DESIGN OF FLEXIBLE HIGH RISE STRUCTURE TO CATER TO HUMAN COMFORT CRITERIA AND STRUCTURAL STABILITY

By

MOHAMAD NAZRIN B ZAINALABIDIN

FINAL PROJECT REPORT

Submitted to the Civil Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Civil Engineering)

Universiti Teknologi Petronas
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

DESIGN OF FLEXIBLE HIGH RISE STRUCTURE TO CATER TO HUMAN COMFORT CRITERIA AND STRUCTURAL STABILITY

by

Mohamad Nazrin B Zainalabidin

A project dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Civil Engineering)

Approved:

AP IR Dr Shahir Liew
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

June 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohamad Nazrin B Zainalabidin

ABSTRACT

This project is carried out to design flexible high rise building to cater to human comfort and structural stability. The wind force can result in the vibration of the building in which can induce the discomfortness to the occupants if the motion experience exceeds the perception level. This project is carried out to analyze and design high structure in Malaysia that meets the human comfort criteria. This project will require knowledge of wind force and human perception threshold levels. Acceleration of the wind is taken as the parameter to evaluate the human perception level. The design and analysis are based on ASCE 7-05.Two models of high structures in Malaysia have been chosen and analysis has been carried out on the subjects.

ACKNOWLEDGEMENTS

I would like to thank everyone who has been involved directly or indirectly that contribute to the completion of this project:

First and foremost, I am thankful to Allah the most gracious, for blessing me with the knowledge and patience that has been crucial towards the completion of this project.

Secondly, I would like to thank AP IR Dr Shahir Liew, for the help and guidance throughout my Final Year Project. Without his contribution, I would not be able to finish this project successfully.

Special thanks to all my friends especially Johann Khuzaimi Kalana and Ruzaidi Ab Aziz for their tremendous support during the difficult time of completing the project.

Finally, this project is dedicated to my parents, Mr Zainalabidin Sarbani and Mdm Suhidah Paidar for their undivided love and encouragement throughout my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

RMS	Root Mean Square
ASCE	American Society of Civil Engineers
BLWTL	Boundary Layer Wind Tunnel Laboratory

CHAPTER 1
INTRODUCTION

1.1 Background Study

This project is carried out to design a flexible high rise building to cater to human comfort and structural stability. This project focuses more on the design and analysis of the high rise building in Malaysia which is taking in to consideration the effect of wind. Dynamic wind pressure imposed force which can induce wide range of response to the occupant, ranging from anxiety to acute nausea. Motion resulting from the wind can vary greatly in duration and intensity, thus affecting the physiological and psychological state of the occupant in which will result in undesirable condition of the building.

In this study, acceleration has been taken as the parameter to evaluate the human threshold perception as the basis for human comfort in high rise building. Basically, building that has the height greater than 10 stories are very responsive to the wind load. Moreover, the advancement of architectural technology, structural innovations and lightweight construction nowadays have led to the design of light and flexible modern building which is more prone to the wind motion. In building that is experiencing motion, the objects may vibrate and if the building has a twisting action, its occupant may get an illusory sense that the world outside is moving, creating the symptoms of vertigo and disorientation. The resulting dynamic stress may induce motion that may disturb the comfortness of the building occupant.

However there are no specific international standards for comfort criteria. Nevertheless there are parameters which are considered influential to determine human response to vibration:

- Period
- Amplitude

- Body orientation
- Visual
- Acoustic cues

1.2 Problem Statement

Human comfort engineering, specifically on the wind effect is not a common practice in the design of the high rise building in Malaysia. The wind force can result in the vibration of the building in which can induce the discomfortness to the occupants if the motion experience exceeds the perception level. The art of designing high rise building in the windy climate is not only to ensure the structure can withstand the wind force steadily, but as well to keep the motion of the building within the comfortable limit in which is more challenging than meeting the strength requirements of the building itself. The designer must ensure there are no undesirable motions that could adversely affect the occupants. However, no international standard has been achieved on the comfort criteria itself.

1.3 Objectives and Scope of Study

It would be prohibitively expensive to construct a building that would not move perceptly in the worst storm. Consequently, since some motions are inevitable, the goal is to determine levels of motion and rates of occurrence that is acceptable to the building occupants. Therefore the objectives and scopes of the study are:

- To understand and analyze the wind effect on the high rise structures in Malaysia
- To determine the effects of wind loading with regard to human comfort criteria
- To study the parameters that is being used in evaluating human comfort
- To establish and determine the human comfort level in high rise building in Malaysia

CHAPTER 2
LITERATURE REVIEW

The rapid growth of tall building and towers has fascinated mankind nowadays. High structures and towers has been the symbol of power and economic stability for many countries and it is certainly has put the nation on the map of the world. Response to demand of high population of people in big city has lead to the construction of high structures for residence. From the engineering perspective, Bryan and Alex [1] state that, tall building can be defined as one that, because of its height, is affected by lateral forces due to wind or earthquake actions to an extent that they play an important role in structural design.

Human comfort influenced in the design of high rise building has been taken seriously nowadays. The use of high strength material and advanced structural system has produced lighter system and has been widely used in the building of high rise in which has increased the sensitivity of building towards the effect of wind. Bryan and Alex [1] in his book mentioned that although there are yet no universally standard for comfort criteria, it is generally agreed that acceleration is the predominant parameter in determining human response to vibration, but other factor such as period, amplitude, body disorientation, visual, acoustica cues and even past experience can be influential too.

There are two types of acceleration that is normally being used to evaluate perception level namely, the peak value and RMS (root-mean-square) value. Scholars have been debating on which value is giving the most accurate result. Some scholars believe that degree to which a person objects to a certain magnitude of vibration will be evaluated by its average effect over a period of time while the other school of thought reasoned that, a person is affected at most on the peak of acceleration and tend to forget the lesser one. Nevertheless majority of the research on motion perception thresholds has been presented in terms of RMS.

Boggs. D [2] in his study, RMS acceleration is practical to be used in evaluating human threshold perception level. This is because, the RMS value is much simpler to evaluate, and more likely to result in consistency and uniformity among various agencies engaged in predicting vibration in a proposed building, or in evaluating the vibration in an existing building.

The study on human comfort level has begun in the early 1970's. Hansen et al [3] were the first to give subjective reason that high rise has low frequency motion. After a wind storm they perform a study on two buildings and have deduced that 2% of population could perceive motion. This is in combination of calculated top floor acceleration of two building, led to the proposal to limit the 6 year RMS acceleration to 0.005g (0.049 m/s^2). Irwin [4] on one hand has calibrated his motion perception threshold (maintaining the frequency dependence) with Hansen et al's. A slight adjustment was made to use the 5 years interval instead of 6 years recurrences interval. However, both [4,5] have agreed that perception threshold level is the best criteria to evaluate human comfort.

On the other hand, based on ISO2631-2 [5] complaints regarding building vibrations in residential situations are likely to arise from occupants of building when the vibration magnitudes are slightly in excess of perception level. Although there are two different measurements on the human response, it is agreed that, vibrations is one of the main factor that influenced the human comfort in the building.

Bryan and Alex [1] also discovered that, if tall flexible structure is subjected to lateral or torsional deflections of the wind loads, the resulting oscillating motion can induce response of discomfort to the occupant which resulting to the undesirable building. The study conducted by Denoon et al [6] which state that effects of motion on cognitive performance envisaged that if wind-induced building motion in an office environment impacts on cognitive performance, it results in a loss of productivity to the tenant with consequent financial implications. Similarly, cognitive performance deterioration in air traffic controllers during strong winds, which are some of the most stressful work times, could lead to a greater chance of errors being made. The study has been supported by K.C. S Kwok et al [7] in his report which has mentioned that, prolonged exposure to vibration in wind sensitive building can cause discomfort, affect task concentration, nausea and migraine. According to Bryan and Alex the perception of building movements depends largely on the degree of stimulation of the body's central nervous system, the sensitive balance sensor within the inner ears playing a crucial role in allowing both linear and angular acceleration to be sensed.

Irwin [8] in his article mentioned that keeping the motions of the tower within comfortable limit is often a biggest challenge than meeting structural strength requirements. Bryan and Alex in their study discovered that wind loading becomes significant for building over 10 stories high and progressively more with increasing height.

It would be really expensive to build a building that would not move perceptively in the worst storm or a severe earthquake. Consequently, since some motions are inevitable, the goal is to determine levels of motion and rates of occurrence that are both economic and acceptable to the building occupants.

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification

This methodology section will briefly show the pre-determined track of accomplishing the project. The project will be carried out for two semesters. The projects flows are as the flow chart below. The first three blocks are done in the first part of the project which is in the FYP 1.

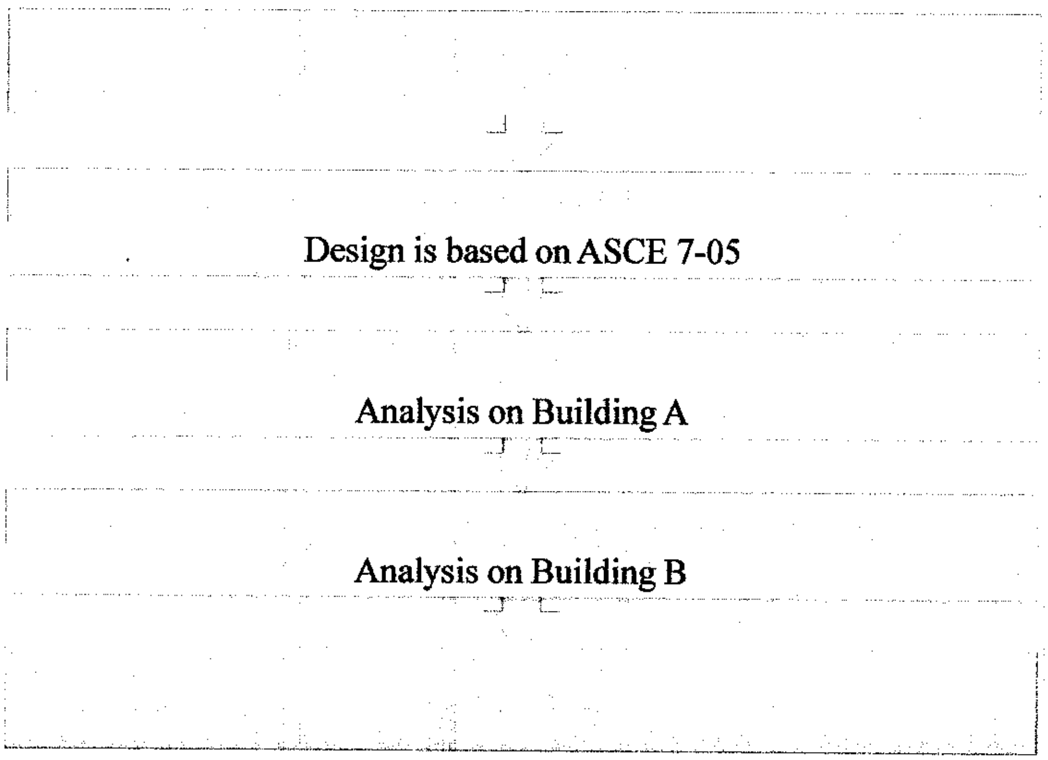


Figure 1 Work Flow Chart

3.2 Research and Literature Review

The main approach of the project is to analyze the design of the high rise building focusing on the wind factor with the effect to the human comfort and later to come out with the proper design taking into account the subject mentioned. The author has been doing research on the relevant journals and books that might be beneficial to the project. Among the journals and the books that have been selected are as the followings:

