

Wind-induced torsional aerodynamic loads on low and medium height buildings

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ABSTRACT: Since there is limited information about wind-induced torsional loads on buildings, wind tunnel tests were carried out on a series of buildings with low and medium heights. Four buildings (scale 1:400), having the same horizontal dimensions but different heights (6, 12, 25 and 50 m), were tested in a simulated open terrain exposure for different wind directions (i.e. from 0° to 180° every 15°). The synchronized wind pressure measurements on the rigid building model allowed estimating the instantaneous shear forces and torsional moments. All results were normalized and presented in terms of mean and peak values of shear and torsional coefficients representing two load cases (torsion and shear load). Furthermore, the experimental results were compared with the existing torsion- and shear-related provisions in the National Building Code of Canada (NBCC 2010), the American Society of Civil Engineers Standard (ASCE/SEI 7-10) and the European Code (EN 1991-1-4). The results demonstrated significant discrepancies among the provisions of these wind standards from one side and the wind tunnel results from another in evaluating torsional wind loads on low and medium height buildings. The findings of this study could assist to improve the analytical methods to evaluate wind-induced torsional loads on low and medium height buildings.

KEYWORDS: Torsion, wind loads, codes, low buildings, medium height buildings, structural design

1 INTRODUCTION

The common characteristics of wind-induced loads on building envelopes continuously vary in temporal and spatial dimensions. The variation of local wind pressures on building claddings and the total effective wind forces (base shear/overturning moment) on the main structural building systems of low and medium rise buildings have been investigated extensively in the past few decades (Krishna, 1995, Stathopoulos and Dumitrescu, 1989, and Sanni et al, 1992). However, studies on wind-induced torsional loads on low and medium height buildings are very limited. Discrepancies have been found when wind-induced torsional load provisions for low and medium height buildings in three well known building codes and standards (American, Canadian, and Eurocode) were compared by Elsharawy et al. 2011. Wind-induced torsion has been measured in the wind tunnel for three low-rise buildings with different aspect ratios (length/width = 1, 2, and 3) in open terrain exposure by Isyumov and Case, 2000. The study suggested that applying partial wind loads, similar to those implemented for the design of tall buildings, would improve the design of low buildings until more pertinent data become available. Recently, three low rise buildings having the same horizontal dimensions but different roof angles (0° , 18.4° , and 45°) located in open terrain exposure were tested by Elsharawy et al. 2012. The results were also compared to the current wind load provisions and it was found that the American standard introduces torsional moment in line with the experimental data, while the Canadian and Eurocode provisions underestimate the torsional moment on low buildings.

In the current study, wind-induced torsional loads on low and medium height buildings were examined in the boundary layer wind tunnel. Building model (scaled at 1:400) has been used to represent four actual buildings having the same horizontal dimensions but with different heights. All buildings were tested in open exposure for different wind directions. The synchronized wind tunnel measurements were presented in terms of shear, and torsional coefficients. Furthermore, the experimental results were compared with wind provisions in the NBCC 2010, ASCE/SEI 7-10 and EN 1991-1-4.

2 WIND TUNNEL STUDIES

All experiments were carried out in a boundary layer wind tunnel with a working section approximately 12.2 x 1.80 m and an adjustable roof height ranging between 1.4 and 1.8 m. A turntable of 1.2 m diameter is located on the test section of the tunnel and allows testing of models for any wind direction. A new automated Traversing Gear system has been installed to give the capability of measuring wind characteristics at any spatial location around a building model inside the test section. A geometric scale of 1:400 has been recommended for the simulation of the most important variables of the atmospheric boundary layer under strong wind conditions.

2.1 Building models

The basic building model used for the experiments was fabricated from plexiglass and scaled at 1:400. Figure 1 shows the model and the location of 146 pressure taps on its side walls. The roof does not have any pressure taps, since the uplift force does not contribute to torsion or horizontal shear forces. The model was tested at different building heights representing four actual buildings with heights (6, 12, 25 and 50 m). Model dimensions and the tested building heights are given in Table 1.

