Deterministic Analysis of Wind Loads Effects on High-Rise Buildings

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ABSTRACT

This paper studies the effect of mean wind velocity on tall building. Wind velocity, wind profile and wind pressure have been considered as a deterministic phenomenon. Wind velocity has been modelled as a half-sinusoidal wave. Three exposures have been studied B, C, and D. Wind pressure has been evaluated by equation that joined wind pressure with mean wind velocity, air density, and drag coefficient.

Variations of dynamic load factor for building tip displacement and building base shear have been studied for different building heights, different mode shapes, different terrain exposures, and different aspect ratios of building plan. SAP software, has been used in modelling and dynamic analysis for all case studies.

Results For different building heights considered maximum dynamic load factor (DLF) occurs in height range from 100-150m because fundamental building frequency is so close as to dominate wind frequency. Effect of higher modes become insignificant for height greater than 175m. Effect of three different terrain exposures B, C, and D on DLF for tips displacement and building base shear have been insignificant effect on response of tip displacement and building base shear. . Finally, effect of aspect ratio λ for different building heights with dynamic load factor (DLF) for tips displacement and for building base shear have λ approaching 2, fundamental building frequency is so closed to dominate wind frequency.

KEY WORDS: dynamic load factor, frequency, terrain.

التحليلات المحددة لتأثير أحمال الرياح على البنايات العالية متعددة الطوابق

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الخلاصة

تمت دراسة تأثير الرياح في معدلاتها ، سرعة الرياح ، مقطع الرياح و ضغط الرياح والذي تم اعتباره كظاهرة محددة ، سرعة الرياح تمت معاملتها كدالة نصف جيبية. تم تصنيف الأرض الى ثلاث مناطق تعرض هي B و C و D. تم تقييم ضغط الرياح من خلال معادلة تربط ضغط الرياح بمعدل سرعة الرياح و كثافة الهواء و معامل الأعاقة.

تمت دراسة تأثير الرياح في معدلاتها ، على اختلاف معامل الحمولة الديناميكية لأقصى ازاحة واكبرقوة قص في القاعدة اخذين بنظر الأعتبار المعاملات التالية: ارتفاع البناية ، خشونة تضاريس المنطقة، طور الأهتزاز، نسبة الطول الى العرض بالنسبة للبناية.

كانت النتائج لعدة ارتفاعات للبناية لأقصى ازاحة واكبر قوة قص في القاعدة مع اختلاف معامل الحمولة الديناميكية تحدث في مدى ارتفاع البناية بين (100-150)م وذلك بسبب معامل الحمولة الديناميكية يزداد عند اقتراب تردد الرياح من أحد ترددات البناية.

بالنسبة لنتائج تأثير طور الأهتزاز مع اختلاف معامل الحمولة الديناميكية لأقصى ازاحة واكبرقوة قص في القاعدة كان التأثير غير مهم عندما يكون ارتفاع البناية اكبرمن 175م.

كانت نتائج تأثير مناطق التعرض الثلاث B و C و D مع اختلاف معامل الحمولة الديناميكية لأقصى ازاحة واكبرقوة قص في القاعدة تأثيرها غير مهم.

اخيرا كان تأثير اختلاف نسبة الطول الى العرض بالنسبة للبناية مع اختلاف معامل الحمولة الديناميكية لأقصى ازاحة واكبرقوة قص في القاعدة عندما تكون λ مساوية الى 2 وذلك بسبب معامل الحمولة الديناميكية يزداد عند اقتراب تردد الرياح من أحد ترددات البناية.

الكلمات الرئيسة: معامل الحمولة الديناميكية ، التردد ، التضاريس.

1. INTRODUCTION

To study the effect of mean wind velocity for high-rise buildings, different parameters have been studied in this study:

1.1 Time Function of Gust Front Winds:

A half-sine wave could be used to describe time-varying feature of windstorms. Even though it may not represent the exact time variation of winds in a typical gust-front, it captures the underlying feature potentially responsible for enhanced loads. At a future time, this description may be revised once a sufficient number of measurements become available and an acceptable description of this function is arrived at based on an ensemble average of such observations. The function is defined as, **Kwon, and Kareem, 2013**.

$$\bar{x}_{G-F}(t) = \bar{x}_o \sin(\frac{\pi}{t_d} t) \qquad (1)$$

where t_d, is pulse duration of the excitation. The simplicity of above expression is an attractive feature, as it requires only a single parameter t_d in addition to $\bar{x}_o$,**Kwon, and Kareem, 2013**.

1.2 Wind Profile:

Every building site has its own unique characteristics in terms of surface roughness and length of upwind terrain associated with the roughness. Simplified code methods cannot account for the uniqueness of the site. Therefore, the code approach is to assign broad exposure categories for design purposes**, Taranath, 2005**.

Similar to the ASCE method, the UBC distinguishes between three exposure categories; B, C, and D. Exposure B is the least severe, representing urban, suburban, wooded, and other terrain with numerous closely spaced surface irregularities; Exposure C is for flat and generally open terrain with scattered obstructions; and the most severe, Exposure D, is for unobstructed coastal areas directly exposed to large bodies of water**, Taranath, 2005**.

Each exposure differs from another exposure in the thickness of boundary layer and power law. Exposure B is depicted with power law $\alpha = 0.14$ with thickness of boundary layer 366m. On the other hand, exposure C is depicted with power law $\alpha = 0.11$ with thickness of boundary layer 274.5m. Finally, exposure D is depicted with a power law $\alpha = 0.09$ with thickness of boundary layer 213.5m**, Taranath, 2005**. Equations below depicted mean wind velocity within the atmospheric boundary layer:

$$\bar{x}(z) = \bar{x}(z_{ref}) \left(\frac{z}{z_{ref}}\right)^{\alpha} \qquad (2)$$

$\bar{x}(z)$ is the mean wind speed at height z above the ground, z_{ref} is the reference height, and α is the power law exponent, depending on the type of the exposure**,Balendra,1993**.

1.3 Wind Pressure:

For calculating the wind pressure, Eq. (3) that is prepared for wind force, should be adjusted by dividing by **B**:

$$F_D = \frac{1}{2}\rho C_D B\left[\bar{x}(z)\right]^2 \quad (3)$$

$$p_D = \frac{1}{2}\rho C_D\left[\bar{x}(z)\right]^2 \quad (4)$$

where p_D is the drag pressure in **Pa**, ρ is the density of air (1.2 kg/m^3), C_D is the drag coefficient, and $[\bar{x}(z)]^2$ is the square of mean wind velocity in m/sec, which, is within the atmospheric boundary layer is described by power law in Eq.(2).

