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COMPARISON OF AMERICAN AND CANADIAN PRACTICES FOR WIND LOAD CALCULATIONS

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ABSTRACT: Various wind standards and building codes are available for evaluating wind loads on buildings with common shapes. International wind standards provided by American Society of Civil Engineers (ASCE 7-05) and National Research Council of Canada (NBC 2005) are among the most commonly used building codes in various parts of the world. This research work is mainly focused on comparing the wind loads obtained using ASCE 7-05 and NBC 2005 provisions. A sixty storey tall building (30 m x 30 m x 220 m.) with box structure is analyzed for wind loads provided by these building codes. A design wind speed of 160 km/hr has been adopted which represents the common wind speed used in coastal areas. The similarities as well as differences in the results have been discussed. A cost comparison is presented to assess the disparities in the wind loads provisions.

Key words: Wind Loads, Tall Buildings.

INTRODUCTION

Wind loads are of major concern while designing structures especially in strong wind regions. Unless properly accounted for, high speed winds can cause major destruction (Simiu and Miyata, 2006). While designing a structure for wind, safety and economy are the most important factors. It is always desirable to economize the design without compromising on safety. Wind standard and codes usually provide wind loads for buildings with common shapes, for complex situations they refer the practitioner for physical simulation in a boundary layer wind tunnel. The present study focuses on building code wind load provisions. Similar study on the comparison of along-wind loads and their effects on tall buildings utilizing major international codes and standards was carried out by Zhou et al. (2002). Some countries do not have their own wind standards and they use one of the major international wind standards. However there are some differences on the standard provisions even for building codes that are in the same continent, such as those provided by American Society of Civil Engineers (ASCE 7-05) and National Research Council of Canada (NBC 2005). This study, therefore, focuses on studying similarities and differences between ASCE 7-05 and NBC 2005 wind load provisions. For this purpose a sixty storey structure (30 m x 30 m x 220 m) has been analyzed for wind loads provided by these two codes and designed by the recommendations of American Concrete Institute (ACI 318-08). A comparison is presented among the shear forces and lateral displacement and finally a cost comparison of the final design, that satisfy same deflection criteria, is included to find out the economical implications of the differences among the two codes.

MATERIALS AND METHODS

ASCE 7-05 wind loads: ASCE 7-05 describes wind load calculations for buildings and other structures in two categories, wind loads on Main Wind Force Resisting System (MWFRS), and all components and claddings. It presents three methods. Methods-1 (Simplified Procedure) mainly deals with low-rise rigid buildings. Method-2 (Analytical Procedure) covers regular shaped flexible structures not subjected to cross wind loading, vortex shedding and instability due to galloping etc. For the structures having unusual shapes or response characteristics, Method-3 is recommended which is Wind Tunnel Procedure. For Method-2, which is used in the present study, velocity pressure is calculated using the following equation 6-15 from ASCE 7-05:

$$q_z = 0.00256 k_z k_{zt} k_d V^2 I \left(\mathrm{lb/ft^2}\right) \quad (1)$$

Where

K_d = Wind directionality factor

K_z = Velocity pressure exposure coefficient (Open terrain)

K_{zt} = Topographical factor

V = 3-second gust speed at 10 m

I = Importance factor

Design wind pressure for MWFRS of flexible building is calculated from the equation 6-19 from ASCE 7-05:

$$P = qG_f C_p - q_i G C_{pi} \quad \left(\text{lb/ft}^2\right) \tag{2}$$

Where

G_f = Gust factor (ASCE 7-05, Eq. 6-8)

C_p = External Pressure coefficient

C_{pi} = Internal Pressure coefficient

$$G_f = 0.925\left(\frac{1+1.7I_z\sqrt{g_Q^2Q^2+g_R^2R^2}}{1+1.7g_vI_z}\right) \quad (3)$$

Where

I_z = Intensity of turbulence

g_Q = Peak factor for background response

g_R = Peak factor for resonant response

g_v = Peak factor for peak response

R = Resonant response factor

Q = Background response factor

NBC 2005 Wind Loads: National Building Code (NBC 2005) is an updated version of National Building Code of Canada (NBCC 1995). Similar to ASCE 7-05, this code also presents three methods. For low and medium rise rigid buildings and claddings of all buildings Static Procedure is presented. Tall buildings and slender structures are covered under Dynamic Procedure. Structures having irregular geometry or subjected to buffeting/channelling effect are recommended to be analysed by Wind Tunnel procedure. The following equation (NBC 2005 1.1.3) is used to calculate Reference Wind Pressure (q):

$$q = 0.00064645\ V^2 \quad (kPa) \tag{4}$$

Design wind pressure (P_e) is provided by following equation (NBC 2005 4.1.7.1):

$$P_e = I_w q C_g \left[\left(C_e C_p \right)_{WW} + \left(C_e C_p \right)_{LW} \right] \quad (kPa) \qquad (5)$$

