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Along and Across Wind Loads Acting on Tall Buildings

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***Abstract*—There is always an increasing need for tall buildings to accomplish the needs of the present day increasing population. In tall buildings, usually wind is the critical load which needs to be considered for the safety and serviceability of the structure. There are two components of wind namely along and acrosss wind load components and their effect needs to be assessed for wind resistant designs. In this paper, along and across wind loads acting on tall buildings located in terrain category IV having height varying from 90m to 240m have been computed as per the Indian standard code IS 875(Part 3): 2015 considering the effect of interferenece. The across and along wind load induced maximum base shears and base moments were compared to assess the governing wind load component acting on a tall RC framed building. It was deduced that the effect of along wind force is governing for up to a height of 150m in the case of long body orientation while it is the across wind force which is governing for all the buildings in case of short body orientation.**

***Index Terms*— Along wind load, across wind load, interference effect, long body orientation, long body orientation, aspect ratio.**

I. Introduction

Increased urbanisation has resulted in housing problems leading to the rise of several multi storeyed buildings. Tall slender buildings are more prone to wind loads especially in cyclone prone areas. Tall buildings being flexible when subjected to randomly varying wind will experience wind forces which acts in the direction of wind known as along wind component resulting from buffeting effects caused by turbulence as well as forces in a direction nearly perpendicular to the flow termed as across wind component. The across wind forces also known as lift or transverse forces arises due to flow separation from the cross section of the structure causing vortices to shed at a particular frequency. Torsional vibrations are also caused by the vortices generated as a result of non-uniform wind pressures acting over the surface of the building and the non-coincidence of center of mass and center of rigidity. If the along-wind responses are assumed to occur in the x-direction, the across-wind response occurs in the y-direction, and the torsional response occurs about the z-axis.

Wind velocity consists of a mean plus a fluctuating component as depicted in Fig.1. A momentary deviation of the fluctuating component from the mean value leads to gust formation [1]. The variation of wind velocity with height is shown in Fig 2. Wind velocity also depends upon the approach terrain and topography [1]. The

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roughness of the earth's surface that leads to wind drag causes turbulence and hence the surface wind speed is much less than the wind speeds at higher levels. There exists a boundary layer depending on the terrain within which the wind speed varies from about zero at the surface to the gradient wind speed at a height termed as the gradient height [2]. When one or more similar or dissimilar bodies are placed downstream or upstream of a structure, the wind induced pressures and forces acting on one get affected by the other. This is termed as interference effect and it will occur irrespective of the bodies being rigid or flexible and is very difficult to quantify in general due to the variability of the situations. When groups of two or more tall buildings are constructed in proximity to each other, the wind flow through them gets deformed and causes higher dynamic pressures and motions especially on the neighboring downstream buildings. Hence interference effect on buildings should not be ignored for a proper designing of the building.

Tall slender structures are sensitive under the dynamic effect of wind. Wind gusts causes fluctuating forces on the structure inducing large dynamic motions including oscillations based on the natural frequency of vibration and the damping of the structure [2]. The wind induced responses can be suppressed by incorporating various techniques like aerodynamic modifications such as corner modifications or major modifications in elevation, use of dampers, appropriate structural systems such as core, diagrid systems, outriggers, bracings etc. For an effective wind resistant design, integrated architectural and structural systems can be adopted after analysing the along and across wind responses.

In this paper, along and across wind loads acting on tall buildings which are 30, 40, 50, 60 ,70 and 80 storeyed located in terrain category IV have been computed as per the Indian standard code IS 875(Part 3): 2015 considering the effect of interferenece. The main objective is to assess which load component governs the tall building design based on the maximum base shear and base moment responses. This will help to plan the building configuration and design the structural systems so as to mitigate the wind induced responses thereby contributing to a performance based wind resistant design and occupant comfort.

