092	97.9	-2.406	28.5	70.188



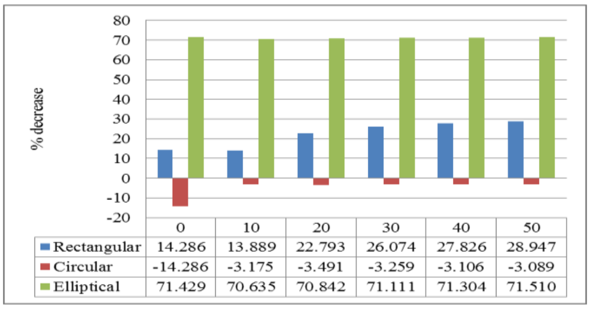
Graph -3: Storey displacement in X-direction



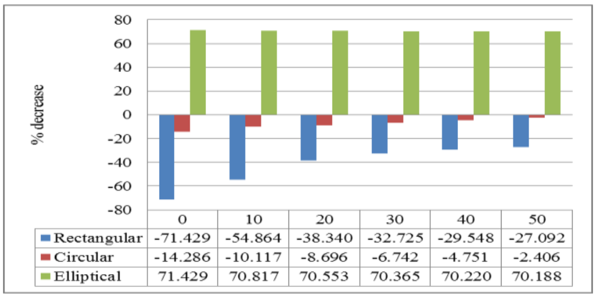
Graph -4: Storey displacement in Y-direction

3.2 STOREY DRIFT

It is the displacement of one level relative of the other level above or below.



Graph -5: % decrease of displacement in X-direction



Graph -6: % decrease of displacement in Y-direction

Table -6: Comparison of Storey drift with gust factor (X-direction)

Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Storey drift	Storey drift	% Decrease	Storey drift	% Decrease	Storey drift	% Decrease
0	0	0.246	0.173	29.675	0.258	-4.878	0.076	69.106
10	30	0.849	0.583	31.331	0.885	-4.240	0.243	71.378
20	60	0.71	0.482	32.113	0.741	-4.366	0.2	71.831
30	90	0.529	0.349	34.026	0.558	-5.482	0.147	72.212
40	120	0.323	0.207	35.913	0.348	-7.740	0.087	73.065
50	150	0.186	0.137	26.344	0.206	-10.753	0.088	52.688

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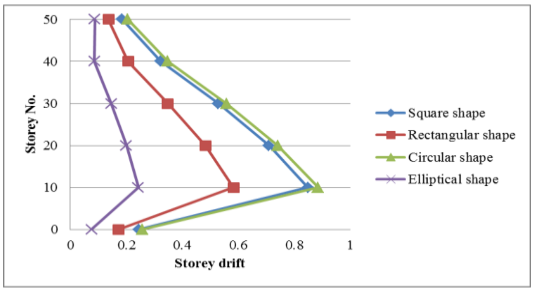
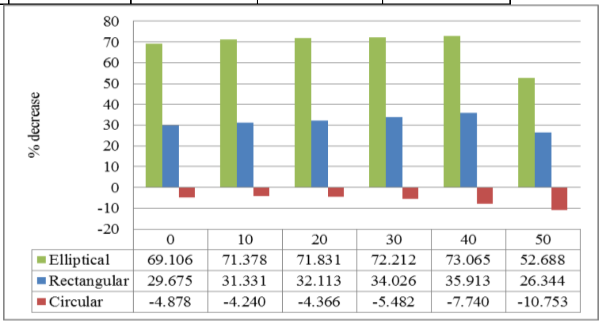
Table -7: Comparison of Storey drift with gust factor (Y-direction)

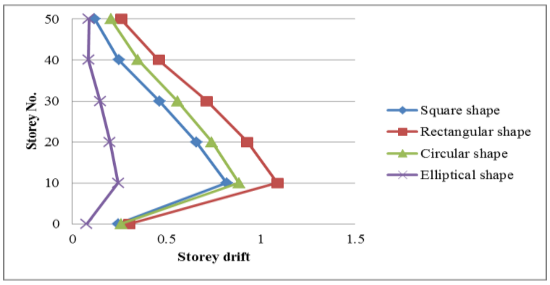
Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Storey drift	Storey drift	% Decrease	Storey drift	% Decrease	Storey drift	% Decrease
0	0	0.244	0.302	-23.770	0.276	-13.115	0.074	69.672
10	30	0.818	1.088	-33.007	0.969	-18.460	0.26	68.215
20	60	0.657	0.929	-41.400	0.81	-23.288	0.232	64.688
30	90	0.462	0.714	-54.545	0.606	-31.169	0.184	60.173
40	120	0.247	0.459	-85.830	0.373	-51.012	0.127	48.583
50	150	0.118	0.259	-119.492	0.221	-87.288	0.114	3.390