- Tall building structures: analysis and design, Bryann Stafford Smith and Alex Coull (1991)
- Acceleration indexes for human comfort in tall building, Daryll Boggs (1995)
- Human response to wind induced motion of building, Hansen, Robert J., Reed, John W., and Vanmarcke, Erik H. (1973)
- Human Response to Dynamic Motion of Structures, Irwin, A.W. (1978)
- ISO 2631-2; Evaluation of human exposure to whole body vibration (1989)
- Perception of vibration and occupant comfort in wind-excited tall buildings, K.C.S Kwok, Peter A. Hitchcock, Melissa. D. Burton (2009)
- Effects of wind induced tall building motion on cognitive performance, Roy. O. Denoon, Richards. D. Roberts, Christopher. W. Letchford, K.C.S Kwok (2000)
- Wind Engineering Challenges of the new Generation of super tall buildings, Peter A. Irwin (2009)
- Four Tall buildings in Madrid; Study of Wind Induced response in Serviceability Limit State, Peter Paul Hoogendoorn, Ramon Alvarez
- ASCE 70-5
- IS0 6987:1998

From the reading, the author found out that, there is few calculations approach that can be applied in the project such as:

- Simple static approach
- Dynamic methods
- Detailed analytical method
- Wind tunnel method

In the design stages, the probable motion of a planned structure can be predicted from a dynamic analysis. The predicted values should be verified by measured motions of the built structure so that possible problems in service may be foreseen.

The predicted accelerations and periods of vibration may then be compared with threshold curves to ascertain whether any problems are likely to be encountered. To obtain the recommended upper limit for human comfort, the acceleration is then compared with ISO 6897.

In the early design stage, the author has been using analytical procedure. Two types of buildings are being considered due to its occupancy rates. Building A is a condominium while building B is a hotel.

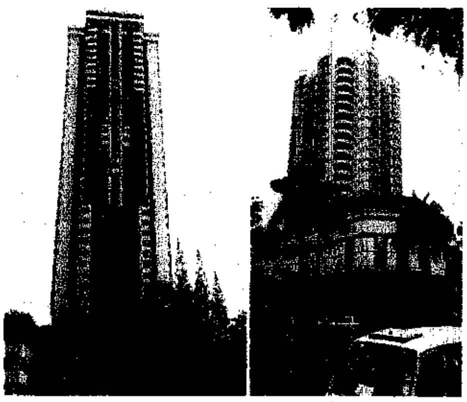


Figure 2 Building A and Building B

3.3 Design Procedures

The design procedures are based on ASCE 7-05 [9][refer appendix A] for wind loads and all information and design procedure shall be referred back to the mentioned manual.

1. The *basic wind speed* **V** and *wind directionality* **K_d**, factor shall be determined in accordance with section 6.5.4
2. An *importance factor* **I** shall be determined in accordance with section 6.5.5
3. An *exposure category* or *exposure categories* and *velocity pressure exposure* coefficient **K_z** or **K_h**, as applicable, shall be determined for each wind direction in accordance with section 6.5.6
4. A *topographic factor* **K_{zt}** shall be determined in accordance with section 6.5.7.
   section 6.5.8
5. A *gust factor* **G** or **G_f**, as applicable, shall be determined in accordance with section 6.5.8
6. An *enclosure classification* shall be determined in accordance with section 6.5.9.
7. *Internal pressure* **GC_{pi}** shall be determined in accordance with section 6.5.11.1.
8. *External pressure* coefficients **C_p** or **GC_{pf}**, or *force coefficient* **C_f**, as applicable, shall be determined in accordance with section 6.5.11.2 or 6.5.11.3 respectively
9. *Velocity pressure* **q_z** or **q_h** as applicable shall be determined in accordance with section 6.5.10
10. *Design wind load* **p** of **F** shall be determined in accordance with section 6.5.12,6.5.13, 6.5.14, and 6.5.15 as applicable.

3.4 Use of Comfort Criteria in Design

Deflection shall be determined from the value obtained from **3.3**

Along wind acceleration is to be determined by using the following formula:

$$a_D = 4\pi^2 n_o^2 g_p r \sqrt{R} \left(\frac{\Delta}{G}\right) \qquad [1]$$

Cross wind acceleration is to be determined by using the following formula

$$a_w = n_o^2 g_p [WD]^{½} \frac{ar}{\rho g \sqrt{\beta}} \qquad [1]$$

where

ρ =average density of the building (kg/m^3)

$A_r = 78.5 \times 10^{-3} [\, V_H / n_o \sqrt{WD}]^{3.3}$ Pa

g = acceleration due to gravity (m/sec^2)

The predicted acceleration may then be compared with the threshold table [figure to ascertain whether any problems are likely to be encountered

CHAPTER 4
RESULT AND CALCULATION

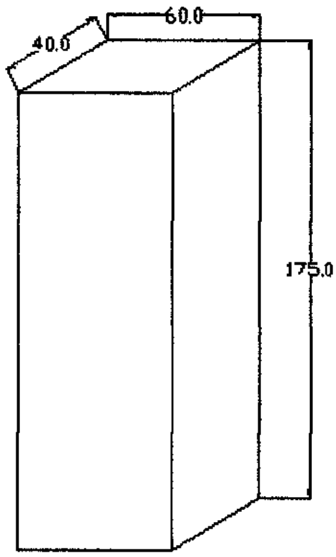


Figure 3 Dimension of Building A

4.1 Analytical Procedure for Building A

Location: Kuala Lumpur

Wind Speed: 33 m/s

$qz = 0.613 * Kz*Kzt*Kd*V^2*I$

Kd (refer appendix B) = 0.85

I (refer appendix C) = 1.15 (category III)

Kzt = 1

Velocity Pressure Kz: (refer appendix D)

Table 1 Velocity Pressure Exposure Coefficient (Kz) According to Height for Building A

Height	Kz
10	0.71
30	1.0
60	1.9
90	1.34
120	1.46
150	1.55
175	1.63

Table 2 Velocity Pressure q_z Based on Height for Building A

Height	Kz	Kzt	Kd	V^2	I	qz
10	0.71	1.0	0.85	1089	1.15	463.3
30	1.0	1.0	0.85	1089	1.15	653
60	1.19	1.0	0.85	1089	1.15	777
90	1.34	1.0	0.85	1089	1.15	874
120	1.46	1.0	0.85	1089	1.15	953
150	1.55	1.0	0.85	1089	1.15	1011
175	1.63	1.0	0.85	1089	1.15	1064

4.1.1 Checking Normal Period of Vibration

T= 0.1 N (by approximation)

$$N = \frac{175-10}{4} + 1$$

= 42 floors

T= 0.1 (42)

= 4.2 second

F= 1/ 4.2 = 0.24 Hz (slender and flexible)

4.1.2 Gust Factor

$$Gf = \frac{0.925\left(1+1.71\check{Z}\sqrt{gq\, Q^2+gr^2R^2}\right)}{1+1.7\, gr\, I\, \check{Z}}$$

From 6.5.8.2

$g_q = 3.4$ $g_r = 3.4$

$$g_r = \sqrt{2\ \ln(3600\, ni)} + \frac{0.577}{\sqrt{2\ \ln(3600\, ni)}}$$

$$= \sqrt{2\ \ln(3600\ 0.24)} + \frac{0.577}{\sqrt{2\ \ln(3600\ 0.24)}}$$

= 3.677 + 0.157 = **3.834**

$$R = \sqrt{\frac{1}{\beta}}\ Rn\ Rh\ R\beta\ (0.53 + 0.47\ RL)$$ [refer appendix E for exposure constants]

$$Rn = \frac{7.47\ N1}{(1+10.3\ N1)^{5/3}}$$ where $N1 = \frac{n1\ Lz}{Vz}$ $Lz = \gamma \left(\frac{z}{10}\right) \epsilon$

= **0.09** $= \frac{0.24(213.42)}{26.73}$ = 213.59

= 1.92 $Vz = þ\left(\frac{z}{10}\right)^{\alpha} V$

= 26.73

$$Rl = \frac{1}{\mu} - \frac{1}{2\mu^2}(1 - e^{2\mu})$$

Where Rl = Rh ($\mu = 4.6\, n1\, \frac{h}{Vz}$)

Rb ($\mu = 4.6\, \in \frac{\beta}{Vz}$)

RL ($\mu = 15.4\, n1\, L/Vz$)

