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WIND EFFECTS ON MULTI-STORIED BUILDINGS: A CRITICAL REVIEW OF INDIAN CODAL PROVISIONS WITH SPECIAL REFERENCE TO AMERICAN STANDARD

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ABSTRACT

For preliminary design including the proportioning of the structure, the variation of wind force on a structure with variation of site parameters and structural parameters should be known. The present study is an effort to achieve the same, primarily based on Indian wind code. The proposed draft of the Indian wind code is also included in the scope of the study. Comparisons of the wind forces obtained by Indian Standard and that by American Standard are also presented for some representative cases to gaze the relative level of protection attributed by Indian wind codes. The study also includes an exhaustive comparison of the wind forces obtained by Force coefficient based static analysis and Gust factor based dynamic analysis interpreting where which method should be used for better protection. The general observations and simple guidelines emerged from the study may prove useful for choosing the appropriate method by design engineers, depending on the requirement of safety, economy and availability of time. The large number of case studies presented in the paper in the form of the variations curves may be used for preliminary design and cross cheeking the results and hence, may prove useful in the design offices.

Keywords: Buildings; medium-rise; high-rise; wind load; wind codes; dynamic effect

1. INTRODUCTION

Codes and Standards are the mainstream of information to the designers of civil engineering structures. 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.

As wind is a randomly varying dynamic phenomenon, it has significant dynamic effect on

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buildings and structures especially on high-rise flexible structures. Codes and Standards utilize the “gust loading factor” (GLF) approach for estimating dynamic effect on high-rise structures. The concept of GLF was first introduced by Davenport [1] in 1967. The last few decades have been witnessed substantial progress in the understanding of the characteristics of wind, as well as the response to the various kinds of structures, and several modifications of GLF have been done by many researchers [2-6] based on first GLF model by Davenport. Most leading Codes and Standards have been adopted these changes and according to the need of the hour Indian wind code [7] has been reviewed and Proposed Draft Code [8] has been prepared.

Indian wind code [7] stipulates that buildings and structures with a height to minimum lateral dimension ratio of more than about 5.0, and buildings and structures whose natural frequency in the first mode is less than 1.0 Hz shall be examined for the dynamic effects of wind. The detailed procedure prescribed in the dynamic analysis of Indian code [7], is based on the values obtained from various figures. Hence, error may creep in the values read from such graphs, especially from the log-log plots. However, due to the simplicity of the procedure, the design engineers are more comfortable in the static procedure for analyzing the typical low, medium and high rise buildings which are widely constructed. It is, therefore, necessary to develop simple guidelines for choosing the method of analysis so that the design office may use it for the assessment of the structural response. Hence, a comprehensive comparative study of the methods given in Indian wind code [7] is undertaken to investigate the effect of the variation of building geometry on aerodynamic loads, in the present study.

Several wind load parameters such as probability based design wind speed, terrain and height effect, GLF, pressure and force coefficients are to be considered to calculate wind loads for design. Various international standards considered these parameters in different ways. Although a similar theoretical basis has been utilized in formulation, considerable differences have been noted among the standards in prediction of various parameters. Hence, the resulting wind effect differs from one Standard to the other [10-11].

This paper also presents a comparative study of the along-wind loads and their effects on buildings of various geometry utilizing current Indian wind code [7], Proposed Indian wind code [8], and ASCE 7-02 [9], respectively.

2. BEHAVIOUR OF WIND

Wind velocity consists of a mean plus a fluctuating component. A momentary deviation of the fluctuating component from the mean value is responsible for creation of gust. Both the components of wind velocity vary with height and depend upon the approach terrain and topography. Figures 1 and 2 show the variation of wind velocity with time and height, respectively. The roughness of the earth's surface, which causes drag on the wind, converts some of the wind's energy into mechanical turbulence. Since the turbulence is generated at the surface, the surface wind speed is much less than the wind speeds at higher levels. For strong winds, the shape of the vertical profile of the wind speed depends mainly on the degree of roughness of the surface. It means the over-all drag effect of buildings, trees and any other projections that impede the flow of wind at the surface. There is a boundary layer within which the wind speed varies from almost zero, at the surface, to the gradient wind speed at a height known as gradient height. The thickness of this boundary layer depends on the type of terrain. The gradient height within a large city centre is much higher than it is over the sea.

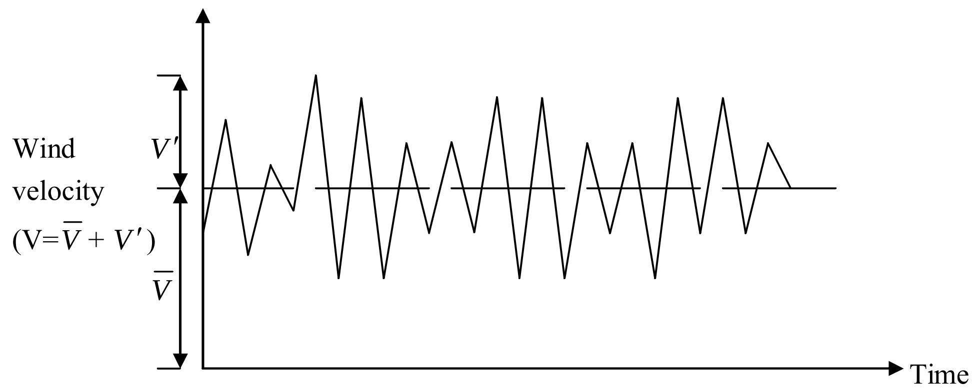


Figure 1. Variation of wind velocity with time

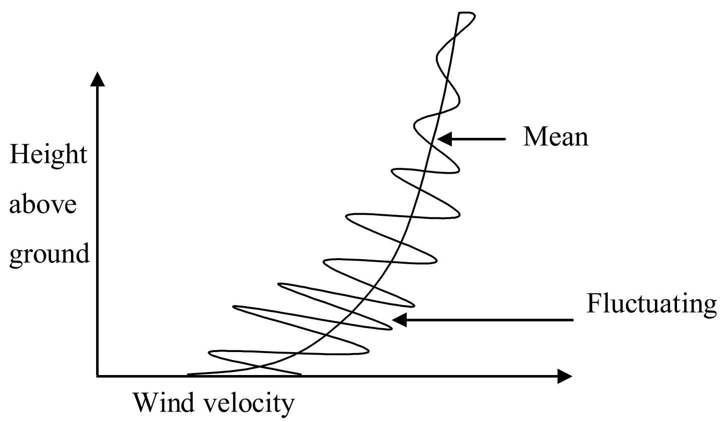


Figure 2. Variation of wind velocity with height

3. PROVISIONS IN CODES AND STANDARDS

Indian wind code IS: 875 (Part 3) - 1987 [7], Proposed Indian wind code [8] and American Standard ASCE 7-02 [9] have been compared in this paper. All the existing and proposed Standards break down the terrain of any given site into 3 to 4 categories which will affect the wind characteristics at that location. Broadly the terrain category given in these Codes and Standards are summarized in Table 1 for quick reference.

Tall, long span and slender structures are sensitive under the dynamic effect of wind. Wind gusts cause fluctuating forces on the structure which induce large dynamic motions, including oscillations. The severity of dynamic motions and wind induced oscillations depend on the natural frequency of vibration and the damping of the structure. All the standards classified the building or structures as rigid and flexible building or structures based on natural frequency. According to all the Standards considered, if fundamental frequency of the building or structure is less than or equal to 1 Hz than it is classified as flexible building or structure other wise it is rigid. However, Indian codes have also considered structures as flexible if height to minimum lateral dimension ratio is more than about 5.0. The procedure for calculating wind loads on these rigid and flexible buildings utilizing Indian Standards [7-8] and American Standard [9] will be discussed here keeping the language and notation presented in each standard unchanged.

Table 1: Exposure categories in Codes and Standards

Description	**IS 875(Part 3) 1987 and IS 875 (Part 3): Draft code**	**ASCE 7-02**
Large city centers with buildings having a height in excess of 25m	Terrain category 4	
Urban, suburban areas, wooded areas	Terrain category 3	Exposure category B
Open terrain with scattered obstructions having height 1.5 to 10m	Terrain category 2	Exposure category C
Flat unobstructed areas exposed to wind flowing over open water	Terrain category1	Exposure category D

3.1 Indian wind code [7]

Indian wind code [7] calculates wind load from three different points of view; (i) The building and structure taken as a whole; (ii) Individual structural elements such as roofs and walls; and (iii) Individual cladding units such as sheeting and glazing including their fixtures. Considering the building and structure as a whole wind load can be calculated by using Force coefficient method or Gust factor method depending on type of building or structure. Three equations are used to calculate wind load according to the Force coefficient method and these are:

$$V_z = V_b \, k_1 k_2 k_3 \; ; \qquad (1)$$

$$p_z = 0.6 V_z^{\,2}; \text{ and} \qquad (2)$$

$$F = C_f A_e \, p_d \, ; \qquad (3)$$

where Vz = design wind speed in m/s at height z; V_b = basic wind speed in meter per second, which is based on the peak gust velocity averaged over a short time interval of about 3 seconds and corresponding to mean heights of about 10m above ground level in an open terrain; k_1 = risk coefficient factor and it is dependent on the design life of the structure and the basic wind velocity. The values are given in Table 1 of IS: 875 (Part 3)-1987 [7] ; k_2=terrain, height and structure size factor given in Table 2 of IS: 875 (Part 3)-1987 [7]; k_3=topography factor given in Section 5.3.3 of IS: 875 (Part 3)-1987 [7]; p_z =design wind pressure in N/m^2 at height z; F= force acting in a direction parallel to the direction of the wind; C_f = force coefficient for the building or structure and depends on the shape of the structures and shall be interpreted from Figure 4 of IS: 875 (Part 3)-1987 [7]; A_e = effective frontal area of the building or structure; and $p_d = p_z$ = design wind pressure.

