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Wind-induced shear and torsion in low-rise and medium-rise buildings: Provisions of National Building Code of Canada 2015

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Abstract

This paper discusses the shear and torsion induced in low-rise and medium-rise buildings, according to wind load specifications provided in NBCC 2015. Results from experimental studies, carried out in wind tunnels were compared with corresponding NBCC 2015 provisions under different upstream roughness conditions. These comparisons demonstrated notable discrepancies for the case of torsion in low-rise buildings.

Further, comparisons between the wind load specifications given in NBCC 2015 and ASCE/SEI 7-10 standard were carried out. Following both sets of provisions, wind-induced shear and torsion were computed and compared for five low-rise and medium-rise buildings with the same horizontal dimensions but different heights. Emphasis was directed towards the cases that create maximum shear forces and/or maximum torsions in order to reflect critical design conditions. For low-rise buildings, the ASCE/SEI 7-10 and NBCC 2015 yield similar shear coefficients but quite different torsional coefficients; while for medium-rise buildings, clear agreement was found, for both shear and torsion. The diversity of the results is discussed and some suggestions for improvement of code provisions are made. A definition for medium-rise buildings was provided.

Key words: Wind loads, code provisions, shear, torsion, low-rise and medium-rise buildings

1. Introduction

Wind loading, especially its torsional effect, plays a critical role on building design. Torsion always occurs even in a perfectly symmetrical building, given that the wind direction toward building wall face is not always perpendicular, and also not distributed uniformly. The equivalent wind force center will not align with the building's center of mass and therefore it will create torsional moments. Moreover, most buildings have inherent eccentricities between the center of mass and that of rigidity. The impacts that wind-induced torsion could cause depend on several conditions, such as: building location, geometry, lateral force-resisting system and its material. Torsion can significantly increase the shear loads applied on the lateral force-resisting system comparing to the conventional loading method, which only considers wind-induced shear. Therefore, the wind torsional effects cannot be neglected and need to be appropriately evaluated by code computations.

According to NBCC 2015, low-rise buildings are those with $H \leq 20$ m and $H/D_s < 1$, where H is the building height and D_s is the smaller plan dimension. All buildings with $H > 20$ m and $H/D_s \geq 1$ are classified as high-rise buildings which may be dynamically sensitive or very dynamically sensitive. A building is classified as dynamically sensitive if its lowest natural frequency is less than 1.0 Hz and greater than 0.25 Hz, its height is greater than 60 m, or its height is greater than 4 times its minimum effective width, w. For a rectangular building the minimum effective width is equal to D_s. A building having its lowest natural frequency ≤ 0.25 Hz or its height more than 6 times its minimum effective width is classified as very dynamically sensitive. However, in the current code, there is not a definition for medium-rise buildings. In this study, a medium-rise building is defined as a building with H greater than 20 m and less than or equal to 60 m or $1 \leq H/D_s \leq 4$.

To investigate the most critical impacts of wind load on medium-rise buildings, along with the conventional full loading case (Case A), three different partial loading cases have been introduced in NBCC 2015 (Cases B, C, D) as shown in Fig. 1. However, several issues have been encountered in the process of determining torsions in load Cases B and D. Firstly, in the torsional load cases, the uniformly distributed wind forces acting on the building are partly reduced (in terms of both magnitude and tributary area) in one or both of the principal directions in order to create the most severe torsional effects on buildings. These effects, along with the effect from the full loading case, are then compared to conclude the most critical scenario in terms of shear and torsional effects. While the subtracted load magnitude is mentioned explicitly in the code, the tributary area remains unclear for load Cases B and D and this creates ambiguities among the NBCC users. Secondly, these load cases do not apply to low-rise buildings, for which the torsional effects are presumably covered by the stipulations of Fig. 2, in which two load Cases, A and B, are specified. However, Stathopoulos et al. (2013) have shown that these provisions may not be adequate for torsion. Although these issues are known for a while, little research has been carried out to address them systematically in order to modify the Canadian wind load specifications accordingly.

Other wind codes and standards address torsional loads differently. For instance, the American standard ASCE/SEI 7-10 specifies that, for low-rise buildings, besides applying higher wind loads on wall corners, only 25% of the full design wind pressure is placed on half of the wall face to account for torsional effects. For other buildings, eccentricities and torsion moments are given explicitly by formulas with wind loads applying on full tributary areas for all load cases. In Eurocode (EN 1991-1-4 2005), the torsional effects are taken into account by changing the uniformly distributed wind load in the windward direction represented by rectangular loading to inclined triangular loading while keeping the same load on the leeward wall face. It also regulates that in some cases, wind loads in locations that create beneficial impacts should be completely removed, but this regulation is not very clear for the users. The Australian/ New Zealand building code (AS/NZS 1170.2 2011) fully neglects the wind-induced torsion for low-rise and medium-rise buildings whereas for high-rise buildings defined by height > 70.0 m, an eccentricity of 20% of the width of windward wall is considered to account for torsion.

2. NBCC 2015 provisions for wind loads on buildings

2.1 General

The objectives of this study are twofold: i) recommend an approach for determining the appropriate tributary areas needed to generate the maximum torsion effects in Case B and Case D recommended in NBCC 2015 for high-rise buildings and applied herein also for medium-rise buildings and ii) examine the adequacy of wind loads (base shear and torsion) determined by the NBCC 2015 through comparisons with results from previous studies and ASCE/SEI 7-10 standard provisions.

The full wind external pressure in NBCC 2015 is given by:

$$p = I_w q C_e C_t C_g C_p \tag{1}$$

where I_W is the importance factor for wind load; q is the reference velocity pressure; C_e, C_t and C_g are the exposure, topographic, and gust effect factor; and C_p is the external pressure coefficient. After the wind pressures are acquired they are multiplied by the corresponding projected/ tributary area to attain the external wind forces acting on the building wall faces. The wind loads are computed for each floor before being summed up to obtain the base shear. The process is carried out for two orthogonal directions. Torsion moments are formed by the unbalance of wind pressures on building wall faces, as specified in the partial loading cases.

For buildings higher than 60 m or the height to minimum effective width ratios > 4.0 or with lowest natural frequency lower than 1.0, the dynamic procedure should be applied. The same provisions to static procedure, including the partial loading cases, shall be followed, except that the exposure factor, C_e and the gust factor, C_g are evaluated differently (NBCC 2015). The lowest natural frequency of the building is recommended to be computed by the following equation:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{\sum_{i=1}^{N} F_i \frac{x_i}{x_N}}{x_N \sum_{i=1}^{N} M_i \left(\frac{x_i}{x_N}\right)^2}} \tag{2}$$

where N is the number of stories; $F_{i,}M_i$ are the lateral load and floor mass at level i^{th}; x_i and x_N are the horizontal deflections of floor at level i and N, respectively.

In some cases, partial loadings can cause severe effects. As already mentioned for high-rise/ medium-rise buildings, four load cases are presented in NBCC 2015 (A, B, C and D). While Cases A and C focus on the effect of shear force, Cases B and D emphasize the torsional impact on structures. The conventional loading method is followed by the Case A when 100% of wind forces are loaded separately in each principal axis. Clearly, this case is found to produce the maximum base shear. The wind loads with the same magnitude are applied on parts of the wall faces to create additional torsions in load Case B. The tributary area of the wind pressure acting on a given story wall face is given as a product of the height of the story under consideration and the horizontal distribution length of the wind load. However, the latter is not provided explicitly by NBCC 2015, which may lead practitioners to different tributary areas, and therefore, different wind forces, and potential false assessments of the torsional effects of wind loads on buildings. Thus, this issue requires clarification. Wind blowing diagonally to the walls can be illustrated equivalently by simultaneous reduced forces. For instance, 75% of full load are applied simultaneously on both wall faces to create Case C. In Case D, 50% of those in Case C are partly subtracted from wall faces. Similar to Case B, the wind projected area in Case D is just mentioned as "reduced from part of projected area". The term "part" needs to be clarified as it raises questions among the code users.

Two load cases are mentioned in NBCC 2015 for low-rise buildings, namely load Case A and Case B, which simulate wind loads applying perpendicular and parallel to the ridge of a building, respectively. As specified in Case B, when acting parallel to the building's ridge, wind forces also create impacts to both sides of the buildings. Also, the wind pressures are different on opposite sides of the building roof. However, the current study only considers buildings with flat roofs. Therefore, these effects can be neglected because the across-wind forces on opposite wall faces eliminate each other. As a result, the two load cases merge into a single case. The wind pressures are defined as shown in Eq. (1). However, for low-rise buildings, instead of determining the external pressure coefficient, C_p, and gust effect factor, C_g separately as in the case of medium-rise buildings, the external peak composite pressure-gust coefficients, C_pC_g are obtained based on the positions of wind loads applied on the wall faces. The other parameters (I_w, q, C_e) are computed in the same way as for high-rise/ medium-rise buildings.

2.2 Torsional load case for medium-rise buildings

In medium-rise buildings, torsional effects are computed by considering the two partial loading cases: Case B and Case D. The tributary area of wind load that could produce the maximum torsions are recommended by using a mathematical method. The method of determining maximum torsion in Case D is illustrated in Fig. 3. The same approach can be adopted to determine the maximum torsion in load Case B, as it is a simplified case of Case D.

