Consideration of Accidental Torsion in Seismic Design of Buildings According to NBCC

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ABSTRACT

Modern building codes have provisions to account for both inherent and accidental torsional effects on the seismic response of building structures. For buildings that are regular in torsion, the 2015 National Building Code of Canada (NBCC) allows two different approaches to take into account accidental torsional effects using response spectrum analysis (RSA) in design: 1) displacing the center of mass (CM) in the analysis, and 2) adding the effects of static torques to the results obtained from RSA. This article presents a numerical study that was performed to compare and examine the adequacy of NBCC provisions for accidental torsional effects. The simulations were conducted on a 3-DOF model of a one-storey, rectangular building laterally braced by a pair of vertical seismic force resisting system (SFRS) elements along each orthogonal direction. The structure was located in Montreal, QC. A comprehensive parametric study was performed to ascertain the influence of key dimensionless variables on the building response when applying both approaches. In each case, design forces for the SFRS elements were determined using RSA and both NBCC approaches for accidental eccentricity. The response parameters studied are the design forces and ductility demand on the SRFS elements. The latter was obtained from nonlinear response history analysis conducted on the designed structures. In the majority of the cases studied, adding the effects of static torques generated SFRS design forces higher than those obtained when accidental torsion was taken into account by displacing the CM in the analyses. The results from NLRHA showed that the SFRS elements designed with the displaced CM generally sustain higher ductility demands compared to those designed with the static torque approach.

Keywords: Seismic Design, Building, Accidental Torsion, NBCC, Ductility Demand

INTRODUCTION

Adequate consideration of torsion in building design is crucial to achieve adequate structural behaviour. For seismic design, torsion is divided in two categories: inherent torsion and accidental torsion. Inherent torsion occurs in buildings when the center of mass (CM) and the center of rigidity (CR) do not coincide. CR is defined as the axis around which the building will rotate when subjected to torsional motion. The geometric center (CG) is located at the building's centroid. In design, the CM is assumed to be located at the CG. However, a distinction is made between the CG and the CM because the actual position of the CM during an eventual earthquake is unknown. The distance between the CG and the CR is the inherent eccentricity (e_{CR}) (Figure 1). Accidental torsion (T_{acc}) can be interpreted as an increase of inherent torsion caused by the added coupling between the torsional and translational motions of the building. This is the result of phenomena which cannot be explicitly modeled during the building design. Such phenomena include uncertainty of the exact position of the CM and the CR, asymmetrical yielding of the elements of the seismic force resisting system (SFRS) and rotational movement of the base of the building[1]. When using response spectrum analysis (RSA) in design, NBCC 2015[2][1] allows two different approaches for taking into account accidental torsion: 1) by adding to the analysis results the effects of static torques equal to $F_x(0.1b)$ (Figure 2), and 2) by displacing the CM by ±0.05b in the analysis (Figure 3), where b is the building dimension perpendicular to loading and F_x is the design seismic load applied at level x. The second approach is however only permitted for structures that have no torsional irregularity. Previous studies [3] have shown that the second method in which the CM is displaced generally gives lower design forces and there is a need to ascertain that the resulting design will lead to adequate nonlinear response. This paper presents a study that was conducted to examine and compare the two different approaches of NBCC 2015 to account for accidental torsion in design. The key parameters used to describe torsional response are the uncoupled frequency ratio Ω, the normalized eccentricity e_{CR}/b and the NBCC factor B used to define torsional sensitivity are first described. The structures studied are then introduced and designed in accordance with the two methods for a range of Ω and e_{CR}/b values. Design forces for the SFRS elements from the two methods are compared. Finally, the ductility demands in the SFRS elements of the structures computed from nonlinear response history analyses are presented and discussed to evaluate the two design approaches.