Rh = **0.128**

Rb = **0.402**

RL = **0.18**

$$R = \sqrt{\frac{1}{\beta}}\, Rn\, Rh\, R\beta\, (0.53 + 0.47\, RL)$$

R = $\sqrt{\frac{1}{0.05}}$ (0.09)(0.138)(0.402) (0.503+ 0.47 (0.18)) = **0.238**

$$Q = \sqrt{\frac{1}{1+0.63\left(\frac{B+H}{Lz}\right)}}$$

$$Q = \sqrt{\frac{1}{1+0.63\left(\frac{60+175}{213.42}\right)}} = 0.774$$

$$Gf = \frac{0.925\left(1+1.71\check{Z}\sqrt{}\, gq\, Q^2 + gr^2 R^2\right)}{1+1.7\, gr\, I\, \check{Z}}$$

$$Gf = 0.\ 925\ \frac{\left(1+1.71\,(0.202)\sqrt{(3.4)^2(0.774)^2 + (3.834)^2(0.24)^2}\right)}{1+1.7\,(3.4)(0.202)}$$

Gf = **0.834**

4.1.3 Design Wind Pressure

P = q Gf Cp - qi (G Cpi)

Table 3 Design Wind Load for Windward Wall based on Height

Height	Qz	Gf Cp	qi (G Cpi)	+ P (kn/m^2)	-P (kn/m^2)
10	0.463	0.667	0.192	0.498	0.114
30	0.652	0.667	0.192	0.624	0.240
60	0.776	0.667	0.192	0.706	0.322
90	0.874	0.667	0.192	0.770	0.386
120	0.952	0.667	0.192	0.822	0.438
150	1.011	0.667	0.192	0.860	0.476
175	1.064	0.667	0.192	0.901	0.511

<u>Leeward wall</u>

$P = 1.064\ (-0.417) \pm 0.192$

$= 0.636\ kn/m^2$

<u>Sidewall</u>

$P = 1.064\ (-0.578) \pm 0.192$

$= 0.807\ kn/m$

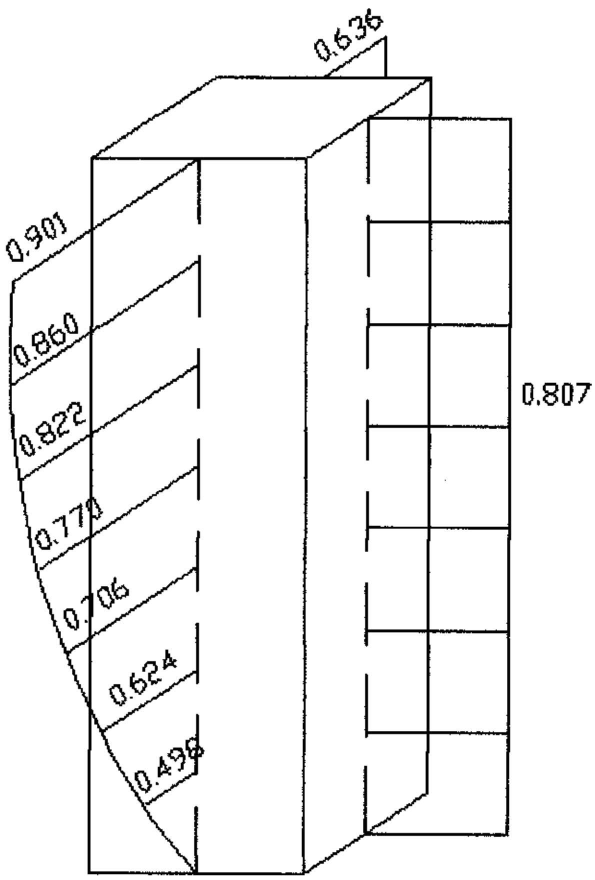


Figure 4 Design Windload for Building A

4.1.4 Calculating the Displacement

P = 2/3 (0.901 kn/m² x 175 m) + (0.631 kn/m² x 175m)

= 216.42 kn/m

$$T = \frac{2\pi}{\sqrt{k/m}}$$

$$K = \left(\frac{2\pi}{T}\right)^2 m$$

$$= \left(\frac{2\pi^2}{4.2}\right) 1209600 \;= 2707091.493 \text{ kn/m}$$

$$K = \frac{3EI}{L^3}$$

$$I = \frac{(175)^3\,(2707091.493)}{3\,(200 \; x \; 10^6)} = 24180.53 \text{ m}^4$$

$\Delta = \frac{PL^3}{3EI}$

$= \frac{(216.42)(175^3)}{3(200 \ x \ 10^6)(24180.53)}$

$\Delta = 8x\ 10^{-5}$m

Allowable displacement $\Delta = \gamma / 300$

$= 175/300$

$\Delta\ = 0.58$m

Therefore; the displacement for the building under wind force is acceptable.

4.1.5 Calculating the Acceleration

Along wind acceleration:

$a_D = 4\pi^2 n_o^2 g_p r \sqrt{R} \left(\frac{\Delta}{G}\right)$

$g_p = 3.6$ (from appendix F) whereas it is a function of the average fluctuation rate υ.

$\upsilon = \frac{n^o}{\sqrt{1+B/R}} = 0.128$

B = 0.6 (from appendix G), R = 0.247

r = 0.32 (from appendix H)

G = 0.834 (gust factor which has been calculated earlier)

$\alpha = 4\ \pi^2\ (0.24)^2\ (3.6)(0.32)\ \sqrt{0.238}\left(\frac{8x\ 10^{-5}}{0.834}\right) = 0.0001$ m/sec²

Cross wind response:

$a_W = n_o^2\ g_p\ [WD]^{1/2}\ \frac{ar}{\rho g\sqrt{\beta}}$ where;

$a_r = 78.5 \text{ x } 10^{-3}\ [\ V_H / n_o \sqrt{WD}]^{3.3}$ Pa

$a_r = 78.5 \text{ x } 10^{-3}\ [33/\ 0.24\ \sqrt{40 \text{ x } 60}]$

$a_r = 2.365$

$a_w = 0.24^2 (3.6) [48.98] \frac{2.365}{(293.68)(9.81)(\sqrt{0.05})}$

$= 0.037$ m/sec^2 (0.3%g) – peak value

Converting into RMS

0.037 x 0.707= 0.026 m/sec^2

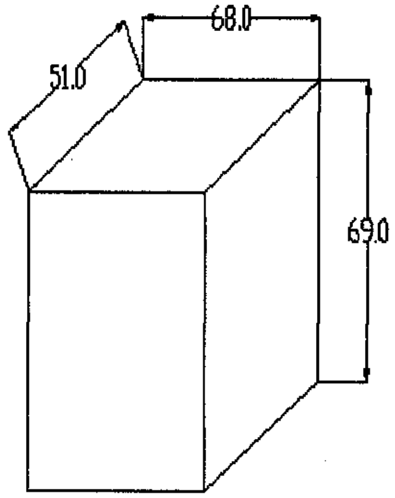


Figure 5 Sketch Figure and Dimension for Building B

4.2 Analytical Procedure for Building B

Location: Miri

Wind Speed: 30.5 m/s

$q_z = 0.613 * K_z * K_{zt} * K_d * V^2 * I$

$K_d = 0.85$

$I = 1.15$

$K_{zt} = 1$

Velocity Pressure K_z: (refer appendix D)

Table 4 Velocity Pressure Exposure Coefficient (Kz) According to Height for Building B

Height	Kz
10	0.723
20	0.874
30	0.985
40	1.068
50	1.138
60	1.195
69	1.242

Table 5 Velocity Pressure (q_z) based on Height for Building B

Height	Kz	Kzt	Kd	V^2	I	qz
10	0.723	1.0	0.85	930.25	1.15	403
20	0.874	1.0	0.85	930.25	1.15	487.18
30	0.985	1.0	0.85	930.25	1.15	549.05
40	1.068	1.0	0.85	930.25	1.15	595.317
50	1.138	1.0	0.85	930.25	1.15	634.336
60	1.195	1.0	0.85	930.25	1.15	666.104
69	1.242	1.0	0.85	930.25	1.15	692.306

4.2.1 Checking for Normal period of Vibration

T= 0.1 N (by approximation)

N= 23

T= 0.1 (23)

= 2.3 second

F= 1/ 2.3 = 0.434Hz (slender and flexible)

4.2.2 Gust Factor

$$Gf = \frac{0.925\left(1+1.71\check{Z}\sqrt{gq\, Q^2+gr^2R^2}\right)}{1+1.7\, gr\, I\, \check{Z}}$$

From 6.5.8.2

$g_q = 3.4$ $g_r = 3.4$

$$g_r = \sqrt{2\ \ln(3600\, ni)} + \frac{0.577}{\sqrt{2\ \ln(3600\, ni)}}$$

3.839 + 0.1503 = **3.986**

$R = \sqrt{\frac{1}{\beta}}\ Rn\ Rh\ R\beta\ (0.53 + 0.47\ RL)$ [refer appendix E for exposure constants]

$Rn = \frac{7.47\, N1}{(1+10.3\, N1)^{5/3}}$ where $N1 = \frac{n1\, Lz}{Vz}$ $Lz = \gamma\left(\frac{z}{10}\right)\epsilon$

= **0.064** = 3.481 = 156.62

$Vz = þ\left(\frac{z}{10}\right)^{\alpha} V$

= 19.57

$$Rl = \frac{1}{\mu} - \frac{1}{2\mu^2}(1 - e^{2\mu})$$

Where Rl = Rh ($\mu = 4.6\, n1\, \frac{h}{Vz}$)

Rb ($\mu = 4.6 \in \frac{\beta}{Vz}$)

RL ($\mu = 15.4\, n1\, L/Vz$)

Rh = **0.132**

Rb = **0.133**

RL = **0.0556**

R= $\sqrt{\frac{1}{\beta}}\, Rn\, Rh\, R\beta\, (0.53 + 0.47\, RL)$

= **0.112**

Q = $\sqrt{\frac{1}{1+0.63\left(\frac{B+H}{Lz}\right)}}$

= 0.803

Gf = $\frac{0.925\,(1+1.71\check{Z}\sqrt{gq\,Q^2+gr^2R^2})}{1+1.7\,gr\,I\,\check{Z}}$

Gf = 0.825

Gf Cp = 0.825(0.8) = 0.66 windward wall

= 0.825 (-0.5) = -0.42 leeward wall

= 0.825(-0.7) = - 0.58 side wall

qi (G Cpi) = 0.692 ($\pm$ 0.18)

