A Simplified Approach on Dynamic Response of Tall Buildings due to Wind loads

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Abstract: In this paper, a simplified approach on dynamic response of tall buildings due to turbulent wind load is proposed to get a proper modification factor used in equivalent static wind load method. The approach undertakes the investigation of turbulent wind loads on high-rise buildings in one of the frequency domain analysis to get Peak Dynamic Response (PDR). This simplified method is developed by using the Power Spectral Density Analysis in Sap 2000. The turbulent wind spectrum, aerodynamic admittance and vertical coherence for buffeting wind loading are estimated using Kaimal spectrum, empirical relationship proposed by Vickery and Spatial Coherence of Davenport . The building models conditions are documented as a data bank. Then, the proposed design method is introduced by using design data bank. Then, the method is analyzed by the case studies with respect to various wind speed and height of storeys. By introducing this proposed method at the initial stage of analysis and design, less controlled parameters in analysis and computational effort in specified regions than standard procedures can be obtained.

Key Words: Simplified Approach, Modification Factor, Peak Dynamic Response (PDR), Power Spectral Density Analysis, and Buffeting Wind Loading

Introduction:

Wind is caused by differences in pressure. When a difference in pressure exists, the air is accelerated from higher to lower pressure areas. In the field of structural engineering, it includes strong winds, which may cause discomfort and extreme winds such as tornado, hurricane. It plays an important role in design of tall structures because it exerts static and dynamic loads with effects on slender structures. Most international codes and standards make use of the Gust Loading Factor (GLF) by Davenport (1961) to determine the equivalent static along-wind loading on a structure. Although the traditional GLF method ensures an accurate estimation of the displacement response, it may fall short in providing a reliable estimate of dynamic response components. A single 'factor' can be assessed to account for dynamic effects resulting from gust fluctuations in buffeting wind load condition. Several analytical models have been developed in the past to calculate this dynamic factor which is multiplied by the static response to give the maximum dynamic response of the structure. This dynamic factor is usually referred to as the "Gust Response Factor". Typical high-rise buildings oscillate in the Along-wind, Across-wind, and Torsional directions The Along-wind motion primarily results from pressure fluctuations on the windward and leeward faces, which generally follows the fluctuations in the approach flow, especially in the low frequency range. Therefore, Along-wind aerodynamic loads may be quantified analytically utilizing quasi-steady and strip theories, with dynamic effects customarily represented by a random vibration based "Gust Factor Approach" [1].

Methodology: The gusts can be considered as static loads if the wind load increases and vanishes in a time much longer than the period for the building. Besides that, the deflection due to wind load for a very stiff structure will not be significant, and the structure also is said 'Static'. If wind gust reaches maximum value and vanish in a time interval much shorter than the period of the structure, it becomes dynamic case. 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 dynamic responses to the wind load depends on wind climate, atmospheric boundary layers, turbulence properties, variations of wind speed with height, aerodynamic forces and turbulence boundary layer [2].

A. Equivalent Static Wind Load Method

The determination of the wind loads is based on ASCE 7-05, which uses average 3 second gusts at 33 ft above the ground as the standard of measurement. The Analytical Method was used to get velocity pressures at each level of the building [3]. The velocity pressure is given by

$$q_z = 0.00256\, K_z K_{zt} K_d V^2 I \qquad \text{Equation (1)}$$

Design wind pressure or suction on a building surface is given by the equation:

$$P_z = q_z \times G_f \times Cp \qquad \text{Equation (2)}$$

Where,

P_z = design wind pressure or suction, in psf
q_z = velocity pressure, in psf
C_p = pressure coefficient
G_f = gust response factor
K_{zt} = topographic factor
I = importance factor
V = basic wind speed, mph
K_d = wind directionality factor

The maximum along-wind displacement can be determined by using the following specifications in ASCE7-05.

$$X_{\max} = \frac{\Phi_{(z)} \rho B H C_{fx} V_z^2}{2 m_1 (2\pi n_1)^2} K G \qquad \text{Equation (3)}$$

B. Gust Response Factor

Gust Response Factor is the ratio of a peak structure response divided by the average response due to the mean wind. GRF normally accounts for a possible resonant "dynamic effect" and a "size effect". The GRF approach consists of specifying a force F which would cause the system to reach its expected peak response if it applied statically. The derivation of the gust response factor proposed by Davenport that eventually found its way into the ASCE [3].