ACCIDENTAL TORSION

Parameters Influencing the Torsional Response

The one-storey building considered in this study is illustrated in Figure 1. The building has a square footprint with plan dimensions a = b. The structure is assumed to have a rigid diaphragm setting the number of degrees of freedom (DOFs) to 3: translations along X and Y directions, u_x and u_y, and rotation about the CG, u_θ. In each orthogonal direction, the building is laterally braced by two vertical SFRS elements that are symmetrically positioned on either side of the CG. An inherent eccentricity e_{CR} is created between the CG and CR in the X direction by increasing the stiffness of the vertical SFRS element Y2 and reducing the stiffness of the SFRS element Y1. Therefore, the building edge located near SFRS_Y2 is the stiff edge and the one close to SFRS_Y1 is the flexible edge. For all cases studied, the total lateral stiffness in the Y direction was kept unchanged and equal to the total lateral stiffness in the X direction. Both SFRS elements acting in the X direction have the same lateral stiffness. The structures with e_{CR} different than zero therefore have coupling between Y translation and rotation.

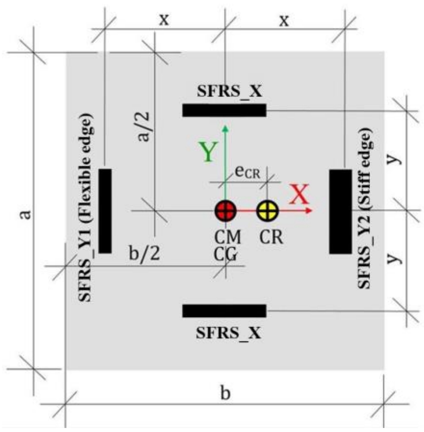


Figure 1: Plan view of the building used for parametric analysis

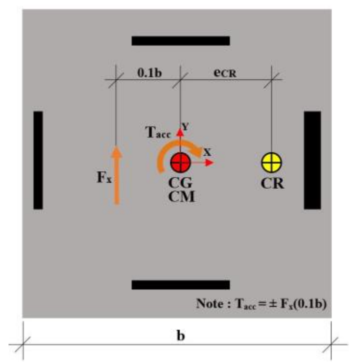


Figure 2: Accidental torsion applied as a static torque

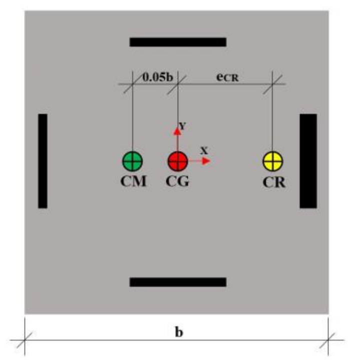


Figure 3: Accidental torsion applied by displacing the CM

Although such a simple building is rarely encountered in practice, it allows reducing the number of variables influencing the elastic torsional response to two main parameters: the uncoupled frequency ratio **Ω** and the normalized inherent eccentricity e_{CR}/b. The uncoupled frequency ratio is defined as:

$$\Omega = \frac{\omega_\theta}{\omega_y} \tag{1}$$

where:

$$\omega_y = \sqrt{\frac{K_y}{m}} \tag{2}$$

$$\omega_\theta = \sqrt{\frac{K_\theta}{mr^2}} \tag{3}$$

$$K_\theta = K_y x^2 + K_x y^2 \tag{4}$$

In these expressions, K_x and K_y are the global translational stiffness in the X and Y directions, respectively, K_θ is the rotational stiffness about the CG, m is the total building mass, and r is the radius of gyration about the CG. If $e_{CR} \neq 0$, the CR and the CG do not coincide and K_θ is no longer the true rotational stiffness of the building. In this case, the true rotational stiffness $K_{\theta CR}$ becomes equal to:

$$K_{\theta CR} = K_\theta - K_y e_{CR}^2 \tag{5}$$

When expressing the rotational stiffness about the CG, the uncoupled frequency ratio Ω can be kept independent from e_{CR}, which simplifies the parametric analysis. It was shown that increasing e_{CR} generates additional coupling between the building translational and torsional motions. In turn, this additional coupling results in greater SFRS element displacements [4].

