Critical Analysis of Wind on vertical tall structures

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Abstract: *Wind induced structural responses, including pressure, are directional dependent. First win speed will not be uniform in all directions. Second the shape and structural properties of the structure will not be axi -symmetric. Consideration of the directionality effect will help to achieve an economical and safe design of structure The wind pressure acting on individual units of a structure can be determined using the pressure coefficient which depends on the overall dimensions of the structure as well as the openings present in the walls of the structure. The numerical example considered in this chapter illustrates the determination of static wind loads by both force coefficient and pressure coefficient methods. Dynamic along-wind analysis procedures using Random Vibration Analysis and codal provisions explained in this paper. For the purpose of along-wind analysis of the structures by the analytical procedure based on random vibration analysis, a FORTAN program was developed. For this purpose, t hree structures have been considered, out of which, two are buildings and one is a chimney. The output of the program is the response of the structure in terms of mean response, peak factor, standard deviation of fluctuating response along the height of the structure.*

1. Introduction

Characteristics of Wind and Wind Velocity

Wind is the motion of air relative to the earth's surface caused by rotation of the earth and differential solar heating. The shear action of surface roughness retards the wind velocity to nearly zero at the earth's surface. The wind velocity gradually increases with height and attains a nearly constant value at a height known as the Gradient Height (Nigam and Narayanan 1994). Layer. The variation of wind velocity within the earth's boundary layer with respect to both height and the approach terrain .

1.2 Wind Response of Structures

Wind analysis methods are well established and available in textbooks and in various international codes and standards on wind load. IS 875 (Part 3) – 1987 is the present Indian Standard available for wind load analysis for buildings and structures. Draft code for wind load [IS 875 (Part 3) – Draft (2015)] was been published in 2015 with some modifications in the wind load assessment procedures. Both the codes have provisions for Static wind load assessment on moderate height structures using a simplified approach and Dynamic load calculation for tall flexible structures using Gust Factor Method (GFM).

2. Literature Review

Solari (1983)has given direct formulae for calculation of the along wind response in terms of gust factor, displacement and acceleration for point-like structures, vertical structures and horizontal structures. The ease of use of these formulae as opposed to the procedures based on use of graphs has been mentioned.

Badruddin et al. (1984) have performed experimental and analytical study on along-wind and across-wind response of three structures located in different terrains. This includes a reinforced concrete tower (330m high), a reinforced concrete chimney (180m high) and a latticed steel tower (45.72m high). The results obtained experimentally and analytically have been compared and presented graphically.

Holmes (1987) proposed the need for a correction factor to accommodate non-linearity in the modeshape of tall buildings which are generally considered to have a linear modeshape in the fundamental vibration mode. An expression for modeshape correction factor has been given by the author which is a function of the power law exponent. The results have been compared to wind tunnel measurement data and they were found to be in agreement with each other.

Gaikwad (2013) has described the procedure of random vibration analysis and the Indian codal provision (IS 4998 (Part 1)) for determination of along-wind response of tall RC chimneys. He has discussed about the various spectra of longitudinal velocity fluctuations proposed in past literatures and has presented the results of variation in response of chimneys depending on the PSD being used in calculation of wind response.

Kwok et al. (1988) carried out an experimental wind tunnel study on a benchmark building (CAARC building) to study the effect of edge configuration of buildings on the response of such tall buildings due to action of wind. Different plan configurations such as plain rectangular plan, rectangular plan with slotted corners and chamfered corners were subjected to wind tunnel testing. The response of the model in along-wind and across-wind directions was studied and it was observed that these modifications in the cross section of the building caused a reduction in the wind-induced response in both directions. The effect of angle of incidence of wind on the model was also studied and it was seen that the response is maximum only when the wind direction is exactly normal to the face of the structure.

3 .Methods of Along-Wind Analysis

Wind analysis methods are well established and are available in textbooks and codes of practices. In the following sections, the rigorous method of Random Vibration Analysis (RVA), which is the analytical procedure for determination of wind response of a structure subjected to action of wind load has been discussed in detail in the following section. Also, the procedure described in the Indian Standard for wind response estimation is studied.

3.1 Random Vibration Analysis

Wind load acting at any point on a structure can be considered as a sum of a mean component and a fluctuating component. The mean component is time-independent but varies along the height of the structure, whereas the fluctuating component varies with both time and height. Thus wind velocity and wind load can both be referred in mathematical terms as Random Processes, whose instantaneous value cannot be predicted accurately. Thus, quantification of the randomly varying wind load is done statistically in terms of Average (mean), Variance, Standard Deviation, Peak value, Power Spectral Density, etc. The response of a structure acted upon by wind load is also obtained in terms of statistical quantities.