The gust factor, G_f required for calculating design wind pressures for the main wind-force-resisting system of the building and can be calculated as

$$G_f = 0.925 \left[\frac{1 + 1.7 I_z \sqrt{(g_Q Q)^2 + (g_R R)^2}}{1 + 1.7 g_v I_z} \right] \qquad \text{Equation (4)}$$

C. Description of Gust Effect Factor in Equivalent Static Wind Load Process

In "Linear-Elastic-Static Analysis", the Dynamic response factor or Gust Effect Factor, G_f is used for the turbulent wind effect. This factor includes non-resonant and resonant part. The energy factor evaluates the normalized wind velocity spectrum at the natural frequency of interest. The size reduction factor or aerodynamic admittance Function accounts for the effect of the area-wide distribution of wind pressure and it is also a transfer function which connects between oncoming wind velocity and induced aerodynamic force. In resonant part, size reduction factor and energy factor are used as the decay factor of turbulent wind. The gust factor for turbulent wind loads in linear static method is determined as shown in figure 1. The gust factor, G_f accounts for additional dynamic amplification of loading in the Along-wind direction due to turbulence and structure interaction. A single gust effect factor of 0.85 for rigid buildings is used in ASCE 7. The gust effect factor G_f does not include allowance for across wind loading effects and dynamic torsional effects [3].

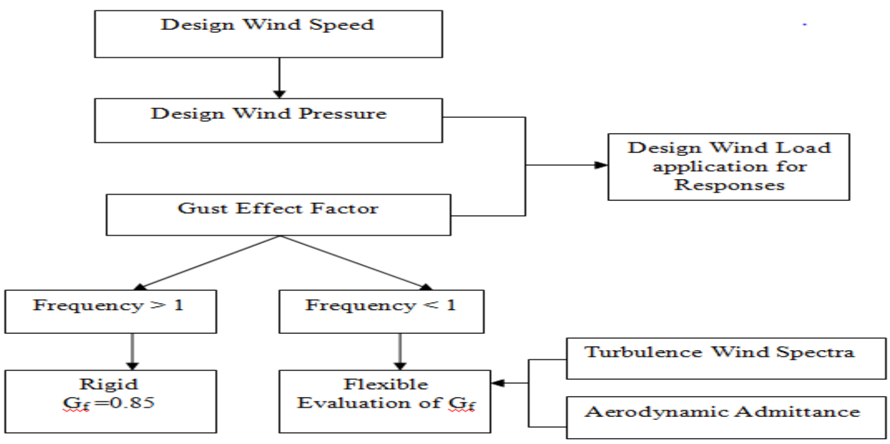


Figure. 1 Flow Chart for Gust Factor Determination in Linear Static Analysis

Analysis: It consists of hypothetical models for case studies with building models conditions for design data bank and a detail description of simplified approach.

1. Case Study

In this paper, total of twelve cases are considered with respect to different building dimension, number of stories and wind speed. They are regular steel moment resisting frames. The hypothetical building models are square plan of steel building with braced frames. Beam and brace connections in the braced frames and gravity frames were modeled as pinned while beam connections in the moment frame were modeled as fully fixed. The floors are all modeled as rigid diaphragms. The building supports were modeled as fully fixed in the moment frame direction and pinned in the braced frame direction. The columns are and all other members are typical rolled W-sections. The LRFD design philosophy was employed and members were designed to satisfy current ASCE 7 load combinations. The building considered in this study mainly are 20 storeyed, 30 storeyed, 40 storeyed and 50 storeyed buildings.