By substitute Eq. (2) into Eq. (4), the drag pressure will be:

$$p_D = \frac{1}{2}\rho C_D\left[\bar{x}(z_{ref})\right]^2\left[\left(\frac{Z}{Z_{ref}}\right)^{\alpha}\right]^2 \quad (5)$$

1.4 Drag Coefficient:

For rectangular buildings, the drag coefficients depend strongly upon aspect ratio λ, which equal to **D/B**,

$$\lambda = \frac{plan\ dimension\ along\ wind\ direction\ \text{“}D\text{”}}{plan\ dimension\ across\ wind\ direction\ \text{“}B\text{”}} \quad (6)$$

See **Table.1, Simiu, and Robert, 1996.**

1.5 Response Spectrum for Wind Load:

Based on above discussions, it is clear that wind drag force and wind drag pressure will be in a quadratic proportional relation with wind velocity, which in turn is a sinusoidal function. Then wind pressure and wind force will be a sinusoidal function with second power order.

Dynamic load factor (DLF) for single degree of freedom systems when subjected to above second power sinusoidal function has been determined numerically based on Matlab routine. Results have been depicted graphically in **Fig.1**.

2.SAP MODELLING:

2.1 Frame Element

Frame element has been used in model of building beams and columns. The frame element is a very powerful element that can be used to model beams, columns, braces, and trusses in planar and three-dimensional structures. A Frame element is modeled as a straight line connecting two points. Each element has its own local coordinate system for defining section properties and loads, and for interpreting output.

Each Frame element may be loaded by gravity (in any direction), multiple loads (concentrated, distributed, strain deformations etc.). Element internal forces are produced at the ends of each element and at a user specified number of equally spaced output stations along the length of the element**, CSI, 2009**.

2.2 Shell Elements:

SAP shell element that could accommodate arbitrary geometry, and which could interact with edge beams and supports, has been used in slab modelling for floors and roofs**,Wilson,2002**.

2.3 Mass Modelling

In SAP, mass and weight serve different functions. Mass is used for the inertia in dynamic analyses, and for calculating the built-in acceleration loads. Weight is a load that one defines and assign to one or more members, and could then be applied to one or more load cases.

SAP offers three different methods, shown in the interactive box below, to generate mass matrix see **Fig**.**2**:

The two approaches in **Fig.2** could be combined together with **From Element and Additional Masses and Loads** option,

In this work, the applied load that consists of dead and live loads have been applied through **From Loads option**.

2.4 SAP Wind Idealization:

2.4.1 Spatial modeling of wind load:

With SAP, the following steps could be followed to define spatial variation in drag wind pressure:

- Create an area with "None" properties (SAP offers such types of area object to be used in cladding modeling).
- Assign uniform pressure to the created area with a magnitude, which depends on story level (calculated from wind profile).

2.4.2 Temporal modelling of wind load:

With SAP, time function is used to define temporal variation in wind pressure.

2.4.3 Load case definition:

Finally, temporal and spatial time variation are merged together through load case definition.

This procedure is called the mode superposition method, or more precisely the mode displacement superposition method**, Clough, and Penzien, 2003**.

3. CASE STUDY:

Structural system for all case studies of this chapter has been assumed as Bundled Tube system, as this system is the most suitable one for considered height range.

Within case studies of these sections, dynamic load factor for mean wind pressure has been determined for different: (Heights, Modes, Roughness, Aspect Ratio, and Gust.

In all case studies, following data have been used, see **Table.2**:

- Building self-weight has been computed automatically by the SAP
- Mean wind speed has been assumed to be 45 m/sec with a sinusoidal time history.
- Slab thickness for floors, roofs, and shear walls has been assumed 0.2m.
- Damping ratio has been assumed 0.03 for all modes**, Arkawa, and Yamamoto, 2004**.

3.1 Height Versus Dynamic Load Factor:

Five buildings with different heights of 60, 120, 180, 240, and 300 m have been considered. For all buildings, plan dimensions have been assumed 63m by 63m.

Exposure B and wind gust time duration of 5 sec have been assumed with all heights with drag coefficient 1.18.

Results for above different heights have been presented, summarized, and discussed in sub-sections below:

For example, one hundred story (300m height) has been presented:

3.1.1 One hundred story high building:

SAP rendering view for the building has been shown in **Fig**.**3**:

Time history for tip displacement and building base shear are shown in **Fig**.**4** and **5**.

3.1.2 Summary of results for different heights:

Variation of tip displacement and building base shear with building height have been summarized in **Table.3**, **Fig**.**6**, and **7**:

From **Table.3** and **Fig**.**6** and **Fig**.**7**, maximum DLF occurs in height range from (100-150)m. Comparing between wind response spectrum that discussed in section 1.5 (reproduce here for convince), one can conclude that within this height range, fundamental building frequency is so close as to dominate wind frequency.

3.2 Modes Versus Dynamic Load Factor:

This section aims to discuss the effect of higher modes on accuracy of estimating DLF under mean wind pressure.

- Dynamic responses for five buildings with different heights (60, 120, 180, 240, and 300 m) have been estimated based on and including (first mode only, first and second mode, and lower 12 modes.

For all buildings, plan dimensions have been assumed 63m by 63m with drag coefficient 1.18 and with gust time 5sec.

Results for tip displacement and building base shear with different modes are summarized in the **Fig**.**8** and **Fig**.**9** below. From these Figures, one can conclude that for buildings that have plan similar to considered in this study, effects of higher modes become insignificant for building height greater than 175m. While for lower heights, at least lowest two modes, they should be considered in building dynamic response.

3.3 Roughness Versus Dynamic Load Factor:

Effects of terrain exposure on DLF have been considered in this section. Wind pressures that are derived based on three different exposures (B, C, and D) have been subjected on buildings with different heights (60, 120, 180, 240 and 300 m). All buildings considered in this section have plan dimensions of 63m by 63m with drag coefficient 1.18 and with gust time 5sec.

Results for DLF for tips displacement and DLF for building base shear versus height for the three terrain exposures have been summarized in **Fig**.**10** and 11. From these Figures, one can conclude that for buildings that are considered in this section, terrain exposure has insignificant effect on response of tip displacement and building base shear.

3.4 Aspect Ratios Versus Dynamic Load Factor:

Effect of aspect ratio for building plan on DLF for tip displacement and building base shear are considered in this section. Aspect ratio in this section is defined as Eq. (6)

Four different "D" values (20, 40, 100, and 200) with constant "B" value of 20m have been considered. These lead to four different aspect ratios "$\boldsymbol{\lambda}$" of 1, 2, 5, and 10. For each aspect ratio, corresponding drag coefficient "CD" has been determined based available wind tunnel data**, Simiu, and Robert, 1996.**

Exposure B, wind gust duration of 5 sec, and building height 150m have been assumed with all case studies of this section.