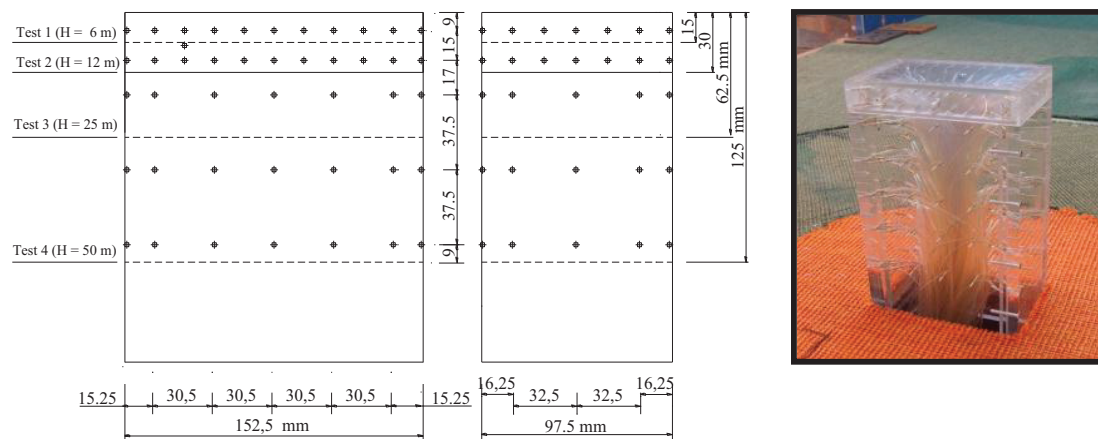


Figure 1. Building model and 146 pressure taps location.

Table 1. Model dimensions and Building heights tested

Building	Dimensions	
	Scaled (1:400, mm)	Actual (m)
Width (B)	97.5	39
Length (L)	152.5	61
Tested heights (h)	15, 30, 62.5, 125	6, 12, 25, 50

2.2 Terrain simulations

An open-country exposure was simulated in the wind tunnel. Figure 2 shows the flow approach profiles of mean wind velocity and turbulence intensity measured using a 4-hole Cobra probe (TFI) for the simulated terrain exposure. The gradient wind velocity is 13.6 m/s at a height of $z_g=70$ cm. The power law exponent for the wind velocity profiles simulated in these tests was 0.16. Although, it is not common for medium height buildings to be situated in open terrain, this exposure was used as a kind of conservatism since higher loads are expected to act on buildings. The pressure measurements on the models were conducted using a system of miniature pressure scanners from Scanivalve (ZOC33/64Px) and the digital service module DSM 3400. All measurements were synchronized with a sampling rate of 300Hz on each channel for a period of 27 sec (i.e. about 1 hour in full scale).

2.3 Analytical approach

Figure 3 shows a schematic representation of external pressure distributions on building envelope at a certain instant, the exerted shear forces (F_X , F_Y) and torsional moment (M_T). Pressure measurements are scanned simultaneously. The instantaneous wind force at each pressure tap is calculated according to

$$f_{i,t} = (P_{i,t} \times A_{\text{effective}}) \quad f_{j,t} = (P_{j,t} \times A_{\text{effective}}) \quad (1)$$

where $P_{i,t}$ and $P_{j,t}$ are instantaneous pressures measured at each pressure tap. The wind forces exerted at pressure tap locations in X- and Y-directions are noted by $f_{i,t}$ and $f_{j,t}$, respectively. For each wind direction, the horizontal force components in X- and Y-directions, and the total base shear, are evaluated according to

$$F_X = \sum_{i=1}^N f_{i,t} \quad F_Y = \sum_{j=1}^M f_{j,t} \quad V = \sqrt{F_X^2 + F_Y^2} \quad (2)$$

where N and M are the numbers of the pressure taps on the longitudinal and transverse directions, respectively. All these forces are normalized with respect to the dynamic wind pressure at the mean roof height as follows:

$$C_{vx} = \frac{F_x}{q_h B h} \quad C_{vy} = \frac{F_Y}{q_h B h} \quad C_v = \frac{V}{q_h B h} \quad (3)$$

Where q_h = dynamic wind pressure at mean roof height (kN/m^2), B = minimum horizontal building dimension (m), and h = mean roof building height (m). The torsional coefficients (C_T) and equivalent eccentricity (e) are evaluated based on

$$C_T = \frac{M_T}{q_h B h L} \quad e(\%) = \frac{M_T}{L * V} \times 100 \quad (4)$$

where L= building length

NBCC 2010 specifies wind loads on low buildings (mean roof height, $h < 10$ m, or $h < \text{width}$, B and $h < 20$ m) and medium-height rigid buildings ($h < 60$ m, $h/B < 4$, lowest natural frequency, $f_n > 1$ Hz). On the other hand, ASCE/SEI 7-10 identifies low buildings as ($h < 18$ m and $h < B$) and medium-height rigid buildings as having $f_n > 1$ Hz. In EN 1991-1-4, low buildings were defined as those with $h < 15$ m while buildings with frames, structural walls with h less than 100 m are introduced structurally as rigid buildings. In this study all tested buildings were assumed to be structurally rigid and follow the limitations stated in the three wind load standards.