Torsional Irregularity

The uncoupled frequency ratio Ω allows to quantify the building torsional stiffness. If $\Omega < 1$, the building torsional stiffness is smaller than the translational stiffness. Low torsional stiffness is caused by either the building having most SFRS elements located close to the CG or low translational stiffness of the SFRS elements [5]. This results in large displacements at the building's stiff and flexible edges that may lead to excessive ductility demand on the structural elements near the edges. Therefore, if possible, buildings with low torsional stiffness ($\Omega < 1$) should be avoided in design[5]. NBCC 2015 recognizes this issue and considers buildings with $\Omega < 1$ as torsionally sensitive or torsionally irregular [6]. However, calculation of Ω is too cumbersome for routine design practice. This is why NBCC uses the parameter B to define torsional irregularity. B is the ratio between the maximum storey edge displacement, δ_{max}, and the average storey displacement, δ_{ave}. The relation between B and the uncoupled frequency ratio Ω for a single-storey building is given in Equation 7 (adapted from [6]):

$$B = \frac{\delta_{max}}{\delta_{ave}} = \frac{\delta_{max}}{(\delta_{max} + \delta_{min})/2} = \frac{1 + \frac{1}{\Omega_{CR}^2}\left(\frac{b}{r}\right)^2 \left(\frac{e_{CR}}{b} + 0{,}1\right)\left(\frac{1}{2} + \frac{e_{CR}}{b}\right)}{1 + \frac{1}{\Omega_{CR}^2}\left(\frac{b}{r}\right)^2 \left(\frac{e_{CR}}{b} + 0{,}1\right)\left(\frac{e_{CR}}{b}\right)} \tag{6}$$

where:

$$\Omega_{CR}^2 = \Omega^2 - \left(\frac{e_{CR}}{r}\right)^2 \tag{7}$$

Figure 4 illustrates the calculation of B. First, a static torque $F_x(0.1b)$ is applied at every storey and the maximum and minimum edge displacements are obtained at each floor. B_x (ratio B at floor x) is computed for every floor and B is taken as the maximum of B_x over the frame height. In NBCC, a building is said to be torsional irregular when B exceeds 1.7. Figure 5 shows the variation of B for different values of Ω and e_{CR}/b for the single-storey building case. As shown, because B is a function of both Ω and e_{CR}/b, B can be smaller than 1.7 even when $\Omega < 1$ for low e_{CR}/b. In other words, a building with low torsional stiffness can be torsionally regular according to NBCC criteria if its inherent eccentricity is small. This is the case for a building with $\Omega = 0.75$ and $e_{CR}/b < 0.04$.