Results of DLF for tips displacement and DLF for building base shear versus aspect ratio are summarized in **Table 4, Fig.12, and 13**. Tables and Figures, show that maximum DLF tip displacement occurs when $\boldsymbol{\lambda}$ approaches 2. Comparing between wind response spectrums discussed in section 1.5, one can conclude that within this λ range, fundamental building frequency is so close to dominate wind frequency.

4. CONCLUSIONS:

- Based on modeling of building beams and columns as frame elements, and modeling of floors, roofs and shear walls as shell elements, and modeling of wind gust as a sinusoidal function, following results and conclusions have been obtained:
- For different building heights considered in this study, it has been noted that the maximum dynamic load factor (DLF) occurs in height range from 100-150m. Within this height range, fundamental building frequency is so close as to dominate wind frequency.
- In an attempt to determine effects of higher modes on dynamic response of tall buildings, different numbers of mode shapes have been included in this study. From tip displacement and base shear results, it has been noted that for buildings, that have a plan similar to that considered in this study, effects of higher modes become insignificant for height greater than 175m. While for lower heights, at least lowest two modes they should be considered in building dynamic response.
- Effects of three different terrain exposures B, C, and D on DLF for tips displacement and DLF for building base shear have been considered. Based on obtained results, it has found that terrain exposure has insignificant effect on response of tip displacement and building base shear.
- Dynamic load factor (DLF) for tips displacement and for building base shear have been determined for different aspect ratios of building plan. Based on obtained results, it is noted that maximum DLF occurs when λ approaching 2, where within this λ range, fundamental building frequency is so closed to dominate wind frequency.

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NOMENCLATURE

A= cross sectional area, m2
B= plan dimension across wind direction, m
C_D= drag Coefficient, unit less
D=plan dimension along wind direction, m
DLF =dynamic load factor $\frac{x_{max}(t_d)}{x_{Static}}$
$\boldsymbol{F_D}$ =drag Force
$\boldsymbol{p_d}$ =drag pressure in Pa
$\boldsymbol{t_d}$ =pulse duration
$\boldsymbol{T}$ period of motion
$\bar{\dot{x}}(z)$ =velocity in time domain, m/sec
$\bar{\dot{x}}(z)$ =mean wind speed, m/sec
$\bar{\dot{x}}(z_{ref})$ =mean wind speed depending on building site, m/sec
$\bar{\dot{x}}_{G-F}(t)$ =mean wind speed on gust front, m/sec
$\boldsymbol{z}$ =height above the ground, m
$\boldsymbol{z_o}$ =roughness length, m
$\boldsymbol{z_{max.}}$ =height where $\bar{V}_{max.}$occurs , m
$\boldsymbol{Z_{ref}}$ =gradient height (thickness of boundary layer) , m
$\boldsymbol{\alpha}$ =power law
$\boldsymbol{\rho}$ =air density
$\boldsymbol{\lambda}$ =aspect ratio D/B, unit less
$\emptyset_n$ =the nth mode shape
$\boldsymbol{\phi}$ =modal Matrix

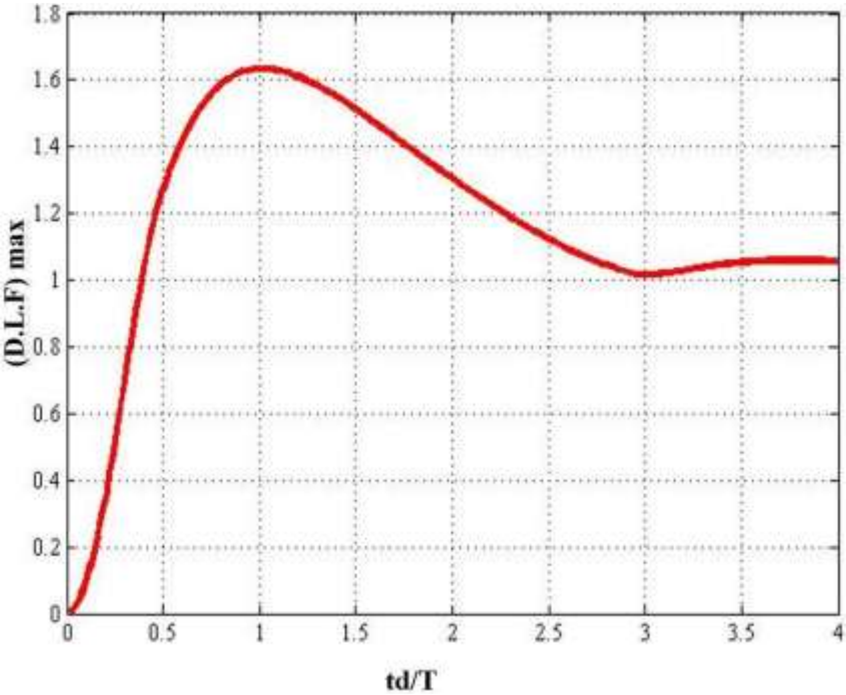

Figure 1. Response spectrum for square of-sinusoidal pressure of duration td

where $\mathbf{t_d}$, is pulse duration of the excitation, **T** is the period of motion, $\boldsymbol{T} = 2\pi\sqrt{\frac{m}{k}}$, $\mathbf{D.L.F} = \frac{x_{max}(t_d)}{x_{Static}}$.

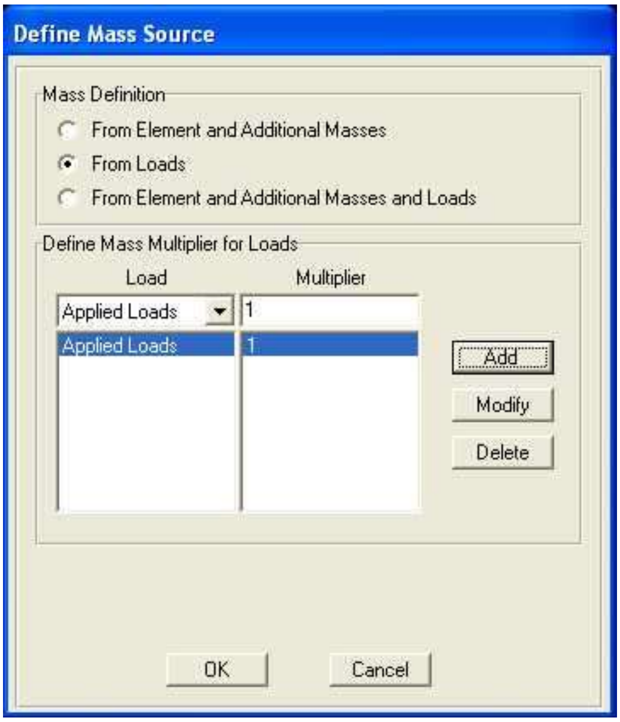

Figure 2. SAP Interactive box for mass definition.