Then the drag force acting on the structure due to wind velocity is given by,

$$F_D(z,t) = \frac{1}{2}\rho_a C_d U^2(z,t)A \qquad 3.1$$

Instantaneous wind velocity is given as the sum of mean and fluctuating component as,

$$U(z,t) = \overline{U}(z) + U'(z,t) \qquad 3.2$$

where, $\overline{U}$= Mean Component of wind velocity (independent of time)

U' = Fluctuating Component of wind velocity (varies with time and height)

On substituting Eq (3.2) in Eq (3.1), and neglecting higher order terms we get,

$$F_D(z,t) = \frac{1}{2}\rho_a C_d \overline{U}^2(z) B_z + \rho_a C_d \overline{U}(z) u'(z,t) B_z$$

$$F_D(z,t) = \bar{F}_d(z) + F_D'(z,t)$$

Where, Bz is the width of the structure at height z, $\bar{F}_d(z)$is the mean wind load and $F_D'(z,t)$is the fluctuating wind load component acting per unit height of the structure.

The response of a structure subjected to an along wind load described by Eq (3.3) is determined by modeling the structure as a multi degree freedom system acted upon by a mean wind load component and a fluctuating wind load component. Thus, the mean deflection of the structure in the along wind direction due to the mean wind load component is given by Eq (3.5)

$$\bar{x}(z) = \frac{1}{2}\rho(C_w + C_l)\sum_{j=1}^{N}\frac{\int_0^H B_z \overline{U}^2(z)\phi_j(z)\,dz}{4\pi^2 n_j^2 M_j} \qquad (3.5)$$

where ϕ_j, $n_j$and $M_j$are the mode shape, natural frequency and generalized mass of the structure in mode and N is the total number of modes considered. If m(z) is the mass per unit height of the structure, then the generalized mass of the structure inj^{th}mode is given by,

$$M_j = \int_0^H \phi_j^{\,2}(z).m(z)dz \qquad (3.6)$$

The fluctuating components of wind velocity and wind load are stochastic quantities whose value is randomly varying with respect to time. Thus their values cannot be predicted accurately. Hence they are defined in terms of Power Spectral Density (PSD). The PSD of the fluctuating along wind deflection [S_x(z,n)] is obtained in terms of PSD of the fluctuating component of the wind velocity [S_u (z)]as shown below.

$$S_x(z,n) = \frac{\rho^2}{16\pi^2}\sum_j \frac{\phi^2(z)C_{Df}^2}{n_j^4 M_j^2\left\{\left[1-(n/n_j)^2\right]^2 + 4\eta_j^2(n/n_j)^2\right\}}$$

where $n_j$is the damping ratio in jthmode, *Coh* (y_1, y_2, z_1, z_2, n)is the across-wind crosscorrelation coefficient and $C_{DF}$is the reduced drag coefficient. PSD of wind velocity hasbeen discussed in detail in section 3.3.2.

If M_1 and M_2 are two points on a structure, having coordinates (y_1,z_1) and (y_2,z_2)respectively, then the PSD of longitudinal velocity fluctuations at those two points arecorrelated in the along-wind and across-wind directions by the along-wind and acrosswind

cross correlation coefficients which are denoted by $N(n)$ and *Coh* (y_1, y_2, z_1, z_2, n)respectively.

Along wind correlation is accounted by considering the reduced drag coefficient (C_{DF})by the following relation.

$$C_{DF}^2(n) = C_w^2 + 2C_w C_l N(n) + C_l^2 \qquad (3.8)$$

If M_1 and M_2 are on the same face of the structure, then $N(n)$ = 1 as there is noseparation between the points in the along wind direction. In other cases, $N(n)$ iscalculated using the following equations.

$$N(n) = \frac{1}{\xi} - \frac{(1-e^{2\xi})}{2\xi}$$

$$\xi = \frac{3.85 n \Delta x}{\bar{U}} \qquad (3.10)$$

3.2 IS : 875 (Part 3) – Draft 2015

Dynamic wind load calculation by the draft code is also done using the Gust Factormethod but with slight modifications. The present wind code uses graphs for calculationof various terms used in Gust factor estimation. This leads to a high degree of manualerror. But the draft code suggests direct and simple formulae for the same which allowsease calculation using computer programs and reduces possibility of errors.

The present code suggests a single value of gust factor for the entire height range of thestructure which is not the actual case. This problem has been sorted out in the draft code,in which Gust factor increases with the height of the structure.

The procedure for wind load calculation by IS: 875 (Part 3) – Draft 2015 has beenprovided in Table 3.1 along with the procedure prescribed in the present code.

3.3.1.1 Power Law

If $U_r$is the wind velocity at a reference height z_r then the mean wind velocity acting atany height z is given by the following empirical expression.

$$\bar{U}_z = U_r \left(\frac{z}{z_r}\right)^{\alpha} \qquad (3.25)$$

where α is the power law coefficient, whose value vary depending on the terrain categorybeing considered. Values of α suggested by Davenport (1965) and ASCE 7-10 has beenprovided in Table 3.2.