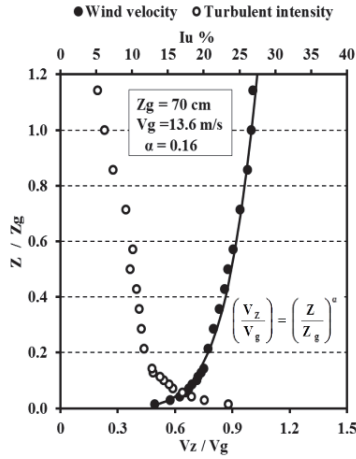


Figure 2. Wind velocity and turbulence intensity profiles for open terrain exposure.

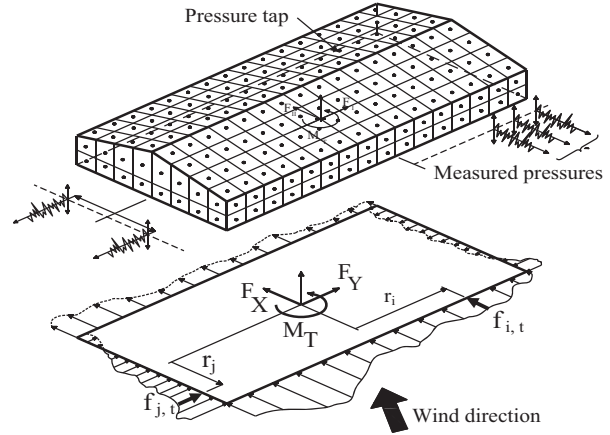


Figure 3. Instantaneous wind pressure distributions, generated wind forces (F_X , F_Y) and torsional moment (M_T).

3 COMPARISON WITH PREVIOUS STUDIES

A comparison with a previous study by Amin and Ahuja, 2012 for building ($L = 37.5$, $B = 15$, $h = 90$ m, scale 1:300, 140 pressure taps) was made using the wind tunnel measurements for building model ($L = 61$ m, $B = 39$ m, $h = 50$ m, scale 1:400, 146 pressure taps). Figure 3 shows the evaluated mean torsion for both buildings for different wind directions. The mean torsion coefficient was calculated based on the following formula

$$C_{T\text{ Mean}} = \text{Mean Base Torsion} / (q_h B h L) = \left(\sum_{i=1}^{i=n} C_{P\text{ Mean}} \times A_{\text{effective}} \times r_i \right) / B h L \quad (5)$$

Where n =number of pressure taps, $C_{P\text{ Mean}}$ = mean pressure coefficient, $A_{\text{effective}}$ = presented area by the pressure tap, r_i = the distance between pressure tap and the building center.

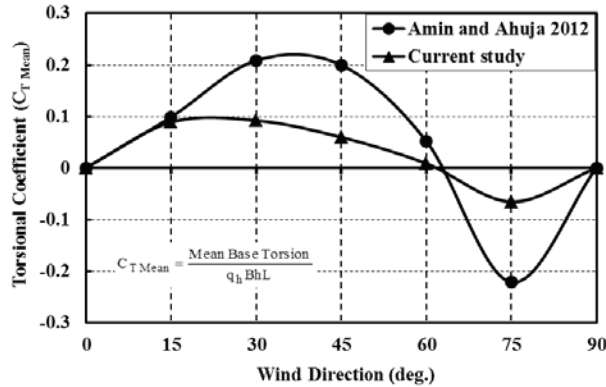


Figure 3. Mean torsional coefficient measured by Amin and Ahuja, 2012 and the current study

Data show relatively good agreement for the variation of the mean torsional coefficient measured in the two studies. The differences seen between the two studies for some wind directions may be attributed to the difference in building dimensions, the scale used, the number of pressure taps.

4 EXPERIMENTAL RESULTS

4.1. Variation of torsion and shear coefficients:

Figure 4 shows the variation of mean and peak shear coefficients (C_{vx} , C_{vy}) with wind direction for the two buildings (6 and 50 m) tested in simulated open-country exposure. The maximum shear forces in x-direction occur for wind directions from 0° to 45° ; while in y-direction when wind is almost perpendicular to building face, i.e. 90° . For the tested buildings, the peak shear coefficients have increased by about 50% with increasing building heights form 6 to 50 m.

