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Along and Across Wind Parameters Acting on Tall Structures

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***Abstract*: As the requirement of high-rise building is increasing, along wind and across wind loading has become one of the most important design criteria to fulfill the condition of strength and serviceability. In this parametric study tall structures with different height and different aspect ratio (6: 1: 1, 6: 1: 2, 6: 2: 1, 3: 1: 1, 9: 1: 1) for a certain basic wind speed zone (50 m/s) and terrain category are analyzed by the formulas given in IS 875 (part3), 2015. All the parameters (natural frequency, gust factor, along and across wind force) are calculated for considered cases and being plotted to find out the relation between the parameters and height and width of the buildings. This study also includes a probable design of a tall building (in terrain category 2) of plane aspect ratio 6:1:2, 6:1:1, 6:2:1 using STAAD.Pro. The maximum nodal reactions at the base of each building are evaluated by STAAD.Pro and the reactions are being compared in a tabular form. Eventually the best possible design criteria for tall building for wind load consideration are being concluded here.**

***Keywords*: along wind load, across wind load, gust factor, tall building, aspect ratio, case study, design by STAAD. Pro**

1. Introduction

Due to increasing urbanization residential building structures are becoming more slender, flexible and wind sensitive and obviously challenging to accommodate more people with a better life style. In structural point of view for construction of high rise buildings wind loading becomes one of the main design criteria to achieve adequate stability, strength and serviceability. Wind loading is basically dynamic loading in three directions i.e. along wind, across wind and torsional direction. The value of wind load mostly depends on two parameters- direction and magnitude of wind flow (Khanduri, 1998). For calculating this load dynamic and aerodynamic damping and wind induced motion need to be characterized. To evaluate Equivalent Static Wind Load (ESWL) for along and across wind direction gust factor approach is utilized by different international codes. In the latest Indian code (2015) only along wind load calculation is done by gust factor approach.

Across wind motion may be created by lateral gustiness of wind or vortex shedding. Vortex shedding causes alternative vortices to create a certain frequency depending on shape of building and velocity of wind. There is no need to consider the effect of vortex shedding if the ratio of length to maximum transverse dimension is less than 2 [Cl9.2 IS 875(part3), 2015]. Various studies have shown that the magnitude of across wind loading is much more than the along wind loading in case of a high rise structure.

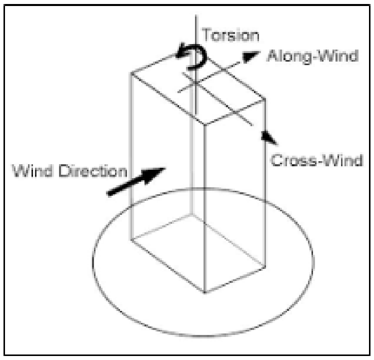


Fig. 1. Along wind, across wind and torsional direction of a tall building.

The magnitude of forces by along and across wind tends to change with the change of terrain category, basic wind speeds, height and plan aspect ratio of buildings. This study estimates how natural frequency, gust factor, along, across wind force changes with varying plan aspect ratio and height(h) of building, terrain category as per IS 875 (part3), 2015.

2. Considered cases

In the present study, residential buildings with aspect ratio (a)6:1:1, (b)6:1:2, (c)6:2:1, (d)3:1:1 and (e)9:1:1 have been considered. Minimum dimension of the buildings has been kept as 12m. So for buildings (a), (b), (c) height become 72m and for the rest of two it becomes 36m and 108m respectively. Basic wind speed is taken as 50m/s and dumping co-efficient (β) = 0.02 as per IS875 (part3): 2015, table 36, Cl10.2. For dynamic wind analysis hourly mean wind speed is used as reference. The direction of wind, acting on the tall building is supposed to be perpendicular to the (h*d) plane.

3. Calculation

A. *Natural frequency formulation*

The fundamental time period by dynamic loading on tall structure with shear wall can be calculated by the formula $T =$

$\frac{0.09*H}{\sqrt{d}}$ .... (1), where H= height of the building and d= maximum base dimension parallel to the applied wind force. Natural frequency is the inverse of that time period. IS8750 (part3): 2015, Cl 9.1 recommends that if the aspect ratio of the building i.e. ratio of height of building to the least lateral dimension of the building is more than 5 and natural frequency in the first mode is less than 1, than it is important to investigate wind induced oscillations. Natural frequency does not depend on terrain category. It only changes with the change of building height and plan aspect ratio.

