ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 3, Issue 1, January 2018

Comparative Study of Codal Provisions for Dynamic Wind Response of Tall Buildings

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Abstract: -- **Wind engineering is an up growing field in structural engineering. It is necessary for us to study it especially for Tall buildings that are prone to wind-induced oscillations. In the recent times, there have been so many catastrophic damages caused by high wind speeds especially in the United States and in the coastal regions of India. This proves that many buildings that are currently in use may not fully wind resistant. The Indian code of practice for wind load on buildings and structures (IS-875 Part-3 1987) included a procedure to determine along wind response of tall structures, while the across wind response and interference effect is not included in the same code. The present Indian specification ie IS 875 (Part -3):2015 included the specification for determining the along as well as across wind response. IS 875 (Part -3): 2015 included a mathematical expression for different parameters such as terrain factor, background factor, upwind velocity fluctuation etc. This paper includes a comparison of IS 875 (Part-3):1987, IS 875 (Part-3):2015 and AS/NZS:1170 (Part 2):2011 for dynamic wind response of tall buildings/structures. The comparison is validated by analyzing tall building for all-terrain categories as per earlier & previous version of Indian specification and with Australian codal provision for wind loading.**

Keywords: **Along Wind, Across Wind, Tall Building, Gust Factor, Terrain Category.**

I. INTRODUCTION

Most international codes and standards included the "gust loading factor" (GLF) approach for assessing the dynamic wind loads and their effects on tall structures/buildings. The concept of the Gust loading factor for civil engineering applications was first introduced by Davenport (1967)1. Several modifications based on the first gust loading factor model by Devenport followed, which include Vellozzi and Cohen (1968), Vickery (1970), Simiu and Scanlan (1996), and Solari (1993 a,b) same was explained in brief by another author (Hajara,2006)3. Variations of these models have been adopted by major international codes and standards. The present Indian Standard (IS 875(part-3):2015) and Australian code (AS/NZS:1170 Part 2):2011) for Wind Loads on Buildings and Structures also recommends Gust Factor (GF) or Gust Effectiveness Factor (GEF) for calculating along wind load and across wind load on flexible slender structures which includes tall buildings. Whereas in the previous revision (IS 875 (part-3):1987) of wind code there is no as such recommendation is given for across wind effect on structure/building. In this paper, the procedure recommended by the present IS code (IS 875 (part-3):2015), previous IS code (IS 875 (part-3):1987) and AS/NZS:1170 (Part 2):2011 have been reviewed. To highlight the comparison, examples of the tall building have been selected and the response has been obtained and compared.

2.1 Tall Building

Tall buildings, Chimneys, Towers etc. are considered wind-sensitive because they are tall and slender structures and undergo wind-induced oscillation in the along and across direction. The building, even though made of steel and concrete, when the wind blows, or an earthquake occurs structure begin to vibrate. A building with height more than or equal to 50 m or having a height to smaller dimension ratio more than 6, then the structure is said to tall or high-rise; Various international codes have given almost similar definitions.

2.2 Along and Across wind

When the response of building is studied in the direction of the wind is called along wind response. The response of the building in a direction perpendicular to the wind is called the across wind response. Tall buildings essentially respond in both along and across wind directions. Whether one is dominant over the other is depend upon the structural characteristics, dimensions, and damping. Determining the along-wind response is better understood and thus has less uncertainty while across-wind is largely empirical and requires wind tunnel experiments.

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Due to the complexity involved in the experimentation, the wind response has been determined theoretically by using various international codes of practice such as the Indian, Australian, and American codes etc. Most of the codes of practice use the gust factor method.

III. CODAL COMPARISON FOR DYNAMIC WIND RESPONSE

As per IS 875 (Part -3) 2015, building and closed structures with a height to minimum lateral dimension ratio of more than 5 Or building and structures whose natural frequency in the first mode is less than 1.0 Hz, shall be examined for dynamic effects of wind.
In IS 875 (Part3)-2015, Aerodynamic roughness heights (Z0, i) for each terrain categories have been included and are used to find out turbulence intensity and mean hourly wind speed. The previous classification of structures into B and C classes have been deleted and accordingly modification factor, k2 is renamed as terrain roughness and height factor. For cyclonic regions, an additional modification factor termed as importance factor has been included in the present version. Simple empirical equations for calculating height variations of hourly mean wind speed and turbulence intensity in different terrains have been suggested in the current revision. In the Gust Factor method for determining along wind response, expressions are included for background factor, size reduction factor, energy ratio, and length scale of turbulence while in previous version plots are given for calculating these parameters, which is quite difficult to calculate exact value. Second revision (IS 875 (Part-3) 1987) is almost silent about the across wind response on structure /building, in present revision (IS 875 (Part-3) 2015) a method for computing across wind response of tall buildings has been included.
The Comparison of IS 875 (Part 3)-1987 and IS 875 (Part 3)-2015 for dynamic wind response are tabulated in table-1.