Where
V = Mean hourly wind speed in m/s
I_w = Importance factor
C_e = Exposure factor (Open terrain)
C_g = Gust effect factor (Eq. 11, User's Guide - NBC 2005 Structural Commentaries)
C_p = Pressure coefficient

$$C_g = 1 + g_b\left(\frac{\sigma}{\mu}\right) \quad (6)$$

Where

g_b = Statistical peak factor for the loading effect

μ = mean loading effect

σ = "Root mean square" loading effect

Description of Structure: The tall building analysed has dimensions 30 m x 30 m x 220 m. It is a reinforced concrete structure having five bays in each direction, 6 m x 6 m each. The building has sixty stories with 3.66 m ceiling height. Number of stories and total height of the structure are selected in such a proportion that it behaves as flexible. A structure having natural frequency less than one is considered flexible. Both codes provide a method to account for the resonance effects for flexible structure. Figure 1. shows the basic plan of the structure.

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42f310cb4110014b7110020000000ffffffff8c50d100d064
2f31ffffffffffff0180ffff0180efff0180ffffffff00000000000
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d01010005000000090200000002 0d000000320a0c00000
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Figure 1: Basic Layout of Structure

Following are some relevant details:

28 days concrete strength, $f_c' = 35$ MPa

Yield strength of steel, $f_y = 420$ MPa

All slabs thickness = 150 mm

All shear walls thickness = 300 mm

Following approximate natural frequency (f) of structure was used to find the initial wind gust factor:

$$f = \frac{10}{\text{No. of Stories}} = \frac{10}{60} = 0.167\ hz \quad (7)$$

Parameters of analysis for ASCE 7-05: Analysis is carried out for a basic wind speed of 160 km/hr (100 mph) applied parallel to global x-axis. This is consistent with globally used wind speed for open terrain/coastal areas. This is, however, more than what is recommended by Building Code of Pakistan for coastal areas (120 km/hr). This is important to note that ASCE 7-05 is based on 3-second gust speed at 10 m (33 ft.) height. ASCE 7-05 describes four different wind load cases. Because this exercise is carried out for the purpose of comparison, therefore, structure is analysed only for case-1, which is explained in Figure 2.

P_{wx} = Windward face design pressure

P_{Lx} = Leeward face design pressure

Figure 2: Full Design Wind Pressure Acting on Both Sides

Following are the parameters used in analysis.

Windward pressure coefficient, $C_p = 0.8$

Leeward pressure coefficient, $C_p = 0.5$

Exposure type: D (Flat, unobstructed areas and water surface outside hurricane prone zone)

Importance factor, I = 1.0

Topographical factor, $k_{zt} = 1.0$

Gust effect factor, $G_f = 1.21$

Directionality factor, $k_d = 0.8$

Velocity pressure exposure coefficient, k_z: It varies with height and can be calculated by the following equation (ASCE 7-05, Eq. C6-4a, 4b):

$$k_z = 2.01\left(\frac{z}{z_g}\right)^{2/\alpha} \qquad \text{for} \quad (15\text{ft.})\, 4.6\text{m} \le z \le z_g$$
(8)

$$k_z = 2.01\left(\frac{15}{z_g}\right)^{2/\alpha} \qquad \text{for} \quad z < 4.6\ \text{m (15ft.)}$$

From Table 6-2 of ASCE 7-05, for exposure D:

$\alpha = 11.5, z_g = 213\,\text{m}\,(700\text{ ft})$

Where

z = Height above ground level in ft.

z_g = Gradient height.

