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Torsional and shear wind loads on flat-roofed buildings

Mohamed Elsharawy *, Khaled Galal, Ted Stathopoulos

Faculty of Engineering and Computer Science, Concordia University, Montréal, Québec, Canada

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ABSTRACT

There is limited information available on wind-induced torsional loads on buildings. This paper presents results of wind tunnel tests carried out on a series of models of low- and medium-rise buildings. Four buildings with the same plan dimensions but different heights (6, 12, 25 and 50 m) were tested in a simulated open terrain exposure for different wind directions. Synchronized wind pressure measurements allowed estimating instantaneous base shear forces and torsional moments on the tested rigid building models. Results were normalized and presented in terms of mean and peak values of shear and torsional coefficients for two load cases, namely: maximum torsion and corresponding shear, and maximum shear and corresponding torsion. Comparison of the wind tunnel test results with current torsion- and shear-related provisions in the American Standard as well as the Canadian and European codes demonstrates significant discrepancies. The findings of this study could assist wind code and standards committees to improve provisions for wind-induced torsional loads on buildings.

1. Introduction

The wind flow characteristics (i.e. attached flow, separation and reattachment) around buildings are critical for the determination of wind forces for building design. Along-wind force fluctuations are mainly generated by approaching flow turbulence, but the fluctuations in across-wind force and torsion are generally dominated by vortex shedding [1], at least for medium-rise buildings. The recent trend toward more complex building shapes and structural systems results in more unbalanced wind loads and larger torsional moments. Thus, re-visiting the wind load provisions is of utmost concern to ensure their adequacy in evaluating torsion on buildings and, consequently, achieve safe yet economic building design. In fact, most of the wind loading provisions on torsion have been developed from the research work largely directed toward very tall and flexible buildings [2–7] for which resonant responses are very significant. However, the dynamic response of most medium-rise buildings is dominated by quasi-steady gust loading with little resonant effect. The limited knowledge regarding wind-induced torsion is apparent in the international wind loading codes and standards uses different approaches in evaluating torsion loads on buildings. Recently, Tamura et al. [8] and Keast et al. [9] studied wind load combinations including torsion for medium-rise buildings. Although the latter study concluded that for rectangular buildings the peak overall torsion occurs simultaneously with 30–40% of the peak overall shear, it should be noted that this observation conclusion was drawn based on testing a limited number of building models. Additional experimental results from testing different building configurations are still needed in order to confirm and generalize such observations.

Furthermore, studies on wind-induced torsional loads on low-rise buildings are very limited. Isyumov and Case [10] measured wind-induced torsion for three low-rise buildings with different aspect ratios (length/width = 1, 2, and 3) in open terrain exposure as modeled in the wind tunnel. It was suggested that applying partial wind loads, similar to those implemented for the design of medium-rise buildings, would improve the design of low-rise buildings until more pertinent data becomes available. Tamura et al. [11] examined correlation of torsion with along-wind and across-wind forces for rectangular low-rise buildings tested in simulated open and urban terrain exposures. Low-rise buildings of different roof slopes were tested by Elsharawy et al. [12] but peak torsions evaluated by current wind provisions were found to be different from the measured peak torsion in the wind tunnel.

This study reports the analysis and code comparison of results from additional measurements carried out in a boundary layer tunnel to investigate shear forces occurring simultaneously with maximum torsion, as well as maximum shears and corresponding torsions on flat-roof buildings of different heights. Results of the study are important for better evaluation of wind-induced torsional loads on low- and medium-rise buildings. Some preliminary results of this research have appeared in Elsharawy et al. [13].

* Corresponding author.
E-mail address: m_els@encs.concordia.ca (M. Elsharawy).

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2. Wind-induced torsion in current wind codes and standards

ASCE 7 [14] specifies wind loads on low-rise buildings (defined as having mean roof height, $h < 18$ m and $h <$ smallest horizontal building dimension, B) and medium-height rigid buildings, defined as having lowest natural frequency, $f_n > 1$ Hz. On the other hand, NBCC [15] identifies low-rise buildings ($h < 10$ m, or $h < 20$ m and $h < B$) and medium-rise rigid buildings ($h < 60$ m, $h/B < 4$, $f_n > 1$ Hz). In EN 1991-1-4 [16], low-rise buildings are defined as those with $h < 15$ m while buildings with frames, structural walls with $h < 100$ m are introduced structurally as rigid buildings. Wind-induced torsion is treated differently in these standards.

2.1. Low-rise buildings

Wind loads on low-rise buildings have not received sufficient attention, particularly when the large investment in such structures is considered. Wind loads generally govern the design of lateral structural systems of low-rise buildings in low seismicity areas and where there is high probability of occurrence of severe wind events. The development of provisions for the evaluation of wind loads on low-rise buildings was based on the research carried out at the University of Western Ontario in the late 1970's, when an extensive experimental program in a boundary layer wind tunnel considered a variety of rectangular low-rise buildings with different dimensions, roof slopes and upstream terrain exposures [17,18]. However, wind-induced torsional loads were not examined in detail. ASCE 7 [14] introduces two load cases in the envelope method to estimate torsion, namely; maximum torsion with corresponding shear and maximum shear with corresponding torsion. NBCC [15] specifies one load case in the static method assigned for low-rise buildings to evaluate maximum shear as well as maximum torsion.