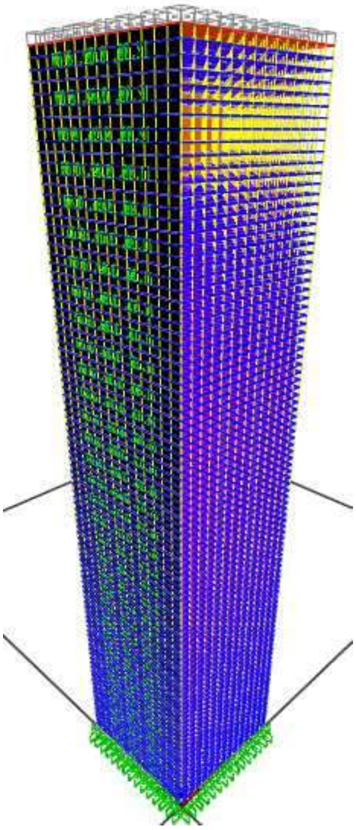

Figure 3. Isometric for 100 stories building.

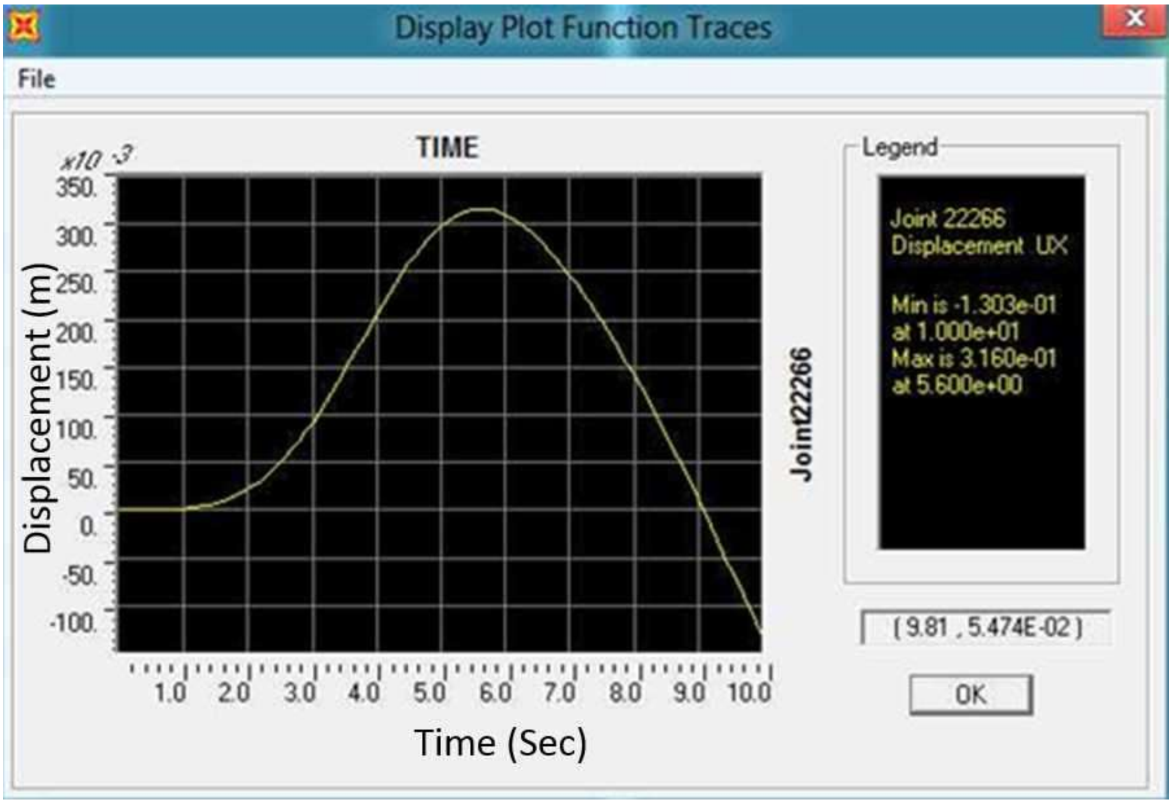

Figure 4. Tip displacement on **10**0 stories.

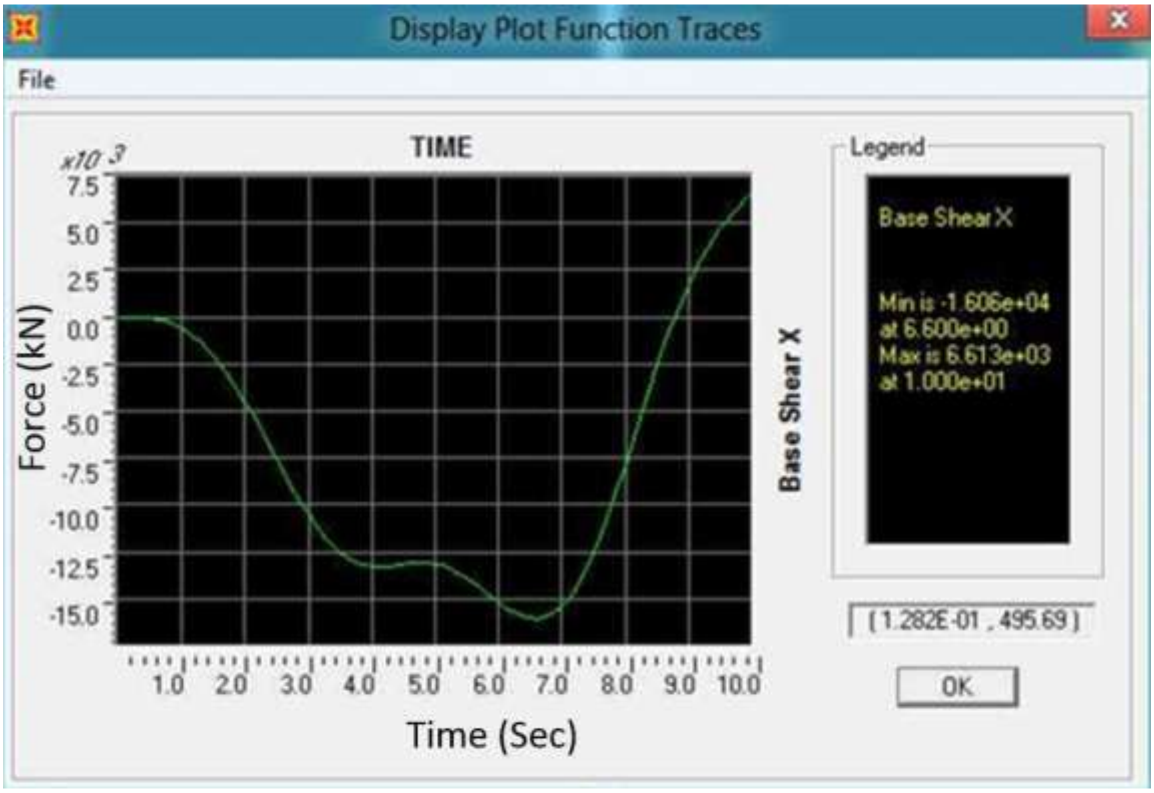

Figure 5. Building base shear at X-coordinate on **100** stories.