IV. RESULT & DISCUSSION

In this paper for the comparison of codes, a tall building of dimension 90 m x 30 m x 30 m with the basis wind speed of 33 m/sec for all four-terrain categories is consider. Height to minimum dimension is less 5 but the natural frequency in the first mode is 0.676 Hz, which is less than 1 Hz, therefore building shall be examined for dynamic response. The dynamic response in both along and across wind directions is calculated and results are compared for different terrain categories using IS 875 (Part-3):1987, IS 875 (Part-3): 2015 and AS/NZS: 1170(Part – 2):2011. The responses of building for different terrain categories as per both the revisions of Indian Wind Code and Australian code are presented in fig.1 to fig.4.

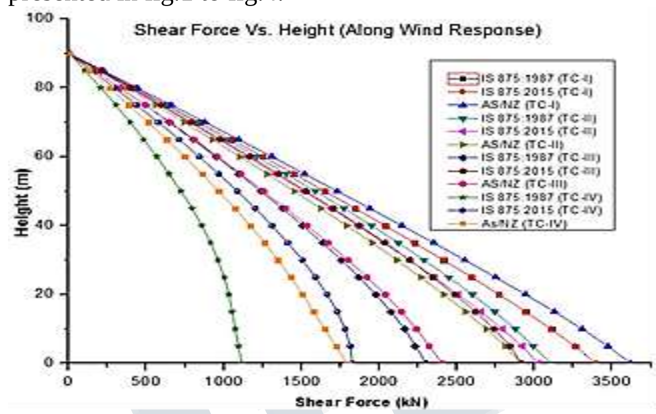

Fig. 1: Shear Force Along Wind Direction

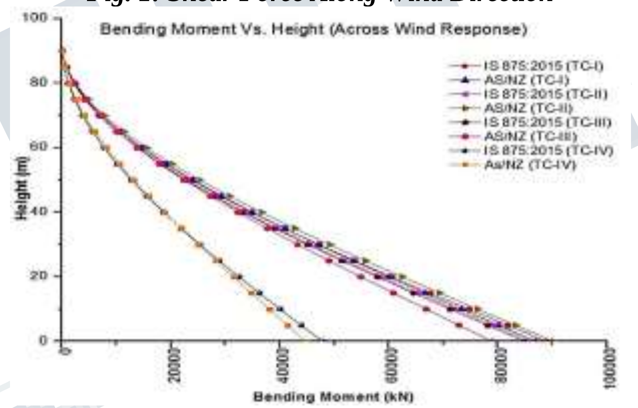

Fig. 2: Bending Moment Along Wind Direction

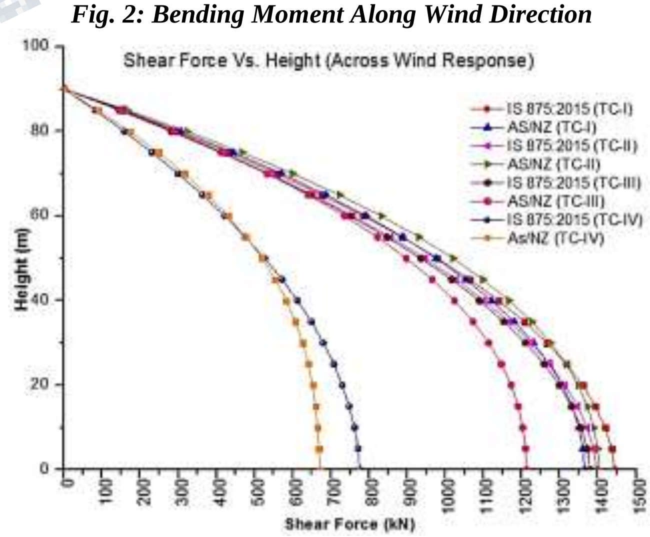

Fig. 3: Shear Force Across Wind Direction

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

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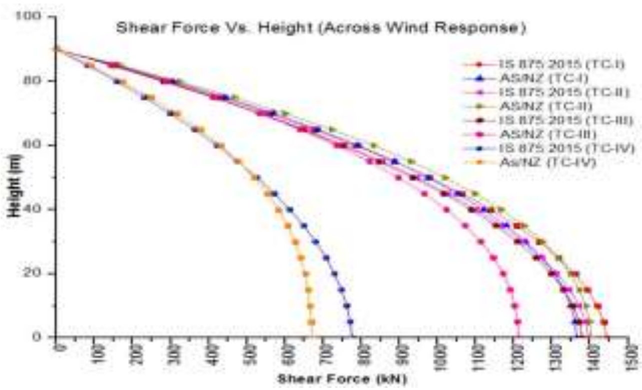