As previously mentioned, the tributary area of the uniformly distributed wind force acting on a given story is given as: $A = l \times h$, where h is the height of the story under consideration, and l is the horizontal distribution length of the wind load. According to NBCC 2015, the horizontal distribution length (mentioned as *a, b, c* and *d* in Fig. 3) are unknown. These values need to be determined so that the corresponding wind forces applied simultaneously in both wall faces of the building create a maximum moment *M*, which is the summation of the moments induced by wind forces in each direction:

$$M = M_x + M_y \tag{3}$$

Herein, *M* is maximum when M_x and M_y reach their highest values. The moment due to wind load along the N-S direction is given by:

$$M_x = p_2 bhe_2 - p_1 ahe_1 \tag{4}$$

where p_1 and p_2 are uniform wind forces acting on the wall faces in the N-S direction; e_1 and e_2 are the eccentricities of p_1 and p_2, respectively; and *a* and *b* are the horizontal distribution length of p_1 and p_2, respectively.

The eccentricities e_1 and e_2 are: $e_1 = L/2 - a/2$, $e_2 = L/2 - b/2$, where $a = L - b$. By substituting these parameters in Eq. (4), it results:

$$\begin{aligned}
M_x &= p_2 bh\left(\frac{L}{2} - \frac{b}{2}\right) - p_1 ah\left(\frac{L}{2} - \frac{a}{2}\right) = p_2 bh\frac{L}{2} - p_2 h\frac{b^2}{2} - p_1 ah\frac{L}{2} + p_1 h\frac{a^2}{2} \\
&= p_2 bh\frac{L}{2} - p_2 h\frac{b^2}{2} - p_1 (L-b)h\frac{L}{2} + p_1 h\frac{(L-b)^2}{2} \\
&= p_2 bh\frac{L}{2} - p_2 h\frac{b^2}{2} - p_1 h\frac{L^2}{2} + p_1 bh\frac{L}{2} + p_1 h\frac{b^2 + L^2 - 2Lb}{2} \\
&= p_1 h\frac{b^2}{2} - p_2 h\frac{b^2}{2} + p_2 bh\frac{L}{2} - p_1 bh\frac{L}{2} \\
&= \left(\frac{p_1}{2} - \frac{p_2}{2}\right) b^2 h + \left(\frac{p_2 L}{2} - \frac{p_1 L}{2}\right) bh
\end{aligned} \tag{5}$$

As can be seen, M_x is a quadratic function of variable *b*. This function reaches its maximum value when its differentiation with respect to *b* is equal to zero, i.e.:

$$\begin{aligned}
M'_x &= (p_1 - p_2)bh + 0.5(p_2 - p_1)Lh = 0 \\
&\Leftrightarrow b = \frac{L}{2}
\end{aligned} \tag{6}$$

Therefore, the maximum torsion due to wind along the N-S direction occurs at $b = a = L/2$. Similarly, M_y is maximum when $c = d = B/2$.

Applying the same procedure, the torsions in Case B are maximum when pressures are applied on half of the wall faces. The maximum torsion effect is chosen by comparing the results of Case B and Case D. The most critical shear effect comes from the maximum value of Case A and Case C.

2.3 Torsional load case for low-rise buildings

In terms of low-rise buildings, only two Cases, namely A and B, are present in NBCC 2015, when torsion is caused by a higher concentration of wind loads in each wall face corner. As opposed to partial loading cases for medium-rise buildings, the tributary areas of wind forces are stated explicitly for low-rise buildings as exhibited in Fig. 4. Torsion moment for these cases is computed by the following formula:

$$M = (p_1 + p_4)e_1(L - y)h - (p_{1E} + p_{4E})e_{1E}yh \quad (7)$$

Herein, y is the width of the end-zone computed as the greater of 6 m and $2z$, where z is the lesser of 10% of the least horizontal dimension or 40% of height, H, but not less than 4% of the least horizontal dimension or 1.0 m.

3. Comparisons between NBCC 2015 and experimental results from previous studies

3.1 Selection of experimental studies from the literature

The first comparisons are made between the wind loads computed by NBCC 2015 and those from wind tunnel tests collected from four previous studies regarding both low-rise and medium-rise buildings under different exposures. The four previous studies chosen are: Isyumov and Case (2000), Keast et al. (2012), Tamura et al. (2003), and Stathopoulos et al. (2013). The configurations of buildings tested in these studies are shown in Table 1, where they are also grouped into low-rise and medium-rise categories. Some assumptions have been made due to the lack of information that is essential for the application of the NBCC 2015 provisions. For instance, the studied buildings are steel structures and the lateral force-resisting systems consist of limited ductility concentrically braced frames. The two largest shear in the two principal wall face directions along with the maximum torsion are selected in each building considering all load cases, for both low-rise and medium-rise buildings in open and urban-terrain areas. Four partial loading cases are considered for medium-rise buildings. For the torsional load Cases B and D, the tributary area has been determined as recommended previously in Eq. (6). For low-rise buildings, shear and torsion are attained following Cases A and B as prescribed in Fig. 4. Based on building properties (geometry, dimensions, and natural frequency), some are computed by the static procedure, while others follow the dynamic procedure. Detailed information about computational procedure for all buildings is provided in Table 2. It is noted that *w* parameter provided in Table 2 is the minimum effective width. For the current study, the ETABS software (CSI 2016) was used to compute the building's natural frequency.

3.2 Shear and torsional coefficients

In order to compare results between studies with different building locations and exposure terrains, maximum base shear forces and torsions are normalized to obtain the shear and torsional coefficients, defined as follows:

$$C_V = \frac{V}{q_H B L} \tag{8}$$

$$C_T = \frac{T}{q_H B^2 L} \tag{9}$$

$$q_H = q C_e \tag{10}$$

where C_V and C_T are shear and torsional coefficients; V and T are the base shear and torsion; B and L are the shorter and longer horizontal dimensions of the building; q_H is the mean dynamic wind pressure at roof height H; q is the reference velocity pressure based on the mean hourly wind speed; and C_e is the exposure factor.

Due to the diversity of coefficient definitions among the past studies, all coefficients given have all been transformed to be consistent with those of the current study. The transformation equations used for each study are provided in Table 3.

3.3 Results and Discussions

In this section, the comparisons between the shear and torsional coefficients resulted from wind tunnel tests and the corresponding code results are depicted in graphs where the vertical axis shows shear or torsional coefficients from wind tunnel tests, while those from NBCC 2015 are placed on the horizontal axis. Each pair of results (experimental and code results) is represented by a point. The closer the point is to the balance line (form an angle of 45^0 with the axes), the better is the agreement between code provisions and experimental results.

Figure 5 compares the torsional coefficients in two separate categories namely low-rise and medium-rise buildings. Clearly, the NBCC 2015 greatly underestimates torsional effects on low-rise buildings through all cases. Thus, all points shown in the graph for low-rise buildings are at noticeable distances to the balance line (experimental results are 6 to 10 times higher than those from NBCC 2015). Moreover, the underestimation in torsional effects of NBCC 2015 for low-rise buildings can be witnessed through the case of the two buildings of Stathopoulos et al. (2013). These two buildings are 20.0 m high (low-rise building) and 30.0 m high (medium-rise building) and have the same horizontal dimensions and exposure conditions. According to the Canadian code computations, the torsional coefficient increases ten times from 0.024 (20.0 m – low-rise building) to 0.26 (30.0 m - medium-rise building). The values from the wind tunnel tests are 0.15 and 0.27, correspondingly, making a smaller jump of about 1.8 times. For medium-rise buildings, all studies give similar results with the computations from NBCC 2015, except for the case of the building of Tamura et al. (2003) in urban-terrain area where the results are overestimated. Furthermore, the NBCC 2015 have resulted slightly higher torsional coefficient values.

In conclusion, torsional effects on low-rise buildings are not assessed properly by NBCC 2015. Conversely, good assessments have been shown in medium-rise buildings with the application of partial loading. Therefore, it was decided to test the effectiveness of the medium-rise building methodology for low-rise buildings although, according to NBCC 2015, partial loading cases are not required for them. Cases B and D are applied to all the low-rise buildings of the previous studies to obtain the maximum torsions. The torsional coefficients resulted from this process are exhibited in Fig. 6. The abbreviation "PL" in the figure implies the results from the partial loading Cases B and D. Much better results are shown clearly as the torsional coefficients of the code are much closer to those provided by the experimental studies. Discrepancies decrease to only within 1.5 times. Evidently, if partial loading cases are applied as for the case of medium-rise buildings, the torsional effects on low-rise buildings can be estimated more appropriately, although somewhat underestimated.

Figure 7 presents the comparisons between shear coefficients obtained from NBCC 2015 and wind tunnel tests. The shear coefficients are computed in two principal wind directions: N-S and W-E. In general, good similarities between the code computations and the test results are present. For low-rise buildings, four out of six shear coefficients computed from NBCC 2015 are nearly equal to the experimental coefficients. However, an underestimating trend is demonstrated. Additionally, shear coefficients adequacy decrease in the N-S direction (the longer wall face). For medium-rise buildings, there is an excellent agreement in seven out of eight cases. The best agreement is found in the results of Stathopoulos et al. (2013) for both terrains (only roughly 1% difference). The largest difference found was approximately 16%, in the case of the 60.0 m high building in the study of Keast et al. (2012), which is also the highest building among all studies.

In brief, with the exception of the underestimated torsional effects for low-rise buildings, the NBCC 2015 seem to evaluate the impact of wind loads on low-rise (shear effects) and medium-rise buildings adequately. Potential remedies can be taken in the case of torsional effects on low-rise buildings by applying the partial loading cases, similar to the case of medium-rise buildings.