Shear velocity of a terrain (u_*) which is useful in determining the spectra of windvelocity and variance of the spectral curve is given by equation (3.26) which depends onthe terrain roughness factor (k). Davenport (1965) has suggested values of k as 0.005,0.015 and 0.05 for open, towns and large cities respectively.

$$u_* = \sqrt{k}.\, U_{10} \qquad (3.26)$$

WhereU_{10} is the wind velocity at 10m height.

Table 3.1 : Values of α suggested in Codes and Literatures

Terrain Category	Power Law Exponent (α)		
	Davenport (1965)	Nigam and Narayanan (1994)	ASCE 7-10
Coastal Exposure	-	0.12	0.1
Open exposure	0.16	0.16	(1/7)=0.143
Sub-urban terrain	0.28	0.28	(1/4.5)=0.222
Centers of towns			
Centers of large cities	0.4	0.4	(1/3)=0.333

Table 3.2 : Shear Velocity correction

Factors for various terrains

Terrain Category	$u_*/u_{*,2}$
Coastal Terrain	0.85
Open Terrain	1.00
Center of Towns	1.33
Center of large cities	1.45

3.3.1.2 Comparison of Wind Profiles

Mean Wind Velocity Profiles were calculated as per Logarithmic law and Power law fordifferent terrains based on the following data.

Terrain	Logarithmic law		Power law
	z_0(m)	u_* (m/s)	α
Coastal Terrain	0.002	2.26	0.12
Open Terrain	0.07	2.66	0.16
Center of Towns	0.8	3.54	0.28
Center of large cities	2.00	3.86	0.4

Based on the data given above, wind velocities have been calculated and it is observedthat both the laws give comparable results. The results have been tabulated in Table 3.5and graphical result based on Logarithmic law has been presented in Fig. 3.1.

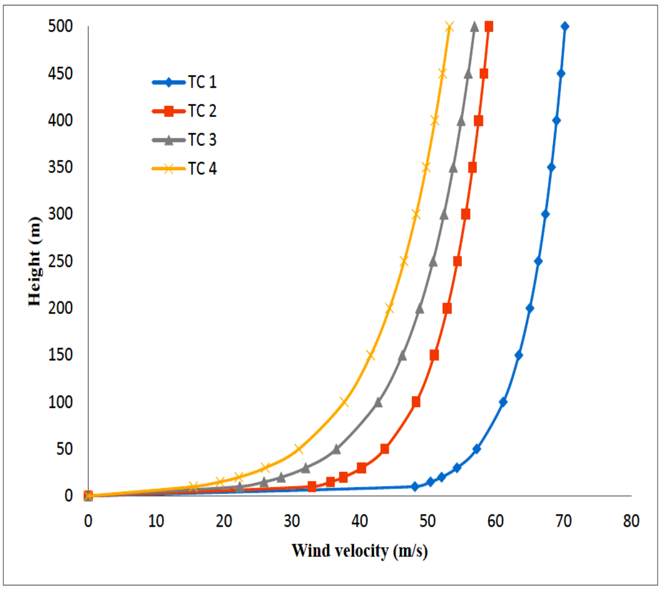

Figure 3.1 : Mean wind velocity profiles for various terrains using Logarithmic Law

4. Numerical Results Of Static Wind Load Analysis

4.1 Introduction

The difference between pressure coefficient method and force coefficient method is explained in section 4.2 by considering a building as an example. The various types of static wind loads acting on different sections of the building have been calculated using this example.

4.2 Static Wind load estimation for a building

The Wind code IS 875 (Part 3) gives provision for calculation of wind load on a building for:

a) The building as a whole,

b) Individual structural elements such as roofs and walls, and

c) Individual cladding units including glazing and their fixings.

The above wind loads have been calculated for an example building given the Explanatory Handbook on IS 875 (Part 3):1987 by IIT Roorkee.

Consider an RCC building located in Delhi, with dimensions 10m x 50m x 18m. The building has 40 openings 1.5m x 1.5m. The structure consists of RC column-beam frame at 5mc/c horizontally and 3mc/c vertically, supporting the walls.