Table 2: Averaging time in codes and standards

	ASCE 7-02	**IS 875 (Part 3) 1978**	**IS 875 (Part 3): Draft code**
Basic wind speed	3s	3s	3s
Gust-loading factor	3s	1hr	3s

The Gust factor method must be considered for the flexible buildings and the more severe of the two estimates, namely 1) by Gust factor method of load estimation and 2) by Static wind method of load estimation, is taken for design. In this method hourly mean wind speed at any height at a particular location is calculated similarly as prescribed by Eqn. (1), with only exception that the terrain category factor k_2 has to be read from a separate table containing a relatively lower value. Further, the along wind load on a strip area (A_e) at any height (z) is given by F_z as follows.

$$F_z = C_f A_e \, \overline{p_z} \, G \tag{4}$$

where C_f and A_e are same as already prescribed by eqn. (3); $\overline{p_z}$ = design pressure at height z due to hourly mean wind and is taken as $0.6V_z^2$ (N/m); G = gust factor = (peak load/ mean load), and is given by

$$G = 1 + g_f r \sqrt{B(1+\phi)^2 + \frac{SE}{\beta}} \tag{5}$$

where g_f = peak factor defined as the ratio of the expected peak value to the root mean value of fluctuating load; r = roughness factor which is dependant on the size of the structure in relation to the ground roughness. The value of $g_f r$ is given in Figure 8 of IS: 875 (Part 3)-1987 [7] as a function of height for different terrain category; B = back ground factor indicating a measure of slowly varying component of fluctuating wind load and is obtained from Figure 9 of IS: 875 (Part 3)-1987 [7]; SE/β = measure of the resonant component of the fluctuating wind load; S = size reduction factor and is obtained from Figure 10 of IS: 875 (Part 3)-1987 [7]; E = measure of available energy in the wind stream at the natural frequency of the structure and is given in Figure11 of IS: 875 (Part 3)-1987 [7]; β = damping coefficient as a fraction of critical damping of the structure and the value is given on the Table 34 of IS: 875 (Part 3)-1987 [7]; $\varphi = g_f r\sqrt{(B)}/4$ and is to be accounted only for building less than 75m high in terrain category 4 and for building less than 25m high in terrain category 3, and is to be taken zero for all other cases. For interpreting the B, S and E from the plots presented in Figures 9-11 of IS: 875 (Part 3)-1987 [7] the following parameters are required

$$\lambda = C_y b/C_z h \quad \text{and} \quad F_o = C_z f_o h/\overline{V_h} \tag{6}$$

where C_y = lateral correlation constant which may be taken as 10 in the absence of more precise load data; C_z = longitudinal correlation constant which may be taken as 12 in the absence of more precise load data; b = breadth of the structure normal to the wind stream; h= height of the structure; $\overline{V_h} = \overline{V}_z$ = hourly mean wind speed at height z; f_o = fundamental natural frequency of the structure; and $L_{(h)}$ = a measure of turbulence length scale and the value can be obtained from plot presented in Figure 8 of IS: 875 (Part 3)-1987 [7].

3.2 Proposed Indian wind code [8]

This draft code also suggests two methods for finding out wind loads considering the building as a whole, likewise the previous version on the basis of same philosophy. According to Force coefficient method the design wind loads are calculated by using the following equations:

$$V_z = V_b\, k_1 k_2 k_3 k_4 \tag{7}$$

$$p_z = 0.6\ V_z^{\,2} \tag{8}$$

$$p_d = K_d K_a K_c p_z \tag{9}$$

and

$$F_z = C_f A_e p_d \tag{10}$$

where V_z = design wind speed at any height z in m/s; k_1= probability factor given in Table 1 of IS: 875 (Part 3): Proposed Draft and Commentary [8]; k_2 = terrain roughness and height factor given in Table 2 of IS: 875 (Part 3): Proposed Draft and Commentary [8]; k_3 = topography factor given in Section 5.3.3.1 of IS: 875 (Part 3): Proposed Draft and Commentary [8]; and k_4 = importance factor cyclonic region given in Section 5.3.4 of IS : 875 (Part 3): Proposed Draft and Commentary [8]; p_z = wind pressure at height z in N/m^2; V_z = design wind speed in m/s at height z; p_d = design wind pressure in n/m^2 at height z; K_d = wind directionality factor given in Section 5.4.1 of IS: 875 (Part 3): Proposed Draft and Commentary [8]; K_a = area averaging factor given in Table 4 of IS: 875 (Part 3): Proposed Draft and Commentary (Proposed IS: 875 Part 3); K_c = combination factor given in Table 19 of IS: 875 (Part 3): Proposed Draft and Commentary [8]; F_z = along wind equivalent static load on the structure at any height z corresponding to strip area A_e; C_f = the force coefficient for the building given in Figure 6 of IS : 875 (Part 3): Proposed Draft and Commentary [8]; A_e = effective frontal area. According Dynamic response factor method the following equations are used:

$$F_z = C_f\, A_e\, p_z\, C_{dyn} \tag{11}$$

where F_z = along wind equivalent static load on the structure at any height z corresponding to strip area A_e; C_f and A_e are same as already prescribed by eqn. (10) ; p_z = wind pressure at height z in N/m^2; C_{dyn} = dynamic response factor (total load / mean load) and is given as follows:

$$C_{dyn} = \frac{1 + 2 \times I_h \left[g_v^2 B_s + \dfrac{H_s g_r^2 SE}{\beta} \right]^{0.5}}{\left(1 + 2 g_v I_h\right)} \tag{12}$$

where I_h = turbulence intensity, obtained from Table 31 of IS: 875 (Part 3): Proposed Draft and Commentary [8]; g_v = peak factor for the up wind velocity fluctuations, which shall be taken as 3.5; B_s = back ground factor, which is a measure of the slowly varying background component of the fluctuating response, caused by the low frequency wind speed variations, given as follows.

$$B_s = \frac{1}{1 + \dfrac{\left[36\left(h - s\right)^2 + 64 b_{sh}^2\right]^{0.5}}{2 I_h}} \tag{13}$$

where h = average roof height of structure above the ground; s = level at which action effects are calculated; and H_s = height factor for resonant response, which is expressed as follows:

$$H_s = 1 + (s/h)^2 \tag{14}$$

where $g_r = \sqrt{2 \log_e \left(3600 f_o\right)}$; and S = size reduction factor given by the expression presented below.

$$S = \frac{1}{\left[1 + \dfrac{4 f_0 h \left(1 + g_v I_h\right)}{V_h}\right]\left[1 + \dfrac{4 f_o b_{oh} \left(1 + g_v I_h\right)}{V_h}\right]} \tag{15}$$

and E = (Π/4) times the spectrum of turbulence in the approaching wind stream= $\dfrac{\pi N}{\left(1 + 70 N^2\right)^{5/6}}$

Further, β= ratio of structural damping to critical damping of a structure and is given in

Table 32 of IS: 875 (Part 3): Proposed Draft and Commentary [8]; b_{sh} = average breadth of the structure between height s and h; L_h = measure of the integral turbulence length scale at height h, and can be expressed as

$$L_h = 100(h/10)^{0.25} \tag{16}$$

f_o = first mode natural frequency of vibration of a structure in the along wind direction in Hertz; b_{oh} = average breadth of the structure between height 0 and h; and N = reduced frequency, and is given by

$$N = f_o\, L_h\, [1+(g_v I_\mathrm{h})]/\, V_{h,} \tag{17}$$

where V_h = design wind speed at height h.

3.3 ASCE 7-02 [9]

The American Standard *ASCE 7-02* [9] prescribes three types of procedures: (i) Simplified procedure, (ii) Analytical procedure and (iii) Procedure based on data available from wind tunnel. The simplified procedure is restricted to low structures with mean roof height less than or equal to 18.3 m. Further, additionally, structure is needed to be rigid. All buildings and structures of regular shape and without having response characteristics involving the effect of across wind loading, vortex shedding, instability due to galloping or flutter are analyzed by analytical procedure. Buildings and structures having unusual shape and response characteristics shall be designed using the experiment results obtained using wind tunnel.

This Standard use two equations to obtained design wind pressure for a building or structure as per analytical procedure. These are:

$$q_z = 0.613 K_z K_{zt} K_d V^2 I \tag{18}$$

where K_d is the wind directionality factor given in Table 6-4 of ASCE 7-02 [9]; K_z is the velocity pressure exposure coefficient given in the appropriate Table 6-3 of ASCE 7-02 [9]; and K_{zt} is the topographic factor given by the following equation.

$$\mathrm{K_{zt}} = (1+\mathrm{K_1 K_2 K_3})^2 \tag{19}$$

where K_1, K_2 and K_3 are given in Figure 6-4 of ASCE 7-02 [9]; q_z is the pressure exerted by the wind flow with a high velocity upon encountering a direct hindrance and is known as velocity pressure; Further, the design wind pressures for low-rise, rigid and flexible buildings are calculated by the following equations and expressed in terms of p as follows.