Table 1
Natural frequency of tall building for different Aspect Ratio

Aspect ratio (h:b:d)	Natural frequency	Aspect ratio (h:b:d)	Natural frequency
6: 1: 2	0.5345	3: 2: 1	1.512
6: 1: 1	0.5345	9: 2: 1	0.504
6: 2: 1	0.756	6: 3: 1	0.9259
3: 1: 1	1.0691	6: 4: 1	1.0691
9: 1: 1	0.356	3: 2: 1	1.512

B. Gust factor formulation for along wind loading as per is 875 (part-3) 2015

Basically gust is a sudden increase in wind speed that lasts less than 20 seconds. In Indian standard for evaluating along wind force or equivalent static wind load (ESWL), design hourly mean wind pressure has to be multiplied by the effective frontal area of building, drag coefficient and Gust factor. In this approach the value of gust factor changes with the change of plan aspect ratio of building as well as height and terrain category and the calculation follows the formulation given in Cl10.2, page-47, IS 875(part3), 20and 15. The values of gust factors for different buildings are evaluated and listed in table 2.

Table 2
Gust factor for different building for different terrain category

Aspect ratio (h:b:d)	GF for T1	GF for T2	GF3 for T3	GF4 for T4
3: 1: 1	1.944	2.15	3.07	4.37
6: 1: 1	1.8976	2.055	2.76	3.71
9: 1: 1	1.879	2.02	2.6	3.34
6: 1: 2	1.845	1.98	2.707	3.64
6: 2: 1	1.807	1.96	2.67	3.5

The table 2 shows that as the terrain category changes from TC1 to TC4, the gust factor increases monotonically. Also, a comparison of first three rows depicts that as the height of the building increases, gust factor decreases slightly for each terrain category.

C. Along wind load calculation

Pressure fluctuations in windward (frontal area of building on which wind hits) and leeward direction in low frequency range, which tends the high rise building to overturn, result along wind load (Davenport, [1967]; Chen & Kareem [2005]). Gust factor approach is developed to calculate equivalent standard along wind loading, moment and deflection for tall structure by about all international codes. All the formulas described in Cl10.2 from IS 875(part3), 2015, are formulated and generalized from wind tunnel testing.

$$F_Z = C_{f,z} A_z p_d \mathrm{G} \qquad (2)$$

Where F_Z = design peak along wind load on building at any height z, $C_{f,z}$ = drag coefficient corresponding to areaA_z, G = gust factor and p_d = design hourly mean wind pressure corresponding to V_{Zd} and obtained by $0.6{V_{Zd}}^2$.

In table 3 design peak along wind load on the top of the different building is listed, taking base of the building as reference (s=0). A closer look in table3 gives the result that along wind force is more in case of short body orientation (wind direction is parallel to the shorter base dimension). In table4 design peak along wind load for different height of a 6:2:1 building for different terrain category is calculated. As height increases along wind force acting on the building also increases rapidly.

Table 3
Along wind loading in (N) for different building for different terrain category

Aspect ratio (h:b:d)	Force for T1	Force for T2	Force for T3	Force for T4
6: 1: 2	5288775	4823563	4812249	3252724
6: 1: 1	2719777	2503137	2453234	1657638
6: 2: 1	2589923	2387420	2373237	1784977
3: 1: 1	122172.6	1096894	1039878	628311
9: 1: 1	4296103	4075630	3872081	2712239

Table 4
Along wind loading in (N) for different height of a 6:1:2 building

Height (m)	Force for T1	Force for T2	Force for T3	Force for T4
0	0	0	0	0
10	489424.39	386868.67	289397.4	89579.52
20	576108.24	483294.54	407902.2	186888.7
30	637609.2	548233.776	488849.22	262697.36
40	686757.37	600974.32	553667.05	326265.15
50	729933.84	647458.52	609779.93	382500.8

D. Across wind load calculation

To compute across (or transverse) loading, wind loading test with special techniques (aero-elastic model test technique) is adopted. For Indian code Gust factor approach is not followed for across wind loading. Across wind load per unit height can be computed by the formula,

$$F_{ZC} = \left(\frac{3M_c}{\mathrm{h}^2}\right)\frac{\mathrm{z}}{\mathrm{h}} \qquad (3)$$