= $\pm$ 0.125

4.2.3 Design Wind Pressure

$P = q\ G_f C_p - q_i (G\ C_{pi})$

Table 6 Design Wind Load for Windward wall based on Height for Building B

Height	Qz	Gf Cp	qi (G Cpi)	+ P (kn/m²)	-P (kn/m²)
10	0.403	0.66	0.125	0.391	0.141
20	0.487	0.66	0.125	0.446	0.196
30	0.549	0.66	0.125	0.487	0.237
40	0.595	0.66	0.125	0.518	0.267
50	0.634	0.66	0.125	0.543	0.293
60	0.666	0.66	0.125	0.561	0.311
69	0.692	0.66	0.125	0.582	0.332

<u>Leeward wall</u>

$P = 0.692\ (-0.41252) \pm 0.125$

$= 0.410$ kn/m²

<u>Sidewall</u>

$P = 0.692(-0.58) \pm 0.125$

$= 0.525$kn/m

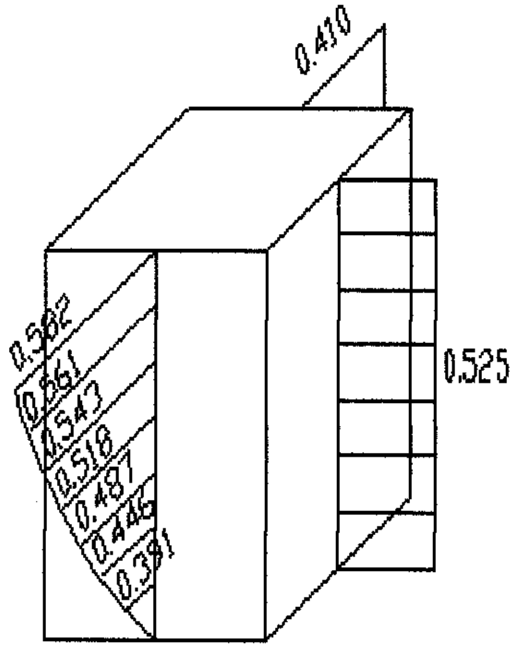


Figure 6 Design Wind Load for Building B

4.2.4 Calculating the Displacement

P = 2/3 (0.582kn/m² x 69 m) + (0.410 kn/m² x 69m)

= 55.06 kn/m

$$T = \frac{2\pi}{\sqrt{\frac{k}{m}}}$$

$$K = \left(\frac{2\pi}{T}\right)^2 m$$

=7143190.552 kn/m

$$K = \frac{3EI}{L^3}$$

$I = 3911\ m^4$

$\Delta = \frac{PL^3}{3EI}$

$=7.708 \times 10^{-6}$ m

Allowable displacement $\Delta = Y / 300$

$= 69/300$

$\Delta = 0.23$m

Therefore; the displacement for the building under wind force is acceptable.

4.2.5 Calculating the Acceleration

Along wind acceleration:

$a_D = 4\pi^2 n_o^2 g_p r \sqrt{R} \left(\frac{\Delta}{G}\right)$

gp = 3.8 (from appendix F) whereas it is a function of the average fluctuation rate υ.

$\upsilon = n_o / \sqrt{1 + B/R}$

$= 0.435 / \sqrt{1 + 0.7/0.112}$

$= 0.162$

B = 0.7 (from appendix G), R = 0.112

r = 0.45 (from appendix H)

G = 0.825 (gust factor which has been calculated earlier)

$\alpha = 4\pi^2 (0.435)^2 (3.8)(0.45\sqrt{0.112}(7.7 \times 10^{-6}/0.825) = 0.0004$ m/sec²

Cross wind response:

$a_w = n_o^2 g_p [WD]^{½} \frac{ar}{\rho g \sqrt{\beta}}$ where;

$a_r = 78.5 \times 10^{-3} [V_H / n_o \sqrt{WD}]^{3.3}$ Pa

$a_r = 78.5 \times 10^{-3} [30.5/ 0.435 \sqrt{51 \times 68}]^{3.3}$

$a_r = 0.1396$

$a_w = 0.24^2 (3.6) [48.98] \frac{0.1396}{(407.89)(9.81)(\sqrt{0.05})}$

$0.00661\ m/sec^2$ (0.06%g) – peak value

Converting into RMS

$= 0.00661 \times 0.707$

$= 0.0046\ m/sec^2$

CHAPTER 5
DISCUSSIONS

The lateral loading due to wind or earthquake is the major factor that causes the design of high rise building to differ from those of low to medium structures. In this project the writer has incorporated the wind effect alone and the analysis of the buildings has shown that, the designs of the buildings are adequate to resist the wind loading as the deflection of the building due to wind load is within the allowable deflection of the building itself.

Many researches have been carried out into the important of physiological and psychological parameters that affect human perception to motion and vibration in the low frequency tall buildings. Evidently, human response to building vibration is a complex mix of psychological and physiological factors. Prior experience, vibration expectation, habituation, personality and even job satisfaction also play an important role, which makes predicting an individual's reaction to building vibration a complex task. Since human perception and tolerance of wind-induced tall building vibration are essentially a subjective assessment, there are significant differences and uncertainties in the building vibration acceptability and occupant comfort criteria and the assessment methodology currently in use. So far, no consensus has been reached among the structural engineers internationally with regard to human comfort criteria. However it is generally agreed that acceleration is the predominant parameter in determining the nature of human response to vibration.

Two different measures of acceleration is being used in this project namely peak value and RMS (root mean square) value. The peak value occurs during a period of time-say 15-20 minutes- while RMS value is the averaged over this same period. Scholars have been debating on which value is best applied for human criteria and yet no international consensus has been achieved. The first school of thought believe that the degree of a person objects to a particular magnitude of vibrations best determined by the average effect over the period of time while on the other hand, it is reasoned that a person tend to be affected most by the largest peak of acceleration. However, the writer chose to use both values as to obtain the best result and to analyze the human comfort from every perspective

In this analysis, the author has considered the along wind response and cross wind response as the prominent criteria to obtained the peak acceleration for the building as the peak acceleration play the biggest role in human comfort criteria. Along wind response or loading is normally due to the buffeting effect and is consist of the component of the mean wind speed and fluctuating wind component. Fluctuating wind is a mixture of gusts of various sizes where large size of gust occurs less often then the smaller gust. Smaller gust normally induced the structure to vibrate at or near one of the building natural frequency. It gives significant dynamic load effect on the structure. Cross wind on the other hand is due predominantly to vortex shedding. Although the maximum lateral wind loading are in the along wind direction, the maximum acceleration of the building, which is significant for human comfort, may often occur in cross wind direction. Therefore, for this project, the author has adopted the cross wind value to evaluate the human comfort criteria of the two buildings. The following summarizes the finding of both along wind loading and across wind loading for both structures.

Table 7 Along wind and Cross wind Acceleration

Building / Wind direction	A (m\sec^2)	B (m\ sec^2)
Along Wind Response	4×10^{-5}	1.226×10^{-4}
Cross Wind Response	6.61×10^{-3}	3.7×10^{-3}

Since the along wind response value is significantly small, cross wind response is considered as the peak acceleration for the building. From the calculation, the peak acceleration obtained for building A is 3.7×10^{-3} m\sec^2 (0.37%g) while building B is 6.61×10^{-3} m\sec^2. The result is being compared to Table 8, where both buildings are categorized in range 1. From the table, human cannot perceive motion in both building during peak wind gust. Based on the result, both buildings are designed with adequate criteria of human comfort. This condition suits the commercial function of the building because the occupants will not experience the physiological and psychological effect of the wind loading that might lead to undesirable condition of the building.

Table 8 Human Comfort Criteria

Range	Acceleration (m/sec^2)	Effect
1	<0.05	Humans cannot perceive motion
2	0.05–0.10	Sensitive people can perceive motion; hanging objects may move slightly.
3	0.1–0.25	Majority of people will perceive motion; level of motion may affect desk work; long-term exposure may produce motion sickness
4	0.25–0.4	Desk work becomes difficult or almost impossible; ambulation still possible
5	0.4–0.5	People strongly perceive motion; difficult to walk naturally; standing people may lose balance.
6	0.5–0.6	Most people cannot tolerate motion and are unable to walk naturally
7	0.6–0.7	People cannot walk or tolerate motion.
8	>0.85	Objects begin to fall and people may be injured

From the analysis also, the author has came out with recommended upper limit to satisfy the comfort criteria of those two buildings. ISO 6897-1984 (appendix I) has been used as the guideline for this purpose. ISO 6897-1984 has proposed that the maximum value of 5 years acceleration at the top occupied floor during the 10 severest minutes of a wind storm, as a function of the vibration frequency. Curve 1, represents the limit for general-purpose building whereas curve 2 represent the comfort criteria for offshore structures. For this purpose, RMS value is adopted as it gives average magnitudes for short periods.

For building A, with natural frequency of 0.24 Hz, the recommended upper limits of acceleration should not exceed 0.048 m/sec^2. RMS value for building A is 0.026 m/sec^2 which is smaller than the upper limits boundary. For building B, with natural frequency of 0.435Hz, the recommended upper limits of acceleration should not exceed 0.038 m/sec^2. RMS value for building B is 0.00428 m/sec^2 which is smaller than the upper limit boundary. Table 9 summarizes the upper limit boundary for both buildings.

Table 9 Upper Limit Boundary

Building	Natural frequency (Hz)	RMS value (m/sec^2)	Recommended upper limit (m/sec^2)
A	0.24	0.026	0.048
B	0.435	0.00426	0.038

The upper limit boundary should be considered during the early stage of designing to avoid excessive levels of vibration under the action of wind, adversely affecting serviceability and occupant comfort.

Another approach that is being used to evaluate human comfort is by using BLTWL (Boundary Layer Wind Tunnel Laboratory). BLTWL provides maximum of 10 years value of peak acceleration for office and residential buildings. The BLTWL maximum ranges are provided in table 6 below. Peak value of both building is being compared to check on whether both building satisfy the BLTWL criteria for human comfort. Note that, a distinction is made between different building occupancy rates as a function of building's use. This reflects during a severe wind storm an office building would probably be evacuated and people will take shelter in their homes.

Table 10 Maximum 10 years Acceleration according to BLWTL

	Range (g%)
Office	20-25
Hotel	15-20
Residence	10-15

Building A (residence): 0.37% g < 10-15 %g

Building B (hotel): 0.0661%g < 15-20%g

From the comparison, both buildings satisfy the range of BLTWL criteria for human comfort.