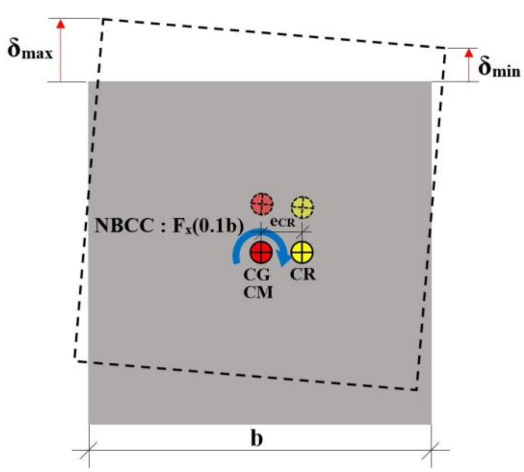


Figure 4: Building plan view illustrating parameter B calculation

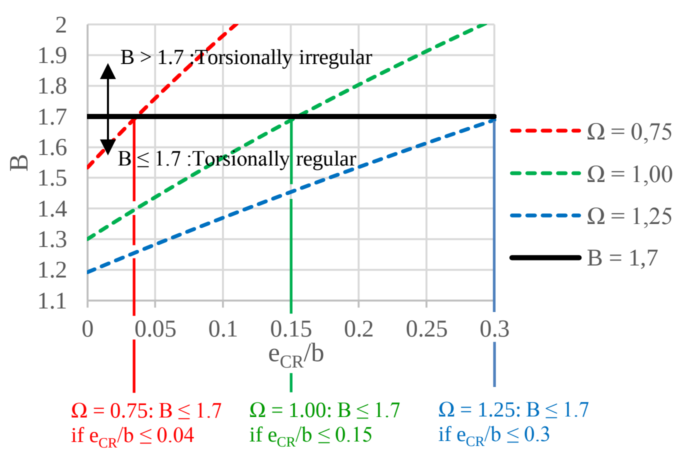


Figure 5: Torsional Irregularity Parameter B

PARAMETRIC STUDY

Building Studied

In this study, the relative stiffness properties of the two SFRS elements along the Y direction were modified to obtain values of the normalized inherent eccentricity e_{CR}/b varying from 0 to 0.3. In all cases, the stiffness of the SFRS elements were such that fundamental period in each direction was kept equal to 0.5 s. In addition, the position in plan of the SFRS elements with respect to the CG were modified in both directions to obtain three different values of Ω: 0.75, 1.0 and 1.25. Figure 6 schematically presents the SFRS configuration considered for each of these three Ω values. For all cases, the ratio y/x was set equal to 0.25, a value that was selected so that the contribution to the SFRS in the Y direction to the torsional stiffness was larger than that of the SFRS elements in the X direction.

Ω = 0.75 (torsionally irregular) Ω = 1.00 (torsionally neutral) Ω = 1.25 (torsionally regular)

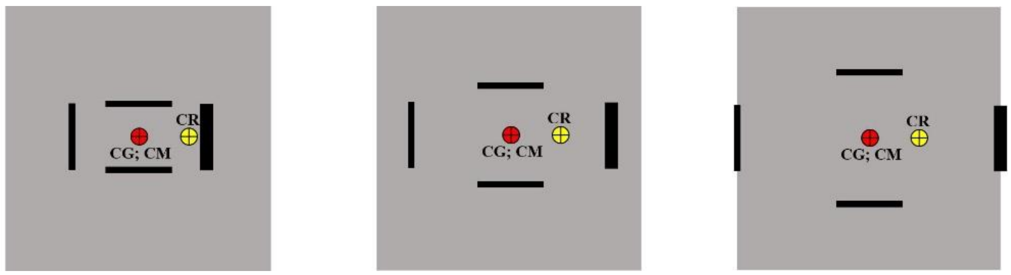


Figure 6: Definition of the parameters considered

The design forces for the SFRS elements acting in the Y direction (F_{SFRS_Yi}) were computed for the different cases defined by the e_{CR}/b and Ω values. The calculations were performed using the two methods of the 2015 NBCC for accidental torsion, T_{acc}, i.e. by displacing the CM by 0.05 b in the RSA or by adding to the results from the RSA the effects of a static torque $T_{acc} = F_x(0.1b)$. For a single-storey building, the seismic design force F_x is equal to the design base shear V_0 = WS where W is the building total seismic weight (W= $m \times g$, where g is the acceleration due to gravity) and S is the design spectral acceleration at the site at the structure lateral period (0.5 s). To isolate the effects of the torsional properties and design method, the calculations were performed assuming uniform response spectrum with S = 1m/s^2. Figure 7 presents the variations of the design forces for each SFRS element normalized by the base shear V_0.

Ω = 0.75 (torsionally irregular) Ω = 1.00 (torsionally neutral) Ω = 1.25 (torsionally regular)