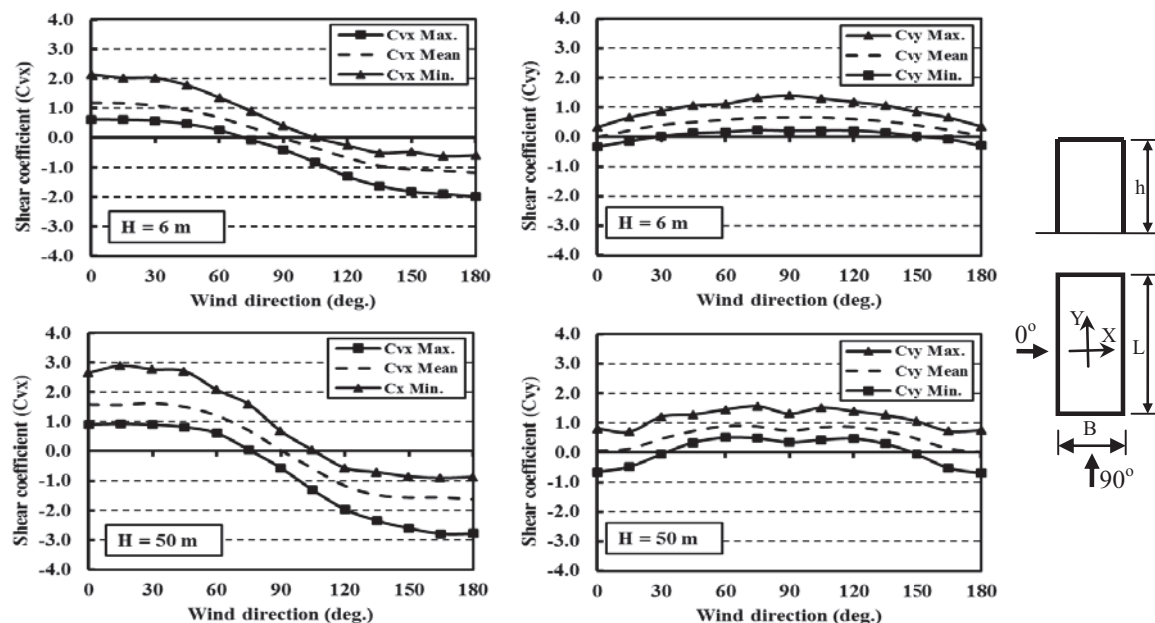


Figure 4. Variation of shear coefficients (C_{vx} , C_{vy}) with wind direction for building models corresponding to 6 and 50 m heights.

Although, the determination of the shear coefficient is important to propose equivalent wind loading, identification of horizontal distribution of these wind loads on building structural system still requires information about the torsional moment. The variation of mean and peak torsional coefficients with wind direction is presented in Figure 5 for buildings (6, 12, 25, and 50 m) in open-country terrain exposure. As a result of the building models having symmetric shapes, mean torsions are zero for wind directions perpendicular to building face, i.e. 0° and 90° . However, there are significant maximum and minimum torsional coefficients for these wind directions due to the lack of wind pressure correlation over the building envelope in the horizontal direction. The maximum torsional moment occurs for wind directions from 15° to 45° for the first three buildings (6, 12, 25 m) while for the 50 m building, two peaks appear at wind directions 30° and 75° . This may be attributed to different characteristics of wind flow interactions with buildings with height lower than 25 m compared to buildings with heights greater than 25 m. For better understanding in this regard, a flow visualization study is scheduled as a part of future tasks in the current research project.

4.2. Most critical torsion and shear coefficients

As it is very well known, the distribution and the magnitude of wind forces on building envelope are linked to the magnitude of torsional moment. Therefore and based on the wind tunnel measurements, two load cases are presented. Case A shows maximum torsion ($C_{T \text{ Max.}}$) and corresponding shear ($C_{V \text{ Corr.}}$) while Case B shows maximum shear ($C_{V \text{ Max.}}$) and corresponding torsion ($C_{T \text{ Corr.}}$). For simplicity, torsional loads can be treated analytically by introducing wind forces (V) with equivalent eccentricity (e) as shown in Figure 6. Tables 2

and 3, for Case A and Case B, show the evaluated coefficients for the critical wind directions for which the maximum torsion and shear were measured. For the 50 m building height, the most critical torsional moments have been measured for wind azimuths 30° and 75° . Thus, it quite significant for the wind provisions to cover these critical torsions for achieving the anticipated proper design for low and medium height buildings.