Fig. 4: Bending Moment Across Wind Direction

Parameter	**IS 875 (Part 3) – 1987 (Second Version)**	**IS 875 (Part 3) – 2015 (Third Version)**	**AS/NZS:1170 (Part 2):2011**
Along Wind Load on Building (F_z)	$F_z = C_f A_e \bar{p}_z G$	$F_z = C_{f,z} A_z \bar{p}_d G$	$F = \sum(p_z A_z)$
Hourly wind speed at height z, in m/s ($\bar{V}_z$/ $\bar{V}_{z,d}$)/$V_{des,\vartheta}$	$\bar{V}_z = \bar{V}_b k_1 k_2 k_3$	$\bar{V}_{z,d} = \bar{V}_b k_1 k_{2,i} k_3 k_4$	$\bar{V}_{des,\theta} = \bar{V}_R M_d (M_{z,cat} M_s M_t)$
Hourly mean speed factor for terrain category / Terrain, Height factor (k_2 /$k_{2,i}$/$M_{z,cat}$	Factor k_2 is tabulated in table 23	$k_{2,i} = 0.143\left[ln\left(\frac{z}{z_{0,i}}\right)\right](Z_{0,i})^{0.07}$ ($Z_{0,1}$= 0.002 , $Z_{0,2}$= 0.02, $Z_{0,3}$= 0.2 , $Z_{0,4}$= 2.0)	Factor $M_{z,cat}$ is tabulated in table 4.1, section 4
Gust Factor (G/C_{dyn})	$G = 1 + g_f r \sqrt{\left[B(1+\Phi)^2 + \right.}$	$G = 1 + r \sqrt{\left[g_v^2 B_s (1+\Phi)^2 + \frac{H_s g_R^2}{\beta}\right.}$	$C_{dyn} = \frac{1 + 2I_h \sqrt{\left[g_v^2 B_s + \frac{H_s g_R^2 SE}{\zeta}\right]}}{1 + 2g_v I_h}$
Roughness Factor	-	$r = 2I_{h,i}$	-

(r)			
Longitudinal turbulence intensity ($I_{z,i}$)	-	Terrain Category – I $I_{z,1} = 0.3507 - 0.0535\ log_{10}\left(\frac{z}{z_{0,1}}\right)$ Terrain Category – II $I_{z,2} = I_{z,1} + \frac{1}{7}(I_{z,4} - I_{z,1})$ Terrain Category – III $I_{z,3} = I_{z,1} + \frac{3}{7}(I_{z,4} - I_{z,1})$ Terrain Category – IV $I_{z,4} = 0.466 - 0.1358\ log_{10}\left(\frac{z}{z_{0,4}}\right)$	Values are tabulated for all terrain category with respect to height (Table 6.1)
Peak factor for upwind velocity fluctuation (g_v)	-	For Terrain Category 1 & 2 $g_v = 3.0$ For Terrain Category 3 & 4 $g_v = 4.0$	3.7
Background Factor (B)	The Value of B is calculated using fig.9 of code which depends upon cross-section of building /structure	$B_s = \frac{1}{\left[1 + \frac{\sqrt{0.26(h-s)^2+0.46b_{sh}^2}}{L_h}\right]}$	$B_s = \frac{1}{\left[1 + \frac{\sqrt{0.26(h-s)^2+0.46b_{sh}^2}}{L_h}\right]}$
Measure of turbulence length scale (L_h)	The Values of L_h is calculated using fig. 8 given in code with respective height and varies as per terrain category	For terrain category 1 to 3 $L_h = 85\left(\frac{h}{10}\right)^{0.25}$ for terrain category 4 $L_h = 70\left(\frac{h}{10}\right)^{0.25}$	$L_h = 85\left(\frac{h}{10}\right)^{0.25}$
Factor for the second order turbulence intensity ($\emptyset$)	$\phi = \frac{g_f r\sqrt{B}}{4}$	$\emptyset = \frac{g_v I_{h,i}\sqrt{B_s}}{2}$	-
Height factor for resonance	--	$H_s = 1 + \left(\frac{s}{h}\right)^2$	$H_s = 1 + \left(\frac{s}{h}\right)^2$