3.4 Discussion on the discrepancies between results from NBCC 2015 and wind tunnel tests

The underestimation in torsions for low-rise buildings is due to the fact that the code does not take partial loading into account. As can be seen in Fig. 2, the higher wind pressures (the factor that produces the torsional effects) are only placed in a small area $y \times h$ in the building's corners, where y is the maximum of 6 m or $2z$. This value, in most cases, is not comparable to half of the wall dimension perpendicular to wind directions, which is shown in Eq. (6) to produce the maximum torsion. This inappropriate pressure distribution also results in small shear coefficients, as illustrated in Fig. 7.

Discrepancies between shear and torsional coefficients in medium-rise buildings provided by NBCC 2015, as shown in Figs. 5, 6 and 7, may be attributed to the lowest natural frequency of the building, f_n. As shown in Table 1, the dynamic procedure was applied for all medium-rise buildings. Wind loads determined by dynamic procedure are controlled by the building natural frequency, which may be not similar between buildings in the current study and the previous studies due to the differences in building materials and lateral force-resisting systems. The assumptions made in the current study may result in different building material, lateral force-resisting system, and damping ratios to the past studies. As a result, dissimilar natural frequencies between buildings occur and directly affect the values of the size reduction factor s, and gust energy ratio at the natural frequency of the structure F, and consequently the gust factor C_g as shown below:

$$C_g = 1 + g_p \sqrt{\frac{K}{C_{eH}} \left(B + \frac{sF}{\beta}\right)} \tag{11}$$

$$s = \frac{\pi}{3} \left[\frac{1}{1 + \frac{8 f_n H}{3 V_H}} \right] \left[\frac{1}{1 + \frac{10 f_n w}{V_H}} \right] \tag{12}$$

$$F = \frac{(1220 f_n / V_H)^2}{[1 + (1220 f_n / V_H)^2]^{4/3}} \tag{13}$$

Herein, g_p is the peak factor, K is a factor related to the surface roughness coefficient of the terrain, C_{eH} is the exposure factor evaluated at the top of the building, B is the background turbulence factor, β is the critical damping ratio in the along-wind direction, f_n is the fundamental frequency, H is the height of the building, V_H is the mean wind speed at the top of the structure, and w is the effective width of windward face of the building.

Computations with steel and concrete structures with different types of lateral force-resisting system were carried out to examine the differences between their wind-induced shears and torsions. The 30.0 m height building of Stathopoulos et al. (2013) is taken as an example. As mentioned previously, the building in this current study is a steel structure with limited ductility concentrically braced frames as lateral force-resisting systems. Two other cases were considered for the comparison purposes, as the buildings were assumed to be moment resisting frame concrete structure and concrete building without a lateral force-resisting system. These buildings were designed for gravity and seismic loads, as well as, a structural analysis software was used to determine the fundamental frequencies of these buildings.

The three buildings have different damping ratio values, ranging from 2% to 5%, and natural frequencies ranging from 0.5 Hz to 1.0 Hz. Although they produce different gust factors C_g, similar torsional coefficients were found for the steel braced-frame building, the concrete building with moment resisting frame and the concrete building without lateral force-resisting system (0.37, 0.369, and 0.35, respectively). In addition, the corresponding shear coefficients computed in both directions were almost identical. Clearly, although building material and lateral force-resisting system directly affect the wind-induced shear and torsion of a building, the differences that they create are not significant.

4. Comparisons between ASCE/SEI 7-10 and experimental results from previous studies

This section presents similar comparisons with those illustrated previously in Figs. 5 and 7. The same buildings were considered using the ASCE/SEI 7-10 standard. Two different procedures, namely Directional and Envelope, are available in ASCE/SEI 7-10 to determine the wind loads. The Directional procedure can be applied to buildings of all heights, while the Envelope procedure is specified only for low-rise buildings. The wind pressure, following the Directional and Envelope procedures, are as follows:

$$p = qGC_p - q_i(GC_{pi})\ (Directional) \tag{14}$$

$$p = q_h[(GC_{pf}) - (GC_{pi})]\ (Envelope) \tag{15}$$

where q is the velocity pressure evaluated at height z above the ground for windward walls and at height h for leeward walls, q_h and q_i are the velocity pressure evaluated at mean roof height h, G is the gust factor, C_p is the external pressure coefficient, (GC_{pi}) is the peak internal pressure coefficient, and (GC_{pf}) is the peak external pressure coefficient. Because it is assumed in the current paper that all buildings under consideration are enclosed, the internal pressure effects have been neglected, since they cancel each other on opposite walls.

The ASCE/SEI 7-10 specifies four partial loading cases for the Directional procedure, and four cases for the Envelope procedure (including two torsional load cases), as shown in Figs. 8 and 9, respectively. Clearly, Cases 1 and 3 of the Directional Procedure are similar to NBCC 2015, but a difference can easily be witnessed in the torsional load cases (Cases 2 and 4). In these cases, the same approach as Cases B and D (see Fig. 9) is used, except that a torsion M_T is defined explicitly and the wind pressure is distributed uniformly over the full tributary area of the building wall face. In terms of low-rise buildings, two additional torsional load cases are added to the Envelope procedure besides two conventional load cases as similar to NBCC 2015. In these additional cases, only 25% of the full wind pressures are applied to half of the building wall, while the rest remain unchanged as the conventional case, which in turn creates a greater amount of torsion comparing to the Canadian provisions.

For low-rise buildings, maximum base shears and torsions are obtained by considering both Directional and Envelope procedures. While the maximum base shears are determined by Case 1 of the Directional procedure, the torsional effect is found to be maximum in Case B (torsion) of the Envelope procedure. For medium-rise buildings, only the Directional procedure is carried out, where Case 1 creates the maximum shear forces. At the same time, the most severe torsional case is determined by either Case 2 or Case 4. After the maximum base shears and torsions have been obtained for all buildings, shear and torsional coefficients are computed following Eqs. (8) and (9).

All the ASCE/SEI 7-10 values are multiplied by 1.53^2 due to the difference between the 3-second and 1-hour wind speed used in NBCC 2015 and ASCE 7-10, respectively. Particularly, the wind speed in NBCC 2015, measured over a period of 1 hour, is 1.53 times smaller than that of the ASCE/SEI 7-10, which is calculated over a period of 3 seconds (Durst 1960).

Figure 10 shows similar torsional coefficient values computed from experimental tests reported in past studies and those computed according to ASCE/SEI 7-10 provisions. For low-rise buildings, the American standard has generated almost the same results as the experimental values on three out of four studies. The study of Tamura et al. (2003) in urban terrain is the only one that gives a notable discrepancy.

Better agreements have been illustrated in the results for medium-rise buildings. The highest difference is from the study of Stathopoulos et al. (2013), where an experimental coefficient is found equal to 75% of that from the American provision. Other findings are very similar: experimental results are roughly 95% of code computations.

Figure 11 compares shear coefficients for low-rise and medium-rise buildings obtained using the ASCE/SEI 7-10 provisions and the respective wind tunnel results. Generally, the discrepancies induced in low-rise buildings are slightly higher than those in medium-rise buildings. All points shown in the graph of medium-rise buildings almost overlap with the 45^{o} line. Stathopoulos et al. (2013) have again given identical values to those provided by the American standard. This resemblance tendency has been previously identified in the case of NBCC 2015 and plotted in Fig. 7. In terms of low-rise buildings, overestimated results were found in the comparisons with Tamura et al. (2003) building in open terrain. This is possible due to the differences in the definition of open terrain used in both cases.

Overall, the ASCE/SEI 7-10 provisions have given analogous shear results comparing to the wind tunnel results.

5. Shear and torsion coefficients in NBCC 2015 and ASCE/SEI 7-10 provisions

In this section, the NBCC 2015 and ASCE/SEI 7-10 wind provisions are applied to five buildings, with the same horizontal dimensions but different heights ranging from 14.8 m (low-rise building) to 43.6 m (medium-rise building). The building heights ascend in a step of 7.2 m. The typical plan and elevation views of the five buildings are presented in Fig. 12, where B and L are the shorter and longer horizontal dimensions. Based on these buildings' configurations and natural frequencies, the wind static procedure is applied for low-rise buildings and the dynamic procedure is applied for medium-rise buildings (see Table 2). All partial loading cases are carried out to seek the highest wind-induced shears and torsions provided by both codes. The results are shown in Fig. 13.

According to NBCC 2015 provisions, the static procedure is applied for the low-rise building (14.8 m), while the medium-rise buildings are computed with the dynamic procedure. Similar to the previous sections, Cases B and D are carried out with the wind tributary area determined following Eq. (6). Very small torsional coefficient is produced from the low-rise building. Thus, the torsional coefficient rises immensely when building class changes from low-rise to medium-rise building (14.8 m to 22.0 m) and can be witnessed easily from the sudden change in the C_T line's alignment in Fig. 13. Moreover, this jump seems to be noticeably high comparing to the average of 1.3 resulted for the same height steps which are: 22.0 m to 29.2 m, 29.2 m to 36.4 m and 36.4 m to 43.6 m. In terms of shear coefficients, the differences are apparently less remarkable. In the N-S direction, the difference between the low-rise and medium-rise buildings is just slightly greater than that between two medium-rise buildings with consecutive heights and decreases largely when it comes to the W-E direction.

Through the good agreement with experimental values (Fig. 10), the ASCE/SEI 7-10 wind provisions are believed to have successfully predicted the wind effects and can be considered a good reference to evaluate the adequacy of other codes. Therefore, the coefficients found in NBCC 2015 are compared with the values provided by the ASCE/SEI 7-10 provisions on the same set of buildings. Significant discrepancies are found regarding torsional coefficients, especially in the case of low-rise buildings. Firstly, the torsional coefficient provided in NBCC 2015 for low-rise buildings is much smaller than that of ASCE/SEI 7-10, implying a serious underestimation of NBCC 2015 in evaluating the wind-induced torsional effects on low-rise buildings. Secondly, for medium-rise buildings, NBCC 2015 has provided torsional coefficients roughly 1.5 times higher than those of ASCE/SEI 7-10. Additionally, this trend increases with the building height and is greater than the 6% difference shown in Figs. 5 and 10 where the same computations were made for smaller buildings. Indeed, the longer horizontal dimension of the buildings in this section (150.5 m) is more than double the maximum dimension from the previous comparisons (61.0 m). Therefore, it can be concluded that the recommended tributary area is conservative for determining the torsional effects of large and high buildings.