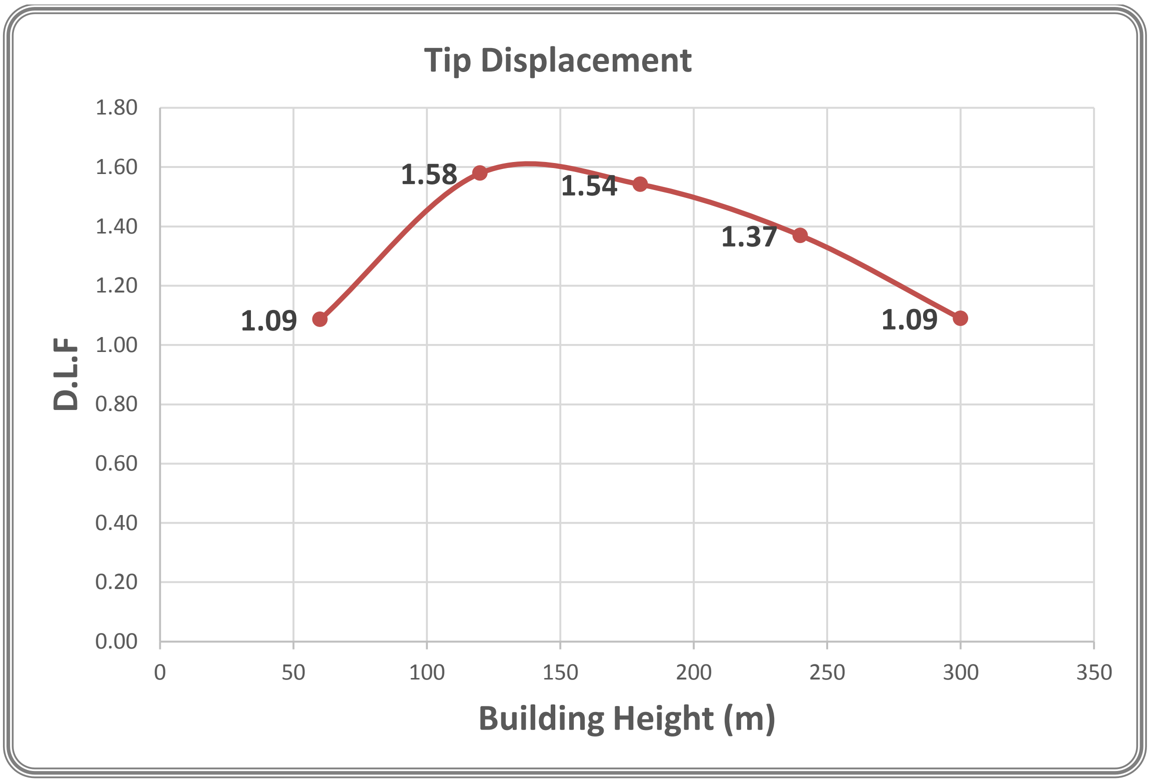

Figure 6. Height versus dynamic load factor for tip displacement.

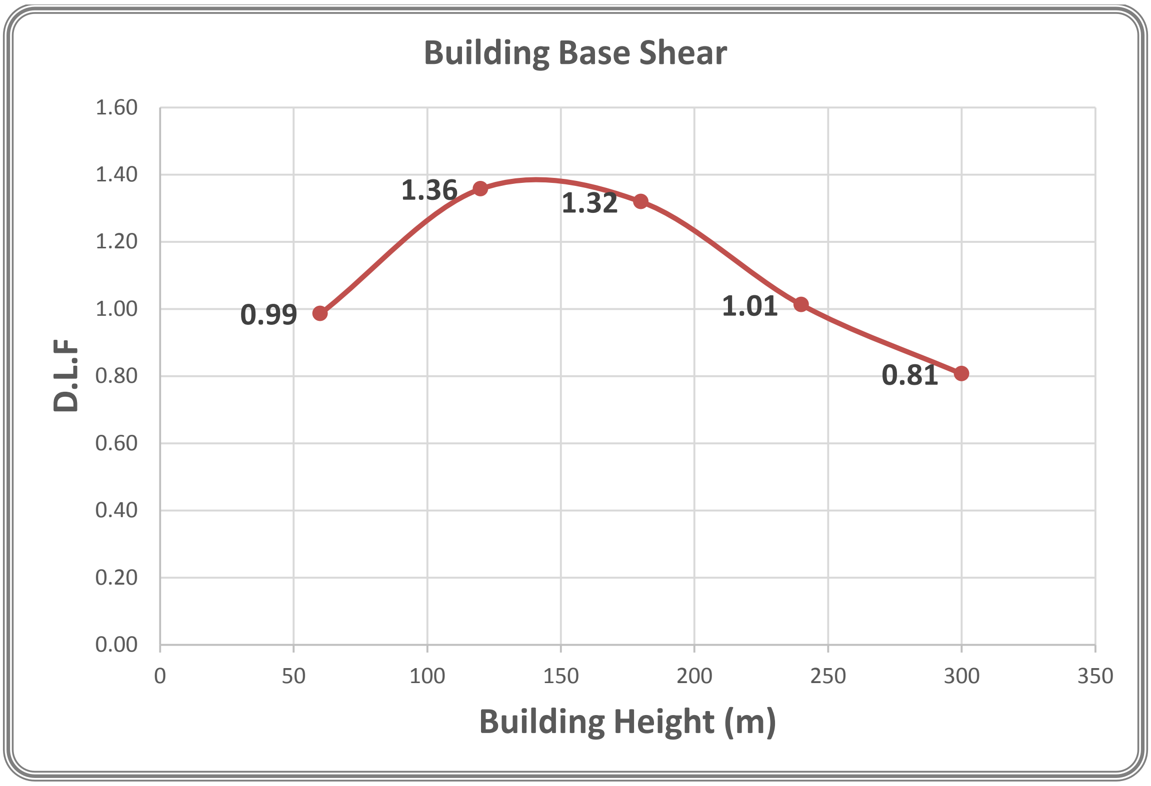

Figure 7. Height versus dynamic load factor for building base shear.