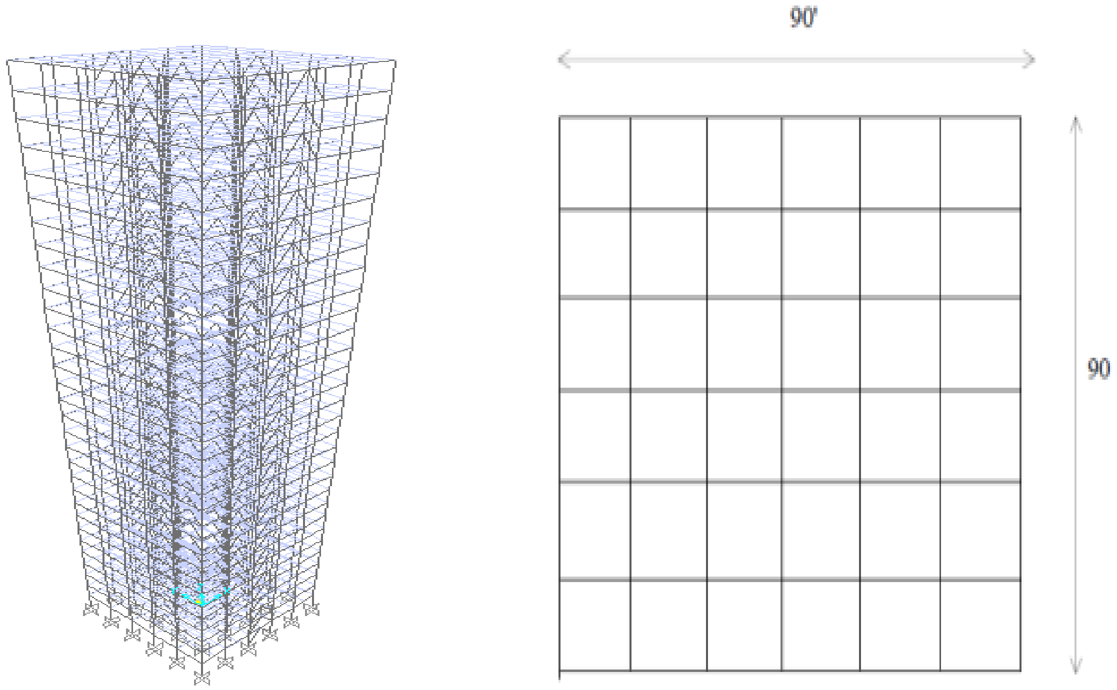


Figure. 2 Three Dimensional and Plan View of the Model Building

The hypothetical case study buildings are firstly considered to evaluate and demonstrate the application of the gust effect factor according to ASCE 7.

Table 1. Building Models Conditions

Model	Storeys	Plan	B (ft)	D (ft)	H (ft)	L/B
Case -1	20 30 40 50	Square	60 60 60 60	60 60 60 60	231 341 495 561	1
Case -2	20 30 40 50	Square	75 75 75 75	75 75 75 75	231 341 495 561	1
Case -3	20 30 40 50	Square	90 90 90 90	90 90 90 90	231 341 495 561	1

Exposure C is chosen for cyclonic wind areas and exposure B is chosen for urban area. Basic wind velocity is considered for 60, 80,100,120 and 140 mph. Maximum displacements at the uppermost occupied floors are estimated using the service state properties with the critical damping ratio of 5%. The first is "natural frequency analysis" that gives the fundamental frequency of vibration of a building. Models are run to obtain approximate natural frequency input for the determination of gust factor in all cases of the analysis.

2. Simplified Approach for Dynamic Analysis

For the dynamic response analysis of a structure under strong winds, the spectral response method in a frequency domain or the step-by-step integration of motion equation in a time domain is used. The first one is linear, i.e., based on the assumption that the properties of a building are independent of its response. If a response of such a system is described in the frequency domain, the random character of the wind loads can be expressed by using spectra. The spectral response method produces a linear deformation of a structure. The generation of artificial (simulated) samples of loading is the easiest and a general way to tackle a specific problem. The simplified analytical method as a frequency domain approach is proposed for buffeting response of Along-wind load only and detail considerations, conditions, assumptions for analysis method are expressed. The application of loading in analysis is done with the flow chart to get peak responses in analysis.

A. Considerations in Analysis

The simplified approach is considered for buffeting response due to wind turbulence. Averaging Time, reference height, exposure categories, mean wind velocity profile were considered for spatial modeling of wind load. Two main parts of the wind load for peak response were combined as mean wind load and turbulent wind load with the consideration of pressure distribution effect and vertical coherence effect with turbulent wind spectrum. The proposed analysis did not consider other aerodynamic phenomena, many environmental specifications for directionality, topography, the level of structural reliability of a building and enclosure condition. The artificial wind spectrum for the creation of turbulent wind for the interest of frequency is Kaimal's spectrum. Also, turbulent length, reference height and reference wind velocity were considered for temporal modeling of wind load. The condition of wind environment and building configuration is the same as in Equivalent Static Analysis.

B. Aerodynamic Admittance

The relationship between wind speed and wind force or pressure acting on a structure can be expressed as a frequency dependent transfer function commonly referred to as the aerodynamic admittance, $\chi(f)$. lt accounts for the transition of the undisturbed wind velocity fluctuations into fluctuating wind-induced pressures. Aerodynamic admittance, χ is use to take accounts the interaction of structure and wind flow. It is a transfer function for the area-wide distribution of wind pressure and it is also a transfer function which connects between oncoming wind velocity and induced aerodynamic force [4]. The following empirical relationship proposed by Vickery is used in this study:

$$\chi(f,b,h,\bar{v}(h)) = \frac{1}{1+\left[\frac{2f\sqrt{A}}{\bar{v}(h)}\right]^{4/3}} \qquad \text{Equation (5)}$$