For rigid building of all height,

$$p = qGC_p - q_i(GCp_i) \;\; (\mathrm{lb/ft^2})\; (\mathrm{N/m^2}); \tag{20}$$

for low-rise building,

$$p = q_h [(GC_{pf}) - (GC_{pi})] \text{ (lb/ft}^2\text{) (N/m}^2\text{)}; \quad (21)$$

and for flexible building,

$$p = qG_fC_p - q_i (GC_{pi}) \text{ (lb/ft}^2\text{) (N/m}^2\text{)} \quad (22)$$

where $q = q_z$ for windward walls evaluated at height z above the ground; $q = q_h$ for leeward walls, sidewalls, and roofs. This can be obtained by substituting $z = h$, where h is the height of the structure and q_h so calculated is considered to be acting over the entire structure. $q_i = q_h$ for windward walls, side walls, leeward walls, and roof of enclosed buildings; and for negative pressure evaluation in partially enclosed buildings; $q_i = q_z$ for positive internal pressure evaluation in partially enclosed buildings where height z is defined as the level of the highest opening in the building that could affect the positive internal pressure. For building sited in wind borne debris regions, if there is any glazing in the lower 60 ft (18.3m) that is not impact resistant or protected with an impact resistant covering then such glazing shall be treated as an opening. For positive internal pressure evaluation, q_i may conservatively be evaluated at height h ($q_i = q_h$); G = gust effect factor for rigid building which is given as follows.

$$G = 0.925\left(\frac{1 + 1.7 g_Q I_Z - Q}{1 + 1.7 g_v I_{\bar{Z}}}\right) \quad (23)$$

$$I_{\bar{Z}} = c(33/\bar{z})^{1/6} \quad (24)$$

where $I_{\bar{z}}$ = the intensity of turbulence at height $\bar{z}$ and where $\bar{z}$ = the equivalent height of the structure defined as 0.6 h but not less than z_{min} for all building heights h; z_{min} and c are listed for each exposure in Table 6-2 of ASCE 7-02 [9]; g_Q and g_v shall be taken as 3.4. The background response Q is given by

$$Q = \sqrt{\frac{1}{1 + 0.63\left(\frac{B+h}{L_{\bar{z}}}\right)^{0.63}}} \quad (25)$$

where B = horizontal dimension of building measured normal to wind direction, in ft (m); h= mean roof height of building or height of structure, except that eave height shall be used for roof angle θ of less than or equal to 10°, in ft (m); and $L_{\bar{z}}$ = the integral length scale of turbulence at the equivalent height given by

$$L_{\bar{Z}} = l(\bar{z}/33)^{\bar{\in}} \quad (26)$$

in which l and $\bar{\in}$ are listed in Table 6-4 of ASCE 7-02 [9].

C_p = External pressure coefficient determine from Figure 6-6 of ASCE 7-02 [9]; (GC_{pi}) = internal pressure coefficient given in Figure 6-5 of ASCE 7-02 [9]; q_h = velocity pressure evaluated at mean roof height h using exposure; (GC_{pf}) = external pressure coefficient given in Figure 6-11A of ASCE 7-02 [9], respectively and G_f = gust factor for flexible building and other structure as detailed below.

$$G_f = 0.925\left(\frac{1+1.7I_{\bar{z}}\sqrt{g_Q{}^2Q^2 + g_R{}^2R^2}}{1+1.7g_vI_{\bar{z}}}\right) \tag{27}$$

g_Q and g_v shall be taken as 3.4 and g_R is given by

$$g_R = \sqrt{2l_n(3600n_1)} + \frac{0.577}{\sqrt{2l_n(3600n_1)}} \tag{28}$$

Further, R, the resonant response factor, is given by

$$R = \sqrt{\frac{1}{\beta}R_nR_hR_B(0.53+0.47R_L)} \tag{29}$$

where $R_n = \dfrac{7.47\,N_1}{(1+10.3N_1)^{5/3}}$ in which $N_1 = \dfrac{n_1L_{\bar{z}}}{V_{\bar{z}}}$; $R_1 = \dfrac{1}{\eta} - \dfrac{1}{2\eta^2}(1-e^{-2\eta})$

for η>0; and $R_l = 1$ for η= 0;

To obtain the values of R_h, R_B, R_L the subscript l shall be taken as h, B, and L respectively, with replacing η with appropriate values as following. $R_1 = R_h$ setting η= $4.6n_1h/\overline{V_{\bar{z}}}$; $R_l = R_B$ setting η = $4.6n_1B/\overline{V_{\bar{z}}}$; $R_l = R_L$ setting η = $15.4n_1L/\overline{V_{\bar{z}}}$; n_1 = building natural frequency; Further, in this context, β = damping ratio, percent of critical; B=horizontal dimension of building measured normal to wind direction, in ft (m); h = mean roof height of building or height of structure, except that eave height shall be used for roof angle θ of less than or equal to 10°, in ft (m); L = horizontal dimension of a building measured parallel to the wind direction; and $\overline{V_{\bar{z}}}$ = mean hourly wind speed (ft/s) at height z determined from the equation, $\overline{V_{\bar{z}}} = \bar{b}\left(\dfrac{\bar{z}}{33}\right)^{\bar{\alpha}} V\left(\dfrac{88}{60}\right)$; where $\bar{b}$ and $\bar{\alpha}$ are constants and the values are given in Table 6-2 of ASCE 7-02 [9].

3.4 Comparisons of Standards

The effects of wind load and the calculation of the same by various methodologies depend on the mean wind velocity profile, turbulence intensity, wind spectrum, turbulence length scale and correlation structure of the wind field. In each Standard, the wind velocity or pressure distribution along the height is influenced by the local topography, surrounding terrain, probability factor and basic wind speed. Basic wind speed in the wind loading Standards is associated with speed at 10m height above ground in flat and open terrain. However, averaging time for the basic wind speed and gust factor vary in various Standards. A summary of averaging time for basic wind speed and gust factor used in codes and Standards is given on Table 2. Reduction of averaging time, on one hand implies the increase in design wind speed and on the other hand, decreases in gust factor. Thus, the static wind force will be higher for less averaging time while it will be difficult to predict whether the wind force calculated incorporating the dynamic effect will increase or decrease depending on the averaging time. However, the results predicted may prove useful in understanding and interpreting the effect of this parameter in a better way.

Turbulence intensity is dependent on the size of the structure in relation to the ground roughness. In Indian wind code [7] the roughness factor r together with peak factor g_f is given in graphical form which is the measure of turbulence intensity present in the wind. The value of turbulence intensity has to be readout from table given in Proposed Indian wind code [8] where as in ASCE 7-02 [9] this value has to be determined by using equation and the parameters used in the equation has to be readout from tables. It is observed that turbulence length scale given in Indian wind code [7] and ASCE 7-02 [9] is dependant on terrain category, but Proposed Indian Code [8] prescribe a length scale formulation independent of terrain, though data in Counihan [12] suggested that it is a decreasing function of terrain roughness. The correlation structure of the fluctuating wind velocity is reflected in the background factor and the size reduction factor.

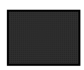
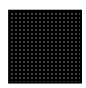
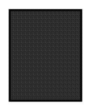
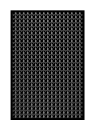
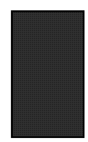
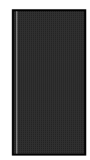
In dynamic analysis it is observed that a large part of Gust factor method of Indian wind code [7] uses values of various parameters from plots and there is a possibility of human error, especially in log-log plots. On the other hand ASCE 7-02 [9] is very easy to follow with charts and tables making values readily available without the extensive use of plots to determine values. However, in Proposed Indian code [8], the process is equation based and very easy to follow.

4. DETAILS OF CASE STUDY

In this study, to investigate the effect of variation of the aspect ratio (referred as R_A in rest of the paper) and height of building under aerodynamic load, seven different aspect ratios are chosen which are namely, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2. The height of the buildings are considered to have as 3, 5, 10, 15, 20, 25, 30 and 35- storeys corresponding to each of the aspect ratio. The height of each storey is taken as 3.5m, and each bay i.e., the centre to centre distance between frames are considered to be 5 m in all cases. Thus, a total 56 different buildings are considered to investigate the influence of various parameters on the wind loads. The lateral dimension of the buildings perpendicular to the wind direction is taken as 20m for all cases. Table 3 represents the rectangular building plans with the wind direction. All the buildings are analyzed by Force coefficient method and Gust factor method guided by Indian wind code [7] at different terrain categories to investigate the effect of ground roughness on the wind loads. Buildings with height less than 40m situated in terrain category 4 could not be considered for dynamic analysis because, the parameter $g_f r$

is not available in the corresponding Figure 8 of IS: 875 (Part 3)-1987 [7] given in the wind code. So 3,5 and 10-storied buildings are not considered at this terrain. In comprehensive comparative study of wind loads and their effects on buildings utilizing Indian wind code [7] and ASCE 7-02 [9], the same buildings are considered. All these buildings are analysed for each exposure category. Additionally, the results obtained for the two above mentioned codal provisions are compared with the results obtained due to the provisions of Proposed Indian Code [8] for a restricted number of cases of 5, 10 and 15 storied building with aspect ratio 0.5, just to have an idea about the implication of the same on calculated lateral force. It is further considered that these buildings are located at urban area with exposure B which is similar to what is specified through terrain category 3 on all the sides. However, it should be mentioned that effect of topography is not considered in this overall study. So, basic wind speed is taken as 50 m/s and the probability factor is considered 1 for this basic wind speed.