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

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response (H_s)			
Size reduction factor (S)	S is given in Fig. 10 of code and value depend on reduced frequency	$S = \frac{1}{\left[1+\frac{3.5 f_a h}{\bar{V}_{h,d}}\right]\left[1+\frac{4 f_a b_{0h}}{\bar{V}_{h,d}}\right]}$	$\boldsymbol{S = \frac{1}{\left[1+\frac{3.5\eta_a h(1+g_v I_h)}{\bar{V}_{des,\theta}}\right]\left[1+\frac{4\eta_a b_{0h}(1+g_v I_h)}{\bar{V}_{des,\theta}}\right]}}$
Gust Energy Factor (E)	E is given in fig.11 of code, value depends upon natural frequency, hourly mean wind speed, and turbulence intensity.	$E = \frac{\pi N}{(1+70.8\,N^2)^{5/6}}$	$E = \frac{\pi N}{(1+70.8\,N^2)^{5/6}}$
Reduced frequency (F_o /N)	$F_o = \frac{C_z f_o h}{\bar{V}h}$	$N = \frac{f_a L_h}{\bar{V}_{h,d}}$	$N = \frac{\eta_a L_h (1+g_v I_h)}{\bar{V}_{des,\theta}}$
Peak factor for resonant response (g_R)	-	$g_R = \sqrt{2\ln(3600\, f_a)}$	$g_R = \sqrt{2\log_e(600\, f_o)}$
Across wind load per unit height at height z.	-	$F_{z,c} = \left(\frac{3M_c}{h^2}\right)\left(\frac{z}{h}\right)$	$W_e(z) = 0.5\rho_{air}[V_{des,\theta}]^2\, d\, C_{fig}\, C_{dyn}$
Across wind design peak base bending moment.	-	$M_c = 0.5\, g_h \bar{p}_h b h^2 (1.06 - 0.06\,k)\sqrt{\frac{\pi C_{fs}}{\beta}}$	$\boldsymbol{M_c = 0.5\, g_R b h^2 \left(\frac{0.5\rho_{air}[V_{des,\theta}]^2}{(1+g_v I_h)^2}\right)\left(\frac{3}{k+2}\right)}$

Notations: C_f / $C_{f,z}$ – Drag force coefficient of the building /structure, Az – effective frontal area of building/structure at any height z , $\bar{p}_d$ /$\bar{p}_z$ – design hourly wind pressure , z – height above the ground , h- height of structure above mean ground level, $\bar{V}_b$ - regional basic wind speed , k_1 – Risk Coefficient , k_2 /$k_{2,i}$ – Terrain height factor , k_3 –Topography factor , k_4 –Importance factor for cyclonic regions ,$Z_{0,i}$ - aerodynamics roughness height for i^{th} terrain , $b_{0,h}$- average breadth of the building /structure between 0 to h, f_a – first mode natural frequency of the building/structure in along wind direction in Hz , f_c– first mode natural frequency of the building/structure in across wind direction in Hz , k – a mode shape power exponent , C_{fs}- Cross wind force spectrum , M_c – Across wind peak base bending moment, Fz,c – Across wind load per unit height at height z.

V. CONCLUSION

The computation of along Wind Load as per the previous code IS 875 (part 3) – 1987 is cumbersome and difficult to program as it uses various charts. The present code IS 875 (part 3)-2015 uses 3-second gust speed for computation of Gust factor (Dynamic Response factor) and gives a set of expressions to evaluate the Gust factor for along wind response. IS 875 (Part-3) 2015 included the provision for calculating wind response in across wind direction. Provision for dynamic along wind force in the Indian and Australian specification is almost same.

For 90 m tall building, in the terrain category -1 and terrain category -2, gives higher values of shear force and bending moment in along wind direction for the codes considered for comparison. The response is near about same as per both revisions. Along wind response in terrain category -3 and terrain category -4, the present code (IS 875(Part-3)2015) gives comparable higher values than the previous revision

ISSN (Online) 2456-1290

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(IS 875 (Part-3) 2015). Shear force and bending moment in across direction for all four-terrain categories are calculated, and getting higher values for terrain category -1. The response is approximately similar in terrain category –2 and terrain category – 3 in across wind direction.

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