Indian Journal of Science and Technology Vol. 3 No. 5 (May 2010) ISSN: 0974- 6846

Wind effects on tall building frames-influence of dynamic parameters

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Abstract
In the recent past many tall buildings and high rise towers are being built in India. The impact of wind loads are to be considered for the design of these towers on par with steel towers like transmission towers, microwave towers, cooling towers and very tall multistoried building towers. Several failures of structures have occurred in India due to wind. The IS 875 Part-3 deals with wind loads on different types of structures. In the present work, the Gust Effectiveness Factor Method is used ,which is more realistic particularly for computing the wind loads on flexible tall slender structures and tall building towers. In this paper frames of different heights are anlaysed and studied

Keywords: Wind loads; dynamics; wind velocity; gust pressures; mean hourly wind.

Introduction

The development of modern materials and construction techniques has resulted in the emergence of a new generation of structures that are often, to a degree unknown in the past, remarkably flexible, low in damping, and light in weight. Such structures generally exhibit an increased susceptibility to the action of wind. Accordingly it has become necessary to develop tools enabling the designer to estimate wind effects with a higher degree of confidence than was previously required. Wind engineering is the discipline that has developed, primarily during the last few decades from effects aimed at developing such tools. It is the task of the engineer to ensure that the performance of structures subjected to the action of wind will be adequate during their anticipated life from the standpoint of both structural safety and serviceability. Under the action of wind flow, structures experience aerodynamic forces that include the drag (along-wind) force acting in the direction of the mean wind, and the lift (across-wind) force acting perpendicular to the direction. The structural response induced by the wind drag is commonly referred to as the along wind response. Xinzhong (2008) studied the frequency domain analysis of along wind response to transient nonstationery winds.

It has been recognized that in the case of modern tall structure which are more flexible lower in damping and lighter in weight than their predecessors, the natural frequencies of vibration may be in the same range as the average frequencies of occurrence of powerful gusts and that, therefore, large resonant motions induced by wind may occur, which must be taken into account in design. Davenport (1967) presented the procedure and formulation of dynamic gust factor. Structures that have performed inadequately or that have failed owing to lift and/or aerodynamic moment effects include slender towers and stacks, tall buildings, and suspended span bridges. Individual structural members, cables and power lines, may also be susceptible to aerodynamic, effects involving across wind and/or torsional response.

Wind effects on static structures

In the case of static structures the flow interacts only with the external shape of the structure. When the structure is very stiff, deflections under the wind loads will not be significant, and the structure is said to be “Static”. As the lowest mode frequencies are high, there is little energy in the spectrum of atmospheric turbulence available to excite resonance. The only design loading parameter of importance is the maximum load likely to be experienced in its lifetime. The parameters most relevant to the assessment of design loading are Influence functions, size parameters of the structure, load duration and assessment of load for design.

Wind effects on dynamic structures

In the case of dynamic structures, there is an additional interaction with the motion of the structure. When the structure is sufficiently flexible, the response to wind loads is significant to the design of the structure. The conventional approach to the analysis of dynamic response of lightly damped structures is by resolving the response into the natural modes of vibration, characterizing each normal mode as a set of model parameters: 1) Model shape, 2) Model mass, 3) Model stiffness and 4) Model damping. Using these parameters a frequency response function can be defined that describes the dynamic characteristics of the structures.

Wind loads on tall buildings

The wind load is the most important factor that determines the design of all buildings over 10 storeys. Buildings taller than 10 storeys would generally require additional steel for lateral system. Under the action of a natural wind, gusts and other aerodynamic forces will continuously affect a tall building. The structure will deflect about a mean position and will oscillate continuously. Swami (1987) studied that if the wind energy that is absorbed by the structure is larger than the energy dissipated by structural damping, then the amplitude of oscillation will continue to increase and will finally lead to destruction. The structure will become aerodynamically unstable. The structural forms used today have greater flexibility combined with less mass and damping than those used for traditional structures of the past. These factors have increased the importance of wind in design consideration. For estimations of the overall stability of a structure and of the local pressure distribution on the building, knowledge of the maximum steady or time averaged wind loads is usually sufficient. Hence for this purpose the I.S code ascertains the importance of wind induced oscillations or excitations.