Parameters of analysis for NBC 2005: Dynamic procedure is adopted for analysis as per NBC 2005 recommendation for building with total height more than 120 m (394 ft.). Note that NBC 2005 is based on a mean hourly wind speed unlike ASCE 7-05, which uses 3-second gust speed. Therefore mean hourly wind speed corresponding to 3-second gust speed of 160 km/hr (100 mph) is calculated by applying a conversion factor of 1.52 (Durst, 1960) yielding in 105.3 km/hr (65.79 mph). NBC 2005 describes exposure A for open terrain so it is used in the analysis in comparison with exposure D (open terrain) of ASCE 7-05. Similar to ASCE 7-05, NBC 2005 also talks about four different load cases. Case-A is selected corresponding to case-1 of ASCE 7-05, which applies full wind pressure on windward and leeward sides with zero eccentricity. Following are some relevant parameters used in analysis:

Wind ward pressure coefficient, C_p = 0.8

Lee ward pressure coefficient, C_p = 0.5

Importance factor, I_w = 1.0

Gust effect factor, C_g = 2.23

Exposure factor C_e is calculated from following formula (NBC 2005 4.1.7.1):

$$C_e = \left(\frac{h}{10}\right)^{0.28} \qquad 1.0 \le C_e \le 2.5 \qquad (9)$$

An important point to note about NBC 2005 is its criterion on lateral deflection of tall buildings. NBC 2005 imposes maximum lateral deflection limitation of 1/128 to 1/1000 of the building height. Further, 1/500 should be used unless other drift limitations are specified. Following limit is used in this exercise:

$$\text{Maximum Lateral Deflection}, \Delta_{max} = \frac{1}{500} \times (220 \times 1000) = 440 \text{ mm (17.3 in.)}$$

RESULTS AND DISCUSSION

A general purpose finite element program SAP 2000 (CSI Reference Manual) was used from analyses. At the first stage, analysis was carried out with no shear walls present in the structure, as shown in Figure 1. It exhibited very large lateral deflection at the top. To control lateral deflection, shear walls were successively introduced at several locations. Figure 3 shows the arrangement of shear walls for which the maximum lateral deflection (Δ_{max}) falls within the permissible limit (440 mm) for wind loads based on both ASCE 7-05 and NBC 2005. The difference between the two codes is that ASCE 7-05 requires a shear wall thickness of 240 mm (9.5 in.) whereas NBC 2005 requires 290 mm (11.5 in.) to bring the Δ_{max} with in limit. With 240 mm (9.5 in.) shear wall thickness ASCE 7-05 exhibit Δ_{max} = 423.93 mm (16.69 in.) and with 290 mm (11.5 in.) thickness NBC 2005 shows Δ_{max} = 412.75 mm (16.25 in.). It has been noted that the major difference lies on the wind directionality reduction in ASCE 7-05 wind loads (k_d = 0.8). Figure 4 shows the first three modes of structure due to wind load. Generally, for flexible structures, only first three modes are important. First mode is most critical as is exhibits maximum lateral deflection.