C. Spatial Coherence of the Wind Pressure

The correlation between wind speeds at different locations in a wind field can be described using spatial coherence functions. Coherence functions describe the correlation as a function of frequency and separation. Hence, the coherence function provides the spatial variation among the turbulence components in three-dimensional wind fields. Coherence describes the correlation between two signals as a function of frequency. A value of 0 indicates that the signals are completely uncorrelated while a value of 1 indicates perfect correlation. In the computation of response of long span structures and high-rise structure, spatial correction of wind pressure cannot be ignored. For large span structure, horizontal spatial correction should be considered. For high-rise structures, vertical spatial correction must be taken into account. Davenport (1967) presented a correction function which is related to frequency n and distance between two points [1].

$$J_1 = \frac{2B^2}{(AC_y)^2}(e^{-AC_y} + AC_y - 1) \qquad \text{Equation (6)}$$

$$J_2 = \exp\left(-\frac{AC_z}{B}\left|z_1 - z_2\right|\right)$$ Equation (7)

$$A = \frac{2n\varepsilon B}{\bar{V}_{z_1} + \bar{V}_{z_2}}$$ Equation (8)

$$\varepsilon = \frac{\sqrt{1+r^2}}{1+r}$$ Equation (9)

$$r = \frac{C_y B}{C_z H}$$ Equation (10)

Where, J_1, J_2 = horizontal coherence and vertical Coherence

C_y, C_z = decay factors
B = width of the structure
H = height of the structure
n = frequency of the structure
$\bar{V}_{z_1}, \bar{V}_{z_2}$ = mean wind velocity

D. Assessment Procedure for Simplified Method

The three assumptions in the proposed analysis method were made. The total overall wind loads was applied as joint force on top of the buildings for the spatial modeling of mean wind Load. Then these forces were reduced with the effect of vertical coherence and aerodynamic admittance as fluctuated wind load. For the creation of turbulence wind PSD function by using specified wind spectrum, Kaimal wind spectra with respect to turbulence length, wind velocity, frequency of the building was used. Kaimal wind spectrum is implement arbitrary power spectral density (PSD) to use for turbulent wind velocity spectrum in analysis. The formation of the along-wind load spectrum, $S_{FF}(f)$ is as the following equation [5].

$$S_{FF}(f) = \left[C_d \rho_{air} \bar{v}(h) A \chi(f,b,h,\bar{v}(h))\right]^2 S_{vv}(f,h,\bar{v}(h))\gamma(r,n)$$ Equation (11)

Where , A = exposed surface perpendicular to the wind direction
b = width of the plan perpendicular to the wind direction
C_d = the drag coefficient
f = natural frequency of the structure
h = height of the building
S_{vv} = the spectrum of the along-wind velocity
v(h) = the mean wind speed at the top
ρ_{air} = the density of the air
χ = the aerodynamic admittance function
$\gamma(r,n)$ = the spatial coherence

In this study, combination of applied joint force by considering coherence and power spectral density curve is done to get RMS or standard deviation value for turbulent wind effect. The spectral density of the generalized force is obtained from the assumption of integration of mean wind load with vertical coherence effect and pressure admittance effect only. The spectral density of the generalized force takes the form

$$S_{p_i^*}(n) = \rho^2 C_D{}^2 B^2 \chi^2(n) \int_0^H \int_0^H \phi_i(z_1)\phi_i(z_2)\bar{U}(z_1)\bar{U}(z_2)\sqrt{S_{u_1}(n)}\sqrt{S_{u_2}(n)}\gamma(r,n)dz_1 dz_2$$ Equation (12)