For comparison purposes, three low-rise buildings with flat roofs (width, $B = 16$ m and height, $h = 12$ m) having horizontal aspect ratios ($L/B = 1$, 2, and 3) located in an open terrain exposure have been analyzed by American, Canadian and European codes and standards. Both envelope and static methods stated in the ASCE 7 [14] and NBCC [15] were applied for the studied low-rise buildings, in addition to the analytical method specified for all building heights in EN 1991-1-4 [16]. In the envelope method (ASCE 7 [14]), the external pressure coefficients (GC_{pf}) on building envelope are estimated for low-rise buildings using figure 28.4-1 and the directionality factor (K_d) was taken as 1. The torsional load case was specified by removing 75% of the full wind load on half of building surfaces, as indicated in figure 28.4-1 (ASCE 7 [14]). As for the static method of NBCC [15], the external peak pressure coefficients (C_gC_p) are provided for low-rise buildings in figure I-7 of Commentary I. Calculations were carried out considering open terrain exposure. Static method values were increased by 25% to eliminate the implicit reduction (0.8) due to directionality issue. Similarly, for EN 1991-1-4 [16], the external pressure coefficients for vertical walls of rectangular plan buildings are calculated using figure 7.5 and table 7.1 available in Section 7. The non-uniform distribution of wind loads were simulated by applying triangular load [16]. The wind velocity was adjusted by using the well-known Durst curve given in the ASCE 7 [14] Commentary, figure C26.5.1. All ASCE 7 [14] values were multiplied by 1.51^2 and EN 1991-1-4 [16] values by 1.06^2 in order to consider the effect of the 3-s and the 10-min wind speed respectively in comparison to the mean-hourly wind speed in NBCC [15].

The results were presented in terms of shear and torsion coefficients and equivalent eccentricity. The shear coefficient, torsional coefficient and equivalent eccentricity in transverse direction were estimated as per Eqs. 1–3, respectively, where q_h is the dynamic wind pressure at building mean roof height:

$$C_V = \frac{\text{Base shear force}}{q_h B h} \tag{1}$$

$$C_T = \frac{\text{Base torsional moment}}{q_h B h L} \tag{2}$$

$$e\ (\%) = \frac{\text{Base torsional moment}}{\text{Base shear force} * L} 100 \tag{3}$$

Fig. 1 presents the results for torsional loads evaluated by ASCE 7 [14], NBCC [15], and EN 1991-1-4 [16] for the three low-rise buildings. As can be clearly seen, significant differences are found among the three national codes/standards in evaluating the torsional moment. For building with an aspect ratio (L/B) of 3, NBCC [15] estimates torsion which is hardly equal to one third of the ASCE 7 [14] and EN 1991-1-4 [16]. The distribution of wind loads introduced in torsional load case is very different in these codes. ASCE 7 [14] introduces equivalent eccentricity that is approximately 18% of the building length while NBCC [15] and EN 1991-1-4 [16] have eccentricities of about 4%, and 8% of the building length, as Fig. 1 shows. Clearly, NBCC [15] provides significantly lower values for the torsional moment on the three low buildings considered in this comparison.

2.2. Medium-rise buildings

The National Building Code of Canada was the first to adopt the effect of wind-induced torsional loads on buildings in its provisions. Since the early 1970's and till 2005, the NBCC subcommittee

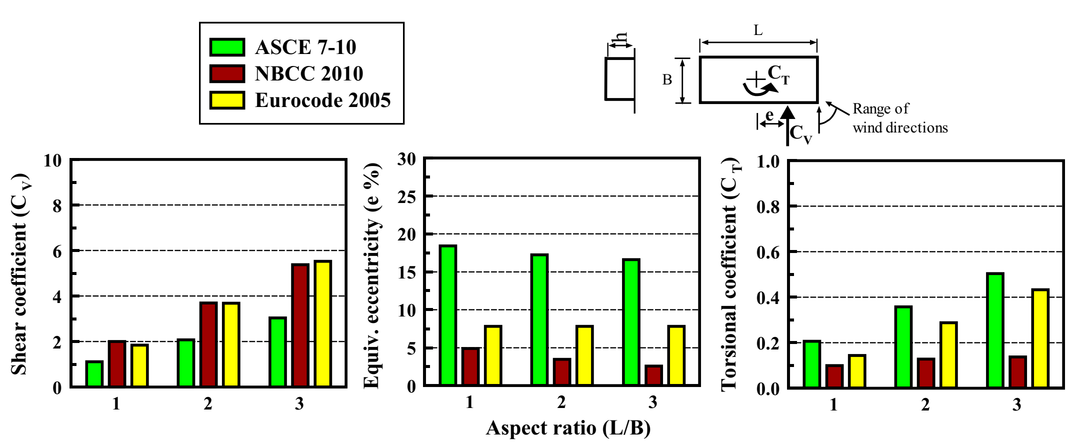

Fig. 1. Comparison of torsion load case in wind code and standard provisions for three low-rise buildings with aspect ratios (L/B) = 1, 2, and 3.