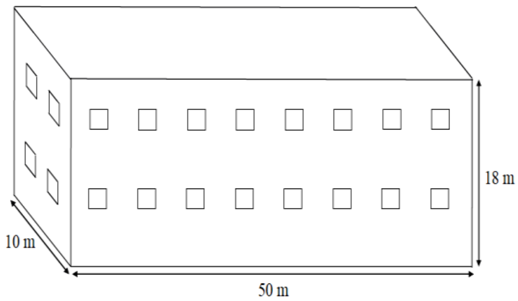

Figure 4.1: 3-Dimensional view of the building

Table 4.2:Calculation of Net Pressure Coefficients on the walls

External Pressure Coefficients (Cpe)		
Wall	Cpefor Wind angle (θ) = 0°	Cpefor Wind angle (θ) = 90°
A	**0.7**	**-0.5**
B	- 0.48 (= - 0.4 - 0.08)	0.5
C	**-0.7**	**0.8**
D	0.7	-0.1
Net Pressure Coefficients (Cpnet= Cpe-Cpi)		
Wall	Net Pressure Coefficients (Cpnet)	
A, B	+ 0.7 – (-0.2) = +0.9 (Pressure)	
	- 0.5 – (+ 0.2) = - 0.7 (Suction)	
C, D	+ 0.8 – (-0.2) = + 1.0 (Pressure)	
	- 0.7 – (+ 0.2) = - 0.9 (Suction)	

Table 4.3: Design wind pressure acting on individual structural units

The individual structural elements like walls, and individual cladding units like glazing and their fixings are designed for the load obtained by multiplying the design wind pressure from Table 4.3 at the required height above the ground surface with their respective surface areas.

Random Vibration Analysis Results

The details of the structures provided in section 5.3 have been given as input to the FORTRAN program. The output of the program is the along-wind response of the structures in terms of mean response, peak factor, standard deviation of fluctuating response, gust factor, peak response of the structure, Bending moment and Shear force along the height of the structure. These results have been provided in the following sub-sections for the structures described in the previous section.

4.3 Structure 1: 200m Building

The PSD that was actually used Simiu and Scanlan (1986) was the PSD proposed by Simiu (Eq (3.32)). The output of the FORTRAN program using PSDs suggested by Davenport (1961), Harris (1968), Kaimal (1972) and Simiu (1974) have been presented in Table 5.1 along with the numerical results given in the literature from

Table 4.3: RVA results of 200m building

	X_{mean} (m)	K_x	σ_x (m)	G	X_{peak} (m)
Simiu and Scanlan (1986)	**0.184**	**3.63**	**0.074**	**2.46**	**0.452**
Simiu's PSD	0.186	3.64	0.083	2.62	0.488
Kaimal's PSD	0.186	3.66	0.077	2.51	0.467
Harris's PSD	0.186	3.67	0.092	2.82	0.524
Davenport's PSD	0.186	3.70	0.094	2.88	0.535

Note: X_{mean} is the mean response of the building in m,

$X_{peak}$is the maximum response (mean + fluctuating) of the building in m,

$K_x$is the peak factor,

$\sigma_x$is the standard deviation of response in m, and

Mode	Natural Frequency (Hz)		Damping Ratio (%)
	Menon and Rao (1996)	Present study	
Mode 1	0.148	0.163	1.5
Mode 2	0.654	0.715	2.1
Mode 3	1.649	1.713	4.3

Structure 3: 400m Chimney

The 400m chimney was modeled using SAP2000, FEM model of the two-noded single-element beam was developed by discretizing it into 36 elements, as considered in the literature [Menon and Rao (1996)].

The natural frequency details given in the literature has been tabulated in Table 5.3 with SAP2000 and the values seem to be very much comparable.

For both the buildings first vibrational mode with linear mode shape and constant lumped masses along the height was considered. In case of chimney, SAP2000 was used model it as a vertical cantilever beam and modal analysis was performed on the FEM model. The required data of the structures were given as input to the FORTRAN program and the along wind response of the structures were obtained. Responses from various PSDs discussed in Chapter 3 were obtained and the results have been compared with each other and also with results presented in the literature from which they have been taken. Also the results codal analyses have been presented.

6.1 Conclusion

In the present work, methods of along wind analysis of tall and slender structures have been discussed in detail. This includes the rigorous method of Random Vibration Analysis (RVA) and methods available in Indian Standard for wind load calculation [IS : 875 (Par1987 and IS : 875 (Part 3) – Draft 2015]. The RVA procedure considers the modal properties and geometric properties of the structure, and the wind characteristics in the terrain in which the structure is located in order to give the response of the structure in terms of mean and fluctuating displacement, Gust factor, Shear force and Bending Moment. Only wind load, Shear force and Bending moment results can be determined using codal procedures.

Two important wind velocity profiles and various Power Spectral Density functions proposed in past literatures useful

6.2 Scope of Future work

- Random vibration analysis for across wind response analysis of structures can be done.
- Random vibration analysis for torsional response of structures can be studied.
- Combined response (along-wind, across-wind and torsional responses) of slender structures due to action of wind can be studied.
- Wind response analysis of other structures such as bridges, cables, transmission towers, etc. can be performed.
- Ways to include higher modes of vibration for buildings can be worked out.

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