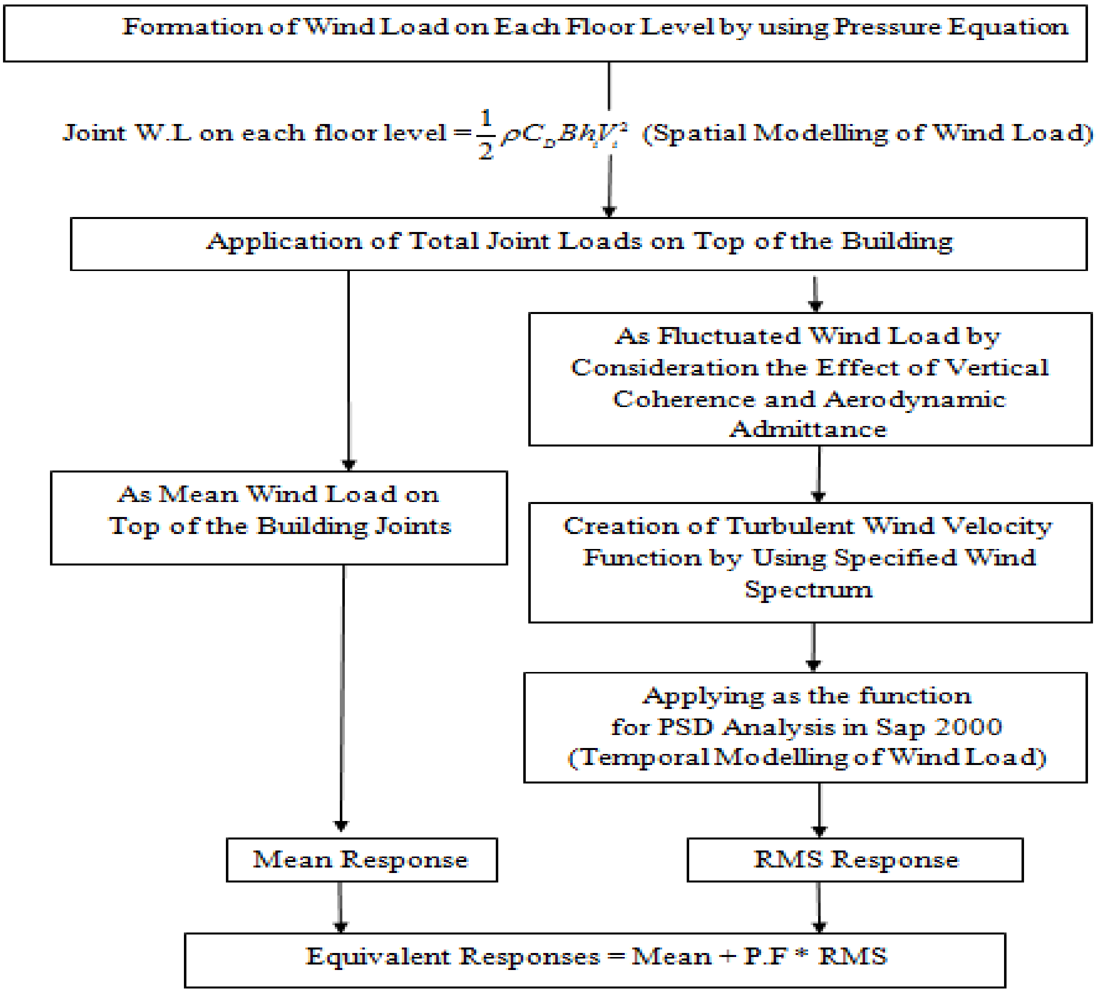
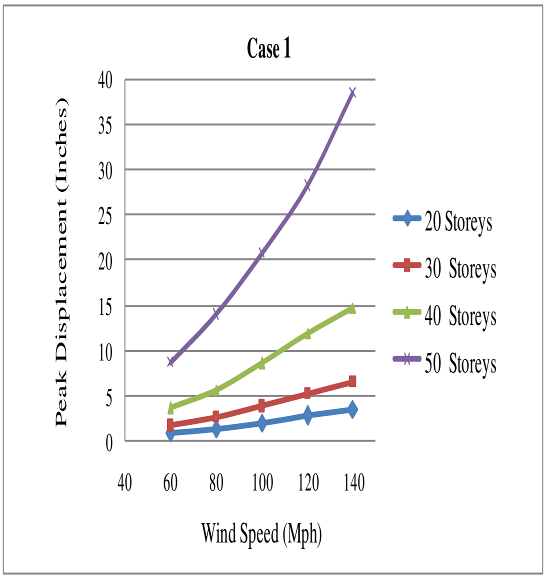
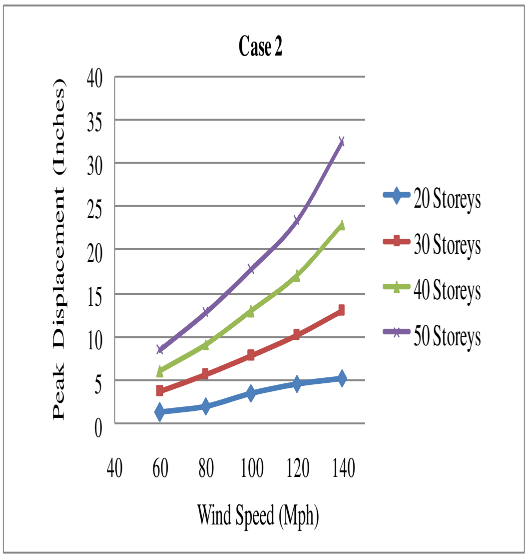


Figure. 3 Simplified Analysis Process

Result: To compare responses of tall buildings due to wind loads using dynamic and static analysis, three case study models for square buildings are analyzed in this study. For making the comparison of analysis results, the peak displacement results of 20 storeyed, 30 storeyed, 40 storeyed and 50 storeyed buildings are determined. Then the modification factor used in static analysis for the response of dynamic wind load is determined from the results of the two analyses. Then, this leads to a useful parameter for the wind resistant design for high-rise buildings. Also, the comparison of peak displacement in two analyses with NALD is presented. The NALD serves as a web-based on-line computational framework for use in the preliminary design of high-rise buildings subjected to wind loads [6].