Table 3: Rectangular building plans with respective wind direction considered in this study

Typical building plan	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Aspect ratio	0.5	0.75	1	1.25	1.5	1.75	2
Shape							
Direction of wind blow	↑	↑	↑	↑	↑	↑	↑

5. RESULTS AND DISCUSSIONS

5.1 IS 875 (Part 3): 1987 [7]

The change in the base shear and storey shear due to the variation of R_A and height of building is studied considering seven different aspect ratios and for each aspect ratio eight buildings with varying height are considered. All this buildings have been analyzed by both the Force coefficient method and Gust factor method considering all the terrain categories. The results of these analyses have been plotted as the ratio of base shears and the ratio of storey shears determined from the Gust factor method and the force coefficient method, as function of the number of stories. During the dynamic analysis, the variation of the gust factor with aspect ratio, height of building and terrain category has been observed, as such variation may provide useful input for understanding the variation of lateral wind force.

5.1.1 Variation in Gust Factor

*T*he gust factors of the existing wind code [7] have been determined for all the buildings considering each terrain category. The results have been plotted in Figures 3(a) -3(d) as gust factor versus number of stories and the curves has been marked with their corresponding R_A. Comparing Figures 3(a), (b), (c) and (d), it is observed that the terrain roughness has significant influence on gust factor. With the increase in the terrain roughness, the product of peak factor and roughness factor ($g_f r$) increases significantly.

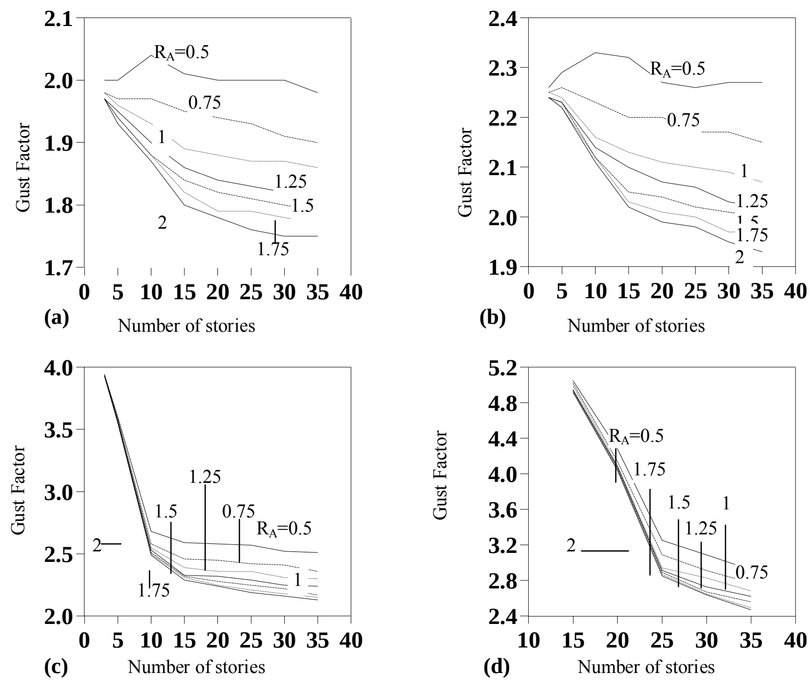


Figure 3. Variation of gust factor with the height of building considering different aspect ratio for each building at (a) terrain category 1; (b) terrain category 2; (c) terrain category 3 and (d) terrain category 4

As a result the gust factor also increases for each of the building. However, such increase seems to be very sharp for lower stories. As the number of stories increases, such effect becomes subdued. In each terrain category and for each building it is observed that the value of the gust factor decreases as the aspect ratio increases. In fact, it may be well understood from Figure 3c that the gust factor for 3 and 5 storied buildings are very high as compared to 10-storied building and sharply decreases with the increase in number of stories from 10-35. Broadly the same trend is also observed in terrain category 4 (Figure 3d) for 15-35 storied buildings. However this trend is subdued for terrain category 1 and 2. This is due to the fact that the excitation by the background turbulence is more significant for the buildings with height less than 25m in case terrain category 3 and for the buildings with height less than 75m in case of terrain category 4. In fact, for building with lower height, the eddies formed due to the surrounding structures of similar height become considerable and it also renders considerable effect making background turbulence significant. The results also show that the gust factor reduces with the increase in storey height, as the value of $g_f r$ reduces with increase in height of the structure perhaps to incorporate the effect of increased lateral period of the system.

5.1.2 Effect of variation in number of stories on ratio of base and storey shears obtained by Gust factor method and Force coefficient method

The ratio of the base shears obtained by the Gust factor method to the Force coefficient method are presented in Figures 4(a), (b), (c) and (d) for terrain category 1, 2, 3 and 4. Additionally, the ratios of storey shears are shown in Figures 5-8 for the terrain category 1, 2, 3 and 4. The results have been plotted as base shear versus number of stories of the building and storey shear versus number of stories of the building. The curves are marked with their corresponding R_A. The ratios of storey shears are given at the 5^{th}, 10^{th}, 15^{th}, 20^{th}, 25^{th}, and 30^{th} storey level. Figures 4(a) and (b) show that the ratio of base shears obtained by Gust factor method are very close to the same obtained by Force coefficient method for 3 and 5-storied building and these values are generally within a range of 1-1.1 for the terrain category 1 and 2. In both the terrain categories with the increase in number of stories up to 15 the ratio of base shear also increased and found to be up to around 1.35 occurring for building with number of stories more than or equal to 15. These observations point out that for the buildings with number of stories less than 15 even the Force coefficient based static method can be used. The same trend is observed in case of the ratio of storey shear in Figures 5 and 6. The ratio of storey shear for 10-storied building at the 10^{th} storey level is within 1.13-1.24 in terrain category 1 and 1.1-1.22 in terrain category 2, while the same at 15^{th} storey level for buildings having storeys more than 15 is within 1.25-1.38 considering R_A less than 1. These results show that for terrain category 1 and 2 Gust factor based dynamic analysis must be carried out for buildings with more than 15 storeys having aspect ratio less than 1. In Figure 4c different trend is observed. With the increase in the building height from 3-storied to 10-storied the ratio of base shear decreased from 1.2 to less than 1 and beyond 10 stories with the increase in the number of stories the ratio again increased. It is seen that the maximum value of the ratio of base shear is 1.2 for 35-storied building. For terrain category 3 similar trend is observed in case of storey shear also (Figures 7a and b). However, it is observed in this case, the ratio of storey shear is more than 1.3 for buildings having more than 25 storeys with aspect ratio, R_A=0.5 at 25^{th} storey level (Figure 7e). Figure 4d shows that the ratio of base shear which is less than 1 further decreased with the increase in the number of stories up to 25 and above 25 the variation is low. Figures 5-8 also show that with the increase in the storey level the ratio of the storey shear increased. Thus, this study indicate that the base shear or storey shear obtained from Force coefficient based method multiplied by 1.2 for terrain category 3 may replace the Gust factor based analysis. On the other hand, for terrain category 4, values obtained from Force coefficient based method itself may safely replace the use of Gust factor based method.

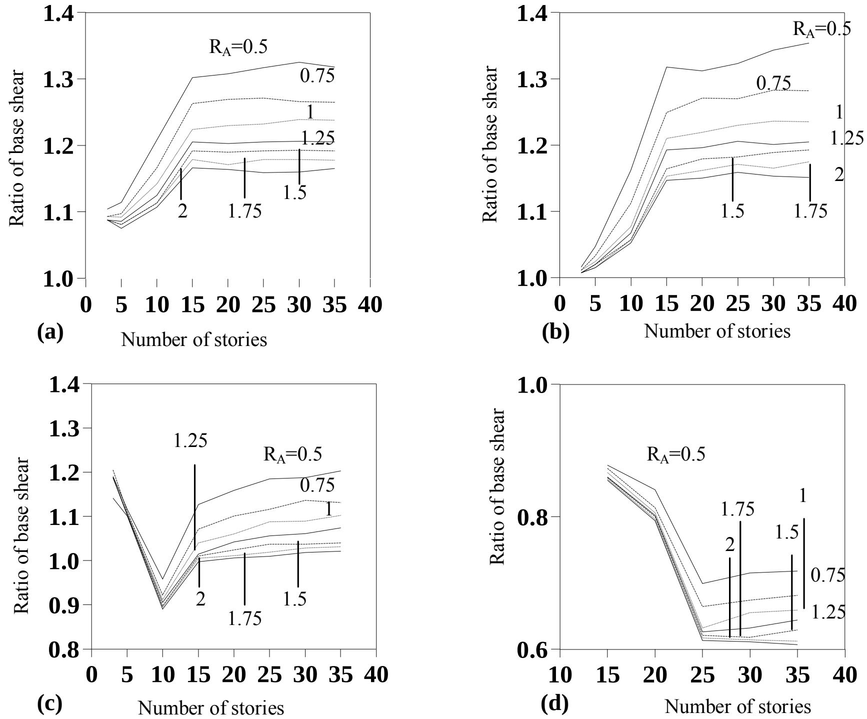


Figure 4. Variation of the ratio of base shear obtained from gust factor method considering dynamic effect of wind to that obtained from force coefficient method for buildings with varying height and varying aspect ratio at (a) terrain category 1; (b) terrain category 2; (c) terrain category 3 and (d) terrain category 4