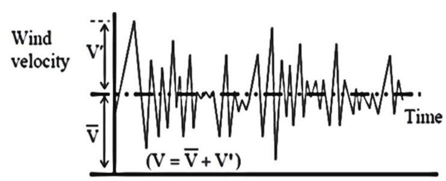

Figure 1. Variation of wind velocity with time [1]

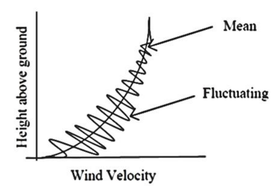

Figure 1. Variation of wind velocity with height [1]

II. Literature Studies

Mendiz et al. (2007) outlined wind load computation in the context of Australian Wind Code by illustrating its benefits over simplified approaches and reviewed various advanced levels for wind resistant design such as use of dampers, criteria for safety and serviceability as well as the use of wind tunnels or CFD for wind load estimation for better results. Halder and Dutta (2010) studied the variation of wind force on buildings of varying storeys 3-35 and aspect ratio with variation of site parameters and structural parameter based on Indian wind code IS: 875 (Part 3) – 1987 and compared the wind forces so obtained with that of the proposed Indian code and the American standard ASCE 7-02. Comparison of wind force calculation by Force coefficient based static analysis and Gust factor based dynamic analysis were also conducted to arrive at guidelines for estimating the design wind force in a simple form. It was observed that base shear estimated for low to high rise buildings by Indian wind code is 1.30- 1.90 times the same estimated by ASCE 7-02. Venanzi and Materazzi (2012) proposed a semi analytical procedure for aeroelastic across wind response of square tall buildings assuming no vortex shedding occurs. Vyavahare et al. (2012) generalized the procedure recommended in AS/NZS 1170-2: 2002 for across wind estimation using Artificial Neural Network inorder to obtain the across wind response for a building with given (h:b:d) ratio. Yi et al. (2013) evaluated the dynamic characteristics and wind-induced responses of a 420 m high tall building in Hong Kong during the passage of typhoons from field data such as wind speed, wind direction, acceleration and displacement responses using a monitoring system and assessed the accuracy of the GPS system installed in the building. GPS allows capturing both resonant and backgrounding displacements that contribute the total displacement of the building while accelerometers could only measure the resonant displacements. It was deduced that the damping ratios within 1.0– 2.0% of critical are reasonable for the wind-resistant analysis of super-tall buildings for serviceability consideration. Amin and Ahuja (2013) investigated experimentally the effects of side ratios and wind directions on wind pressure distribution on rectangular building models of similar plan area and height. It was deduced that for building models having same cross section, change in side ratio does not significantly affect the general magnitude of peak pressures and peak suctions and it is the wind angle which governs the pressure acting. It was also observed that absolute value of mean and RMS pressure coefficients on leeward face increased up to a side ratio of 0.64 and beyond that, they decreased with increase in side ratio. Young-moon et al. (2014) proposed a method for estimating the across and along wind responses of buildings for the preliminary design stage based on numerically simulated across and along-wind loads in the time domain using known across and along-wind load spectra from a wind tunnel experiment.

From the literature survey, it was observed that there is a need to analyse the along wind and across wind induced responses in order to assess which one induces a maximum response to a tall building so that an effective building design can be formulated. Wind direction and the building orientation play a major role in the wind responses which also needs to be assessed while designing. The IS 875 (Part 3) has been recently revised incorporating empirical formulas to estimate both along and across wind loads which is being used here to assess the wind loads.

III. Wind Load Calculation as per IS 875 (Part 3):2015

For preliminary design including the proportioning of the structure, the variation of wind force on a structure must be known. The wind loading codes are primarily based on comprehensive data on wind speeds collected by the meteorological departments and the results of the research carried out to understand wind characteristics and its effect on structures, based on these data and experiments made in wind tunnel. The IS 875 (Part 3): 2015 recommends use of force coefficient method or gust factor method for the calculation of wind loads depending on the type of building or structure.

Accordingly, dynamic analysis needs to be conducted for wind load computation if the aspect ratio i.e. height to minimum lateral dimension ratio is more than 5 or the natural frequency in the first mode is less than 1.0. Based on studies on tall rectangular buildings, the code recommends considering an interference factor (IF) as a multiplication factor for the wind loads corresponding to isolated buildings to take into account the interference effect of another interfering tall building of same or different height. The interference zones have been categorized into four zones as per the code based on the distance of the interfering structure location.