Conversely, in terms of shear coefficients, Fig.13 shows that both codes have given similar results regardless of building height. Thus, although the discrepancies fluctuate with the ascending building heights, the two codes only give differences within 10%. Excluding the results of low-rise buildings, all shear coefficients resulted from the NBCC 2015 are higher than those from the ASCE/SEI 7-10. It is also noticeable that the gap between the shear coefficients computed for the low-rise building (14.8 m height) and those for the 22.0 m high building (medium-rise) is significantly higher comparing to the difference between the other medium-rise buildings. For example, the shear coefficients of the 14.8 m high building in both orthogonal directions are on average about 50% of those of the 22.0 m high building. The average between the other medium-rise buildings is almost 80%. However, this difference does not imply any underestimation in shear computations in low-rise buildings as similar trend between code provisions and wind tunnel test results has been found in previous sections.

6. Recommendations

Some recommendations are made here to improve the adequacy of the NBCC 2015 provisions in terms of torsional effects.

For low-rise buildings, according to Fig. 6, the application of wind partial loading cases into low-rise buildings has significantly improved the torsion assessments of NBCC 2015, although some discrepancies still occur. However, by adding two torsional load cases and distributing the wind pressure on building faces differently from NBCC 2015, the American standard provisions have yielded closer coefficients to results from wind tunnel tests (Figs. 10 and 11). Therefore, it is recommended that the torsion methodology provided by ASCE/SEI 7-10 for low-rise buildings to be applied to the NBCC 2015.

For medium-rise buildings, by applying the wind pressure on half of the wall area (Eq. 6), Case B and Case D have resulted in adequate torsions (Fig. 5). However, when the building horizontal dimensions and height increase, this method can provide conservative results with an increasing trend, as can be seen in Fig. 13. Meanwhile, the ASCE/SEI 7-10 standard can provide more appropriate results regardless of building configurations, as is indicated through the comparisons with experimental coefficients in Fig. 10. Consequently, the adequacy of torsional results in medium-rise buildings can be improved in the NBCC 2015 provisions by explicitly defining an additional moment and eccentricity in each torsional loading case as in the ASCE/SEI 7-10.

7. Summary and Conclusion

Results from previous wind tunnel tests have shown that the NBCC 2015 provides adequate assessment of wind effects on low-rise and medium-rise buildings with the only exception of torsional effects on low-rise buildings, which are underestimated significantly. Load cases B and D, available for medium-rise buildings, have been applied, and yielded improved results, although still low compared to the experimental results.

Through the comparisons with ASCE/SEI 7-10, good agreement in shear computations has been found between the two sets of provisions. For medium-rise buildings, if the wind loads are placed on half of the building wall in Case B and Case D, appropriate results can be obtained from the NBCC 2015 although conservative torsions may arise when the building horizontal dimensions and height raise. The comparisons also show that the torsional effects evaluated by NBCC 2015 for low-rise buildings are seriously underestimated.

In conclusion, it is suggested that the ASCE/SEI 7-10 torsion methodology to be applied in future editions of NBCC for both low-rise and medium-rise buildings in order to attain appropriate torsional evaluations.

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Table 1: Building dimensions and exposure conditions.

Study name		Isyumov and Case (2000)	Tamura et al. (2003)	Keast et al. (2012)	Stathopoulos et al. (2013)
Type of building exposure in experiments		Urban	Urban/Open	Open	Open
Low-rise buildings	B (m)	9.75	30		39
	L (m)	29.26	42.5		61
	H (m)	4.88	12.5		20
Medium-rise buildings	B (m)				39
	L (m)				61
	H (m)				30
	B (m)		25	20	39
	L (m)		50	40	61
	H (m)		50	60	40

Table 2: Computation procedure for the buildings in the previous and current studies according to NBCC.

Study	f_n	H/w	H (m)	Procedure
Computation procedure for the buildings in the previous studies according to NBCC				
Isyumov and Case (2000)	4.10	0.50	4.88	Static
Tamura et al. (2003)	1.60	0.42	12.5	Static
	0.40	2.00	50	Dynamic
Keast et al. (2012)	0.33	3.00	60	Dynamic
Stathopoulos et al. (2013)	1.00	0.51	20	Dynamic
	0.67	0.77	30	Dynamic
	0.50	1.03	40	Dynamic
Computation procedure for the buildings in the current study according to NBCC 2015				
Current study	1.19	0.39	14.8	Static
	0.79	0.58	22	Dynamic
	0.54	0.77	29.2	Dynamic
	0.46	0.96	36.4	Dynamic
	0.37	1.15	43.6	Dynamic

Table 3: Original and transformed definition of shear and torsional coefficients in previous studies.

Study (Experimental)	Shear coefficient		Torsion coefficient	
	Original definition	Transformed definition	Original definition	Transformed definition
Isyumov and Case (2000)			$C_T = \frac{T}{q_H BLH}$	$C_T = \frac{T}{q_H BLH} \times \frac{H}{B} = \frac{T}{q_H B^2 L}$
Tamura et al. (2003)	$C_V = \frac{V}{q_H LH}$	$C_V = \frac{V}{q_H LH} \times \frac{H}{B} = \frac{V}{q_H BL}$	$C_T = \frac{T}{q_H LHR}$	$C_T = \frac{T}{q_H LHR} \times \frac{HR}{B^2} = \frac{T}{q_H B^2 L}$ $R = (B^2 + L^2)^{0.5}/2$
Keast et al. (2012)	$C_V = \frac{V}{q_H LH}$	$C_V = \frac{V}{q_H LH} \times \frac{H}{B} = \frac{V}{q_H BL}$	$C_T = \frac{T}{q_H L^2 H}$	$C_T = \frac{T}{q_H H^2 L} \times \frac{H^2}{B^2} = \frac{T}{q_H B^2 L}$
Stathopoulos (2013)	$C_V = \frac{V}{q_H B^2}$	$C_V = \frac{V}{q_H B^2} \times \frac{B}{L} = \frac{V}{q_H BL}$	$C_T = \frac{T}{q_H B^2 L}$	$C_T = \frac{T}{q_H B^2 L}$

Figures

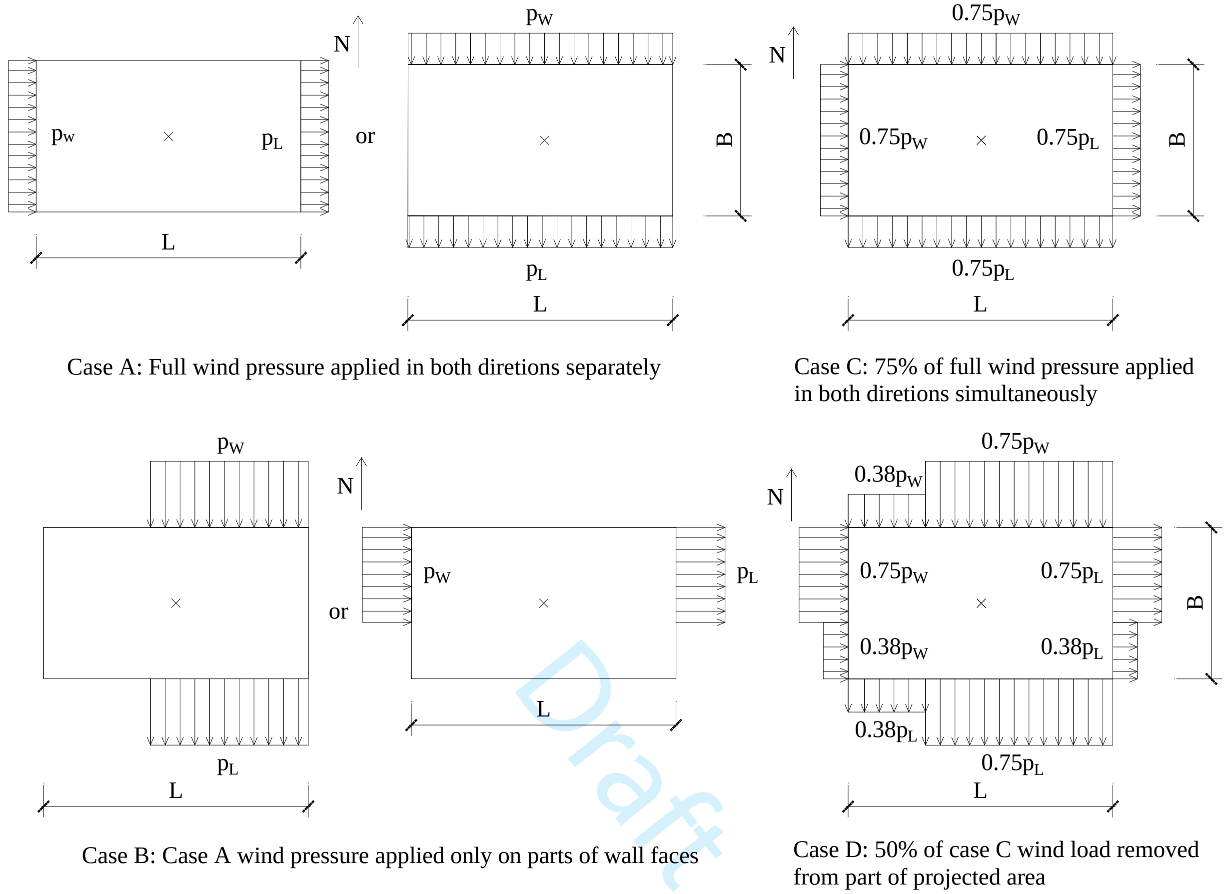
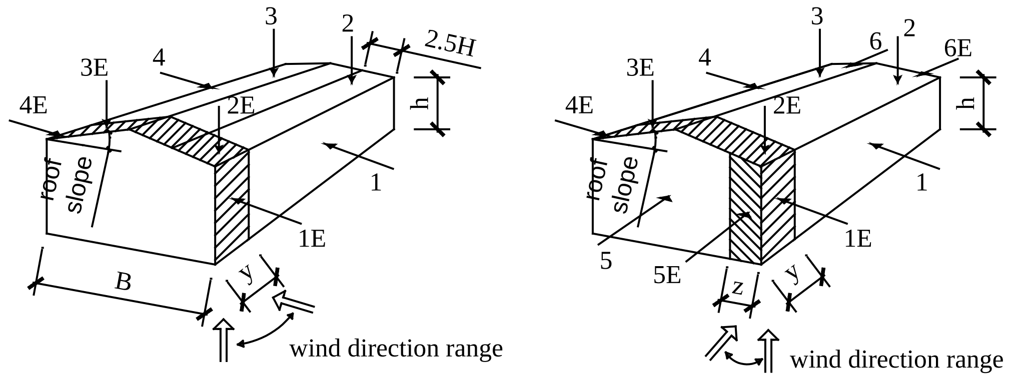