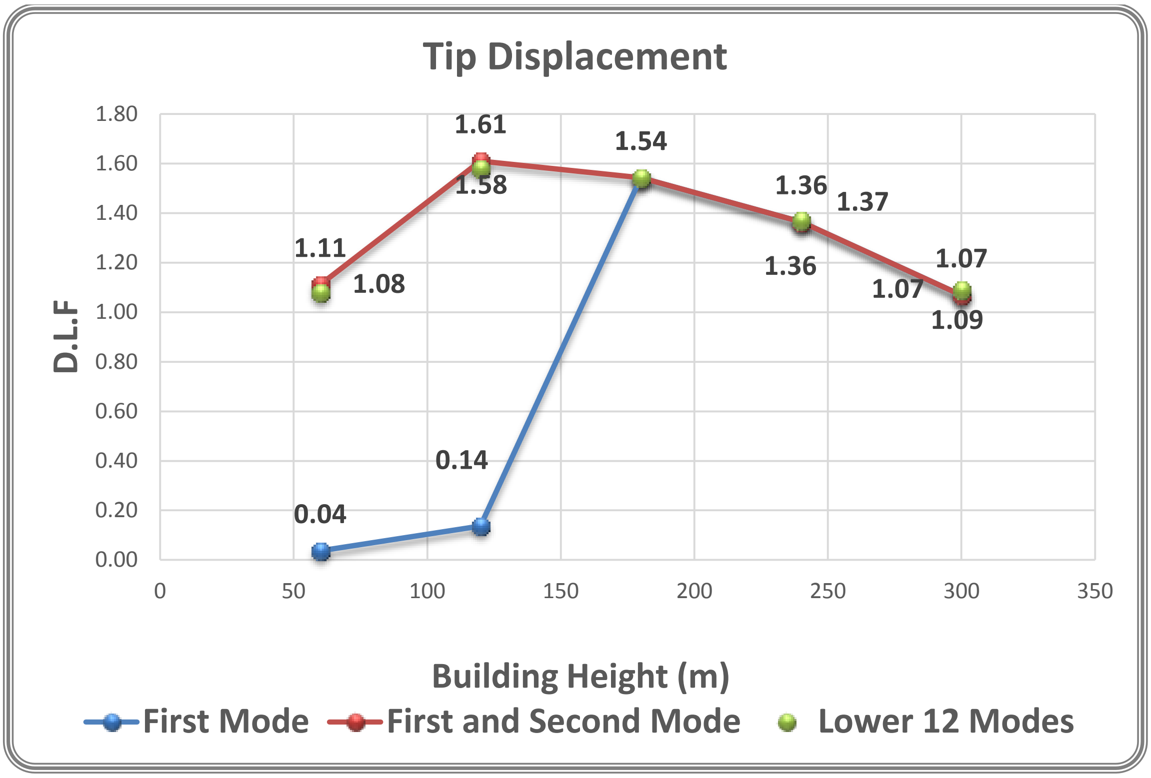

Figure 8. Modes versus dynamic load factor for tip displacement.

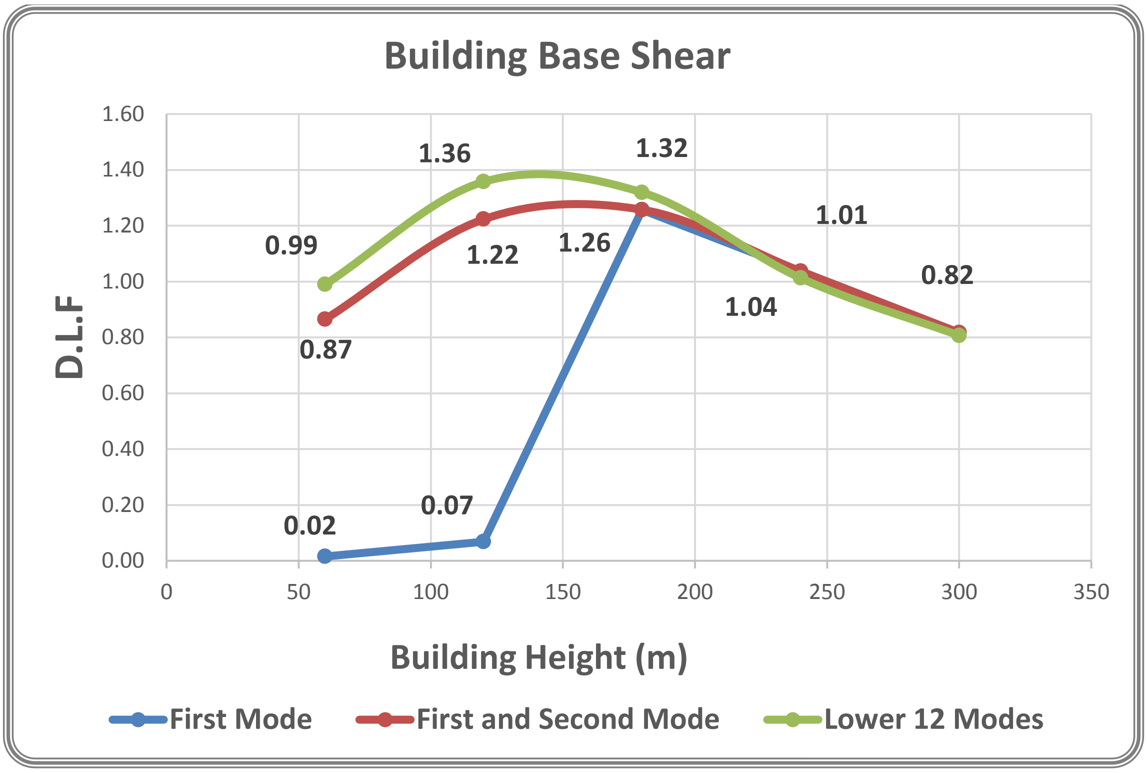

Figure 9. Modes versus dynamic load factor for building base shear.