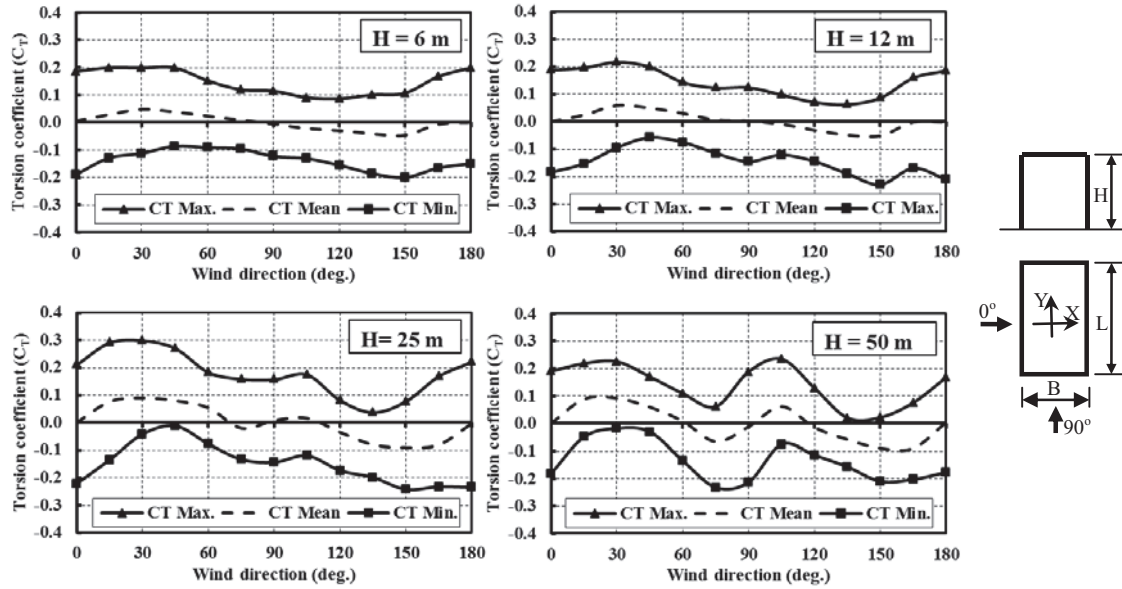


Figure 5. Variation of mean and peak torsion coefficients with wind direction for four different building heights (6, 12, 25, and 50m)

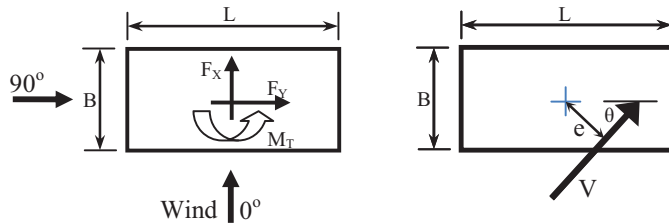


Figure 6. Horizontal wind force and torsional moment and its equivalent eccentric force.

The maximum equivalent eccentricity has been reported of about 16% of building largest horizontal dimension for building with height 50 m. The maximum ratio between the corresponding shear (associated to maximum torsion, Case A) to the maximum base shear (full load - Case B) was 74% for the 25 m high building. As indicated in many past wind tunnel studies, wind-induced torsion always exists even for wind direction for which the maximum full shear force occurs. The current study demonstrates that maximum shear is mostly associated with equivalent eccentricity about 5%. This is in line with the following statement given in ASCE/SEI 7-10, (Commentary part, C27.4.6),

“...wind tunnel studies often show an eccentricity of 5% or more under full (not reduced) base shear. The designer may wish to apply this level of eccentricity at full wind loading for certain more critical buildings even though it is not required by the standard. The present more moderate torsional load requirements can in part be

justified by the fact that the design wind forces tend to be upper-bound for most common building shapes."

Table 2. Case A: Maximum torsion ($C_{T \text{ Max.}}$) and corresponding Shear ($C_{V \text{ corr.}}$)

Building height (m)	Wind azimuth	Wind tunnel measurements			
		$C_{T \text{ Max.}}$	$C_{V \text{ Corr.}}$	θ	e (%)
6	30°	0.20	1.40	89.90°	14.20
12	30°	0.22	1.65	71.35°	13.30
25	30°	0.24	2.00	77.13°	11.80
50	30°	0.23	1.90	72.35°	11.92
50	75°	0.23	1.50	23.67°	15.32

Table 3. Case B: Maximum shear ($C_{V \text{ Max.}}$) and corresponding torsion ($C_{T \text{ corr.}}$)

Building height (m)	Wind azimuth	Wind tunnel measurements			
		$C_{V \text{ Max.}}$	$C_{T \text{ Corr.}}$	θ	e (%)
6	0°	2.15	0.04	88.61°	1.96
12	15°	2.40	0.05	84.60°	2.66
25	30°	2.71	0.15	84.80°	5.50
50	15°	2.90	0.16	87.01°	5.42

5 INSTANTANEOUS WIND FORCES ON BUILDING SURFACES

The wind flow characteristics (i.e. attached flow, separation, and reattachment) around buildings are critical for the determination of torsional moment (M_T). The non-uniform distribution of the generated wind loads in the horizontal directions is the main reason for generating torsional moment. Figure 7 shows measured integrated wind forces on building with height 25 m in X and Y axes for the critical wind directions, i.e. 0° , 90° , and 30° as the peak torsional moment occurs.