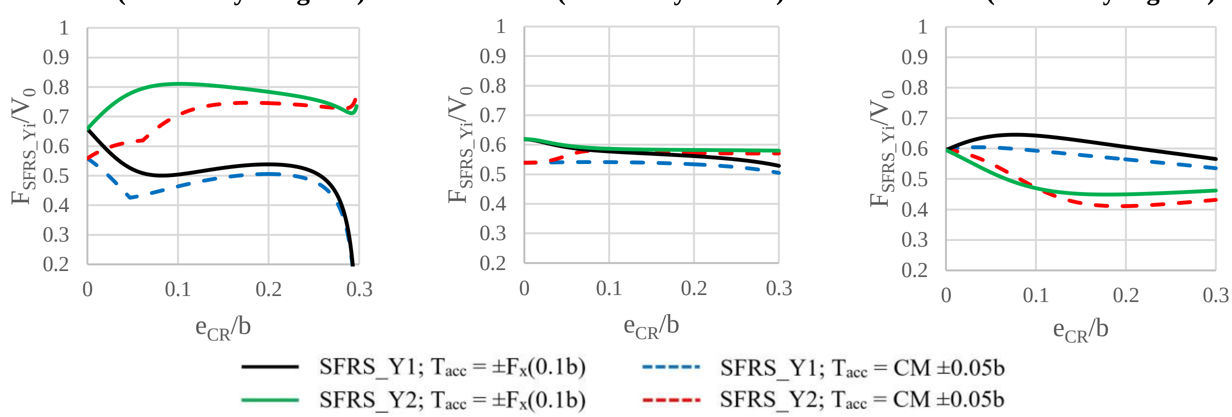


Figure 7: Comparison between normalized SFRS element design forces obtained by applying accidental torsion as a static torque to those obtained by displacing the CM for a uniform spectrum

Design forces are generally higher when accidental torsion effects are represented by a static torque compared to the values obtained by displacing the CM in the analysis. The differences are largest for torsionally irregular buildings (Ω = 0.75) when e_{CR}/b ranges from 0.02 to 0.1. For these structures, the static torque approach results in design forces up to 20% larger than those obtained by displacing the CM. This is because the eccentricity in seismic design forces used to compute the static torque is 0.1b, which is twice the 0.05b distance by which the CM is displaced. The longer level arm therefore generates larger torsional moments. Also, when displacing the CM farther from the CR, the coupling between torsional and translation motions is more significant. This added torsional coupling increases the torsional response and resulting forces but reduces translational response and, therefore, the base shear. Adding a static torque only increases torsional forces and does not alter the base shear. For the other structures, both accidental torsion methods yield design forces that are within 5% of each other.

Design of the Buildings

The structures were then redesigned assuming they were built on a class C site in Montreal Quebec. In this case, the site specific NBCC design spectrum was used. Figure 8 shows the normalized design forces on the Y1 and Y2 SFRS elements obtained from the methods permitted in NBCC 2015 for accidental torsion: if $B \leq 1.7$, the building has no is torsional irregularity and accidental torsion can be applied by either displacing the CM by $\pm$ 0.05b or applying the static torque $\pm F_x(0.1b)$. Conversely, if $B > 1.7$, the building has torsional irregularity and accidental torsion must be applied by means of a static torque.