5.1.3 Effect of variation in aspect ratio of the building on ratio of base and storey shears obtained by Gust factor method and Force coefficient method

The variation of the ratio of base shear and the ratio of storey shear with the variation of R_A of the buildings presented in the graphical form point out the significance of the R_A for calculating the base shear and storey shear under the dynamic effect of wind. It is observed from Figures 4-8 that base shear as well as storey shear calculated considering dynamic effect through Gust factor is larger if wind facing side is larger. Figures 4a and b show that the base shear obtained by the Gust factor method is increased by more than 1.3 times the base shear obtained by the force coefficient method for the buildings with R_A=0.5, whereas this value is more than 1.2 with R_A=1. Figure 4c exhibits the same trend. However, in this case, the maximum increase in base shear according to Gust factor analysis is near about 1.2 as compared to that obtained by force coefficient method for R_A=0.5, For R_A less than 0.75 base shear obtained by both the methods are very close. Further, Figure 4 (d) indicates the base shear calculated considering the dynamic effect is lower.

In case of storey shear it is observed that with the increase in the storey level the storey shear obtained by the Gust factor method increased by more than 1.4 times (Figure 6f) as compared to the storey shear obtained by Force coefficient method for R_A=0.5. This indicates that the dynamic effects are more significant in the upper storey level with the lower value of R_A. The similar trend is also corroborated in Figures 5 and 7.

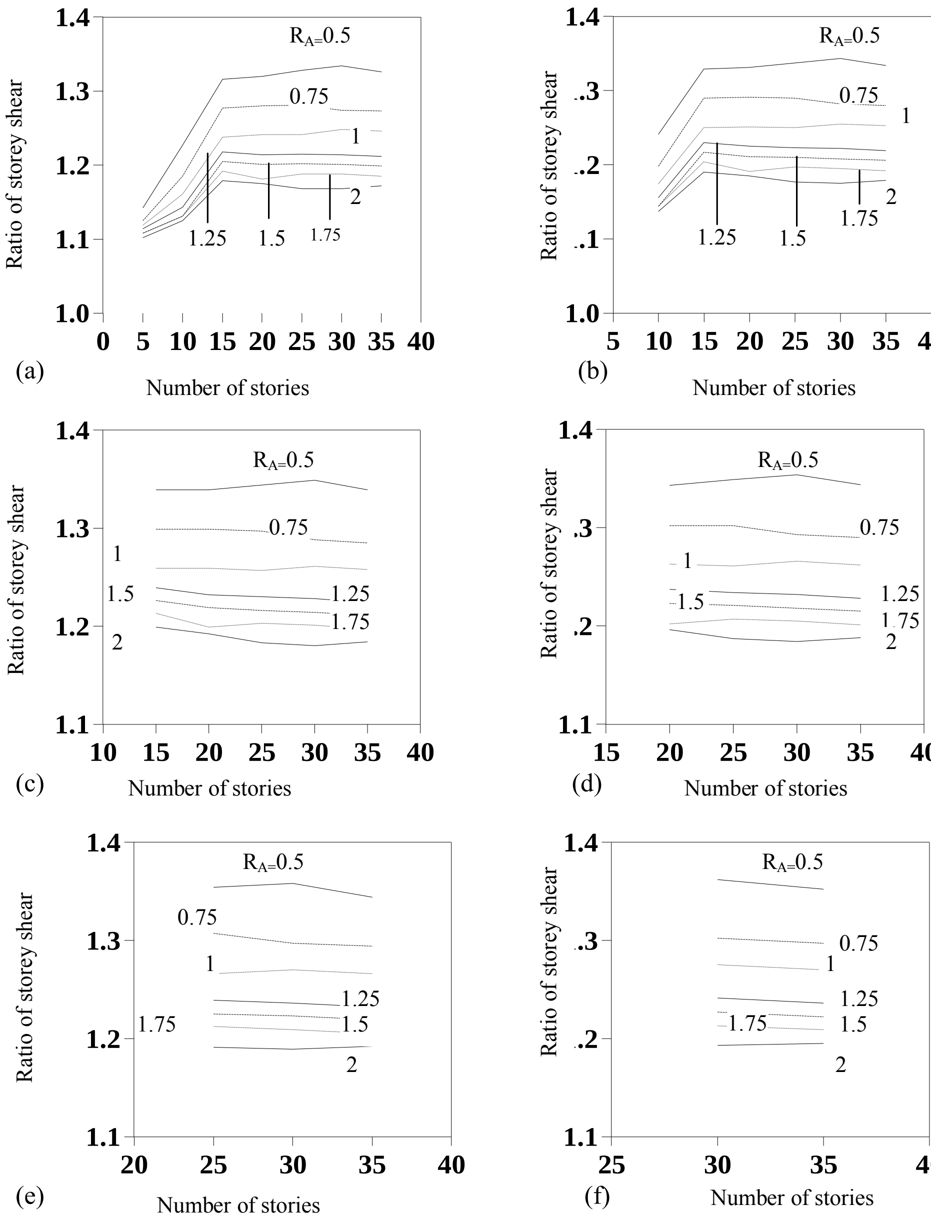


Figure 5. Variation of the ratio of storey shear obtained from gust factor method considering dynamic effect of wind to that obtained from force coefficient method for buildings with varying height and varying aspect ratio for terrain category 1 at (a) 5th storey level; (b) 10th storey level; (c) 15th storey level; (d) 20th storey level; (e) 25th storey level and (f) 30th storey level

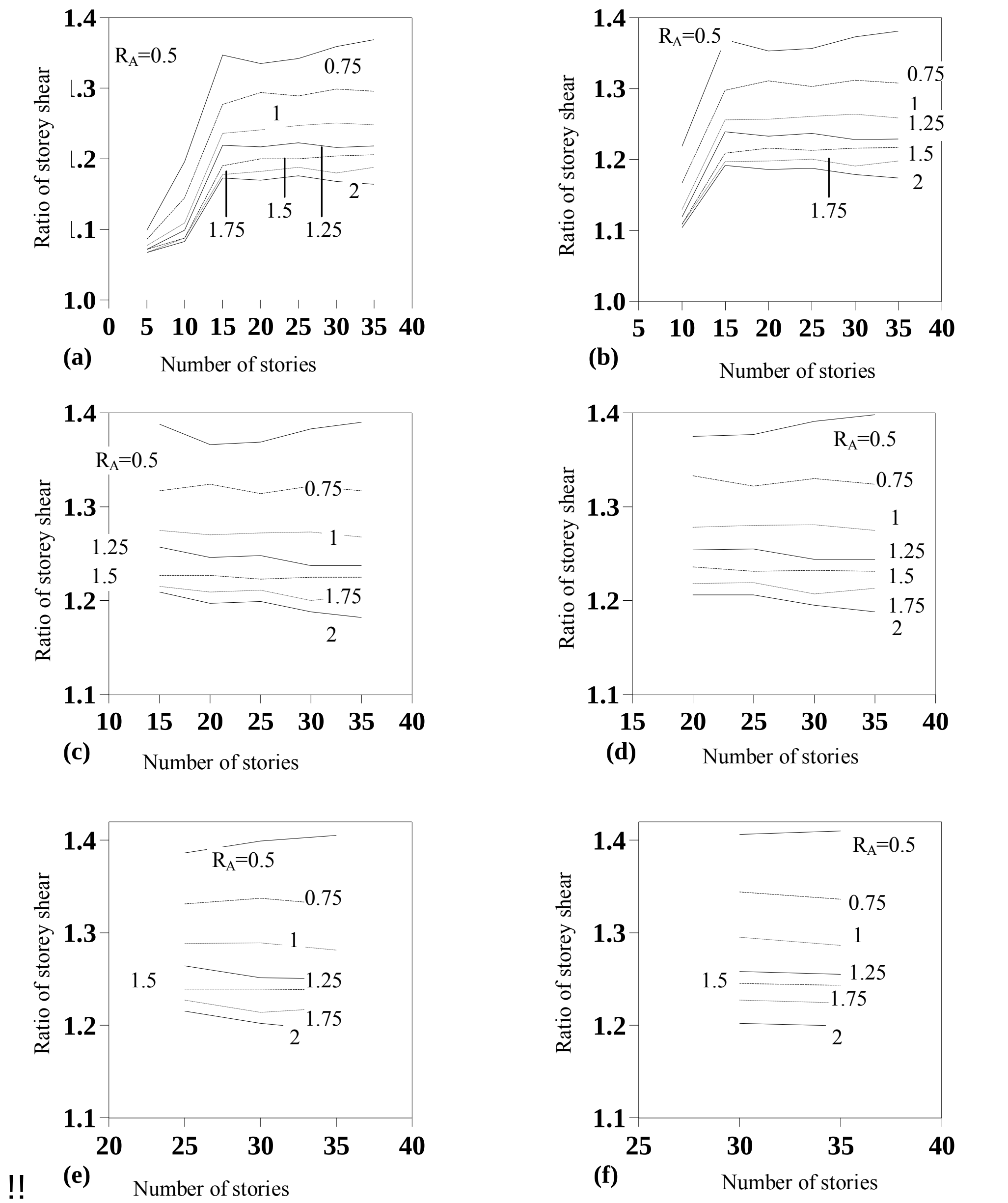


Figure 6. Variation of the ratio of storey shear obtained from gust factor method considering dynamic effect of wind to that obtained from force coefficient method for buildings with varying height and varying aspect ratio for terrain category 2 at (a) 5th storey level; (b) 10th storey level; (c) 15th storey level; (d) 20th storey level; (e) 25th storey level and (f) 30th storey level