Fig. 1: Load cases for medium-rise buildings after NBCC 2015.



Load case A: winds generally perpendicular to ridge

Load case B: winds generally parallel to ridge

Roof slope	Building surfaces - Case A							
	1	1E	2	2E	3	3E	4	4E
0^o to 5^o	0.75	1.15	-1.3	-2.0	-0.7	-1.0	-0.55	-0.8

Roof slope	Building surfaces - Case B											
	1	1E	2	2E	3	3E	4	4E	5	5E	6	6E
0^o to 90^o	-0.85	-0.9	-1.3	-2.0	-0.7	-1.0	-0.85	-0.9	0.75	1.15	-0.55	-0.8

End-zone width y should be the greater of 6m or 2z, where z is the gable wall end-zone defined for Load Case B below. Alternatively, for buildings with frames; the end-zone y may be the distance between the end and the first interior frame.

End-zone width z is the lesser of 10% of the least horizontal dimension or 40% of height, H, but not less than 4% of the least horizontal dimension or 1m.

Fig. 2: Load cases for low-rise buildings after NBCC 2015.

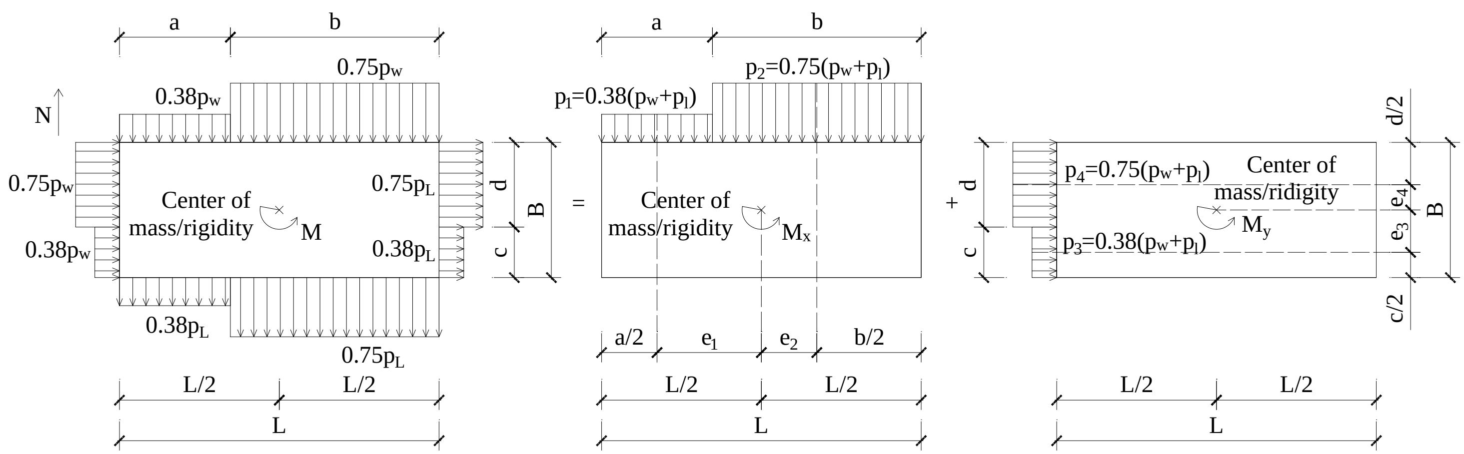
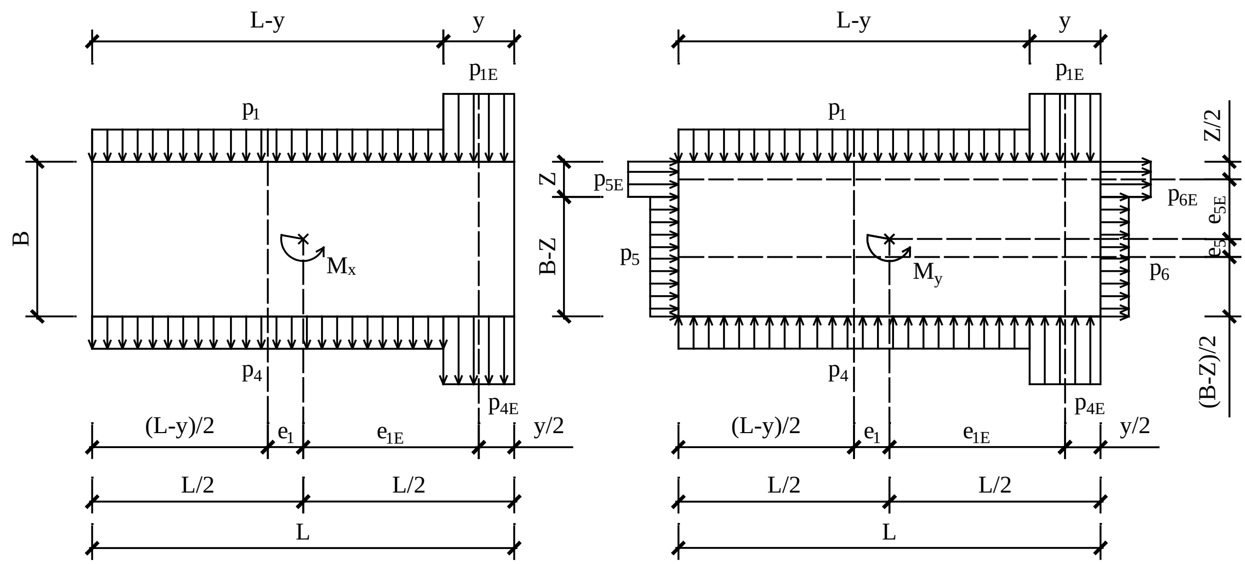


Fig. 3: Load Case D for medium-rise buildings analyzed in *x* and *y* directions.



Load case A: winds generally perpendicular to ridge

Load case B: winds generally parallel to ridge

End-zone width y should be the greater of 6m or 2z, where z is the gable wall end-zone defined for Load Case B below. Alternatively, for buildings with frames; the end-zone y may be the distance between the end and the first interior frame.

End-zone width z is the lesser of 10% of the least horizontal dimension or 40% of height, H, but not less than 4% of the least horizontal dimension or 1m.

Fig. 4: Load cases for low-rise flat roof buildings according to NBCC 2015 provisions.

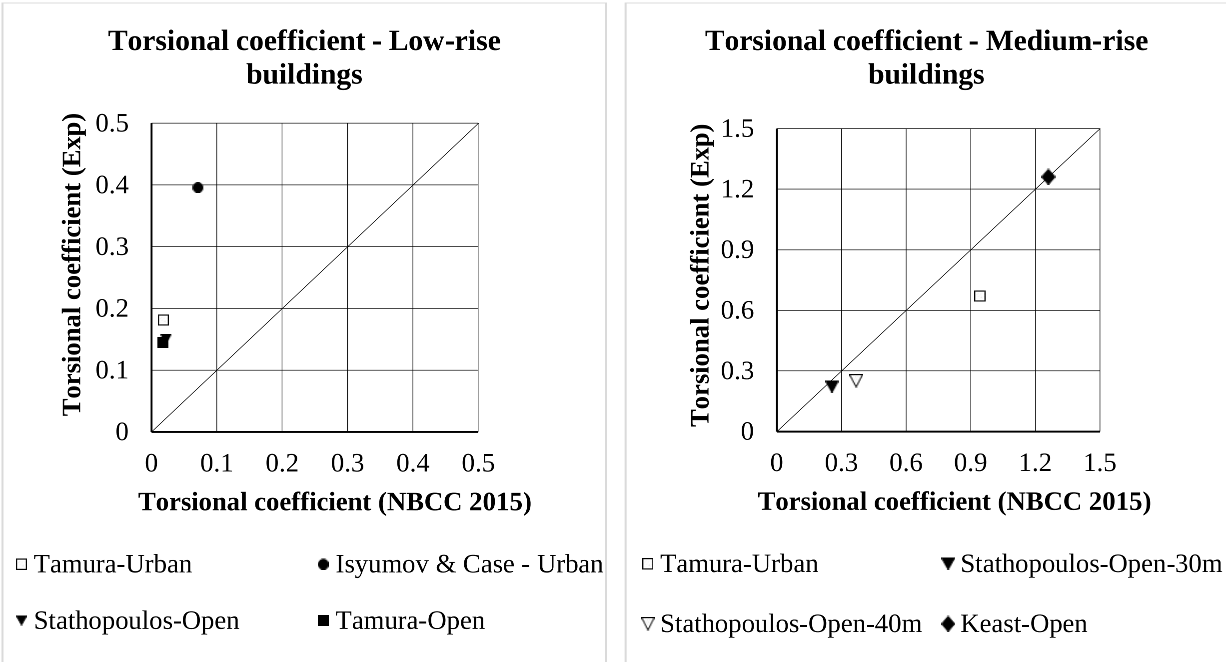


Fig. 5: Comparison of torsional coefficients for low-rise and medium-rise buildings in NBCC 2015 with experimental results from previous studies.