Where F_{ZC} = across wind load per unit height at height z, h= total height of building, M_c = across wind design peak base moment for enclosed building which can be computed by the empirical formula given in Cl 10.3 IS 875 (part 3): 2015. In this case base moment formulation depends on crosswind force spectrum coefficient (C_{fs}), which can be calculated from given graphs for some specific aspect ratios of buildings (6:1:1, 6:2:1, 6:1:2, 3:1:1, 9:1:1). From wind load testing it is demonstrated that tall buildings are more sensitive towards across wind direction and for square building the value of across wind loading is maximum. Table 5 also gives the result that for short body orientation across wind loading become much more than long body orientation.

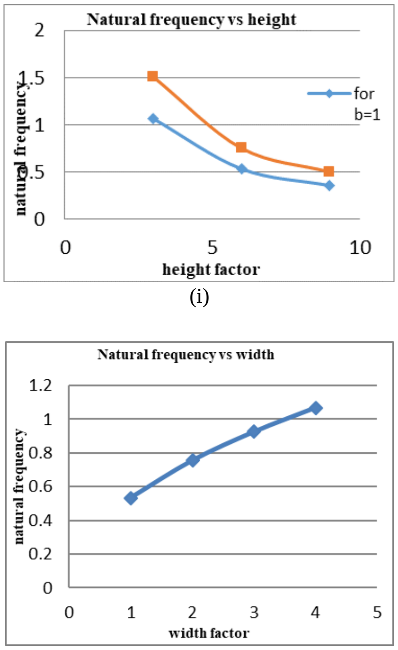
Table 5
Across wind loading in (N/m) for different building for different terrain category

Aspect ratio (h:b:d)	Force for T1	Force for T2	Force for T3	Force for T4
6: 1: 2	187940.94	130411.85	106397.6	44747.3
6: 1: 1	297160.71	218707.326	108093.75	47818.37
6: 2: 1	30380.672	23569.37	21064.61	8645.57
3: 1: 1	43036.307	33752.39	32803.41	11369
9: 1: 1	301925.56	270992.34	223634	89053.2

4. Result

A. *Relation between natural frequency and aspect ratio and height of building*

The fundamental time period by dynamic loading on tall structure with shear wall from table1 are plotted to compare in figure2 (i) & (ii). Figure 2(i) depicts the relation between height factor (3, 6, 9 implies 36, 72, 108m) and natural frequency for different width (b) of building (1, 2 implies 12m and 24m). This graph shows that if the height increases natural frequency decreases parabolically. If width of a building increases graph will be shifted upward, natural frequency for each building increases. Figure2 (ii) describes the relation between width and natural frequency at first node of buildings. If width (or base dimension parallel to wind direction) increases natural frequency will also increase. Here maximum natural frequency (0.5345) occurs when width factor is 4 (48m) and minimum (1.0691) when width factor is 1 (12m).



(i)

2(ii)

Fig. 2. (i) Profile of natural frequency for different height factor of building (ii) Profile of natural frequency for width factor of building

B. *Variation between gust factor and aspect ratio and height of building*

Gust factor method is introduced in all the codes to calculate ESWL for factoring up the mean load. In figure3 height of buildings and their corresponding gust factor are plotted. The graph demonstrates that the value of gust factor decreases as height of building increases (36, 72 and 108m). For lower terrain category (TC) the rate of change of gust factor is more i.e. graph becomes much steeper.

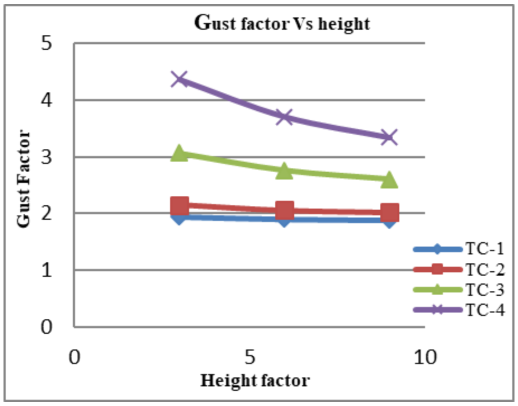


Fig. 3. Profile of gust factor for different height factor of a building for 4 TC

Figure 4 illustrated the relation between gust factor and plane aspect ratio of buildings, which depicts that gust factor for square building, is higher than other rectangular aspect ratios (Eimani- Kaleshar et al. 2006). For further change of plan aspect ratio gust factor decreases.