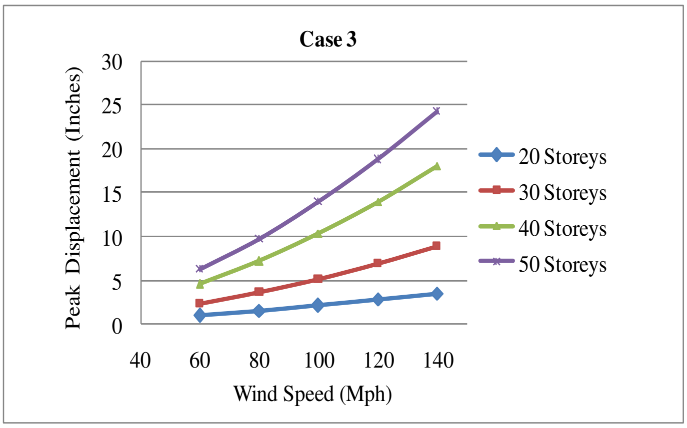


Figure.4 Comparison of Peak Displacement from Simplified Analysis (PSD)

The difference in displacement responses can be found in higher storey buildings. The simplified method obtains more similar responses with analysis of ASCE 7 for lower wind speed and lower storey buildings. When the building was higher, the peak displacement will be increased dramatically. Linear static analysis gives exact displacement results although it could not show the exact acceleration value. In this study, only the displacement responses of two analyses were compared. .