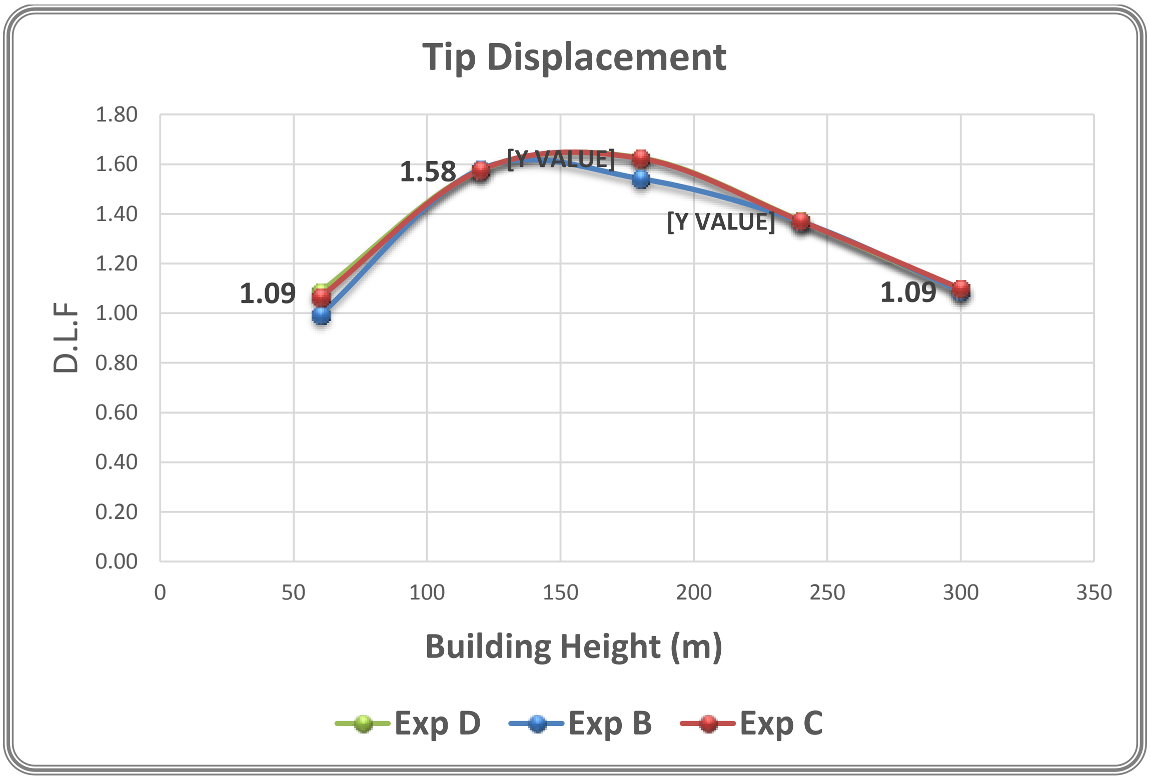

Figure 10. Roughness versus dynamic load factor for tip displacement.

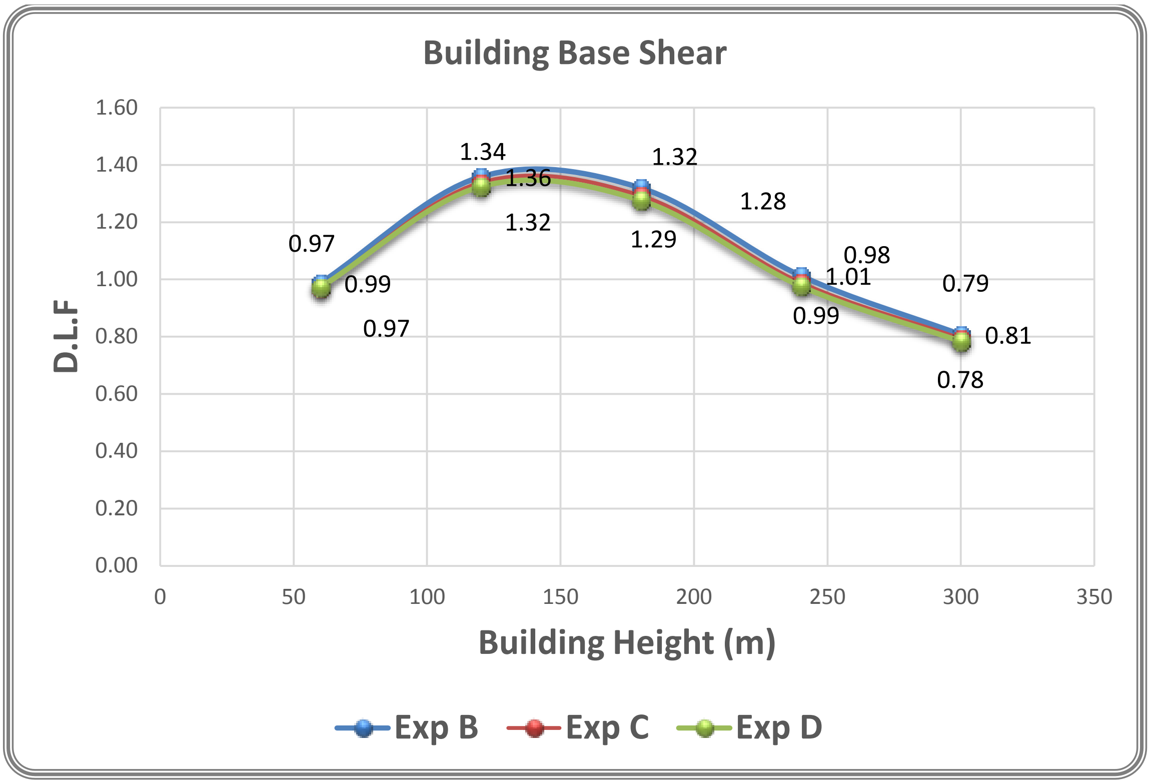

Figure 11. Roughness versus dynamic load factor for building base shear.