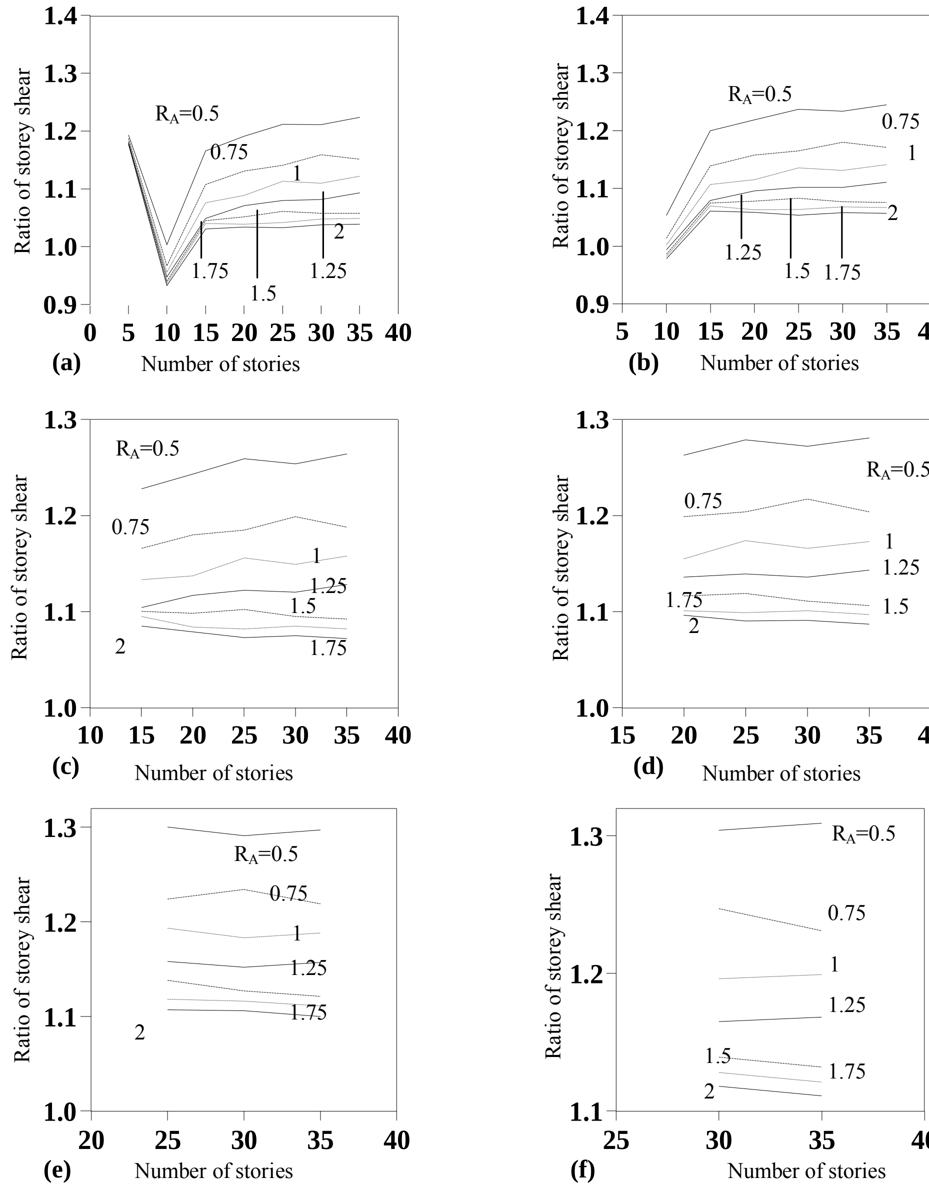


Figure 7. Variation of the ratio of storey shear obtained from gust factor method considering dynamic effect of wind to that obtained from force coefficient method for buildings with varying height and varying aspect ratio for terrain category 3 at (a) 5th storey level; (b) 10th storey level; (c) 15th storey level; (d) 20th storey level; (e) 25th storey level and (f) 30th storey level

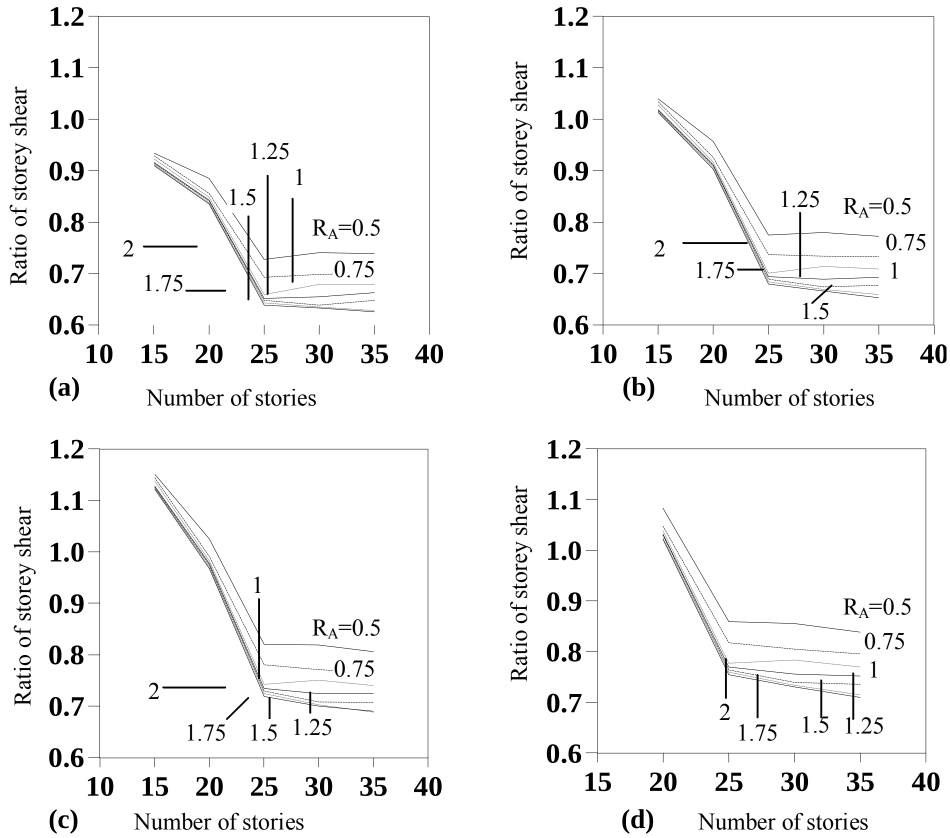


Figure 8. Variation of the ratio of storey shear obtained from gust factor method considering dynamic effect of wind to that obtained from force coefficient method for buildings with varying height and varying aspect ratio for terrain category 4 at (a) 5th storey level; (b) 10th storey level; (c) 15th storey level; (d) 20th storey level; (e) 25th storey level and (f) 30th storey level

5.1.4 Effect of terrain category on ratio of base and storey shears obtained by Gust factor method and Force coefficient method

Figures 4-8 can also be studied to understand the importance of the terrain roughness on the response of buildings under the action of wind. For terrain category 4 the base shears (Figure 4d) obtained by the Gust factor method are lower than the base shear obtained by the Force coefficient method for all the cases considered in this study. In addition to this Figure 8 shows that the storey shears obtained by both the methods are nearly equal to each other for 15 and 20-storied building for terrain category 4. For all other cases in the same terrain, storey shears obtained by the Gust factor method are much lower than the same obtained by Force coefficient method. This indicates that the Force coefficient method governs the response of buildings under the action of wind in terrain category 4. For terrain category 1 and 2 the gust factor based analysis provides larger value of base shear and storey shear, as compared to the same obtained by Force coefficient method as may be recognized from

Figures 4(a), 4(b), 5 and 6. In case of terrain category 3, the ratio of base shear decreases with the increase in the building height for low rise buildings (Figure 4c). Beyond building with 10-storeys increasing trend in the ratio of base shear is observed further. The same trend is observed in case of storey shear (Figure 7 a and b) too. However, in this case the storey shear calculated using Gust factor method is 1.3 times the same obtained by force coefficient method for buildings more than 25 stories and having R_A = 0.5 (Figure 7e). This reemphasizes the need of carrying out Gust factor based analysis beyond 25 stories with low aspect ratio, particularly for terrain category 3.