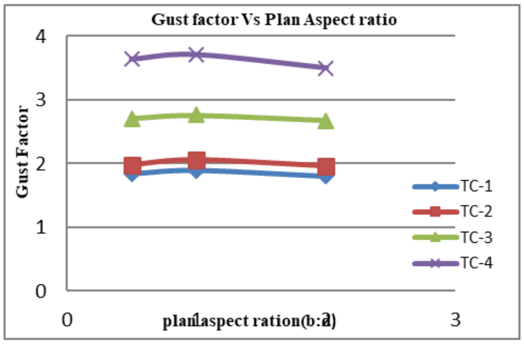


Fig. 4. Profile of gust factor for different plan aspect ratio of a building for 4 TC

C. *Variation of along wind loading with different height and aspect ratio of building*

In case of tall building the magnitude of along wind loading is less than across wind loading. Figure5 has illustrated the relation between aspect ratio and along wind force and the outcome depicts that along wind force decreases with increase of aspect ratio. The value of wind loading falls down rapidly when aspect ratio is 1 (square building). For further increase of aspect ratio the rate of change of along wind force become less. So from this graph it can be demonstrated for square building would undergo less along wind loading.

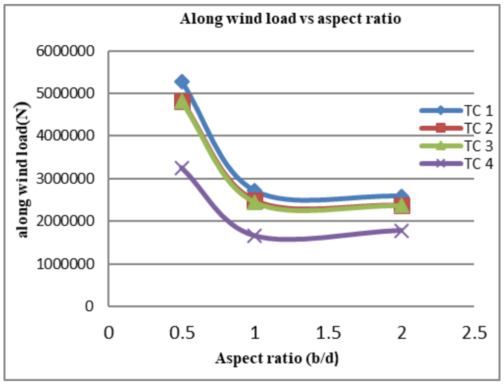


Fig. 5. Profile of along wind force for different height factor of a building for 4 TC

Figure 6 reveals that if height of building increases (36, 72, 108m) the value of along wind force also increases linearly. For lower terrain category the graph becomes more stepper.

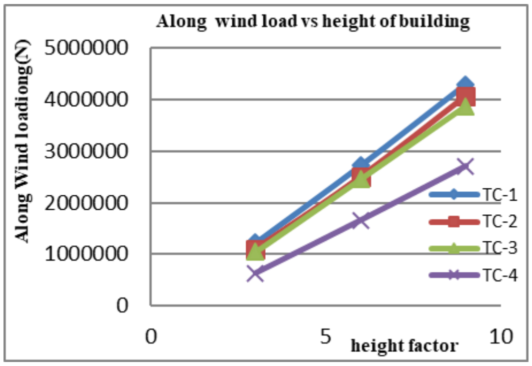


Fig. 6. Profile of along wind force for different plane aspect ratio of a building for 4 TC

D. Relation between across wind load vs different aspect ratio and height of building

The relation between across wind loading per unit length and aspect ratio of building is plotted in figure7, which shows that across wind loading for structure with square aspect ratio is much more than non- square aspect ratio. At first value of across wind loading increases with increase of aspect ratio. For square building it reaches the maximum value, further increasing of aspect ratio will cause significant decrease in across loading. For terrain category 1 this change is much prominent in compare to other terrain categories.

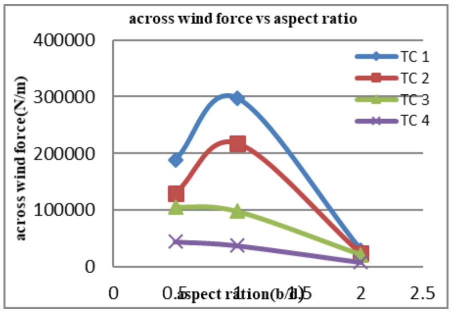


Fig. 7. Profile of across wind force for different plane aspect ratio of a building for 4 TC

Figure 8 shows that if height is not tall enough (36 meter) the value of across wind load in also low. So across wind loading is only taken in considering if the height of building is enough high. With increase in height across wind loading also increases.