Nature of wind in atmosphere

Wind means the motion of air in the atmosphere and is caused by differences in temperature over earth's surface. The wind speed increases from zero at ground level to a maximum at a height called gradient height. The magnitude of fluctuating component of the wind speed, which is called the gust, depends, on the average time. In general, smaller the averaging interval, greater is the magnitude of the gust speed.

Basic wind speed

Davenport (1982) gave the procedure for developing design wind speeds. The wind speed recorded at DPT stations is analyzed to obtain the extreme wind speeds. The DPT has averaging time of about 3 seconds, analysis gives gust velocities averaged over 3 seconds and they correspond to 10metre height for the open terrain.

Design wind speeds for static structures

Design wind speed (Vz) at any height can be calculated as follows:

$V_Z = V_b K_1 K_2 K_3$ (1)

Where,

V_b = Basic wind speed in m/s

V_z = Design wind speed at any height z in m/sec

K_1 = Probability factor; K_2 = Terrain, height and structure size factor

K_3 = Topography factor

Design wind pressure:

The design wind pressure at any height above mean ground level shall be obtained by the following relationship between wind pressure and wind velocity.

P_z = design pressure at height "z" due to hourly mean wind.

$p_z = 0.6\, v_z^2$ Eq. (2)

Where P_Z = Design wind pressure in N/m² at height "z",

Vz = Design wind velocity in m/s @ height "z".

Thus, static wind loads are computed based on the considerations of the design wind speed and the height of the structure. The other properties of the structure like size, stiffness, damping, etc., are not considered.

Gust effectiveness factor method (AS PER IS-875 PART-III-1987)

As discussed already, Gust Effectiveness Factor Method is a more realistic and rational approach to deal with wind loads on tall building towers.

Hourly mean wind speed with height:

The variation of hourly mean wind speed with height shall be calculated follows.

$V_z' = V_b{*}K_1{*}K_2{*}K_3$ (3)

Where V_z' = hourly mean wind speed in m/s at height "z"; V_b = basic wind speed in m/s; K_1= Probability factor; K_2 = Terrain and height factor; K_3 = Topography factor.

Along wind load

Along wind load on structure on strip area (Ac) at any height (z) is given by:

$F_z = C_f{*}A_e{*}P_z{*}G$ (4)

Where,

F_z = along wind load on the structure at any height z corresponding to strip area Ac,

C_f = force coefficient for the building,

A_e= effective frontal area considered for the structure at height "z",

P_z = design pressure at height "z" due to hourly mean wind obtained as $0.6\, V_z'^2$ (N/m^2)

G=gust factor (peak load/mean load) and is given by:

$$G = 1 + g_f\, r \sqrt{\left[B(1+\Phi)2 + \frac{SE}{\beta}\right]} \quad (5)$$

g_r = peak factor defined as the ratio of the expected peak value to the root mean value of a fluctuating load, and

r = roughness factor which is dependent on the size of the structure in relation to the ground roughness.

The value of 'gf r' is obtained from (IS 875 PART-3)

B = background factor indicating a measure of slowly varying component of fluctuating wind load and is obtained from (IS 875 PART-3),

S= Size reduction factor is obtained from (IS 875 PART-3),

E=measure of available energy in the wind stream at the natural frequency of the structure is obtained from (IS 875 PART-3),

$\frac{SE}{\beta}$ = Damping coefficient (as fraction of critical damping) of the structure.

$\Phi = g_f r \sqrt{B}$ /4 and is to be accounted only for buildings less than 75m height in terrain category 4 and for buildings less than 25m height in terrain category 3, and is to be taken as zero in all other cases.

$\lambda =$ Cy b / Cz h and $F_o = C_z f_o h / \bar{V}_z$

Where

Cy=lateral correlation constant which may be taken as 10 in the absence of more precise load data,

Cz= longitudinal correlation constant which may be taken as 12 in the absence of more precise load data,

b=breadth of a structure normal to the wind stream. h=height of a structure

$\bar{V}h=\bar{V}z$=hourly mean wind speed at height "z", Fo=natural frequency of the structure, and $L_{(h)}$ =a measure of turbulence length scale.