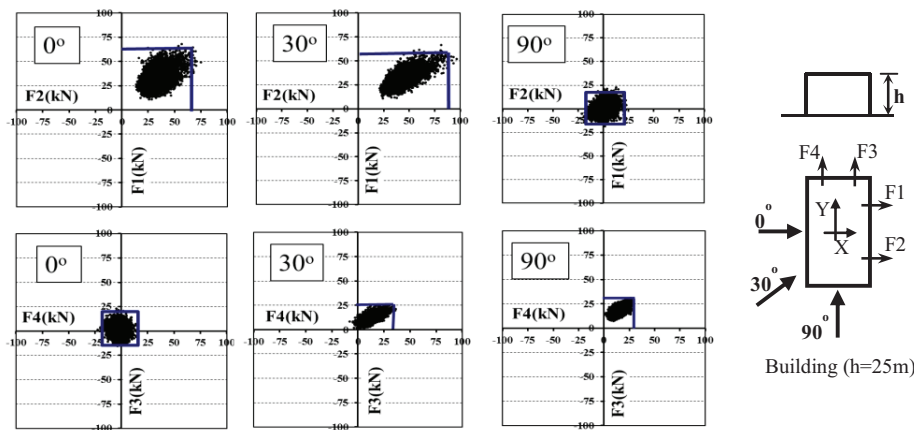


Figure 7. Horizontal forces in X and Y directions for azimuths 0° , 30° , and 90° for which maximum torsions were measured for building with height = 25 m.

Since all buildings have symmetric shapes and structural systems, the center of rigidity is located at the middle of building plan. Identification of the wind forces (F1 to F4) around the vertical building axis may allow better understanding for the relation between the generated torsion and wind direction. In case of perpendicular wind (0° and 90°), the forces (F1 and F2) vary with the same magnitude ranges and the trend line for these values has almost slope 1:1, and the correlation coefficient is very small (0.003). Similarly, the F3 and F4 values vary in

the same manner for the same wind directions. This justifies the fact of the zero mean-torsion measured while having relatively maximum and minimum torsions for these wind directions. For wind direction 30° , the magnitude range of (F_2) generated on the side close to wind is about double the force range of (F_1) generated on the far side. The trend line for the F_1 and F_2 values has slope equal to 2:3 while the correlation coefficient is 0.38. Accordingly, this could explain why the maximum torsion occurs for wind direction 30° .

6 CODE PROVISION COMPARISONS WITH WIND TUNNEL RESULTS

The results of the wind tunnel tests (Case A and Case B) for the tested building heights were compared to the values for base shear force and torsional moment evaluated by NBCC 2010, ASCE/SEI 7-10 and EN 1991-1-4.

6.1. NBCC 2010

In NBCC 2010, the static method (called herein NBCC 2010-S1) is introduced for low buildings while the simplified method (called herein NBCC 2010-S2) is proposed for rigid buildings with intermediate height. The static method calculations for the torsional and shear coefficients were derived based on figure I-7 of NBCC 2010, Commentary I, where the external peak (gust) pressure coefficients ($C_p C_g$) are provided for low buildings. Likewise, for the simplified method, the external pressure is taken from Figure I-15, Commentary I. Partial and full load cases were considered to estimate maximum torsion and corresponding shear, as well as maximum shear and corresponding torsion. Calculations were carried out considering the open terrain exposure. Static method values were increased by 25% to eliminate the implicit reduction (0.8) due to directionality issue.

6.2. ASCE/SEI 7-10

The three analytical procedures stated in ASCE/SEI 7-10 to evaluate wind loads were applied for this comparison. The envelope method (ASCE 7-10-E) appropriate for low buildings ($h < 18$ m and $h < B$) where h and B are the mean roof height and the least horizontal dimension respectively, figure 28.4-1 is used to get the external pressure coefficients (GC_{pf}). The basic (transverse) and torsional load cases presented in ASCE 7-10, figure 28.4-1 are used to estimate the maximum torsional moment and the maximum base shear. Directional methods-Part 1 and Part 2 (called in this paper ASCE 7-10-D1 and ASCE 7-10-D2), proposed in ASCE/SEI 7-10 to be used for all building heights, are also considered in this comparison. External pressure coefficients were collected from figure 27.4-1. Pressure coefficients are provided in table 27.6-1 for buildings with height up to 48.8 m. ASCE 7-10 calculations were carried out considering the open terrain exposure C. Also, the directional factor was taken as 1.