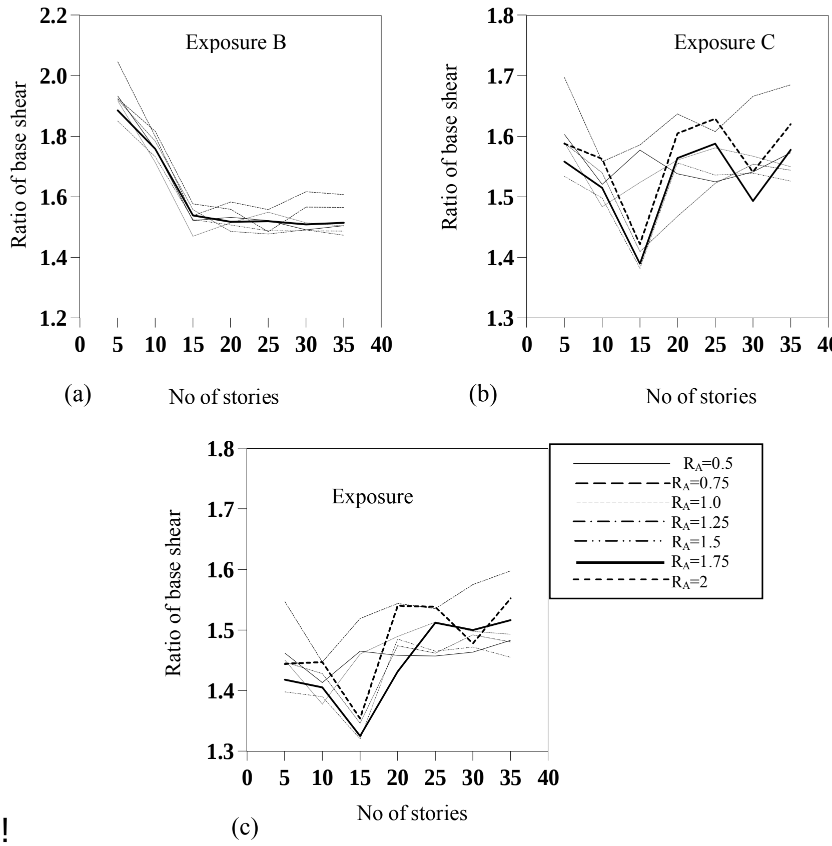


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Figure 9. Variation in ratio of base shear obtained by Indian wind code (IS 1989) to that obtained by ASCE 7-02 (ASCE 2002) in different exposure i.e., terrain category

5.2 Comparison of Indian Standard and American Standard [7, 8, and 9]

Indian Standard [7-8] and American Standard [9] deal with wind load parameters differently. Hence, the only way to compare the standards quantitatively is to compare lateral loads on building as obtained by the different standards. This section presents the variation in base shear and storey shear obtained by Indian wind code [7] and ASCE 7-02 [9] for the buildings considered. While apply codal provisions, buildings with frequency less than 1 are considered as flexible and dynamic effect of wind is considered with the application of Gust factor for these types of buildings. Further, the buildings with frequency greater than 1, static method as prescribed in both the codes are used. Figures 9 (a), (b) and (c) show the variation of ratio of base shear obtained by Indian wind code [7] to that obtained by ASCE 7-02 [9] for exposure B, C and D which are similar to what is specified through terrain categories 3, 2 and 1 respectively. Figures clearly indicate that Indian Standard gives much higher value of base shear in all terrain categories. Figures 9 (b) and (c) show that the base shears obtained by Indian wind code [7] are 1.32 to 1.70 times the same obtained by ASCE 7-02 [9] at exposure C and D i.e., conditions similar to terrain categories 2 and 1. At exposure B (Figure 9a), the variation in ratio of base shear is in a range of 1.47 to 2.

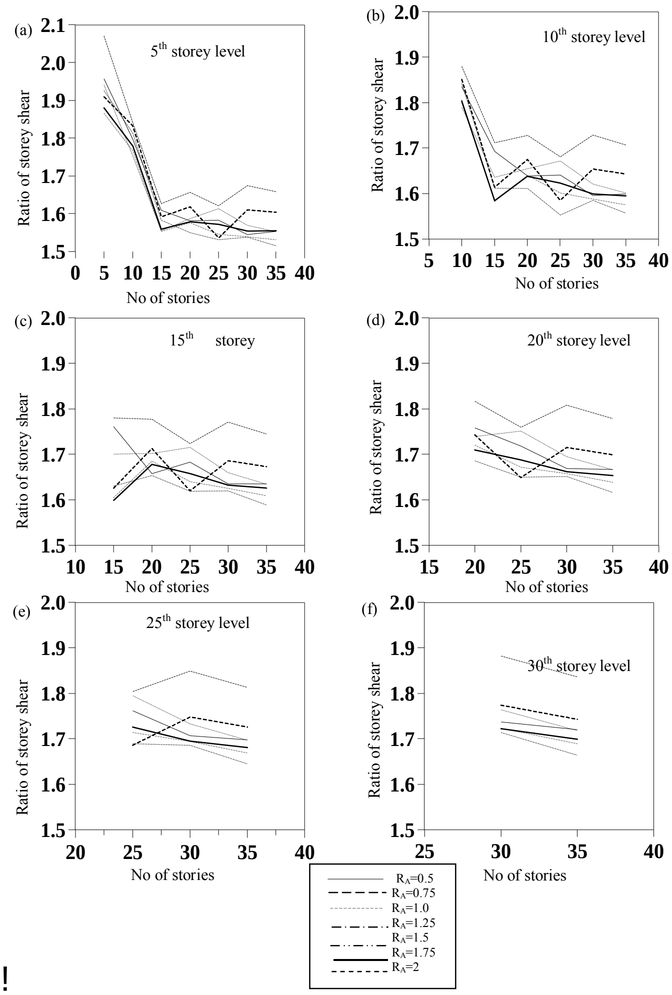

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Figure 10. Variation of the ratio of storey shear obtained by Indian wind code (IS 1989) to that obtained by ASCE 7-02 (ASCE 2002) at terrain category 3

The similar trend is observed in Figures 10, 11 and 12, respectively, where the variation in storey shear is represented by the ratio of storey shear calculated using the provisions of same two standards, for the class of buildings considered. The Figures show that ratio of storey shear further increases with the increase in the storey level and at the 30th storey level the ratio shoots up to 1.88 at exposure B while to 1.84 and 1.70 at exposure C and D, respectively (Figures 10f, 11f and 12f). This indicates that the margin of extra force obtained as per Indian code primarily originates from the extra lateral force applied at top storeys.

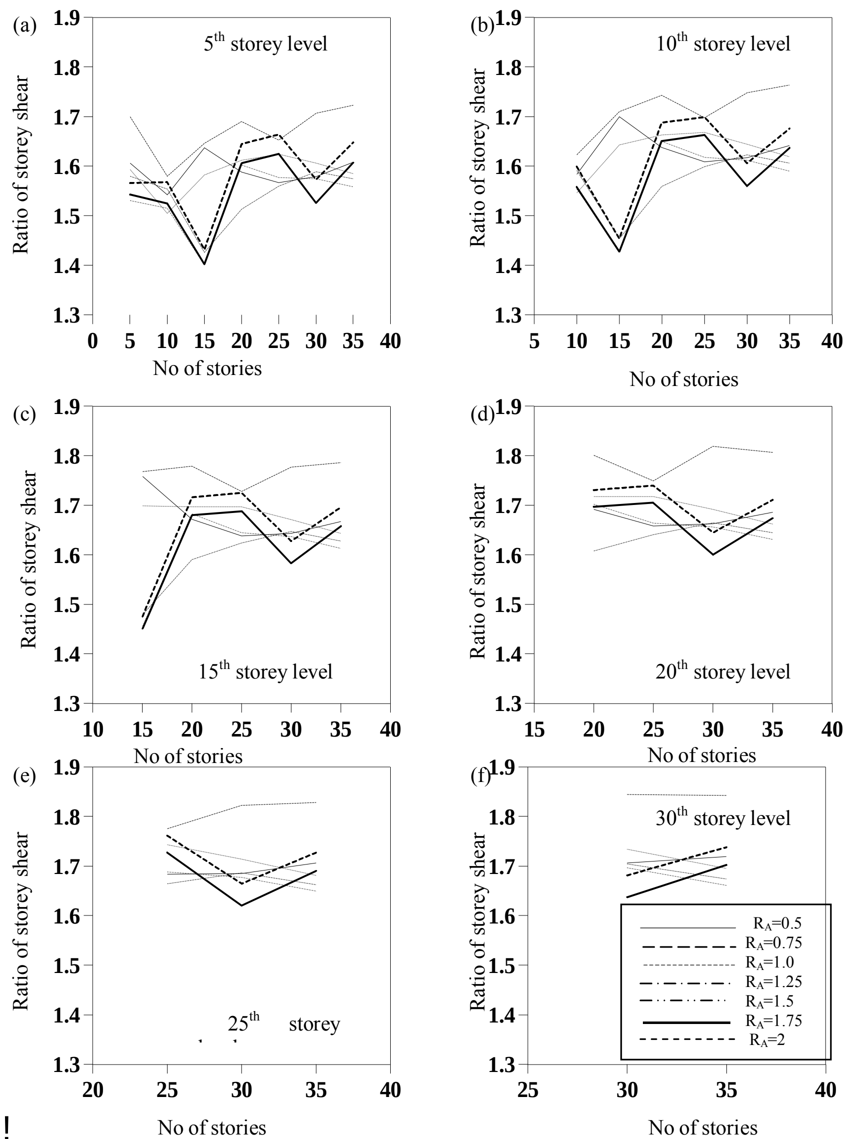

Figure 11. Variation of the ratio of storey shear obtained by Indian wind code (IS 1989) to that obtained by ASCE 7-02 (ASCE 2002) at terrain category 2