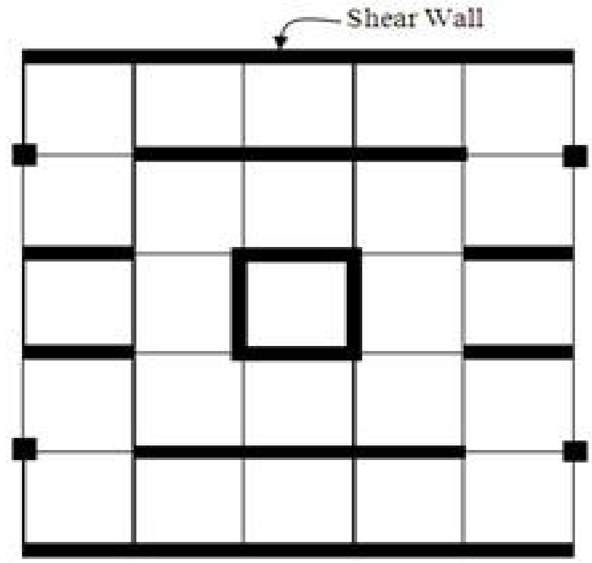

Figure 3: Final Arrangement of Shear Walls

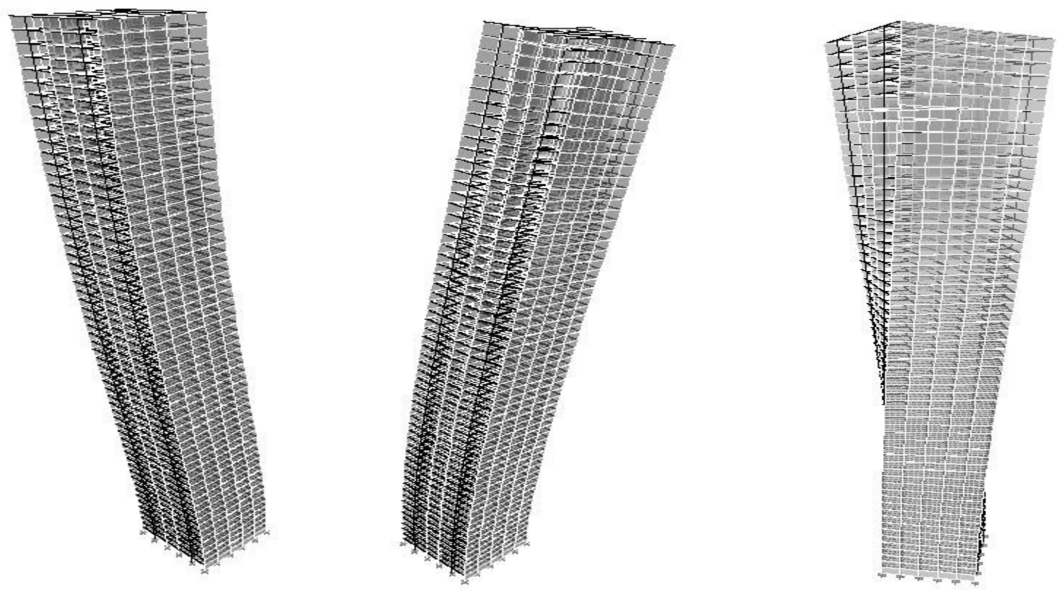

Figure 4: First Three Modes of Structure

Figure 5 and 6 present a comparison between lateral deflections and storey shear forces for wind loads based on ASCE 7-05 and NBC 2005 provision. It is clear that ASCE 7-05 provides low storey shear (Figure 6) compared to NBC 2005 wind loads.

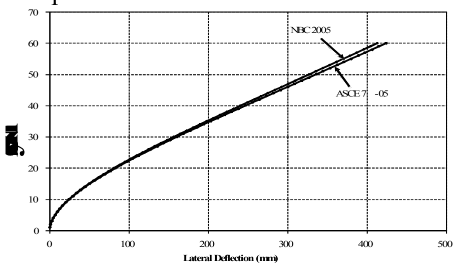

Figure 5: Comparison of Lateral Deflection

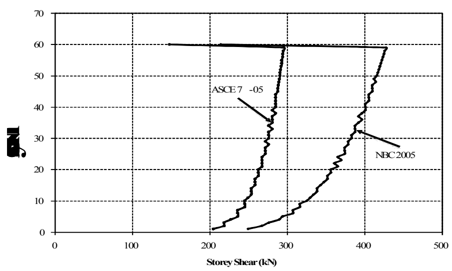

Figure 6: Comparison of Storey Shear

Design for Wind Loads: After finalising the analysis, design of reinforced concrete (RC) members (beams and columns) was carried out according to ACI 318-08. For comparisons purposes structure is only designed for factored wind loads (1.6W). Because wind forces are only applied in x-direction therefore rectangular columns are provided and almost all shear walls are oriented in x-direction. Column sizes are finalised in a manner that they require reinforcement 1% to 2% of the cross sectional area, in this way a better comparison could be drawn.

Material and Cost Comparison: Finally the cost comparison is presented between the design based on wind loads of ASCE 7-05 and NBC 2005. The major difference is in thickness of shear walls therefore quantities of concrete are calculated for shear walls only. A comparison of the amount of material and cost is presented in Table 1. Unit rate of 100 \$/yard^3 is considered for concrete.

Table 1: Material and Cost Comparison

Shear Walls			
Amount of Concrete (yard^3)		Cost (\$)	
ASCE 7-05	**NBC2005**	**ASCE 7-05**	**NBC2005**
10,133	12,267	10,13,300	12,26,700

Conclusions: This study was focused on comparing American and Canadian for the calculations of wind loads on regular shaped tall buildings. A sixty storey flexible building was analyzed and designed for wind loads provided by ASCE 7-05 and NBC 2005. Considering the boom in the tall building construction in Pakistan, this exercise is hoped to shed some light on the use of international building codes. NBC 2005 results in 21% more material cost for shear walls than that of ASCE 7-05. If construction cost is also included the difference will be even larger. It is noted that the difference between the two codes is mainly due to the directionality factor (k_d), which ASCE 7-05 suggests as 0.8, while there is no similar reduction factor provided by NBC 2005. One general observation is that NBC 2005 is written in a simple manner and relatively easier to implement. Other major codes like Australian (AS/NZ 1170.2), British (BS 6399-2: 1997) and International Building Code (IBC 2006) should also be compared with ASCE 7-05 and NBC 2005. Comparison is also recommended for eccentric wind forces which produce torsional effects.

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