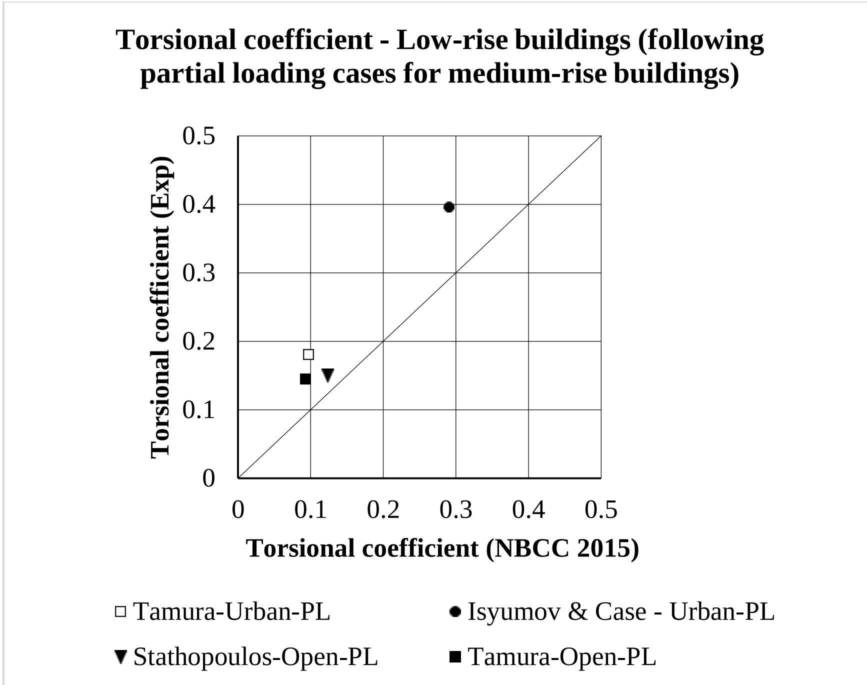
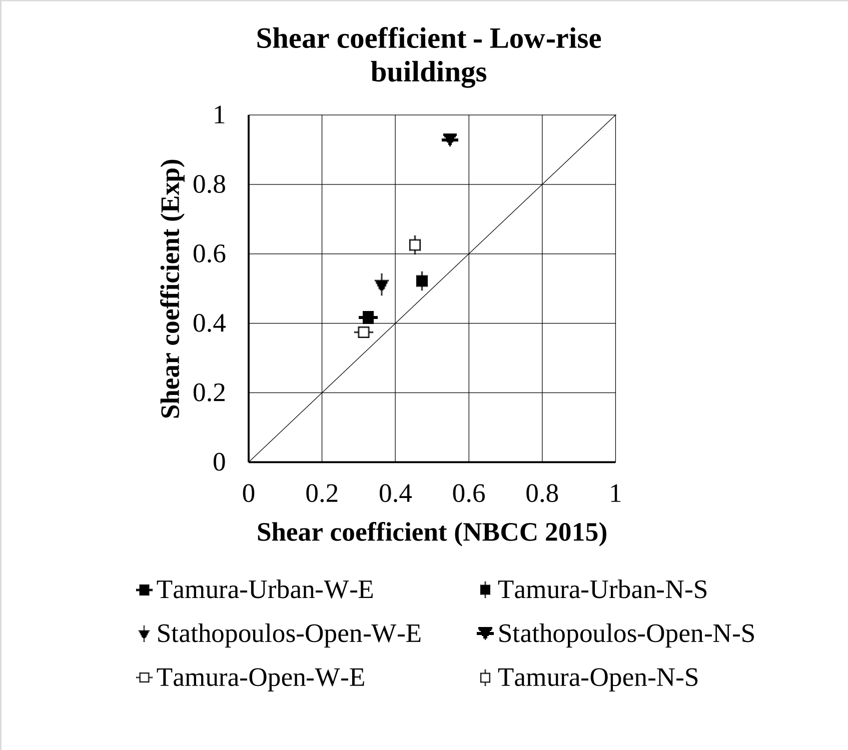


Fig. 6: Comparison of torsional coefficients for low-rise buildings in NBCC 2015 (following partial loading cases for medium-rise building, PL) with experimental results from previous studies.



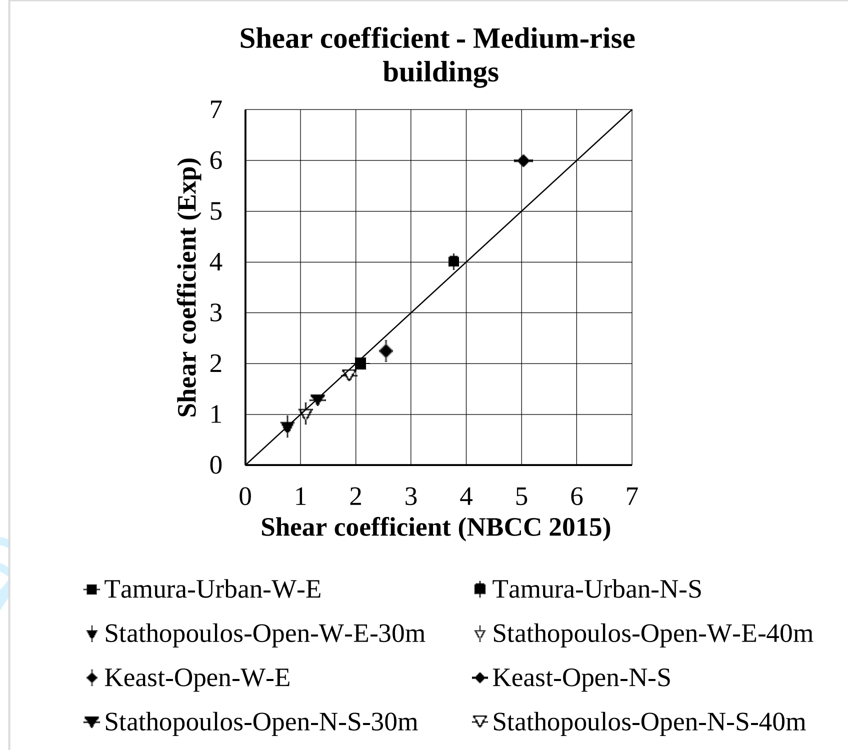


Fig. 7: Comparison of shear coefficients for low-rise and medium-rise buildings in NBCC 2015 with experimental results from previous studies.