Details of the present study

Parameters considered for study

The present study includes the study of nature and variation of gust pressures. For this study, multistory frames ranging from 20 to 100 storeys are considered. From this the variation of gust pressures with height will be clearly known. By considering single bay and two bay frames in all the cases, the influence of the size of the building on gust pressures will be known.

The IS code (875 part-III-1987) has suggested an empirical rule to compute the fundamental frequency for multi-storeyed frames. This is grossly approximate and doesn't take into consideration the size of the building and the relevant dynamic properties of the structure. In the present study, dynamic analysis of the frame is conducted, and the actual fundamental frequency is computed in different cases. Gust pressures are computed based on actual frequencies for comparison.

Details of frames

In the present analysis, multistory frames of 20, 40, 60 and 100 storeys with one bay and two bays are considered. The typical size of column is 0.3 m X 0.49 m. The size of beam is 0.3 m X 0.4 m. The height of each storey is 3.5 m.

Gust pressures

A computer programme is written for the Gust Effectiveness Factor Method. Gust factors and gust pressures are computed using the programme. The computed values of gust factors for different frames considered are obtained for single and two bays. The gust pressures are also computed for all the frames under consideration with one and two bays.

Axial forces in columns

The computed values of axial forces in columns based on Gust effectiveness factor method and static method are obtained for all the frames with one and two bays.

Results and discussions

Criticality of wind loads for the design of multi-storeyed frames

In structures of normal height, even upto 20 storeys height, dead and live loads are predominant. The wind loading effects are covered by the increase of permissible stresses as recommended by the I.S. code (IS 875 Part 3). Hence, for the design of buildings of low to medium height the wind effects are usually ignored.

As the height of the building frames increase, the wind effects become gradually considerable. In the case of very tall slender frames they even become predominant compared to dead and live load effects. Very tall slender building frames are flexible in nature and as a result they interact with the wind dynamically and the safety and the stability of structure may become critical. Hence, for design of very tall frames, a thorough study of wind effects and investigation of criticality are very much necessary. This is particularly so in regions where wind is more critical than earthquakes.

Variation of gust pressures with height

Swami (2009) showed that in general, gust pressures increase with height in the case of multistory frames of different storeys. The variation of gust pressures with height for typical frames is plotted and shown in Fig. 1 to 4. In the case of a 20 storey building the pressures increase from 1.13 kN/m² to 2.52 kN/m² in the case of single bay and from 1.11 kN/m² to 2.48 kN/m² in the case of two bay. In general, the increase in gust pressures is about 18% over a height between 3.5 m to 70 m in the case of a 20- storey frame.

In the case of 60 storey frame, the increase in gust pressures is more than 21% over a height up to 180 m. Similarly in the case of 100 storey frame the increase over a height of 280 m is more than 23% Hence, it is clear that the gust pressures increase with height of the frames, become considerable and may even become critical in the case of very tall buildings.

Static pressures versus gust pressures

By comparing the values of wind pressures computed by static method and the Gust Effectiveness Factor Method, it can be seen that the gust pressures are more than the static pressures. For example, in the case of 20-storeyed single bay, the gust pressures are more than the static pressures by 15 to 38% from 3.5 m to 70 m. For a 20-storeyed two bay they are 13 to 37%. Similarly, in the case of 60-storeyed single bay the difference is from 33 to 58% and 60-storeyed two bay the difference is from 31 to 57% from 3.5 m to 210 m. The Gust Effectiveness Factor Method takes into consideration the aspect ratio and the size effect which influences the force co-efficient in the case of multistoried buildings. The static method does not consider the size of the building and the dynamic properties of the building except the height. Hence, the gust pressures are safer compared to static pressures, particularly in the case of tall, slender multistoreyed frames.