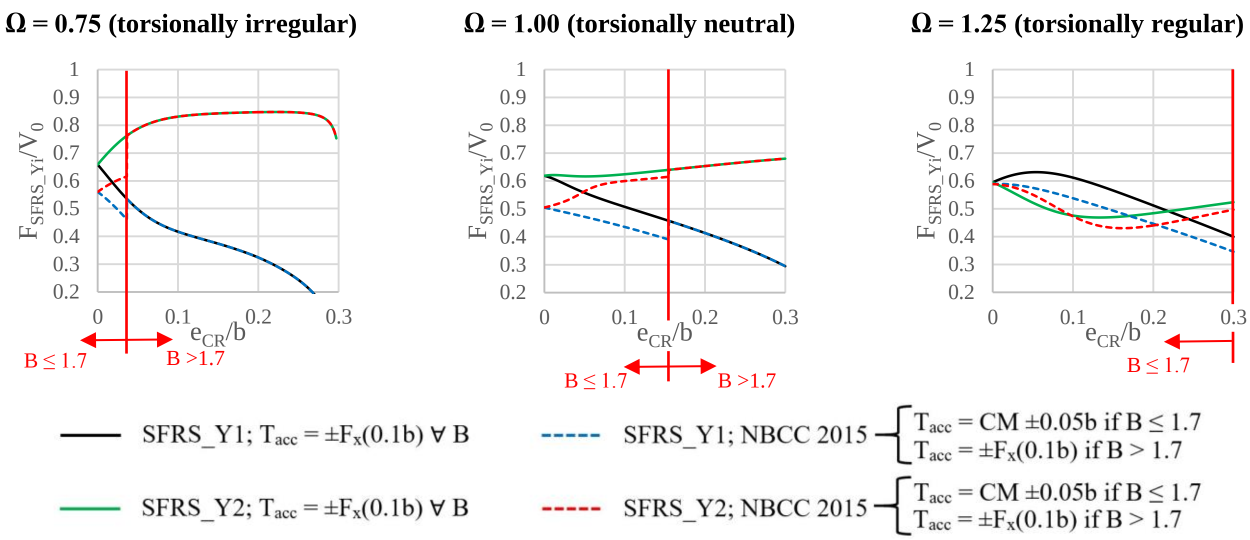


Figure 8: Comparison between SFRS element design forces obtained by the two NBCC 2015 methods for accidental torsion Montreal class C

As shown, buildings with $\Omega = 0.75$ and $\Omega = 1.0$ exhibit a discontinuity in their SFRS element design force curves when following NBCC requirements. This is caused by the fact that buildings having $\Omega \leq 1$ with low values of e_{CR}/b have B values that can be smaller than 1.7. Therefore, buildings with $\Omega = 0.75$ and $e_{CR}/b \leq 0.04$ or $\Omega = 1$ and $e_{CR}/b \leq 0.15$ are considered as torsionally regular and accidental torsion can by applied by displacing the CM. Before the discontinuity, design forces obtained with accidental torsion included as a static torque are 5% to 15% greater than those with accidental torsion applied by displacing the CM. However, when larger values of e_{CR}/b are exceeded, buildings become irregular in torsion and accidental torsion can only be applied by adding the effects of static torques. At this point, the two set of SFRS element design forces merge because accidental torsion is modeled in the same manner for both. Buildings with $\Omega = 1.25$ show no discontinuity or overlapping in the SFRS design forces because the structures are torsionally regular for all e_{CR}/b values considered. Also, for buildings with $\Omega = 1.25$, SFRS element design forces resulting from the static torque method are, on average, only 5% greater than the design forces from the method with displaced CM. These small differences in design forces are in agreement with NBCC 2015 as the method involving the displacement of the CM is only permitted for torsionally regular structures.

Ductility demand on the SFRS elements

A second objective of this study was to investigate the influence of the design method for accidental torsion on the nonlinear seismic response of the structures, with focus on the ductility demand imposed on the SFRS elements. This was achieved by performing nonlinear response history analysis (NLRHA) of the building structures designed in the previous section. In the numerical model, the yield strength of the SFRS elements were obtained by reducing the elastic design forces by the ductility-related factors R_d. Two values were considered, 3.0 and 5.0, to represent moderately ductile and ductile systems, respectively. Moreover, NLRHA were performed on two building sets. One set of buildings designed with the NBCC provisions for accidental torsion (Set 1), and one set of buildings designed without consideration of accidental torsion (Set 2). For Set 1 buildings, NLRHA were performed on buildings models which included an accidental eccentricity of the mass of $\pm$0.05b, as recommended in the Commentary J to NBCC 2015[7]. For Set 2 buildings, mass eccentricity was not considered in NLRHA. NLRHA were performed using an ensemble of 11 ground motion records representative of the Montreal site class C condition. Selection and scaling of the ground motion records was done in accordance with the guidelines of the

NBCC 2015 Commentary J. Figure 9 shows the response spectrum for 11 ground motions calibrated on a Montreal class C design response spectrum.