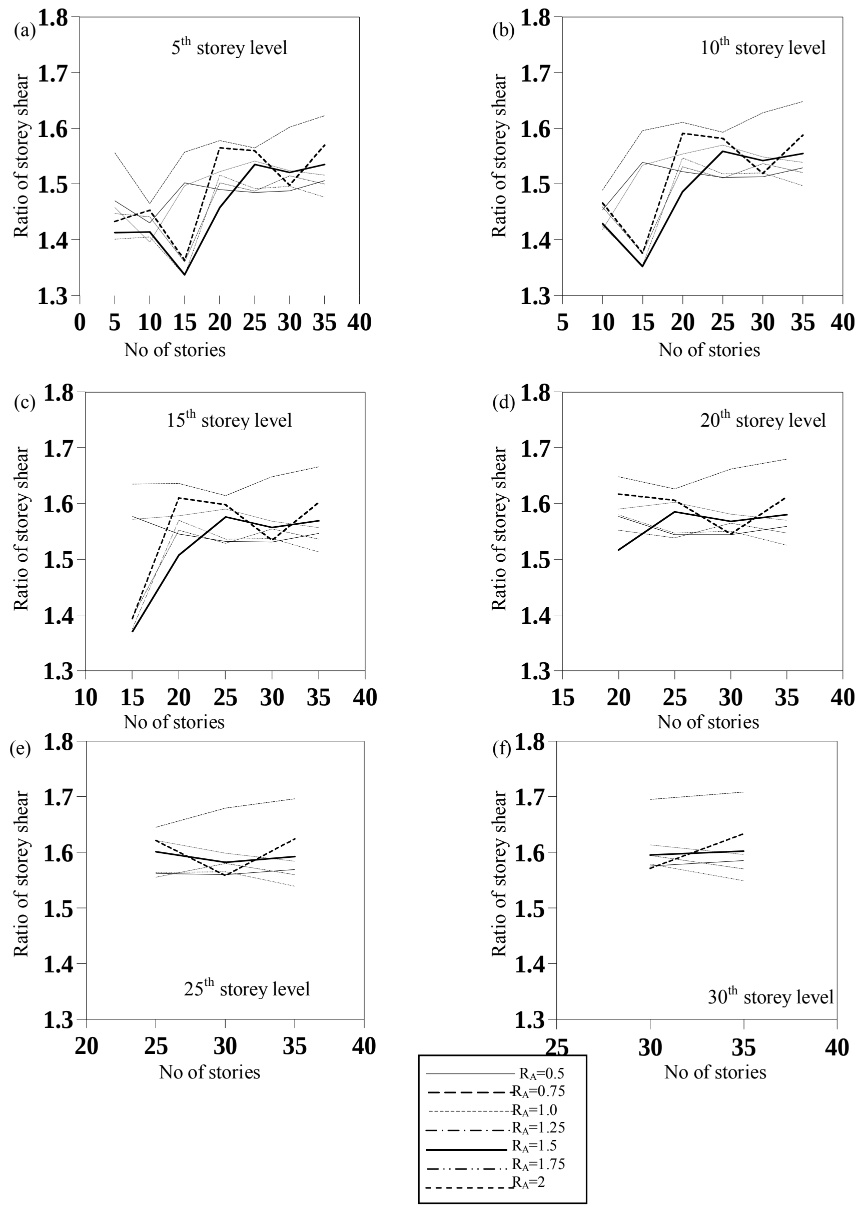

Figure 12. Variation of the ratio of storey shear obtained by Indian wind code (IS 1989) to that obtained by ASCE 7-02 (ASCE 2002) at terrain category 1

To high light the comparison among Indian wind code [7], Proposed Indian Code [8] and ASCE 7-02 [9] three buildings with 5, 10 and 15 storeys having $R_A = 0.5$ are considered as a representative of low, medium and high rise buildings, respectively. Table 4 shows the results of computation of gust factor for 15 storied building using Codes and Standards. It is observed that the gust factor in ASCE 7-02 [9] and Proposed Indian Code [8] are based on

3s averaging time. The value of gust factors obtained by Indian wind code [7], which is based on 1hr averaging time, are found to be significantly larger than the values obtained by its other two counterparts. These effects are ultimately manifested in final wind force calculation. Their effects can be properly gazed by comparing wind force per unit effective frontal area. To present a representative picture about the same, this quantity, F_z/A_e, at 15th storey level have been presented in Table 4. It shows considerable differences between the wind pressures obtained as per different codes and Standards. This indicates the difference in level of protection attributed to similar structures under similar wind loading conditions but designed as per different codes.

Table 4: Results of computation using IS: 875 (Part 3)-1987, Proposed IS: 875 (Part 3) and ASCE 7-02 for 15-storied building at terrain category 3 which is similar to exposure B

Parameters	**IS 875 (Part 3) 1987**	**IS 875 (Part 3) Proposed**	**ASCE 7-02**
Basic wind speed (m/s)	50	50	50
Peak factor	product of peak factor and roughness factor	g_v=3.4 g_R = 3.95	$g_v = g_Q = 3.5$ g_R = 4.09
Turbulence intensity	($g_f r$) = 1.45, represents turbulence intensity	I_h = 0.188	I_z = 0.302
Background factor	B = 0.7	Bs = 0.461	Q = 0.81
Resonant response factor	SE/β = 0.497	SE/β = 0.176	R = 0.512
Gust factor	G = 2.59	C_{dyn} = 0.897	g_f = 0.935
wind force per unit effective frontal area (F_z/A_e) at 15th storey level in KN/m^2	2.49	1.98	1.41

Table 5 represents the variation in the ratio of base shears obtained by existing and proposed Standards [7-8] to that obtained by American Standard [9]. The table shows that the base shear obtained by existing Indian wind code [7] is 1.52-1.93 times and that obtained by Proposed Indian wind code [8] is 1.33-1.44 times the same obtained by ASCE 7-02 [9].

Table 5: Variation of the ratio of base shear obtained by Indian wind codes (IS 875(Part 3)-1987; Proposed IS 875) to that obtained by ASCE 7-02 (ASCE 2002)

No of stories	**Base shear (KN)**			**Ratio of base shear (existing IS/ASCE)**	**Ratio of base shear (proposed IS/ASCE)**
	IS 875 (part 3) 1987	**Proposed IS 875**	**ASCE 7-02**		
5	491.79	368.03	254.4	1.93	1.45
10	1130.12	869.85	643.27	1.76	1.35
15	1911.98	1680.5	1256.41	1.52	1.34

6. CONCLUSIONS

In this study, the response of low to high rise buildings with various aspect ratios (R_A) have been evaluated under the action of wind in different terrain categories utilizing Static analysis and Gust factor based dynamic analysis as suggest in Indian wind code (IS 1989) to judge the effect of variation in building configuration under the action of wind. Such a study is needed to arrive at guidelines for estimating the design wind force in a simple form either being on the safe side or being on economic side applying designers judgement as per the requirement. Beside this, a comparative study of current Indian wind code [7], Proposed Indian wind code [8] and ASCE 7-02 [9] has been carried out to assess the salient features of similarity and dissimilarity in these Standards. The large number of case studies presented here may lead to the following broad conclusions.

1. The study shows that force Coefficient method gives conservative results in the terrain category 4 for all buildings with all heights, exhibiting the ratio of the base shear and the ratio of the storey shear obtained by the Gust factor method to the force coefficient method less than 1.
2. The buildings with number of storeys more than 25 and aspect ratio, R_A, less than 0.5 in terrain category 3 are sensitive to the dynamic effect of wind. Hence, Gust factor method should be used to predict the response of these buildings if situated in terrain category 3. Otherwise force coefficient method may be used to have safe values of design wind forces.
3. The buildings having more than 15 storeys and aspect ratio, R_A, less than 1 should be analysed by the Gust Factor method in terrain categories 1 and 2. However, for R_A greater than 1 force coefficient method may give safe values for predicting the response of the buildings under the action of wind.
4. The base shear estimated for low to high rise buildings by Indian wind code [7] is 1.30-1.90 times the same estimated by ASCE 7-02 [9], while that estimated by Proposed draft [8] of the same code is in a range 1.34 – 1.45 times. This extra margin may provide a scope of compensation in some other steps of the design by applying the judgement of the designers, if required to attend the economy.

The study shows that tall structures behaving flexibility, with the low aspect ratio providing larger wind facing side may have the severest dynamic effect if situated in terrain category 1 and 2 implying less number of tall structures in the surroundings. Such structures may need to be analysed for wind force more carefully. Further, since most of the wind codes are based on similar principles, the conclusions 1 to 3 may be broadly applicable for most of the wind codes. These guidelines may prove useful for choosing the appropriate method by design engineers, depending on the requirement of safety, economy and availability of time. The large number of case studies presented in the paper in the form of the variations curves may be used for preliminary design and cross cheeking the results and hence, may prove useful in the design offices.

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