Variation of gust factor with height

It can be seen that the overall gust factor decreases with the height of building. For example, the gust factor is 3.09 for the 20-storey building with single bay and the

Indian Journal of Science and Technology Vol. 3 No. 5 (May 2010) ISSN: 0974- 6846

Fig. 1. Variation of the static & gust pressures with height of a 20-storeyed building (1-bay)

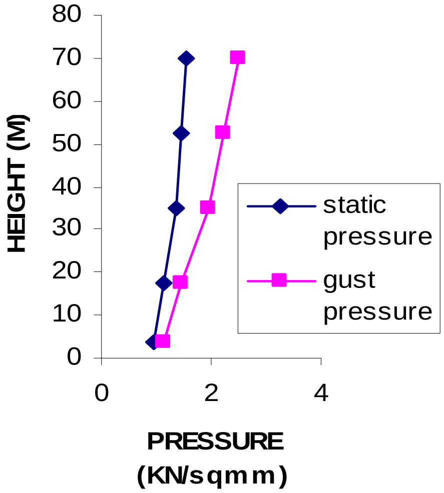


Fig. 2. Variation of the static & gust pressures with height of a 20-storeyed building (2-bay)

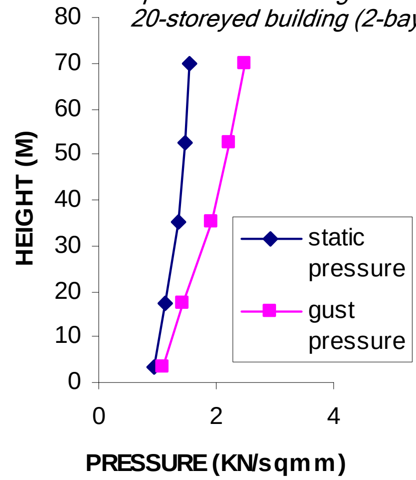


Fig. 3. Variation of the static & gust pressures with height of a 60-storeyed building (1-bay)

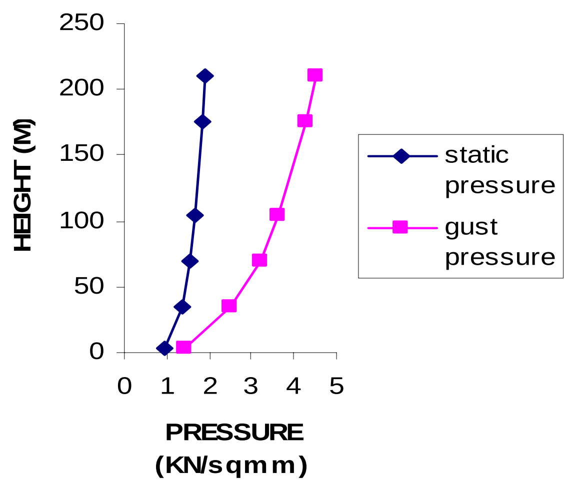


Fig. 4. Variation of the static & gust pressures with height of a 60-storeyed building (2-bay)

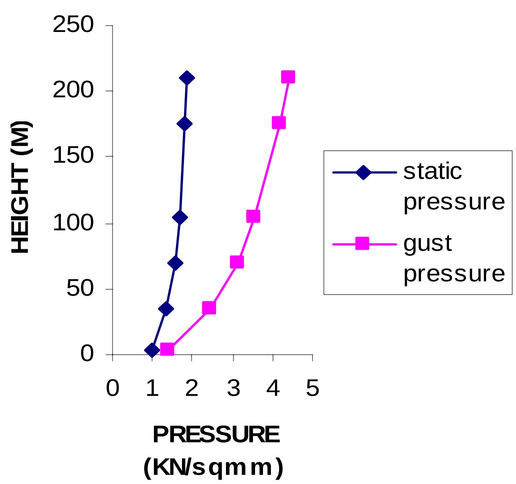


Fig. 5 Variation of the axial loads with height of 20-storeyed (1-bay)

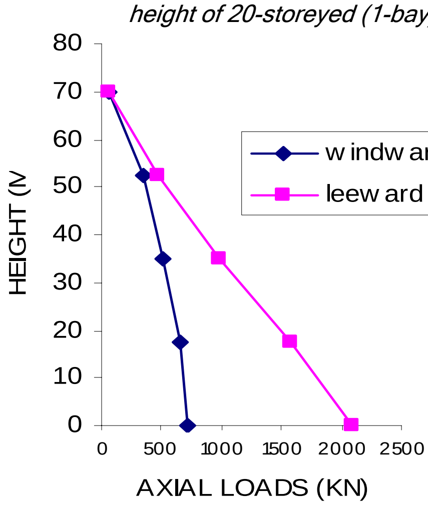
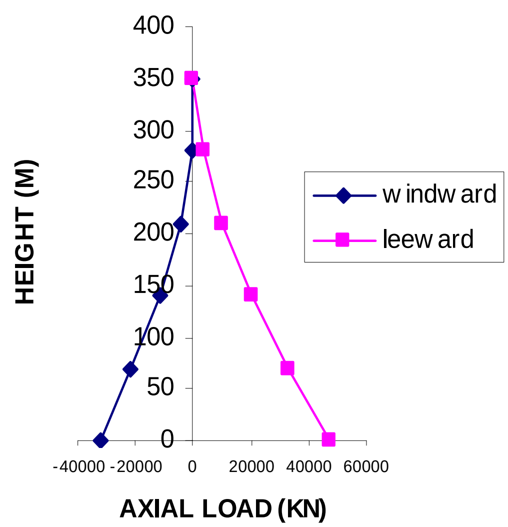