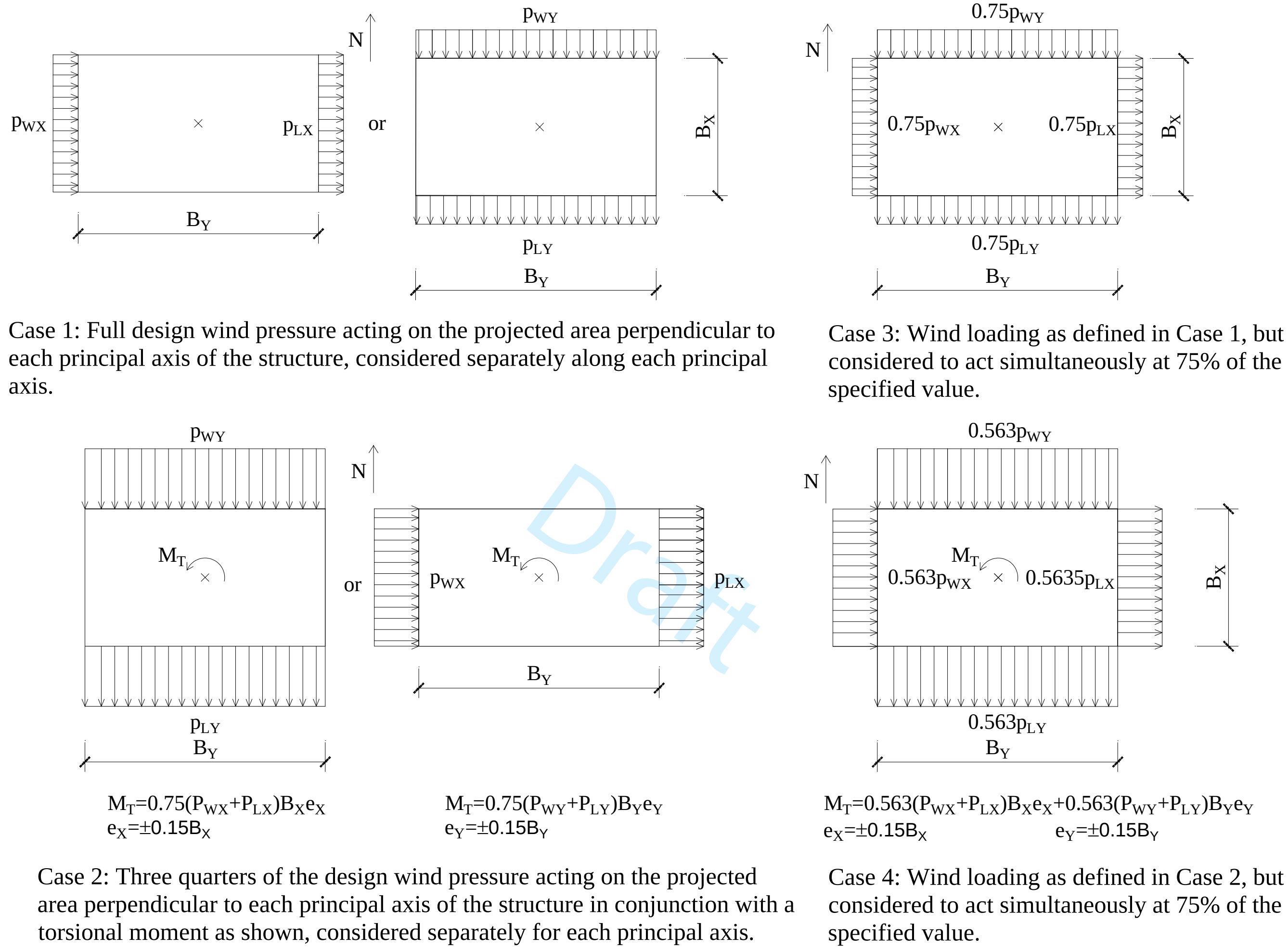
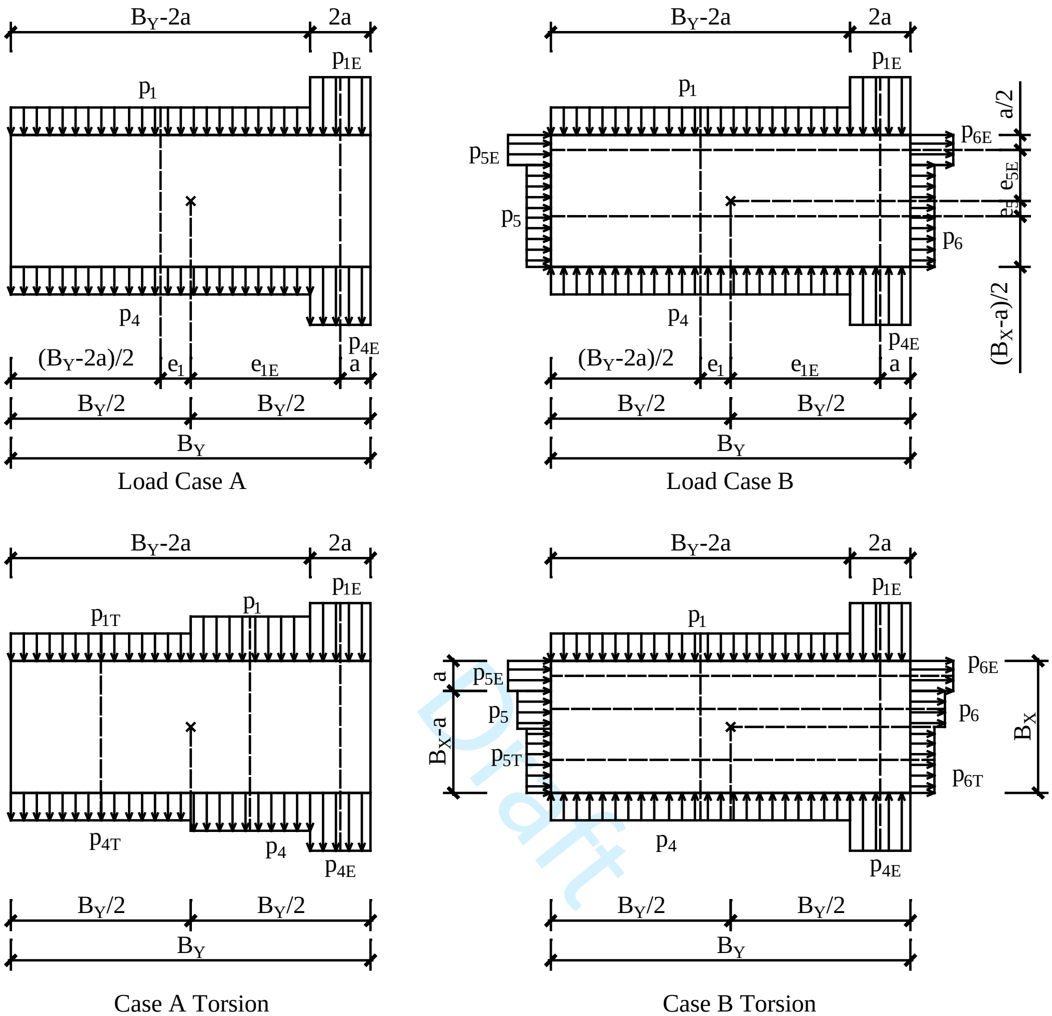


Fig. 8: Partial loading case for the Directional procedure after ASCE/SEI 7-10.



a: 10% of least horizontal dimension or 0.4h, whichever is smaller, but not less than either 4% of least horizontal dimension or 3ft (0.9m)

Fig. 9: Partial loading cases for the Envelope procedure after ASCE/SEI 7-10.

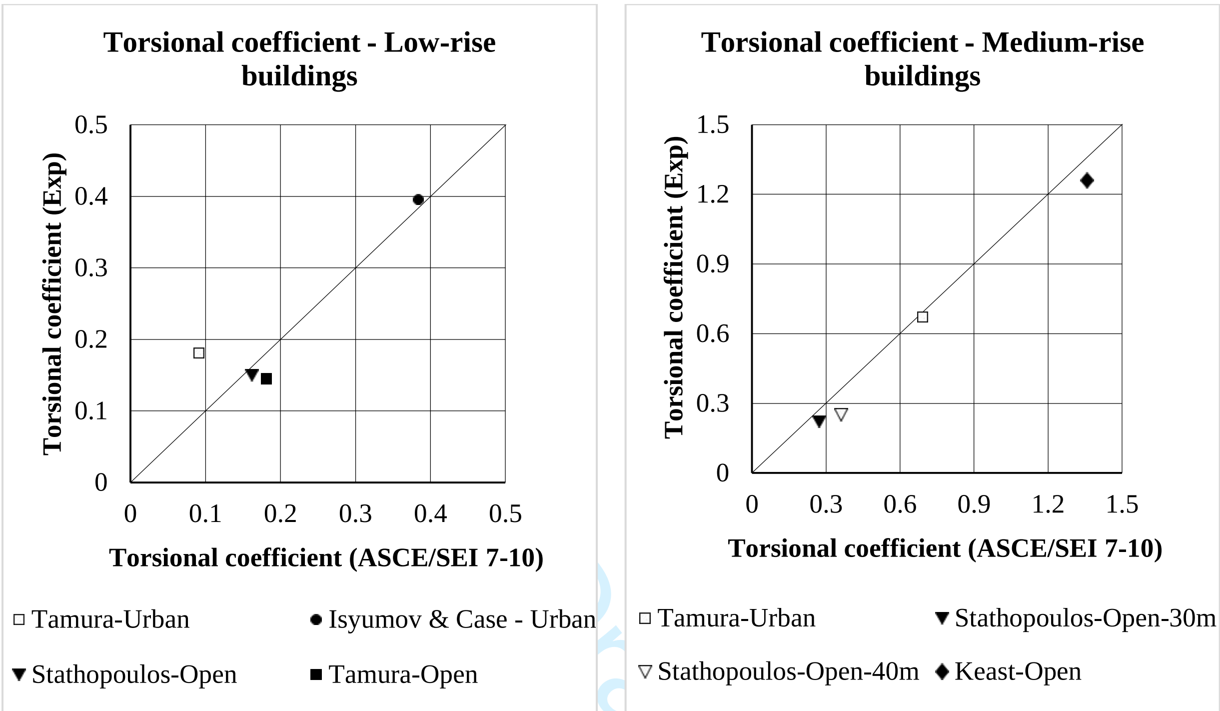


Fig. 10: Comparison of torsional coefficients for low-rise and medium-rise buildings in ASCE/SEI 7-10 with experimental results from previous studies.