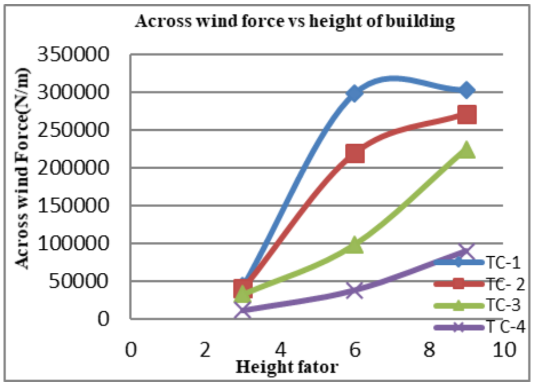


Fig. 8. Profile of across wind force for different height factor of a building for 4 TC

5. Design of a tall building using STAAD.Pro

The structural designs of three buildings 6:1:2, 6:1:1 and 6:2:1, with proper along and across wind loading, dead load and live load as well as the probable load combinations for terrain category 2, are done by using STAAD.Pro with proper beam, column and slab design. Each floor height has been adopted as 3m and 3*3m² grid is used in design purpose, taking minimum dimension of structure as 12m. So height of the building becomes 72 meter consisting 24 storeys. Column and beam size has taken as 300*300 mm² and slab thickness as 150mm. Grade of steel and concrete used here is respectively Fe 415 and M25. The view of the base of the buildings with fixed end and with proper wind direction is shown in figure 11. The maximum reaction at nodes, created at the base of each building are analyzed by STAAD.Pro, and listed in table7. This design is safe, sustainable and serviceable.

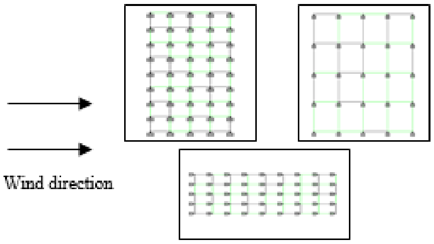


Fig. 9. Bases of buildings with different plan aspect ratio 12:24, 12:12, 24:12 respectively

Table 7
List of maximum base nodal reaction for various plan aspect ratios of building

Plane aspect ratio (b*d)	Maximum base nodal reaction, + value (KN)	Maximum base nodal reaction, - value (KN)
1: 2	4617	-2350
1: 1	14593	-13504
2: 1	3352.5	-1085.3

From table 7, it can be concluded that for square building the ultimate maximum wind loading is much more than rectangular ones. If wind blows parallel to shorter length or short body orientation, the maximum base reaction would be more than long body orientation.

Figure 10 shows rendered view of a building of 12:24 plan aspect with probable wind directions, designed by Staad.Pro. Wind direction is perpendiculater to 72*24 planes. One combination of across and along wind direction is demonstrated in this figure.

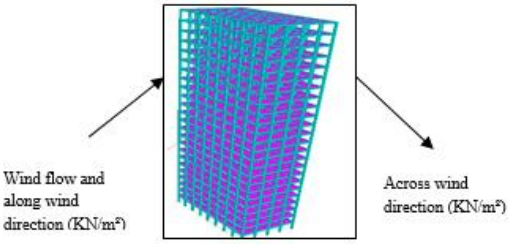


Fig. 10. Rendered view of 6:1:2 building with a combination of wind force (along, across)

6. Conclusion and Discussion

With the continuous increase of height of building, along and across wind loading has become one of the most important design criteria. Here in this parametric study the variation of the wind parameters with respect to different aspect ratio, height, and terrain category are measured as per IS 875 (part3), 2015, which can conclude that-

a) Natural frequency decreases with height and follows a parabolic relation and increases with width of building.
b) Gust factor is maximum for square building and decreases slightly with height of building
c) Along wind force decreases rapidly for square building and increases linearly with increasing height of building. Across wind loading is maximum for square building and increase with height of building. For tall structure across wind loading is more than along wind direction. Lower terrain category (open land) always gives higher along & across force.
d) For overall wind load calculation on tall structure, the wind loading become maximum for the square building. For short body orientation (wind direction is parallel to shorter length of base) both along and across wind increase significantly. So if width of the building (b) reduced maximum nodal base reaction will also reduce. Here base reaction for 6:2:1 is less than that of 6:1:2 building.

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