6.3. EN 1991-1-4

The Eurocode defines one unified analytical method that can be used for predicting the wind forces on all building types regardless of height. Torsional effects are taken into account by applying non-uniform pressures and forces, as shown in EN 1991-1-4, Figure 7.1. A triangular wind load is applied on the windward surface with a rectangular load on the leeward face of the building. External pressure coefficients for vertical walls of rectangular plan buildings are calculated using Figure 7.5 and Table 7.1 available in section 7, while for the external pressure of duo-pitch roofs, values are provided in the same section (Figure 7.8 and Table 7.4a).

All ASCE/SEI 7-10 values were multiplied by 1.51^2 and EN 1991-1-4 values by 1.06^2 in order to consider the effect of the 3-sec and the 10-min wind speed respectively in comparison to the mean-hourly wind speed in NBCC 2010.

Figure 8 summarizes the results for Case A (see Table 2). Peak torsional coefficients, corresponding shear, and equivalent eccentricity are evaluated either by the wind tunnel study or by the provisions of standards considered. Case B (see Table 3) comparison results, maximum shear, corresponding torsion and equivalent eccentricity are presented in Figure 9.

In the first instance, European code shows very good agreement with torsions measured in the wind tunnel for low and intermediate height buildings, see Figure 8. However, the applied wind load (i.e. corresponding shear) and the corresponding equivalent eccentricity are different from the measured values, given that torsional coefficients are always products of force coefficients times eccentricities. For low buildings, the envelope method in ASCE/SEI 7-10 shows relatively good agreement with the measured torsion, although decreasing the eccentricity from about 18% to 15% will improve its performance. Also, the static method in NBCC 2010 underestimates torsion on low buildings significantly. On the other hand for medium height buildings, the wind load procedures in the NBCC 2010 and the ASCE/SEI 7-10 overestimate torsion in some case significantly. Regarding Case B, Figure 9 indicates clearly that the static and envelope methods for low buildings in NBCC 2010 and ASCE/SEI 7-10 respectively succeed to predict maximum shear forces. All other methods in the three provisions overestimate shear forces on low and medium height buildings, as shown in Figure 9. Based on the results presented in Figures 8 and 9, it could be recommended that applying 75% of the full wind loads (i.e. maximum shear measured in Case B) with equivalent eccentricity 15% will improve torsion evaluation for low and medium height buildings.