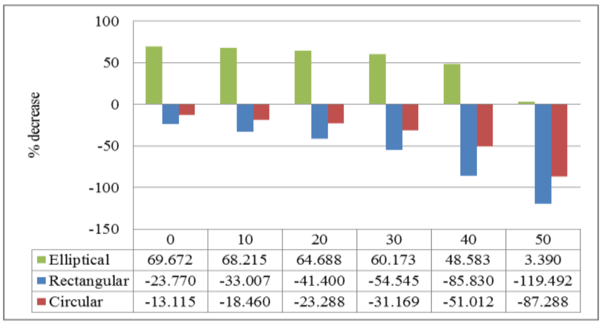
Graph -7: Storey drift in X-direction



Graph -9: % decrease of storey drift in X-direction



Graph -8: Storey drift in Y-direction



Graph -10: % decrease of storey drift in Y-direction

3.3 STOREY SHEAR

The summation of design lateral forces at levels above the storey under consideration.

Table -8: Comparison of Storey shear with gust factor (X-direction) (kN)

Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Storey shear (KN)	Storey shear (KN)	% Decrease	Storey shear (KN)	% Decrease	Storey shear (KN)	% Decrease
0	0	12573.615	8915.481	29.094	12282.829	2.313	3969.000	68.434
10	30	11068.875	7859.618	28.994	10806.057	2.374	3498.495	68.393
20	60	8805.45	6265.258	28.848	8487.108	3.615	2783.305	68.391
30	90	6210.885	4339.087	30.137	5967.661	3.916	1965.336	68.357
40	120	3352.275	2338.503	30.241	3214.616	4.106	1058.619	68.421
50	150	314.535	218.360	30.577	300.688	4.403	99.469	68.376

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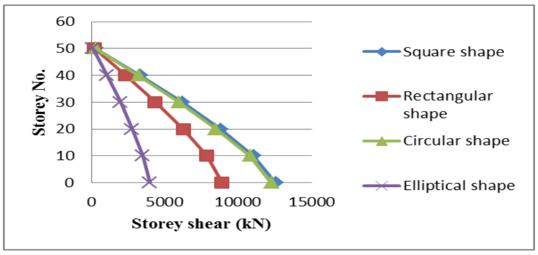
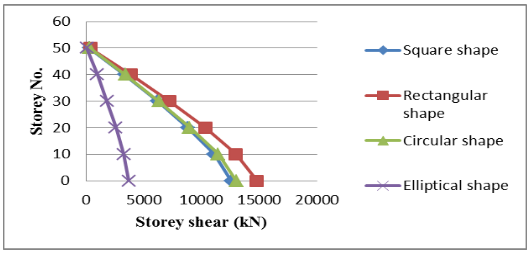
Table -9: Comparison of Storey shear with gust factor (Y-direction) (kN)

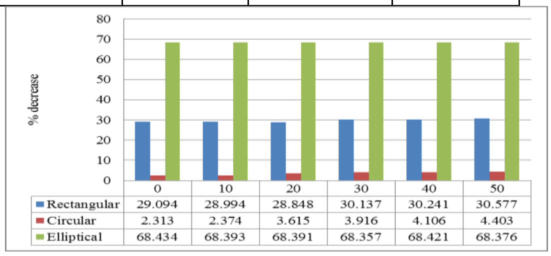
Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Storey shear (KN)	Storey shear (KN)	% Decrease	Storey shear (KN)	% Decrease	Storey shear (KN)	% Decrease
0	0	12587.025	14815.455	-17.704	13013.246	-3.386	3727.399	70.387
10	30	11081.385	13002.693	-17.338	11448.710	-3.315	3272.592	70.468
20	60	8817.96	10313.509	-16.960	8991.669	-1.970	2595.666	70.564
30	90	6210.885	7257.578	-16.853	6322.492	-1.797	1824.255	70.628
40	120	3352.275	3881.193	-15.778	3405.835	-1.598	982.173	70.701
50	150	314.535	361.898	-15.058	318.557	-1.279	91.655	70.860



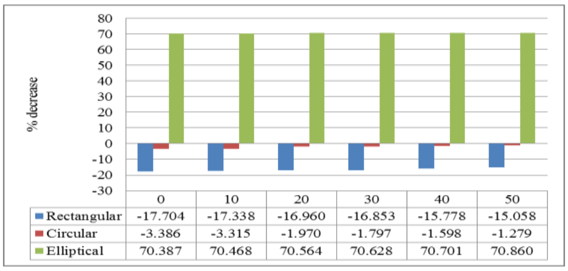
Graph -11: Storey shear in X-direction



Graph -12: Storey shear in Y-direction



Graph -13: % decrease of Storey shear in X-direction



Graph -14: % decrease of Storey shear in Y-direction

3.4 AXIAL FORCES

Axial forces of column which is common in various shape of buildings is taken for the comparison of results of all the buildings.