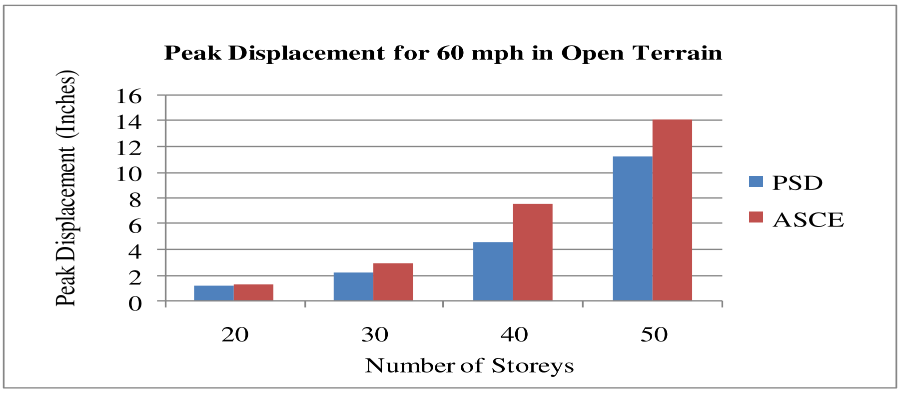


Figure.5 Comparison of Peak Displacement from Two Analyses for 60 mph

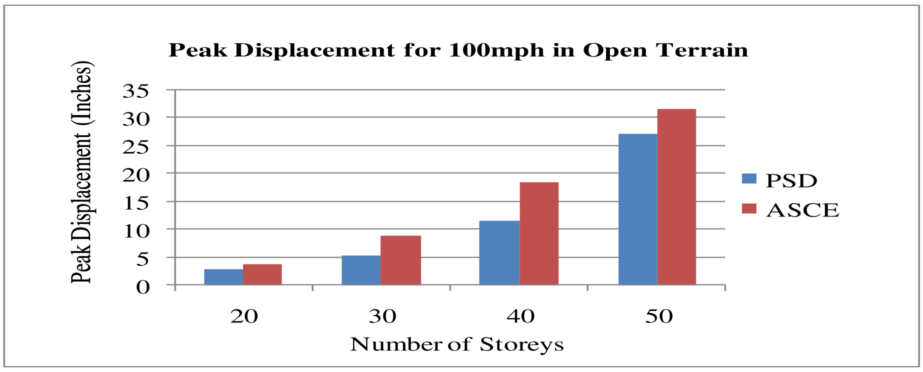


Figure.6 Comparison of Peak Displacement from Two Analyses for 100 mph

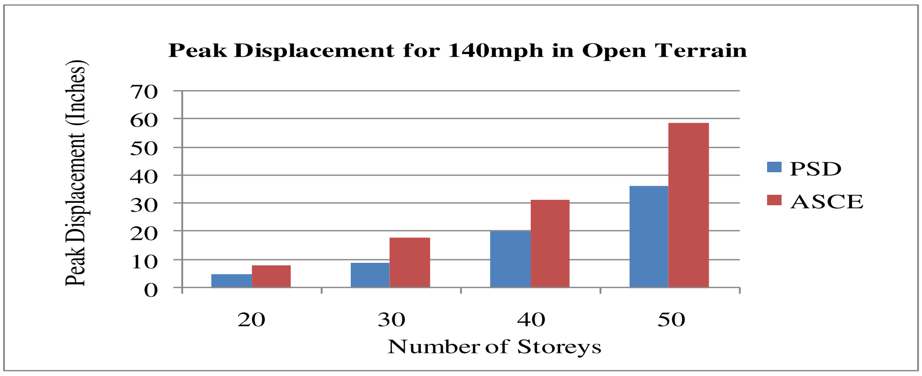


Figure.7 Comparison of Peak Displacement from Two Analyses for 140 mph

Also, the modification between two analyses was done for the determination of dynamic wind load. This modification factor can be applied in the determination of exact response of dynamic analysis by multiplying with the maximum response of static analysis. The modification factor was higher in less plan aspect ratio for low wind speed and then gradually decreases when the building width and wind speed were larger. The minimum modification factor was found in higher stories and larger wind speed. Thus, it was underestimated and deviated from reality of the analysis.

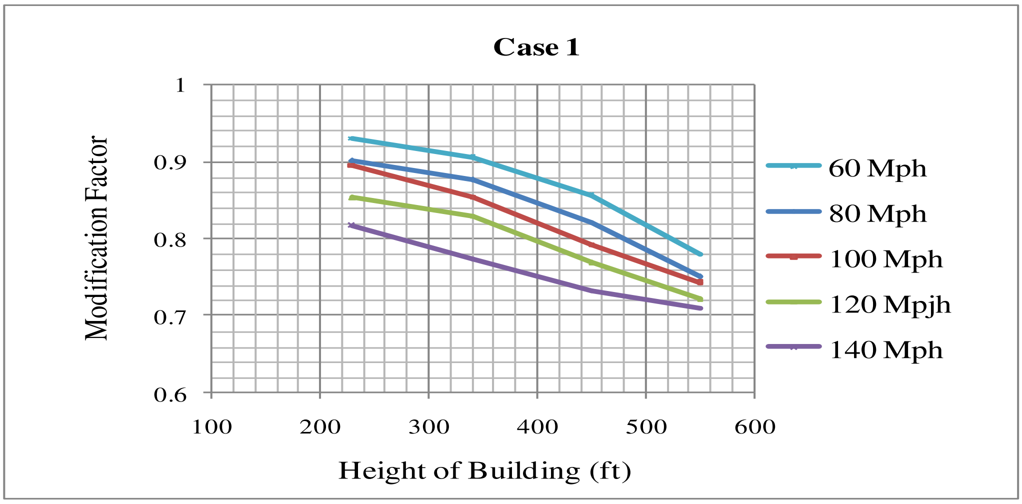


Figure.8 Modification Factor for Static Analysis (ASCE)

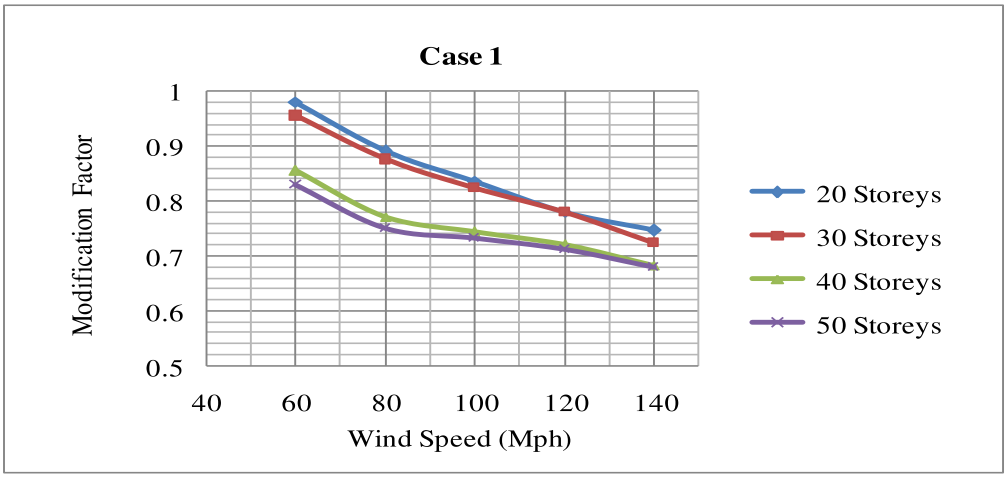


Figure.9 Modification Factor for Static Analysis (ASCE)