CHAPTER 6

ECONOMIC BENEFITS

High rise structures mainly serve the function as an occupiable space for office, residence or hotel. Millions of money is invested to build tall structure with the hope of more money in return. With increasing urbanization, high land prices in cities make ever-taller building economically viable. With the advancement of the technology, building with a lightweight material is built to reduce the overall cost of constructing the building. In short, constructing a high rise is not only to cater to human needs, but nowadays it has become a great investment to gain more money. Therefore, a slight fault in the design of the building might lead to the reduction in value and loss of money of the building.

High rise structures are exposed to the wind imposed loading. Wind has created a variety of problems in a tall structure and has become a major concern to building owner, insurers and engineers alike. Severe windy climate is the largest single cause of economic and insured losses due to natural disaster. The estimated annual wind disaster in the USA alone is USD 6 billion. The damage to structure and ensuing cleanup is likely to affect the market price of the property itself.

Human comfort is one of the many factors that contribute to the value of the high rise with regard to wind imposed loading. Top floor of the building is most likely to sway as the result of the wind force and it has become the greatest concern of the top occupants of the building. Excessive motion of the building may result in the physiology and psychology effect of the occupants which may raise complaints about the building. In some other cases, workers who work on top of the floor who experienced annoyed motion might leave the workplace or cannot be able to perform his work and this can lead to the losses of the business.

The following are examples of the buildings which have suffered great losses financially due to the negligence in incorporating human comfort criteria in its design.

6.1 Case study 1: John Hancock Tower, Chicago

The building upper floor occupants suffer from the motion sickness when the building swayed in the wind. Many complaints have been raised by the occupants who forced the owner to take action to minimize the effect. To stabilize the movement, contractors installed a device called a tuned mass damper on the 58th floor. The installment of the damper has cost USD 3 millions. However, despite the damper, the building could have fallen over under a certain kind of swing. Therefore 1500 tons of braced steel were added which has cost another USD 5 millions.

6.2 Case study 2: Gulf and Western Building, New York

As a result of wind stress, the 44 story building developed cracks in stairwells and interior walls. In addition, office workers on the top floors frequently complained of motion sickness during the windy day. To fix these problems, the owner invested USD 10 millions to add massive steel braced to steady the structure.

The above losses can be avoided if in the early stage of designing, human comfort criterion is being taken into account. Tuned mass damper and massive steel braced are among the options to solve the excessive wind motion induced to the building. Although it cost a fortune, however, if it is planned earlier, it would save a lot more money in the future.

CHAPTER 7
CONCLUSIONS AND RECOMMENDATION

7.1 Conclusions

From the analysis, both buildings have satisfied the human comfort criteria. Both buildings have been categorized in range 1 where human cannot perceive motion. Both buildings also have met the criteria of BLWTL and upper recommendation limits for acceleration. From this analysis also, the writer proved that, building in Malaysia do not face this kind of problem because the country doesn't face a severe windy climate.

Apart from that, based on the dynamic analysis, the designs of both buildings are adequate in resisting the wind load as there is no likelihood of excessive deflections due to lateral loading.

However, although both buildings satisfy the criteria of human comfort, not many engineers in Malaysia are aware of this aspect. Human comfort criteria should be emphasized in the early stage of the design when it comes to high structures.

From the study as well, acceleration is proved to be the predominant parameter to evaluate human threshold perception levels for human comfort criteria.

7.2 Recommendation

It is recommended that although building in this country does not have much problem with wind load, human comfort criteria should always be considered. Engineers and designers are recommended to take into account the human comfort criteria on every design of high rise. Every engineer should be equipped with the exposure and knowledge of human comfort engineering from the early years of tertiary education. With the advancement in construction technology and the rapid growth of tall structures, this knowledge might come in handy for the future engineers.

The writer also would like to recommend this study should be carried out in details in the future for a better understanding on the human comfort engineering generally. Accurate result can be obtained by using appropriate software and wind tunnel testing.

REFERENCES

1. Tall building structures: analysis and design, Bryann stafford Smith and alex Coull (1991)
2. Acceleration indexes for human comfort in tall building, Daryll Boggs (1995)
3. Human response to wind induced motion of building, Hansen, Robert J., Reed, John W., and Vanmarcke, Erik H. (1973)
4. Human Response to Dynamic Motion of Structures, Irwin, A.W. (1978)
5. ISO 2631-2; Evaluation of human exposure to whole body vibration (1989)
6. Effects of wind induced tall building motion on cognitive performance, Roy. O. Denoon, Richards. D. Roberts, Christopher. W. Letchford, K.C.S Kwok (2000)
7. Perception of vibration and occupant comfort in wind-excited tall buildings, K.C.S Kwok, Peter A. Hitchcock, Melissa. D. Burton (2009)
8. Wind Engineering Challenges of the new Generation of super tall buildings, Peter A. Irwin (2009)
9. ASCE 7-05, Minimum Design for Building and Other Structures, Chapter 6 (2005) [appendix A]
10. Feblowitz, Joshua C. 2010. "Confusing The Wind: The Burj Khalifa, Mother Nature, and the Modern Skyscraper." Student Pulse Academic Journal 2.01. Retrieved from: <http://www.studentpulse.com/a?id=124>

APPENDICES

Appendix A

ASCE 7-05

Code

tural Dynamics

fome

→ AIMAN

Chapter 6
WIND LOADS

RAL

. Buildings and other structures, including the Main Resisting System (MWFRS) and all components and reof, shall be designed and constructed to resist wind ified herein.

ed Procedures. The design wind loads for buildings uctures, including the MWFRS and component and ments thereof, shall be determined using one of the ocedures: (1) Method 1—Simplified Procedure as Section 6.4 for buildings meeting the requirements rein; (2) Method 2—Analytical Procedure as speci- on 6.5 for buildings meeting the requirements speci- (3) Method 3—Wind Tunnel Procedure as specified 6.

Pressures Acting on Opposite Faces of Each rface. In the calculation of design wind loads for and for components and cladding for buildings, the m of the pressures acting on opposite faces of each ace shall be taken into account.

num Desi Wind Loading. The design wind load, by any one of the procedures specified in Sec- all be not less than specified in this section.

n Wind-Force Resisting System. The wind load to e design of the MWFRS for an enclosed or partially lding or other structure shall not be less than 10 lb/ft^2) multiplied by the area of the building or structure to a vertical plane normal to the assumed wind direc- sign wind force for open buildings and other struc- not less than 10 lb/ft^2 (0.48 kN/m^2) multiplied by the

ponents and Cladding. The design wind pressure nts and cladding of buildings shall not be less than e of 10 lb/ft^2 (0.48 kN/m^2) acting in either direction surface.

ITIONS

ng definitions apply only to the provisions of

ED: Acceptable to the authority having jurisdiction.

IND SPEED, V: Three-second gust speed at 33 ft the ground in Exposure C (see Section 6.5.6.3) as n accordance with Section 6.5.4.

G, ENCLOSED: A building that does not comply irements for open or partially enclosed buildings.

G ENVELOPE: Cladding, roofing, exterior walls,

BUILDING AND OTHER STRUCTURE, FLEXIBLE: Slender buildings and other structures that have a fundamental natural frequency less than 1 Hz.

BUILDING, LOW-RISE: Enclosed or partially enclosed buildings that comply with the following conditions:

1. Mean roof height h less than or equal to 60 ft (18 m).
2. Mean roof height h does not exceed least horizontal dimension.

BUILDING, OPEN: A building having each wall at least 80 percent open. This condition is expressed for each wall by the equation $A_o \geq 0.8A_g$ where

A_o = total area of openings in a wall that receives positive external pressure, in ft^2 (m^2)

A_g = the gross area of that wall in which A_o is identified, in ft^2 (m^2)

BUILDING, PARTIALLY ENCLOSED: A building that complies with both of the following conditions:

1. The total area of openings in a wall that receives positive external pressure exceeds the sum of the areas of openings in the balance of the building envelope (walls and roof) by more than 10 percent.
2. The total area of openings in a wall that receives positive external pressure exceeds 4 ft^2 (0.37 m^2) or 1 percent of the area of that wall, whichever is smaller, and the percentage of openings in the balance of the building envelope does not exceed 20 percent.

These conditions are expressed by the following equations:

1. $A_o > 1.10A_{oi}$
2. $A_o >$ 4 sq ft (0.37 m^2) or $>0.01A_g$, whichever is smaller, and $A_{oi}/A_{gi} \leq 0.20$

where

A_o, A_g are as defined for Open Building
A_{oi} = the sum of the areas of openings in the building envelope (walls and roof) not including A_o, in ft^2 (m^2)
A_{gi} = the sum of the gross surface areas of the building envelope (walls and roof) not including A_g, in ft^2 (m^2)

BUILDING OR OTHER STRUCTURE, REGULAR-SHAPED: A building or other structure having no unusual geometrical irregularity in spatial form.

BUILDING OR OTHER STRUCTURES, RIGID: A building or other structure whose fundamental frequency is greater than or equal to 1 Hz.

BUILDING, SIMPLE DIAPHRAGM: A building in which both windward and leeward wind loads are transmitted through floor and roof diaphragms to the same vertical MWFRS (e.g., no structural separations).