Table -10: Comparison of Axial forces in column with gust factor (X-direction) (kN)

Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Axial forces (kN)	Axial forces (kN)	% Decrease	Axial forces (kN)	% Decrease	Axial forces (kN)	% Decrease
0	0	16642.4241	16366.337	1.659	16703.1668	-0.365	16753.4	-0.667
10	30	13949.2225	13600.285	2.501	14004.3564	-0.395	13851.9	0.698
20	60	10899.3488	10540.476	3.293	10974.3874	-0.688	10677.9	2.032
30	90	7590.0918	7285.692	4.010	7666.9083	-1.012	7343.04	3.255
40	120	4072.5453	3880.404	4.718	4125.5469	-1.301	3890.89	4.461
50	150	375.8143	352.193	6.285	379.8881	-1.084	351.499	6.470

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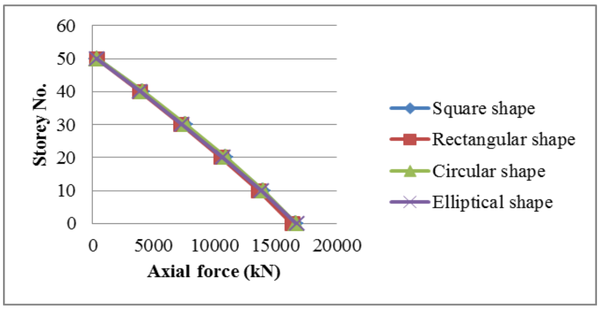
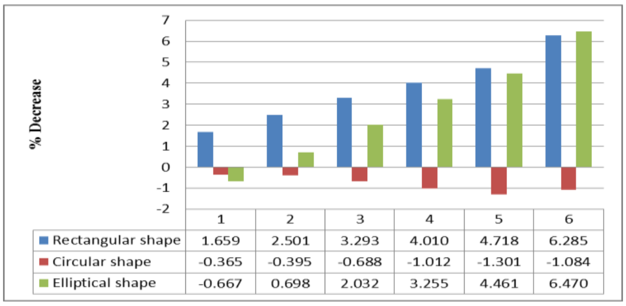
Table -11: Comparison of Axial forces in column with gust factor (Y-direction) (kN)

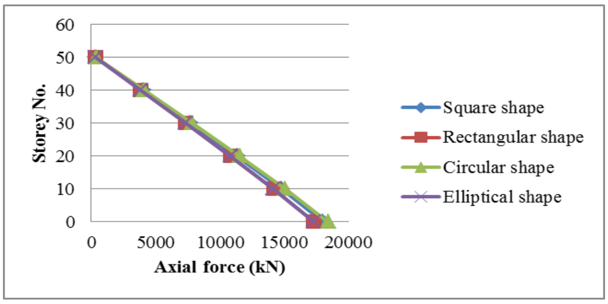
Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Axial forces (kN)	Axial forces (kN)	% Decrease	Axial forces (kN)	% Decrease	Axial forces (kN)	% Decrease
0	0	18027.3265	17326.029	3.890	18425.1508	-2.207	17301.9	4.024
10	30	14818.48	14193.903	4.215	15112.3282	-1.983	14180.8	4.304
20	60	11333.7597	10828.216	4.461	11543.5418	-1.851	10826.8	4.473
30	90	7736.748	7374.160	4.687	7871.5251	-1.742	7378.25	4.634
40	120	4074.5636	3871.274	4.989	4137.5269	-1.545	3875	4.898
50	150	370.0923	347.456	6.116	374.2118	-1.113	347.814	6.020



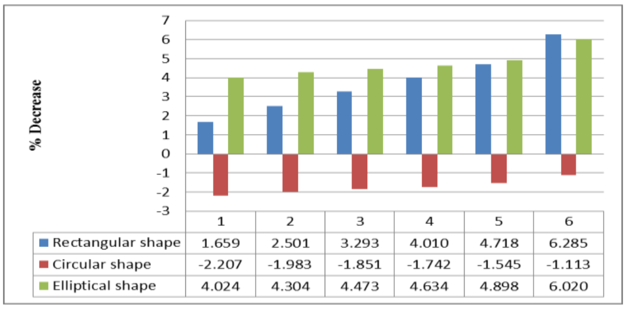
Graph -15: Axial forces in X-direction



Graph -17: % decrease of Axial forces in X-direction



Graph -16: Axial forces in Y-direction



Graph -18: % decrease of Axial forces in Y-direction

3.5 WIND INTENSITY

It is the pressure exerted by the wind on the structure. Following tables and graph shows the variation of wind intensity from square shape to elliptical shape building.