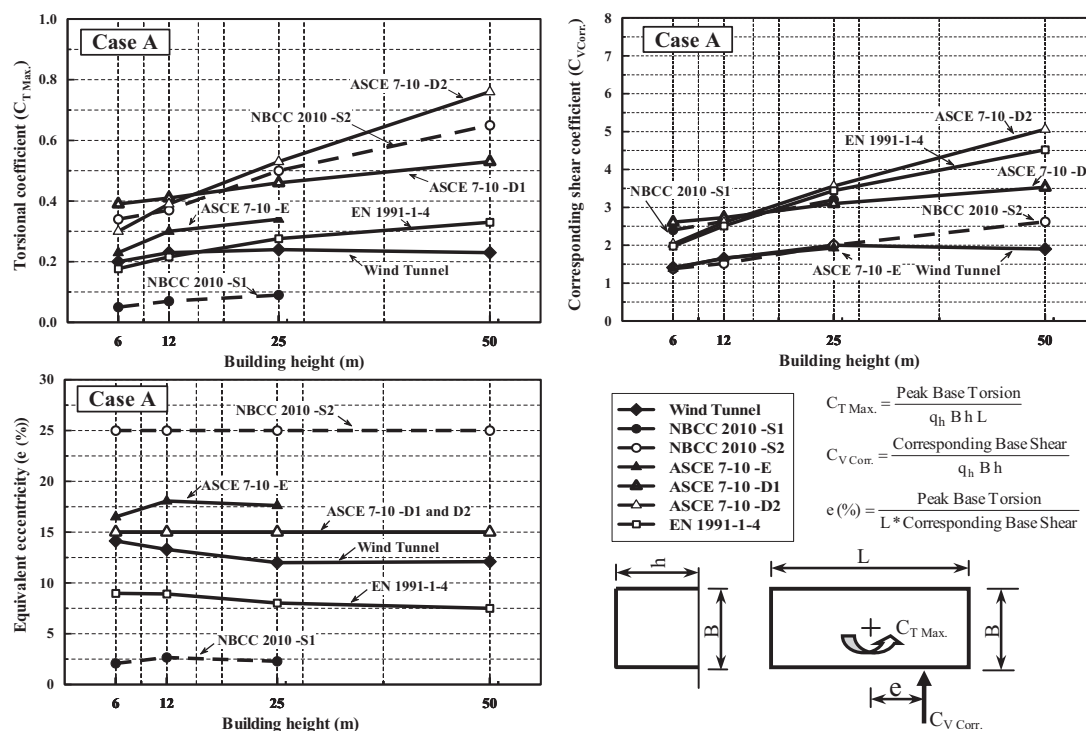


Figure 8. Comparison of torsional load case evaluated by NBCC 2010, ASCE/SEI 7-10, and wind tunnel tests (Case A: maximum torsion and corresponding shear)

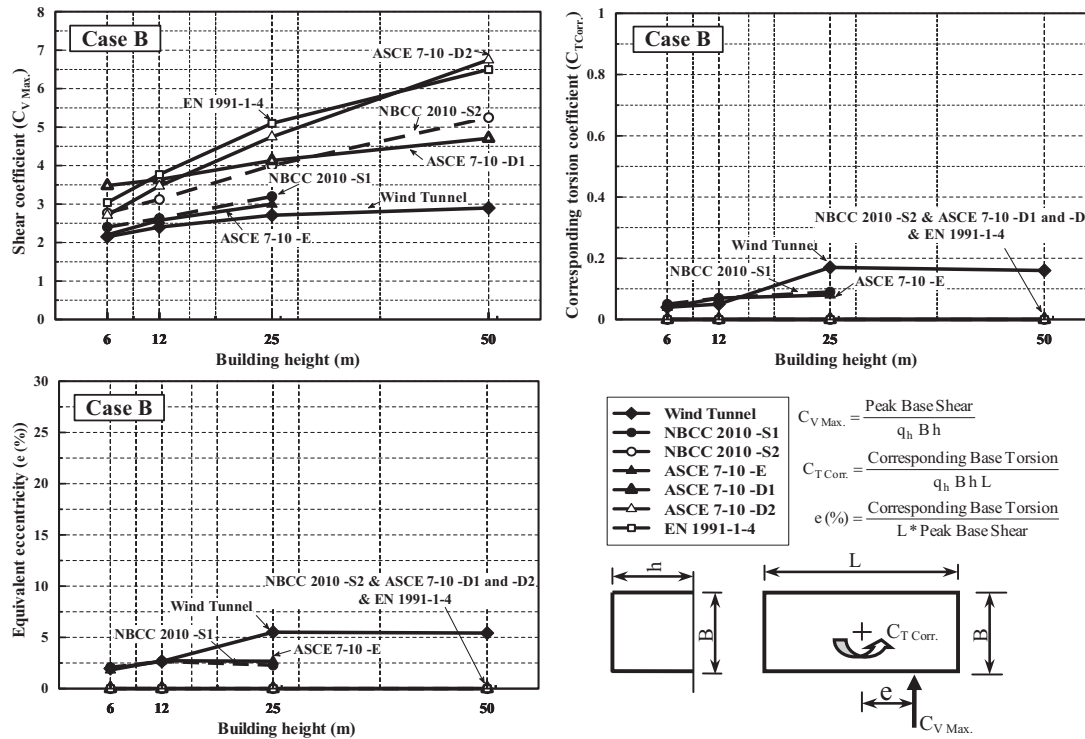


Figure 9. Comparison of shear load case evaluated by NBCC 2010, ASCE/SEI 7-10 and wind tunnel tests (Case B: maximum shear and corresponding torsion).

7 CONCLUSIONS

Wind-induced torsion was measured in the wind tunnel for four buildings having the same horizontal dimensions with different heights ranged from 6 m to 50 m. In addition, the experimental results were compared with wind provisions in NBCC 2010, ASCE/SEI 7-10 and EN 1991-1-4. The comparison results demonstrate the following:

- For low buildings:
 - The static method in NBCC 2010 underestimates torsion significantly.
 - The envelope method in ASCE/SEI 7-10 shows relatively good agreement with the measured torsion.
 - EN 1991-1-4 shows good agreement with the wind tunnel results.
- For intermediate height buildings:
 - Wind load procedures in NBCC 2010 and ASCE/SEI 7-10, overestimate torsion while EN 1991-1-4 shows good agreement with the wind tunnel results.

Until more experimental data become available, it could be recommended that applying 75% of the full wind loads with equivalent eccentricity 15% will improve torsion evaluation for low and medium height buildings.

8 ACKNOWLEDGMENT

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