Fig. 6. Variation of the axial loads with height of 100-Storeyed (1-bay)



value becomes 2.82 for the 100-storey building. This clearly indicates that as the building height increases its flexibility also increases. The fundamental frequencies decrease and overall gust factor decreases. When static wind pressures are computed, as per I.S 875 part-III, it is quite clear that wind pressures increase with height of the building. This increase occurs in the case of gust factor method also. The gust factor decreases with height. Though gust pressures increase with height of the building the variation becomes smaller. Hence, gust pressures are safer for design particularly for structures of greater height and at the same time they are more rational and realistic.

Variation of column axial forces

The Column axial forces are less on the windward side than on leeward side. The variation of axial force with height for typical frame is plotted and shown in Fig. 5 and 6. For example, for a 20-storeyed single bay building, the axial force due to 1.2(DL+LL+WL) at a height of 17.5m is 647 kN on windward side and 1586 kN on leeward side. Also for frames beyond 20-storeyed the windward columns are subjected to tensile axial force. Hence, in the design of columns of tall multistoried frames, the axial compressive forces in the leeward columns are critical and windward columns are to be checked for tensile axial forces.

Variation of column bending moments:

The column bending moments are less on the windward side than on the leeward side. For a typical 20-storeyed single bay frame, the values of moments at a height of 17.5 m above the base are 93 kNm for leeward column and 46 kNm for the windward column. In the case of typical 100-stroreyed single bay frame, moments are 499 kNm and 452 kNm respectively at a height 140 m above the base.

Validity of gust factor method:

From the above discussion it is clear that the gust factor method is very much valid for computing design wind pressures on tall structures. Very tall structures are slender and flexible. The fundamental frequency is lower and the structure dynamically interacts with wind. Wind has two components like mean and fluctuating. Hence the dynamic interaction between tall flexible structures and wind is to be investigated. The possibility of resonance and its influence on the structure are to be clearly known. Hence, the gust factor method gives not only safer design pressures but also it is more rational compared to the static method. Thus, gust factor method gives more confidence to the designer because it takes into account all aspects.

Conclusions

Based on the computed results and the discussion made, the following conclusions are drawn:

- The gust pressures computed by gust effectiveness factor method increase with the height of the building and they are more critical than static pressures and as such gust effectiveness factor method gives critical wind pressures to be considered in the design of tall multistoreyed frames.
- The difference in the values of gust pressures computed for single and two bays is small, however for exact determination of internal stresses, the size effect given by number of bays is to be considered. The size reduction factor increases with the height of the building frame.
- In arriving at the gust effectiveness factor, it is very much necessary to investigate the resonance effects on the basis of actual computed fundamental frequency.
- As the height of building frame increases, the energy content in the fluctuating component of wind also increases.
- The peak factors increase with the height of the building because of the decrease in wind turbulence.
- The overall gust factor decreases from one. building frame to other as the height is increased.
- In the design of columns of tall multistoreyed frames the axial compressive forces in the leeward columns are critical and it is quite predominant when wind is considered.
- The windward columns of tall multistoreyed frames are to be checked in the design for tensile axial forces and they are to be compensated by means of heavy foundations and other dead loads.
- The Column moments due to wind are becoming critical for the design.
- On the whole, the wind pressures computed by the gust effectiveness factor method are not only safer for design but also they are more rational and realistic. This is an important and valid point to be considered for the design of very tall buildings and structures.

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