COMPONENTS AND CLADDING: Elements of the build-

GC_{pf} = product of the equivalent external pressure coefficient and gust-effect factor to be used in determination of wind loads for MWFRS of low-rise buildings

GC_{pi} = product of internal pressure coefficient and gust-effect factor to be used in determination of wind loads for buildings

g_Q = peak factor for background response in Eqs. 6-4 and 6-8

g_R = peak factor for resonant response in Eq. 6-8

g_v = peak factor for wind response in Eqs. 6-4 and 6-8

H = height of hill or escarpment in Fig. 6-4, in ft (m)

h = mean roof height of a building or height of other structure, except that eave height shall be used for roof angle θ of less than or equal to 10°, in ft (m)

h_e = roof eave height at a particular wall, or the average height if the eave varies along the wall

I = importance factor

$I_{\bar{z}}$ = intensity of turbulence from Eq. 6-5

$_2, K_3$ = multipliers in Fig. 6-4 to obtain K_{zt}

K_d = wind directionality factor in Table 6-4

K_h = velocity pressure exposure coefficient evaluated at height $z = h$

K_z = velocity pressure exposure coefficient evaluated at height z

K_{zt} = topographic factor as defined in Section 6.5.7

L = horizontal dimension of a building measured parallel to the wind direction, in ft (m)

L_h = distance upwind of crest of hill or escarpment in Fig. 6-4 to where the difference in ground elevation is half the height of hill or escarpment, in ft (m)

$L_{\bar{z}}$ = integral length scale of turbulence, in ft (m)

L_r = horizontal dimension of return corner for a solid freestanding wall or solid sign from Fig. 6-20, in ft (m)

ℓ = integral length scale factor from Table 6-2, ft (m)

N_1 = reduced frequency from Eq. 6-12

n_1 = building natural frequency, Hz

p = design pressure to be used in determination of wind loads for buildings, in lb/ft² (N/m²)

p_L = wind pressure acting on leeward face in Fig. 6-9, in lb/ft² (N/m²)

p_{net} = net design wind pressure from Eq. 6-2, in lb/ft² (N/m²)

p_{net30} = net design wind pressure for Exposure B at h = 30 ft and I = 1.0 from Fig. 6-3, in lb/ft² (N/m²)

p_p = combined net pressure on a parapet from Eq. 6-20, in lb/ft² (N/m²)

p_s = net design wind pressure from Eq. 6-1, in lb/ft² (N/m²)

p_{s30} = simplified design wind pressure for Exposure B at h = 30 ft and I = 1.0 from Fig. 6-2, in lb/ft² (N/m²)

p_W = wind pressure acting on windward face in Fig. 6-9, in lb/ft² (N/m²)

q = velocity pressure, in lb/ft² (N/m²)

q_h = velocity pressure evaluated at height $z = h$, in lb/ft² (N/m²)

q_i = velocity pressure for internal pressure determination, in lb/ft² (N/m²)

q_p = velocity pressure at top of parapet, in lb/ft² (N/m²)

q_z = velocity pressure evaluated at height z above ground, in lb/ft² (N/m²)

R = resonant response factor from Eq. 6-10

R_B, R_h, R_L = values from Eq. 6-13

R_i = reduction factor from Eq. 6-16

R_n = value from Eq. 6-11

s = vertical dimension of the solid freestanding wall or solid sign from Fig. 6-20, in ft (m)

r = rise-to-span ratio for arched roofs

V = basic wind speed obtained from Fig. 6-1, in mi/h (m/s). The basic wind speed corresponds to a 3-s gust speed at 33 ft (10 m) above ground in exposure Category C

V_i = unpartitioned internal volume ft³ (m³)

$\bar{V}_{\bar{z}}$ = mean hourly wind speed at height $\bar{z}$, ft/s (m/s)

W = width of building in Figs. 6-12 and 6-14A and B and width of span in Figs. 6-13 and 6-15, in ft (m)

X = distance to center of pressure from windward edge in Fig. 6-18, in ft (m)

x = distance upwind or downwind of crest in Fig. 6-4, in ft (m)

z = height above ground level, in ft (m)

$\bar{z}$ = equivalent height of structure, in ft (m)

z_g = nominal height of the atmospheric boundary layer used in this standard. Values appear in Table 6-2

z_{min} = exposure constant from Table 6-2

α = 3-s gust-speed power law exponent from Table 6-2

$\hat{\alpha}$ = reciprocal of α from Table 6-2

$\bar{\alpha}$ = mean hourly wind-speed power law exponent in Eq. 6-14 from Table 6-2

β = damping ratio, percent critical for buildings or other structures

ϵ = ratio of solid area to gross area for solid freestanding wall, solid sign, open sign, face of a trussed tower, or lattice structure

λ = adjustment factor for building height and exposure from Figs. 6-2 and 6-3

$\bar{\epsilon}$ = integral length scale power law exponent in Eq. 6-7 from Table 6-2

η = value used in Eq. 6-13 (see Section 6.5.8.2)

θ = angle of plane of roof from horizontal, in degrees

ν = height-to-width ratio for solid sign

6.4 METHOD 1—SIMPLIFIED PROCEDURE

6.4.1 Scope. A building whose design wind loads are determined ics, shall be designed using recognized literature g such wind load effects or shall use the wind tunnel pecified in Section 6.6.

elding. There shall be no reductions in velocity pres- apparent shielding afforded by buildings and other r terrain features.

Permeable Cladding. Design wind loads deter- Section 6.5 shall be used for air permeable cladding roved test data or recognized literature demonstrate ls for the type of air permeable cladding being

gn Procedure.

basic wind speed V and *wind directionality factor K_d* l be determined in accordance with Section 6.5.4.

importance factor I shall be determined in accordance Section 6.5.5.

exposure category or *exposure categories* and *velocity sure exposure coefficient K_z* or K_h, as applicable, shall letermined for each wind direction in accordance with tion 6.5.6.

opographic factor K_{zt} shall be determined in accor- ce with Section 6.5.7.

ust effect factor G or G_f, as applicable, shall be deter- ed in accordance with Section 6.5.8.

enclosure classification shall be determined in accor- ce with Section 6.5.9.

rnal pressure coefficient GC_{pi} shall be determined in ordance with Section 6.5.11.1.

ernal pressure coefficients C_p or GC_{pf}, or *force coeffi- nts C_f*, as applicable, shall be determined in accordance h Section 6.5.11.2 or 6.5.11.3, respectively.

ocity pressure q_z or q_h, as applicable, shall be deter- ied in accordance with Section 6.5.10.

sign wind load p or *F* shall be determined in accor- ice with Sections 6.5.12, 6.5.13, 6.5.14, and 6.5.15, as licable.

ic Wind Speed. The basic wind speed, *V*, used in nination of design wind loads on buildings and other shall be as given in Fig. 6-1 except as provided in i.5.4.1 and 6.5.4.2. The wind shall be assumed to come horizontal direction.

ecial Wind Regions. The basic wind speed shall be in- here records or experience indicate that the wind speeds than those reflected in Fig. 6-1. Mountainous terrain, d special regions shown in Fig. 6-1 shall be examined for ind conditions. The authority having jurisdiction shall, ry, adjust the values given in Fig. 6-1 to account for al wind speeds. Such adjustment shall be based on me- al information and an estimate of the basic wind speed in accordance with the provisions of Section 6.5.4.2.

stimation of Basic Wind Speeds from Regional Data. In areas outside hurricane-prone regions, re- imatic data shall only be used in lieu of the basic ds given in Fig. 6-1 when (1) approved extreme-value -analysis procedures have been employed in reducing and (2) the length of record, sampling error, averaging

the anemometer have been taken into account. Reduction in basic wind speed below that of Fig. 6-1 shall be permitted.

In hurricane-prone regions, wind speeds derived from simulation techniques shall only be used in lieu of the basic wind speeds given in Fig. 6-1 when (1) approved simulation and extreme value statistical analysis procedures are used (the use of regional wind speed data obtained from anemometers is not permitted to define the hurricane wind-speed risk along the Gulf and Atlantic coasts, the Caribbean, or Hawaii) and (2) the design wind speeds resulting from the study shall not be less than the resulting 500-year return period wind speed divided by $\sqrt{1.5}$.

In areas outside hurricane-prone regions, when the basic wind speed is estimated from regional climatic data, the basic wind speed shall be not less than the wind speed associated with an annual probability of 0.02 (50-year mean recurrence interval), and the estimate shall be adjusted for equivalence to a 3-s gust wind speed at 33 ft (10 m) above ground in exposure Category C. The data analysis shall be performed in accordance with this chapter.

6.5.4.3 Limitation. Tornadoes have not been considered in developing the basic wind-speed distributions.

6.5.4.4 Wind Directionality Factor. The wind directionality factor, K_d, shall be determined from Table 6-4. This factor shall only be applied when used in conjunction with load combinations specified in Sections 2.3 and 2.4.

6.5.5 Importance Factor. An importance factor, *I*, for the building or other structure shall be determined from Table 6-1 based on building and structure categories listed in Table 1-1.

6.5.6 Exposure. For each wind direction considered, the upwind exposure category shall be based on ground surface roughness that is determined from natural topography, vegetation, and constructed facilities.

6.5.6.1 Wind Directions and Sectors. For each selected wind direction at which the wind loads are to be evaluated, the exposure of the building or structure shall be determined for the two upwind sectors extending 45° either side of the selected wind direction. The exposures in these two sectors shall be determined in accordance with Sections 6.5.6.2 and 6.5.6.3 and the exposure resulting in the highest wind loads shall be used to represent the winds from that direction.

6.5.6.2 Surface Roughness Categories. A ground surface roughness within each 45° sector shall be determined for a distance upwind of the site as defined in Section 6.5.6.3 from the categories defined in the following text, for the purpose of assigning an exposure category as defined in Section 6.5.6.3.

Surface Roughness B: Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger.

Surface Roughness C: Open terrain with scattered obstructions having heights generally less than 30 ft (9.1 m). This category includes flat open country, grasslands, and all water surfaces in hurricane prone regions.

Surface Roughness D: Flat, unobstructed areas and water surfaces outside hurricane prone regions. This category includes smooth mud flats, salt flats, and unbroken ice.

6.5.6.3 Exposure Categories

Exposure B: Exposure B shall apply where the ground surface roughness condition, as defined by Surface Roughness B, prevails in the upwind direction for a distance of at least 2,600 ft (792 m)

$$\frac{n_1 L_{\bar{z}}}{\bar{V}_{\bar{z}}} \quad (6\text{-}12)$$

$$\frac{1}{\eta} - \frac{1}{2\eta^2}(1 - e^{-2\eta}) \quad \text{for } \eta > 0 \quad (6\text{-}13a)$$

$$1 \quad \text{for } \eta = 0 \quad (6\text{-}13b)$$

ıe subscript ℓ in Eq. 6-13 shall be taken as h, B, and L, ɾely, where h, B, and L are defined in Section 6.3.

building natural frequency

R_h setting $\eta = 4.6 n_1 h/\bar{V}_{\bar{z}}$

R_B setting $\eta = 4.6 n_1 E B/\bar{V}_{\bar{z}}$

R_L setting $\eta = 15.4 n_1 L/\bar{V}_{\bar{z}}$

damping ratio, percent of critical

mean hourly wind speed (ft/s) at height $\bar{z}$ determined from Eq. 6-14.

$$\bar{V}_{\bar{z}} = \bar{b}\left(\frac{\bar{z}}{33}\right)^{\bar{\alpha}} V \left(\frac{88}{60}\right) \quad (6\text{-}14)$$

$$\bar{V}_{\bar{z}} = \bar{b}\left(\frac{\bar{z}}{10}\right)^{\bar{\alpha}} V$$

and $\bar{\alpha}$ are constants listed in Table 6-2 and V is the basic eed in mi/h.