A. Along wind load

IS 875 (Part 3): 2015 specifies a gust factor or gust effectiveness factor method for calculating along wind load or drag load on flexible slender structures which includes tall buildings. The procedure makes use of hourly mean wind speed to arrive at the Gust Factor. The design peak along wind base bending moment obtained by summing the moments resulting from design peak along wind loads acting at different heights along the height of the building as:

$$M_a = \sum F_z Z \quad (1)$$

The along wind load on a structure on a strip area at any height *z* (m) is given by:

$$F_z = C_{f,z} . A_z . \overline{p_d} . G \quad (2)$$

where $C_{f,z}$ is the drag force coefficient for the building corresponding to A_z, A_z is the effective frontal area considered for the structure at height *z* in m^2, $\overline{p_d}$ is the design hourly mean wind pressure at height *z* due to hourly mean wind and *G* is the gust factor.

B. Across wind load

IS 875 (Part 3): 2015 suggests an empirical formulae for considering the dynamic effects of across wind load flexible structures. The across wind design peak base bending moment M_c for enclosed buildings is given by:

$$M_c = 0.5 g_h \bar{p}_h b h^2 (1.06 - 0.06k) \sqrt{\frac{\pi C_{fs}}{\beta}} \quad (3)$$

where $g_h = \sqrt{2 log_e (3600 f_0)}$, a peak factor in cross wind direction for resonant reponse, $\bar{p}_h$ is hourly mean wind pressure at height h (Pa), k is a mode shape power exponent for representation of the fundamental mode shape and C_{fs} is across wind force spectrum coefficient generalised for a linear mode.

Then, the across wind load distribution on the building obtained from M_c using linear distribution of loads as:

$$F_{z,c} = \left(\frac{3M_c}{h^2}\right)\frac{z}{h} \quad (4)$$

IV. BUILDINGS ANALYSED

Tall RC framed buildings with core and lateral load resisting shear walls of different plan configurations of aspect ratios 3, 4, 5, 6, 7 and 8 having same base area were analysed for along and across wind loads. The basic structural parameters and the RC frame parameters are listed in Table I and Table II respectively. The interfering structures are assumed to locate beyond 4b distance from the building under study that is a beyond a horizontal distance of 120m and hence zone IV is taken. Thus the zone factor is 1.07 [10]. The frequencies of the structure were examined to decide whether dynamic analysis is the appropriate method required. The loads were estimated considering the structure orientation in two ways. First one is the long body orientation in which wind is assumed to act parallel to the longer dimension and the other one is short body orientation in which wind is assumed to act parallel to the shorter dimension.

TABLE I. BUILDING PARAMETERS

Reference name	Aspect ratio (H/B)	Length (m)	Breadth (m)	Height (m)	Base area (m^2)	Number of storeys
A1	3	60	30	90	1,800	30
A2	4	60	30	120	1,800	40
A3	5	60	30	150	1,800	50
A4	6	60	30	180	1,800	60
A5	7	60	30	210	1,800	70
A6	8	60	30	240	1,800	80

TABLE II. BASIC PARAMETERS OF THE STRUCTURE

Plan dimension	30m x 60m
Plan area	1800 m^2
Storey height	3m
Wind terrain category	IV
Wind speed velocity	50m/s
Grade of concrete	M30
Grade of steel	Fe415
Grid size	5m x 5m
Interference zone	Z4

V. RESULTS AND DISCUSSIONS

The along and across wind loads acting on all the buildings considered were computed as per IS 875 (Part 3): 2015. The variation of the natural frequency with respect to aspect ratio of the buildings is shown in Fig 3. It was observed that the natural frequency decreased with increase in the building aspect ratio.

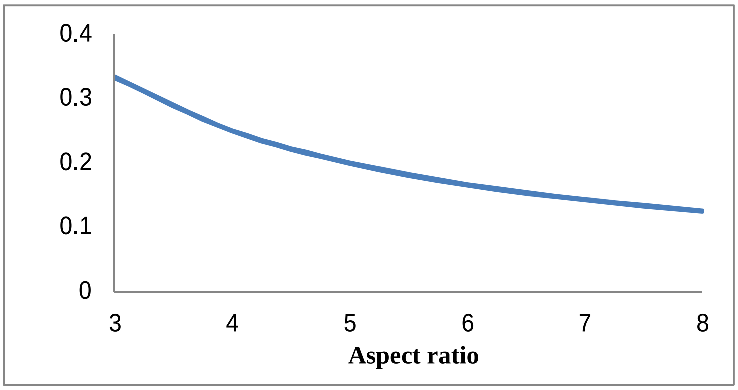

Figure 3. Variation of natural frequency with aspect ratio

The maximum value of natural frequency was obtained 0.33Hz for building with aspect ratio 3 and the minimum one was obtained as about 0.13Hz for the building with aspect ratio 8. Since all the natural frequencies of the buildings obtained were below 1Hz, dynamic method of wind force computation was performed as specified in IS 875(Part 3): 2015.