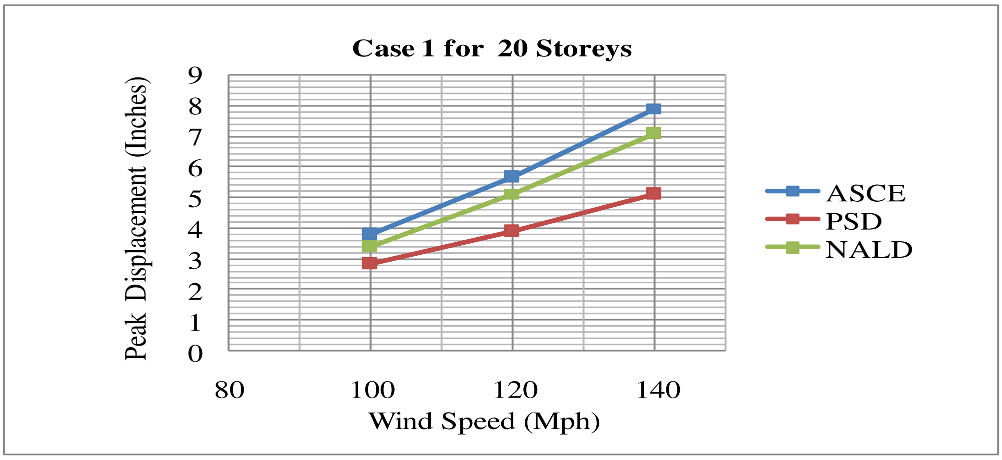


Figure.10 Comparison of Peak Displacement from Three Analyses

When the building width is larger and the building height is greater, the responses of NALD and simplified analysis are nearly similar.

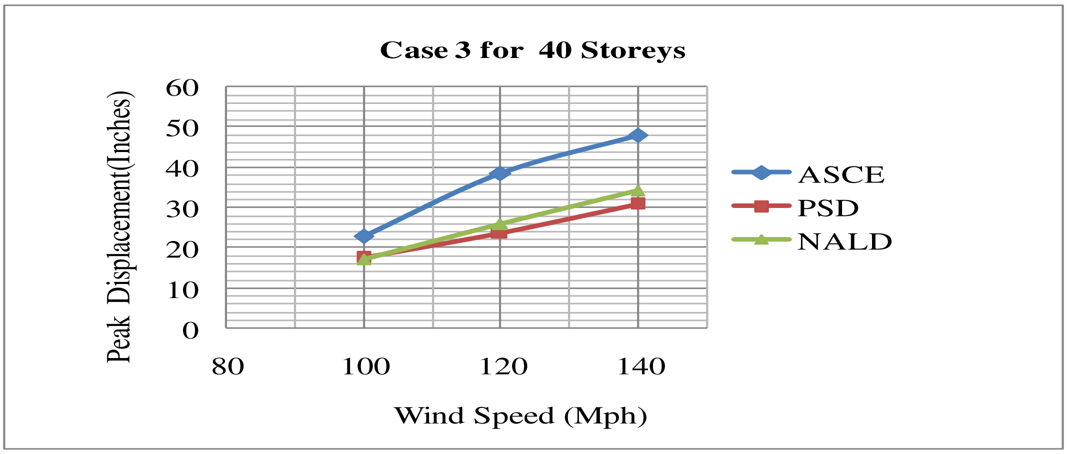


Figure.11 Comparison of Peak Displacement from Three Analyses

Recommendations: In this research, the Power Spectral Density Analysis in Sap 2000 with former defined wind turbulent wind spectra is considered in the determination of the peak dynamic response for buffeting response only. For further study, experimental wind tunnel studies should be carried out to study the actual behaviour and effects of local wind data. Other aerodynamic phenomena should be also considered in this simplified analysis. In addition, the creation of turbulent wind spectrum for local wind pressure on specified region in the country. In addition, a study of the coherence effect of windward and leeward faces for wind load should be conducted. For further study, a study of various load combinations for unbalance torsional wind load should also be conducted.

Conclusion: In this research, the response obtained from the simplified analysis is nearly similar with the one from the equivalent static method in the 20 storeyed and 30 storeyed buildings when lower wind speed. The modification factor is 0.9 for the range of building height up to 300 ft and the maximum wind speed of 100 Mph. And the modification factor is 0.8 for the range of building height up to 300 ft and the maximum wind speed of 120 mph. The modification factor is 0.7 for the range of building height up to 500 ft and the maximum wind speed of 140 Mph. The proposed analysis method will lead to less controlled parameters in analysis, computational effort, less influence factors in specified regions than standard procedures. The simplified analysis is underestimated in larger wind speed and higher buildings. The simplified analysis method is different within 10% for lower wind speed and medium-rise buildings. The simplified analysis is available for the investigation of the local wind pressure fluctuation with the creation of wind spectrum for exact response of dynamic analysis.

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