Rational Analysis. In lieu of the procedure defined in ; 6.5.8.1 and 6.5.8.2, determination of the gust-effect fac-ıy rational analysis defined in the recognized literature is :d.

Limitations. Where combined gust-effect factors and : coefficients (GC_p, GC_{pi}, and GC_{pf}) are given in fig-ɟ tables, the gust-effect factor shall not be determined :ly.

nclosure Classifications.

General. For the purpose of determining internal pres-:fficients, all buildings shall be classified as enclosed, par-ıclosed, or open as defined in Section 6.2.

Openings. A determination shall be made of the amount ings in the building envelope to determine the enclosure :ation as defined in Section 6.5.9.1.

Wind-Borne Debris. Glazing in buildings located in ɔrne debris regions shall be protected with an impact-t covering or be impact-resistant glazing according to ıirements specified in ASTM E1886 and ASTM E1996 r approved test methods and performance criteria. The f impact resistance shall be a function of Missile Levels ıd Zones specified in ASTM E1886 and ASTM E1996.

EPTIONS:

azing in Category II, III, or IV buildings located over 60 ft (18.3 m) ove the ground and over 30 ft (9.2 m) above aggregate surface roofs :ated within 1,500 ft (458 m) of the building shall be permitted to be protected.

azing in Category I buildings shall be permitted to be unprotected.

Multiple Classifications. If a building by definition :s with both the "open" and "partially enclosed" defini-shall be classified as an "open" building. A building that ıt comply with either the "open" or "partially enclosed"

6.5.10 Velocity Pressure. Velocity pressure, q_z, evaluated at height z shall be calculated by the following equation:

$$q_z = 0.00256 K_z K_{zt} K_d V^2 I \text{ (lb/ft}^2) \quad (6\text{-}15)$$

[In SI: $q_z = 0.613 K_z K_{zt} K_d V^2 I$ (N/m^2); V in m/s]

where K_d is the wind directionality factor defined in Section 6.5.4.4, K_z is the velocity pressure exposure coefficient defined in Section 6.5.6.6, K_{zt} is the topographic factor defined in Section 6.5.7.2, and q_h is the velocity pressure calculated using Eq. 6-15 at mean roof height h.

The numerical coefficient 0.00256 (0.613 in SI) shall be used except where sufficient climatic data are available to justify the selection of a different value of this factor for a design application.

6.5.11 Pressure and Force Coefficients.

6.5.11.1 Internal Pressure Coefficient. Internal pressure coefficients, GC_{pi}, shall be determined from Fig. 6-5 based on building enclosure classifications determined from Section 6.5.9.

6.5.11.1.1 Reduction Factor for Large Volume Buildings, R_i. For a partially enclosed building containing a single, unpartitioned large volume, the internal pressure coefficient, GC_{pi}, shall be multiplied by the following reduction factor, R_i:

$R_i = 1.0$ or

$$R_i = 0.5\left(1 + \frac{1}{\sqrt{1 + \frac{V_i}{22{,}800 A_{og}}}}\right) \le 1.0 \quad (6\text{-}16)$$

where

A_{og} = total area of openings in the building envelope (walls and roof, in ft^2)

V_i = unpartitioned internal volume, in ft^3

6.5.11.2 External Pressure Coefficients.

6.5.11.2.1 Main Wind-Force Resisting Systems. External pressure coefficients for MWFRSs C_p are given in Figs. 6-6, 6-7, and 6-8. Combined gust effect factor and external pressure coefficients, GC_{pf}, are given in Fig. 6-10 for low-rise buildings. The pressure coefficient values and gust effect factor in Fig. 6-10 shall not be separated.

6.5.11.2.2 Components and Cladding. Combined gust-effect factor and external pressure coefficients for components and cladding GC_p are given in Figs. 6-11 through 6-17. The pressure coefficient values and gust-effect factor shall not be separated.

6.5.11.3 Force Coefficients. Force coefficients C_f are given in Figs. 6-20 through 6-23.

6.5.11.4 Roof Overhangs.

6.5.11.4.1 Main Wind-Force Resisting System. Roof overhangs shall be designed for a positive pressure on the bottom surface of windward roof overhangs corresponding to $C_p = 0.8$ in combination with the pressures determined from using Figs. 6-6 and 6-10.

6.5.11.4.2 Components and Cladding. For all buildings, roof overhangs shall be designed for pressures determined from pressure coefficients given in Figs. 6-11B,C,D.

6.5.11.5 Parapets.

6.5.11.5.1 Main Wind-Force Resisting System. The pressure coefficients for the effect of parapets on the MWFRS loads

2.4.2 Buildings with $h > 60$ ft (18.3 m). Design wind s on components and cladding for all buildings with $h >$ 3 m) shall be determined from the following equation:

$$q(GC_p) - q_i(GC_{pi}) \text{ (lb/ft}^2\text{) (N/m}^2\text{)} \quad (6\text{-}23)$$

= q_z for windward walls calculated at height z above the ground
= q_h for leeward walls, side walls, and roofs, evaluated at height h
= q_h for windward walls, side walls, leeward walls, and roofs of enclosed buildings and for negative internal pressure evaluation in partially enclosed buildings
= 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 buildings sited in wind-borne debris regions, glazing that is not impact resistant or protected with an impact-resistant covering, shall be treated as an opening in accordance with Section 6.5.9.3. For positive internal pressure evaluation, q_i may conservatively be evaluated at height h ($q_i = q_h$)
= external pressure coefficient from Fig. 6-17
= internal pressure coefficient given in Fig. 6-5.

q_i shall be evaluated using exposure defined in Section

.4.3 **Alternative Design Wind Pressures for Compo- d Cladding in Buildings with 60 ft (18.3 m) $< h <$ 7.4 m).** Alternative to the requirements of Section 2, the design of components and cladding for buildings ean roof height greater than 60 ft (18.3 m) and less than 4 m) values from Figs. 6-11 through 6-17 shall be used e height to width ratio is one or less (except as permitted 5 of Fig. 6-17) and Eq. 6-22 is used.

.4.4 **Parapets.** The design wind pressure on the compo- l cladding elements of parapets shall be designed by the ; equation:

$$_p(GC_p - GC_{pi}) \quad (6\text{-}24)$$

velocity pressure evaluated at the top of the parapet
external pressure coefficient from Figs. 6-11 through 6-17
nternal pressure coefficient from Fig. 6-5, based on the porosity of the parapet envelope

ad cases shall be considered. Load Case A shall consist g the applicable positive wall pressure from Fig. 6-11A 17 to the front surface of the parapet while applying the negative edge or corner zone roof pressure from Figs. gh 6-17 to the back surface. Load Case B shall consist g the applicable positive wall pressure from Fig. 6-11A 17 to the back of the parapet surface, and applying the negative wall pressure from Fig. 6-11A or Fig. 6-17 nt surface. Edge and corner zones shall be arranged in Figs. 6-11 through 6-17. GC_p shall be determined riate roof angle and effective wind area from Figs. 6-11 17. If internal pressure is present, both load cases should ed under positive and negative internal pressure.

sign Wind Loads on Open Buildings with

6.5.13.1.1 **Sign Convention.** Plus and minus signs signify pressure acting toward and away from the top surface of the roof, respectively.

6.5.13.1.2 **Critical Load Condition.** Net pressure coefficients C_N include contributions from top and bottom surfaces. All load cases shown for each roof angle shall be investigated.

6.5.13.2 **Main Wind-Force Resisting Systems.** The net design pressure for the MWFRSs of monoslope, pitched, or troughed roofs shall be determined by the following equation:

$$p = q_h G C_N \quad (6\text{-}25)$$

where

q_h = velocity pressure evaluated at mean roof height h using the exposure as defined in Section 6.5.6.3 that results in the highest wind loads for any wind direction at the site
G = gust effect factor from Section 6.5.8
C_N = net pressure coefficient determined from Figs. 6-18A through 6-18D

For free roofs with an angle of plane of roof from horizontal θ less than or equal to 5° and containing fascia panels, the fascia panel shall be considered an inverted parapet. The contribution of loads on the fascia to the MWFRS loads shall be determined using Section 6.5.12.2.4 with q_p equal to q_h.

6.5.13.3 **Component and Cladding Elements.** The net design wind pressure for component and cladding elements of monoslope, pitched, and troughed roofs shall be determined by the following equation:

$$p = q_h G C_N \quad (6\text{-}26)$$

where

q_h = velocity pressure evaluated at mean roof height h using the exposure as defined in Section 6.5.6.3 that results in the highest wind loads for any wind direction at the site
G = gust-effect factor from Section 6.5.8
C_N = net pressure coefficient determined from Figs. 6-19A through 6-19C

6.5.14 **Design Wind Loads on Solid Freestanding Walls and Solid Signs.** The design wind force for solid freestanding walls and solid signs shall be determined by the following formula:

$$F = q_h G C_f A_s \text{ (lb) (N)} \quad (6\text{-}27)$$

where

q_h = the velocity pressure evaluated at height h (defined in Fig. 6-20) using exposure defined in Section 6.5.6.4.1
G = gust-effect factor from Section 6.5.8
C_f = net force coefficient from Fig. 6-20
A_s = the gross area of the solid freestanding wall or solid sign, in ft² (m²)

6.5.15 **Design Wind Loads on Other Structures.** The design wind force for other structures shall be determined by the following equation:

$$F = q_z G C_f A_f \text{ (lb) (N)} \quad (6\text{-}28)$$

where

q_z = velocity pressure evaluated at height z of the centroid of area A_f using exposure defined in Section 6.5.6.3
G = gust-effect factor from Section 6.5.8
C_f = force coefficients from Figs. 6-21 through 6-23

Appendix B

WIND DIRECTIONALITY K_D

Structure Type	Directionality Factor K_d*
Buildings	
Main Wind Force Resisting System	0.85
Components and Cladding	0.85
Arched Roofs	0.85
Chimneys, Tanks, and Similar Structures	
Square	0.90
Hexagonal	0.95
Round	0.95
Solid Signs	0.85
Open Signs and Lattice Framework	0.85
Trussed Towers	
Triangular, square, rectangular	0.85
All other cross sections	0.95

*Directionality Factor K_d has been calibrated with combinations of loads specified in Section 2. This factor shall only be applied when used in conjunction with load combinations specified in 2.3 and 2.4.