Table -12: Comparison of Wind forces with gust factor (X-direction) (kN)

Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Wind intensity (kN)	Wind intensity (kN)	% Decrease	Wind intensity (kN)	% Decrease	Wind intensity (kN)	% Decrease
0	0	96.457	116.566	-20.847	94.773	1.746	30.172	68.719
10	30	136.446	162.674	-19.223	132.902	2.597	42.915	68.548
20	60	165.272	194.964	-17.965	160.494	2.891	52.061	68.500
30	90	183.979	214.612	-16.651	177.101	3.738	57.981	68.485
40	120	197.028	229.230	-16.344	189.554	3.793	62.695	68.180
50	150	209.786	241.265	-15.006	200.406	4.471	66.310	68.392

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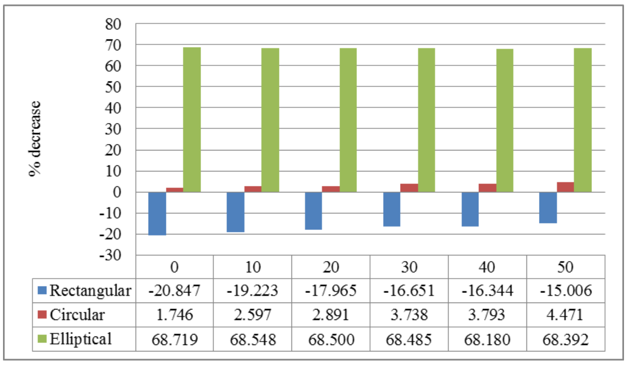
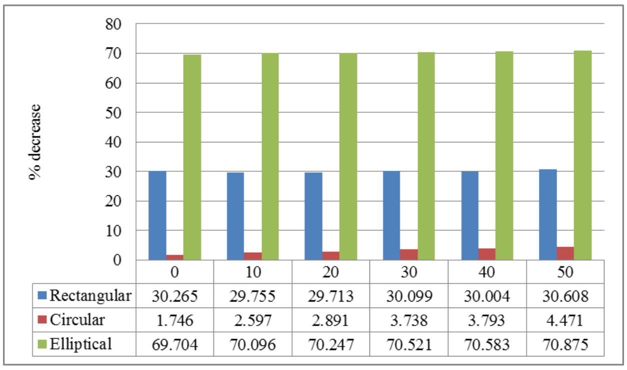
Table -13: Comparison of Wind forces with gust factor (Y-direction) (kN)

Storey No.	Height m	Square	Rectangular		Circular		Elliptical	
		Wind intensity (KN)	Wind intensity (KN)	% Decrease	Wind intensity (KN)	% Decrease	Wind intensity (KN)	% Decrease
0	0	96.457	67.265	30.265	94.773	1.746	29.222	69.704
10	30	136.446	95.846	29.755	132.902	2.597	40.803	70.096
20	60	165.272	116.165	29.713	160.494	2.891	49.174	70.247
30	90	183.979	128.604	30.099	177.101	3.738	54.235	70.521
40	120	197.028	137.912	30.004	189.554	3.793	57.959	70.583
50	150	209.786	145.574	30.608	200.406	4.471	61.101	70.875



Graph -19: % decrease of Wind intensity in X-direction



Graph -20: % decrease of Wind intensity in Y-direction

IV CONCLUSIONS

1. The percentage reduction in peak intensity of wind for circular building is 4.471 %, 68.392 % for elliptical building and it is more by 15 % for rectangular building when compared with square building with gust factor.
2. The percentage reduction in peak displacement is more by 3.08 % in circular building with gust factor in longitudinal direction when compared with square building. The percentage reduction in peak displacement is 70.18 % in elliptical building, it is more by 27 % in rectangular, 2.40 % in circular building when compared with square building with gust factor in transverse direction.
3. The percentage reduction in peak drift is increased by 10.75 % in circular building with gust factor in longitudinal direction when compared with square building. The percentage reduction in peak is decreased by 3.39 % in elliptical building, it is more by 119.49 % in rectangular, 87.28 % in circular building when compared with square building with gust factor in transverse direction.
4. The percentage reduction in peak storey shear is 30.57 % in rectangular building,4.40 % in elliptical building and 68.37 % in circular building with gust factor in longitudinal direction when compared with square building. The percentage reduction in peak drift is decreased by 70.86 % in elliptical building, it is more by 14 % in rectangular, 1.27 % in circular building when compared with square building with gust factor in transverse direction.
5. Buildings having circular or elliptical plan forms have a smaller surface perpendicular to the wind direction, the wind pressure is less than in prismatic buildings.
6. From the above results, with the change in shape of building from square to elliptical the wind intensity, storey drifts, the lateral displacements, storey shear of the building decreased. Hence it is conclude that wind load is reduced by maximum percentage with an elliptical plan.

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