Figure 10 presents the bilinear force-displacement relationship that was adopted to model the nonlinear response of SFRS elements. In the model, k is the SFRS element initial stiffness and F_y is the yield resistance as obtained with R_d factor. The parameter "exp" defines the "sharpness" of the transition from linear to yielding responses. A sharp transition was selected as exp was set equal to 10. A small (0.001) value was assigned to the post-yielding stiffness ratio to avoid numerical errors associated with elements having zero stiffness. The ductility demand for the SFRS elements of the Set 1 and Set 2 buildings is compared using the ratio μ/μ_{ref}, where μ is the ductility demand for Set 1 buildings and μ_{ref} is the ductility demand for the Set 2 buildings. A value higher than 1.0 for this ratio means that the design method for accidental torsion is inadequate as the SFRS elements of the Set 1 building sustain relatively higher ductility demand compared to the reference Set 2 building in spite of the application of the NBCC 2015 provisions for accidental torsion. The accidental torsion design method is therefore considered as adequate if $\mu/\mu_{ref} \leq 1.0$. Figure 11 and Figure 12 show the normalized SFRS ductility demand ratio μ/μ_{ref} for the parameters described above and for R_d equal to 3.0 and 5.0, respectively.

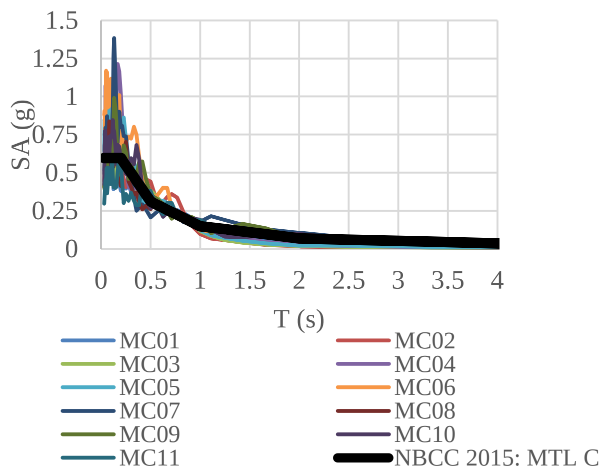
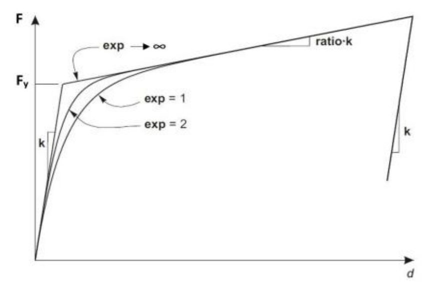


Figure 9: Spectral acceleration SA of ground motions calibrated using Montreal class C design response spectrum



- k: SFRS element stiffness
- F_y: SFRS element yield force
- ratio·k: post yielding stiffness
- exp: coefficient expressing the "sharpness" of the transition from linear to nonlinear behaviour

Figure 10: SFRS wall elements Wen nonlinear force-displacement curve (adapted from [8])