Appendix C
VARIATION FACTOR, I

Category	Non-Hurricane Prone Regions and Hurricane Prone Regions with V = 85-100 mph and Alaska	Hurricane Prone Regions with V > 100 mph
I	0.87	0.77
II	1.00	1.00
III	1.15	1.15
IV	1.15	1.15

Note:

1. The building and structure classification categories are listed in Table 1-1.

Appendix D

VELOCITY EXPOSURE COEFFICIENT K_H AND K_Z

Velocity Pressure Exposure Coefficients, K_h and K_z

Table 6-3

Height above ground level, z		Exposure (Note 1)			
		B		C	D
ft	(m)	Case 1	Case 2	Cases 1 & 2	Cases 1 & 2
0-15	(0-4.6)	0.70	0.57	0.85	1.03
20	(6.1)	0.70	0.62	0.90	1.08
25	(7.6)	0.70	0.66	0.94	1.12
30	(9.1)	0.70	0.70	0.98	1.16
40	(12.2)	0.76	0.76	1.04	1.22
50	(15.2)	0.81	0.81	1.09	1.27
60	(18)	0.85	0.85	1.13	1.31
70	(21.3)	0.89	0.89	1.17	1.34
80	(24.4)	0.93	0.93	1.21	1.38
90	(27.4)	0.96	0.96	1.24	1.40
100	(30.5)	0.99	0.99	1.26	1.43
120	(36.6)	1.04	1.04	1.31	1.48
140	(42.7)	1.09	1.09	1.36	1.52
160	(48.8)	1.13	1.13	1.39	1.55
180	(54.9)	1.17	1.17	1.43	1.58
200	(61.0)	1.20	1.20	1.46	1.61
250	(76.2)	1.28	1.28	1.53	1.68
300	(91.4)	1.35	1.35	1.59	1.73
350	(106.7)	1.41	1.41	1.64	1.78
400	(121.9)	1.47	1.47	1.69	1.82
450	(137.2)	1.52	1.52	1.73	1.86
500	(152.4)	1.56	1.56	1.77	1.89

Notes:

1. **Case 1:** a. All components and cladding.
   b. Main wind force resisting system in low-rise buildings designed using Figure 6-10.

   Case 2: a. All main wind force resisting systems in buildings except those in low-rise buildings designed using Figure 6-10.
   b. All main wind force resisting systems in other structures.

2. The velocity pressure exposure coefficient K_z may be determined from the following formula:

   For 15 ft. $\le z \le z_g$: $K_z = 2.01\,(z/z_g)^{2/\alpha}$

   For $z < 15$ ft.: $K_z = 2.01\,(15/z_g)^{2/\alpha}$

   Note: z shall not be taken less than 30 feet for Case 1 in exposure B.

3. α and z_g are tabulated in Table 6-2.

4. Linear interpolation for intermediate values of height z is acceptable.

5. Exposure categories are defined in 6.5.6.

Appendix E

TERRAIN EXPOSURE CONSTANT

Exposure	α	z_g (ft)	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	ℓ (ft)	$\bar{\epsilon}$	z_{min} (ft)*
B	7.0	1200	1/7	0.84	1/4.0	0.45	0.30	320	1/3.0	30
C	9.5	900	1/9.5	1.00	1/6.5	0.65	0.20	500	1/5.0	15
D	11.5	700	1/11.5	1.07	1/9.0	0.80	0.15	650	1/8.0	7

*z_{min} = minimum height used to ensure that the equivalent height $\bar{z}$ is greater of $0.6h$ or z_{min}.
For buildings with $h \le z_{min}$, $\bar{z}$ shall be taken as z_{min}.

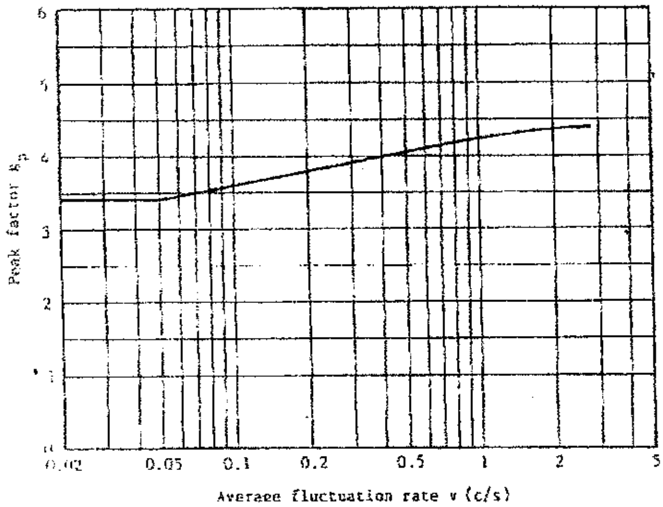
In metric

Exposure	α	z_g (m)	$\hat{a}$	$\hat{b}$	$\bar{\alpha}$	$\bar{b}$	c	ℓ (m)	$\bar{\epsilon}$	z_{min} (m)*
B	7.0	365.76	1/7	0.84	1/4.0	0.45	0.30	97.54	1/3.0	9.14
C	9.5	274.32	1/9.5	1.00	1/6.5	0.65	0.20	152.4	1/5.0	4.57
D	11.5	213.36	1/11.5	1.07	1/9.0	0.80	0.15	198.12	1/8.0	2.13

*z_{min} = minimum height used to ensure that the equivalent height $\bar{z}$ is greater of $0.6h$ or z_{min}.
For buildings with $h \le z_{min}$, $\bar{z}$ shall be taken as z_{min}.

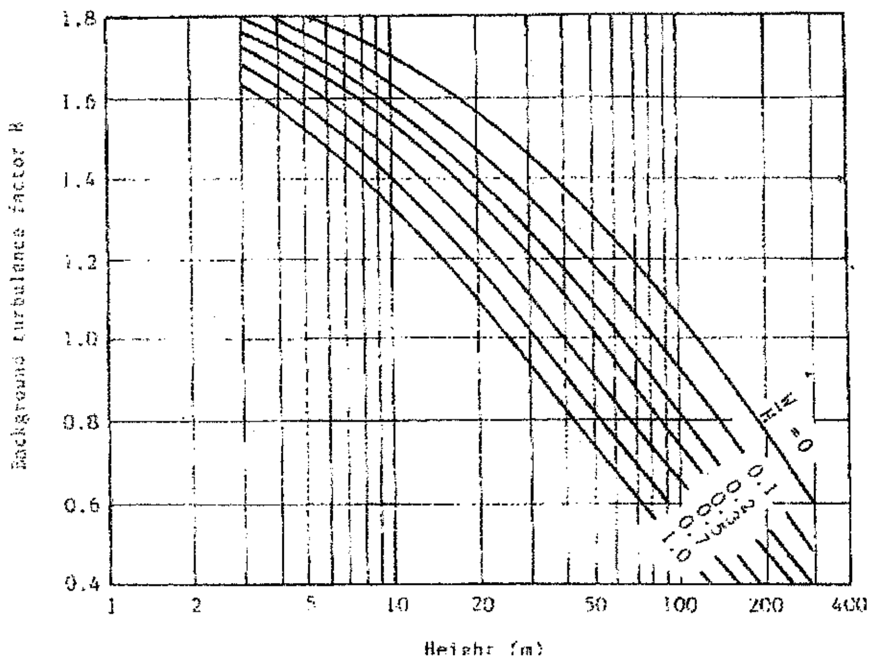
Appendix F

VARIATION OF PEAK FACTOR WITH AVERAGE FLUCTUATION RATE



Appendix G

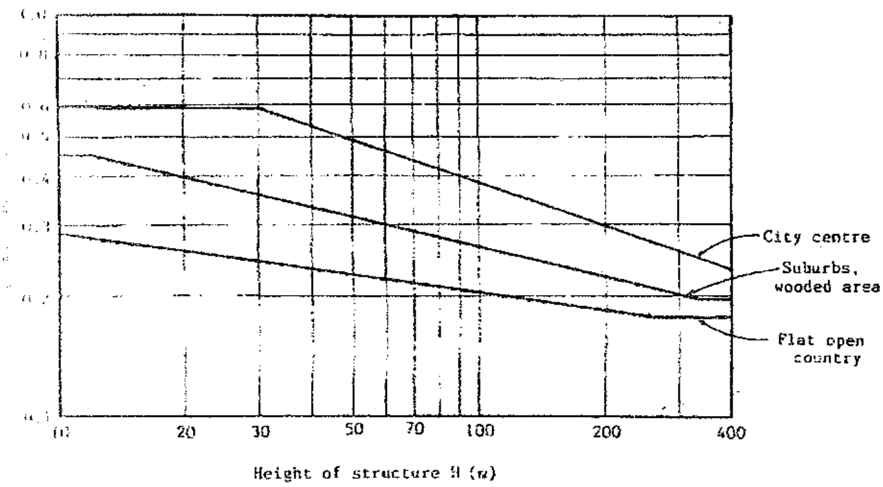
VARIATION OF TURBULENCE BACKGROUND FACTOR WITH HEIGHT AND ASPECT RATIO OF BUILDING



Appendix H

VARIATION OF ROUGHNESS FACTOR WITH BUILDING HEIGHT

426 DYNAMIC ANALYSIS



Appendix I

MAXIMUM 5 YEARS ACCELERATION ACCORDING TO ISO 6897