The along and across wind load induced maximum base shear and maximum base moment obtained for all the buildings considering long body and short body orientation were analysed. The along wind and across wind induced base shear and base moment are listed in Table III and Table IV respectively.

TABLE III. ALONG WIND LOAD INDUCED BASE SHEAR AND BASE MOMENT FOR LONG BODY AND SHORT BODY ORIENTATION

Reference name	Long body orientation		Short body orientation	
	Base shear (kN)	Base moment (kNm)	Base shear (kN)	Base moment (kNm)
A1	1534.88	91256.59	1596.32	94909.22
A2	2156.92	167089.44	2404.66	186257.28
A3	3287.38	313359.24	3326.36	317074.67
A4	4312.04	487639.84	4225.56	477859.72
A5	5431.47	710310.15	5140.45	672251.05
A6	6279.92	931959.67	6173.51	916169.19

TABLE IV. ACROSS WIND LOAD INDUCED BASE SHEAR AND BASE MOMENT FOR LONG BODY AND SHORT BODY ORIENTATION

Reference name	Long body orientation		Short body orientation	
	Base shear (kN)	Base moment (kNm)	Base shear (kN)	Base moment (kNm)
A1	870.81	48830.50	1947.19	109188.30
A2	1805.01	134954.07	2947.57	220379.08
A3	3060.21	286001.13	4601.39	430036.68
A4	4604.21	516359.47	6361.65	713453.14
A5	6960.50	910719.91	8394.68	1098369.54
A6	10054.36	1503455.19	10302.65	1540583.13

It is observed that the across wind induced base shear and base moment are greater for short body orientation for all the buildings. In case of long body orientation, along wind load is governing up to a height of 150m and beyond that it is across wind which is governing. The across wind induced base shear and base moment are greater by a maximum of about 70% with respect to that of along wind induced in case of the short body orientation. For the case of long body orientation, the along wind induced base shear and base moments are greater by about 47% for 90m high building and then with the increase in height its contribution towards a maximum response decreases. Consequently, at a height of 240m, the across wind induced response becomes greater by about 60% for 240m high building. It is also observed that the short body orientation gives maximum across wind responses for all heights and maximum along wind responses for height upto 150m compared to long body orientation. The increased across wind response in case of short body orientation might be due to the reduced surface area to resist the across wind. The maximum values of the wind induced base shear and base moment for both cases are tabulated in Table V.

TABLE V. ALONG AND ACROSS WIND LOAD INDUCED MAXIMUM BASE SHEAR AND BASE MOMENT

Reference name	Along wind load induced		Across wind load induced	
	Base shear (kN)	Base moment (kNm)	Base shear (kN)	Base moment (kNm)
A1	1596.32	94909.22	1947.19	109188.30
A2	2404.66	186257.28	2947.57	220379.08
A3	3326.36	317074.67	4601.39	430036.68
A4	4312.04	487639.84	6361.65	713453.14
A5	5431.47	710310.15	8394.68	1098369.54
A6	6279.91	931959.67	10302.65	1540583.13

The wind induced maximum shear and moments can be used for the wind resistant design of tall buildings.

VI. Conclusions

The following conclusions can be drawn.

(i) Effect of along wind force is governing for up to a height of 150m in the case of long body orientation while it is the across wind force which is governing for all the buildings in case of short body orientation.

(ii) Short body orientation gives the maximum along wind response compared to the long body orientation up to a height of 150m.

(iii) Maximum across wind load responses are obtained in case of short body orientation for all the buildings.

The along and across wind induced maximum responses should be assessed in order to facilitate a performance based wind resistant design.

Future Scope of Work

The future work shall cover

(i) Along and across wind induced responses of tall buildings of different aspect ratio with different aerodynamic modifications.

(ii) Along and across wind induced responses of tall buildings of different aspect ratio with different structural systems.

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