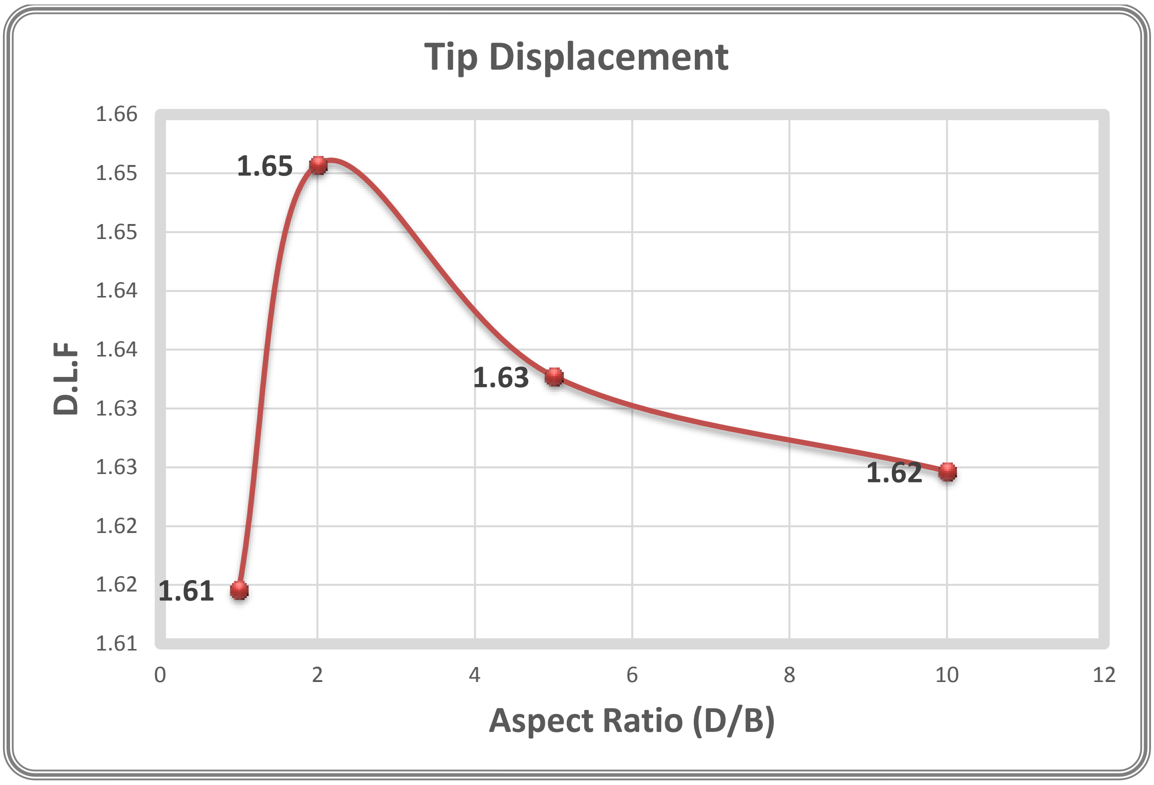

Figure12. Aspect ratios versus dynamic load factor for tip displacement.

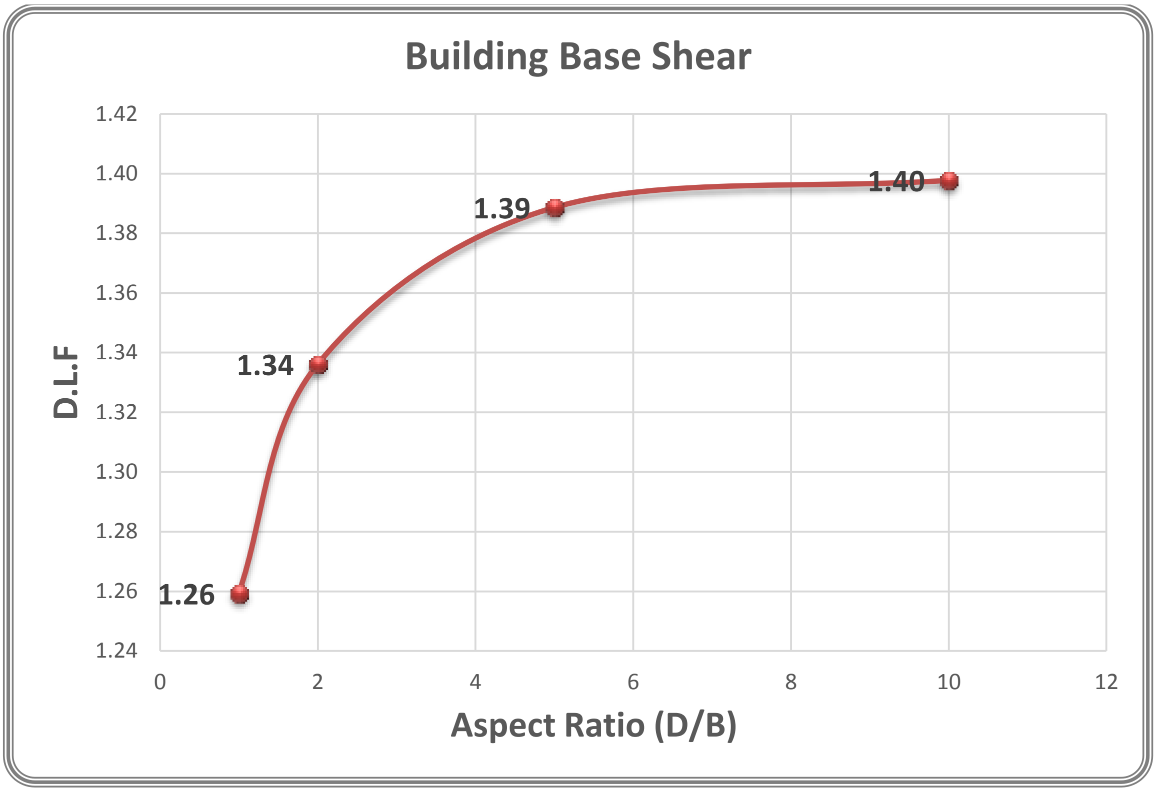

Figure 13. Aspect ratios versus Dynamic load factor for building base shear.

Table 1. Drag coefficients for a rectangular plate normal to smooth flow.

	Rectangular Plate in Normal Wind				Rectangular Plate on Ground Standing on Long Side					
Aspect Ratio	1.0	2.0	5.0	10.0	20.0	40.0	∞	1.0	10.0	∞
C_D	1.18	1.19	1.20	1.23	1.48	1.66	1.98	1.10	1.20	1.20

Table 2. Specifications of structural buildings with loads and cross sections.

Structure	Loads				
	Dead kN/m^2	Live kN/m^2	Line kN/m	Span	Cross Section
Beams	2.5	3.0	-	4.5	0.4 × 0.6
Columns	4.0	1.5	-	3.0	0.5 × 0.5
Portions	-	-	1.5	-	-

Table 3. Different heights with tip displacements and base shear

Building Ht. (m)	Fund. Time Period (sec.)	Static Load		Dynamic Load		DLF	
		Tip Disp. (m)	Building Base Shear (kN)	Tip Disp. (m)	Building Base Shear (kN)	Tip Disp. (m)	Building Base Shear (kN)
60	0.46	0.0201	2419.2	0.022	2386.0	1.09	0.99
120	0.65	0.0165	6066.9	0.026	8237.0	1.58	1.36
180	0.83	0.060	10376.1	0.092	13690.0	1.54	1.32
240	0.98	0.140	15157.8	0.191	15350.0	1.37	1.01
300	1.19	0.290	19901.7	0.316	16060.0	1.09	0.81

Table 4 Aspect ratios versus dynamic load factor on displacement and building base shear.

Aspect Ratio λ	Drag Coefficient C_D	Static Load		Dynamic Load		DLF	
		Tip Disp. (m)	Building Base Shear (kN)	Tip Disp. (m)	Building Base Shear (kN)	Tip Disp. (m)	Building Base Shear (kN)
1	1.18	0.1754	2604	0.2832	3279	1.61	1.26
2	1.19	0.069	2538	0.1139	3391	1.65	1.34
5	1.20	0.0281	2640	0.0458	3666	1.63	1.39
10	1.23	0.0146	2718	0.0237	3799	1.62	1.40