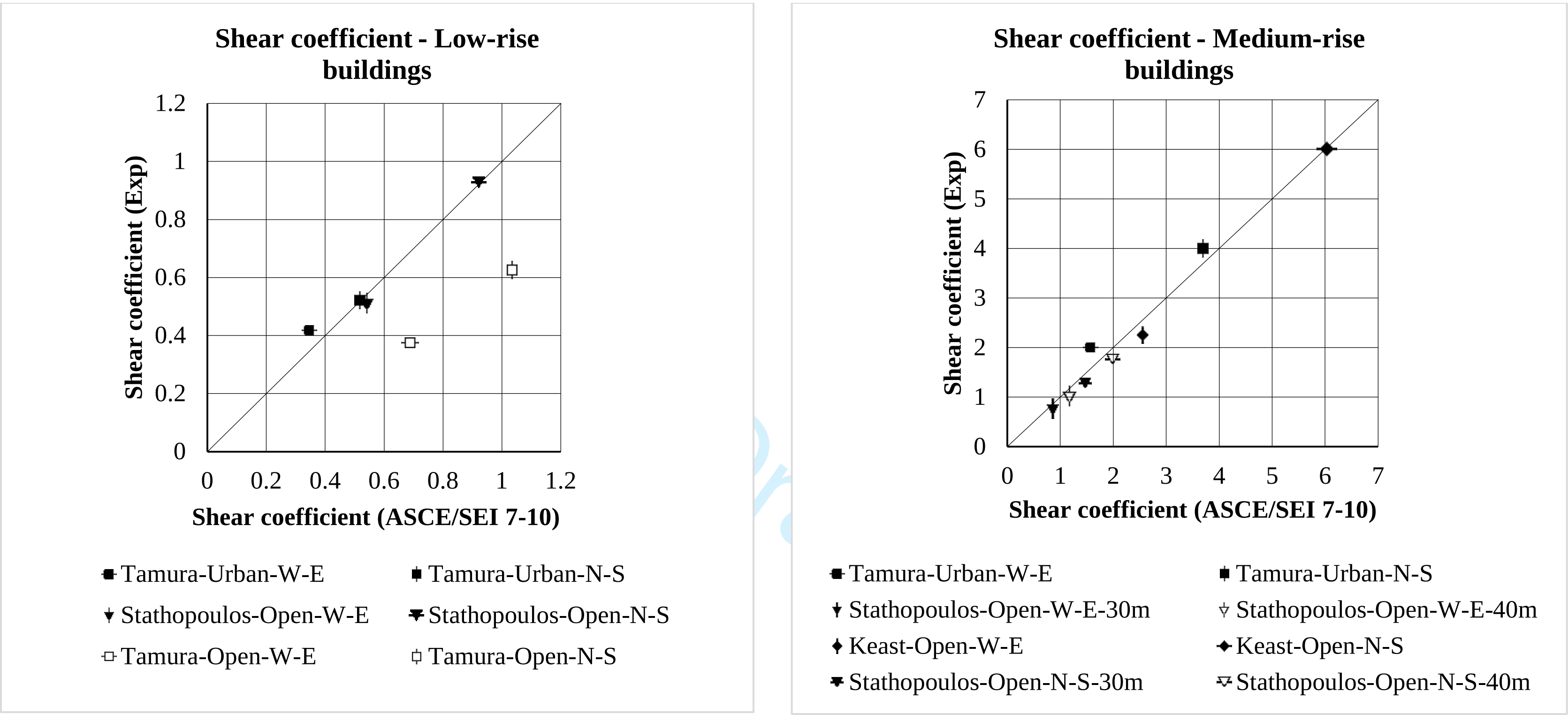
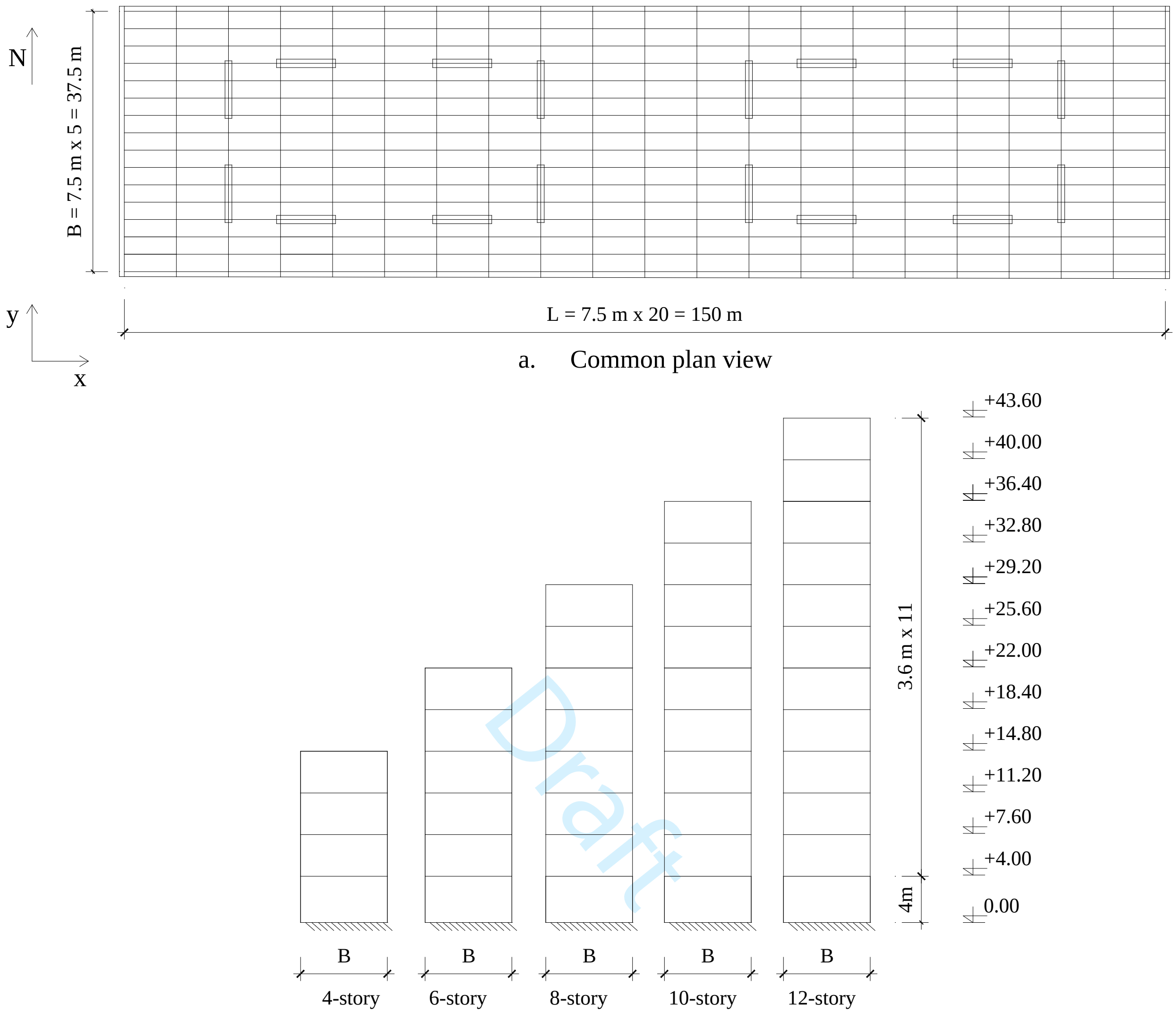


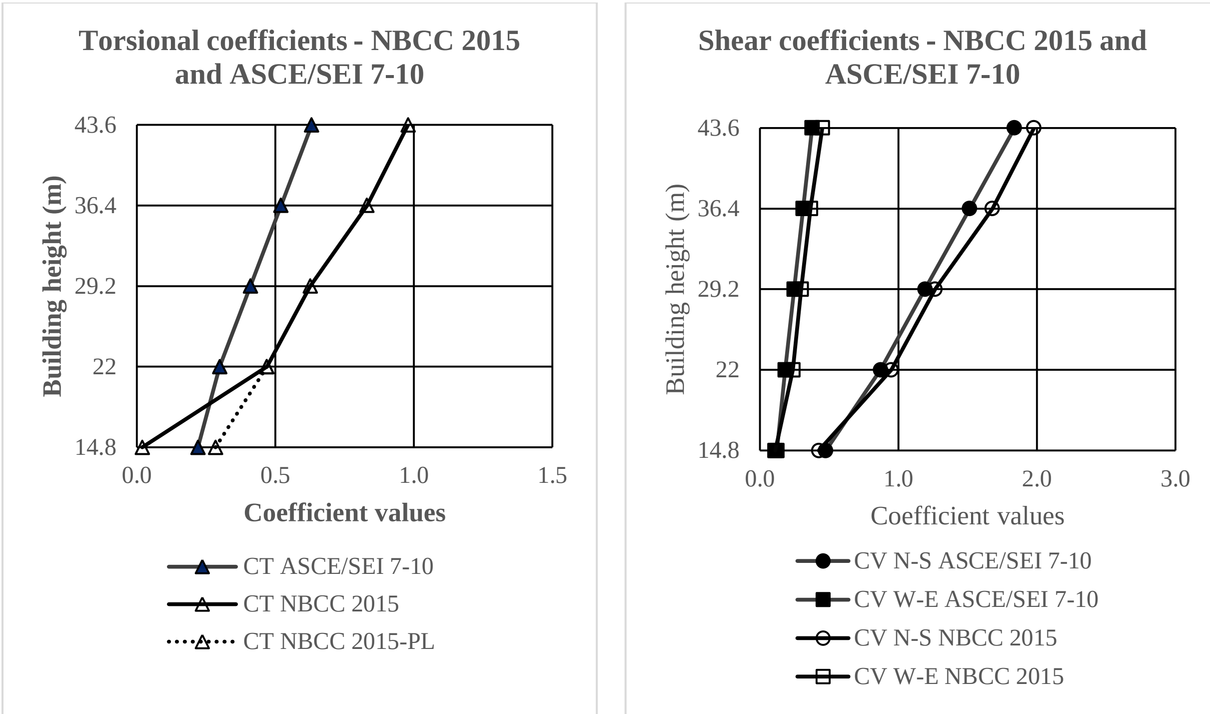
Fig. 11: Comparison of shear coefficients for low-rise and medium-rise buildings in ASCE/SEI 7-10 with experimental results from previous studies.



a. Common plan view

b. Elevation views

Fig. 12: Common plan and elevation views of the buildings in the current study.



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