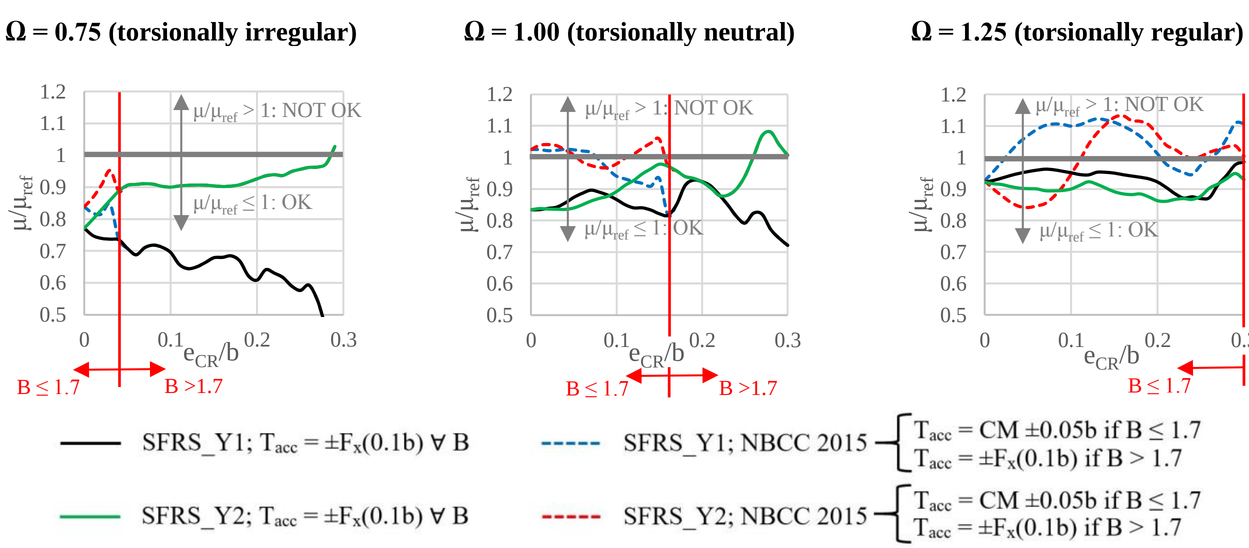


Figure 11: Normalized SFRS ductility demands on SFRS elements designed with R_d = 3.0.

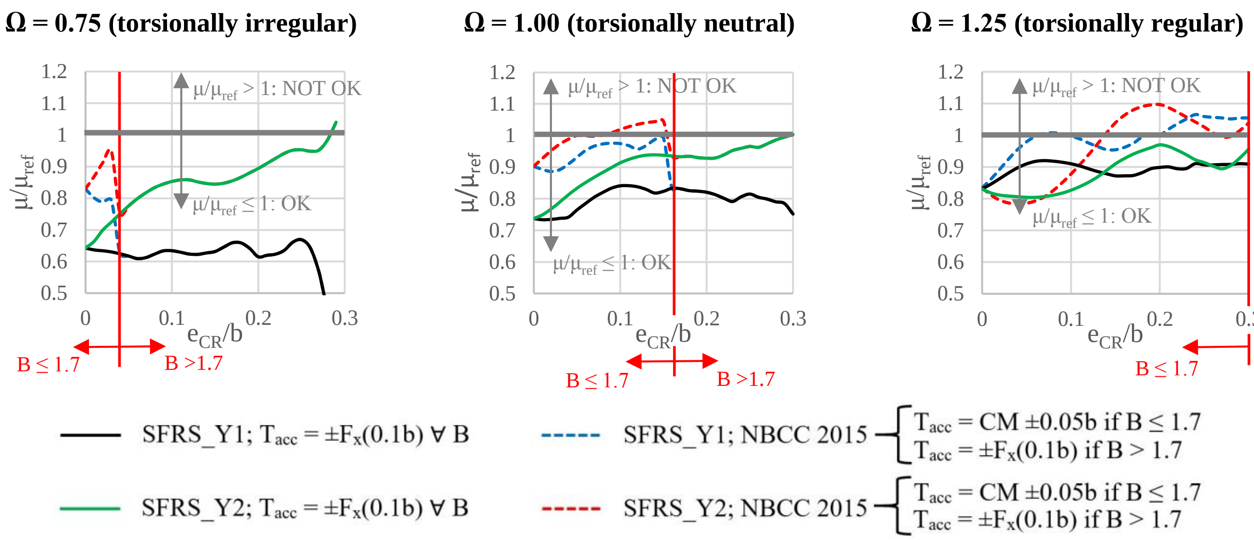


Figure 12: Normalized SFRS ductility demands on SFRS elements designed with R_d = 5.0.

In the figures, solid lines present the results for the SFRS elements designed with accidental torsion applied as a static torque ($T_{acc} = \pm F_x(0.1b)$) for both torsionally regular ($B \leq 1.7$) and irregular ($B > 1.7$) buildings. Dashed lines are for the SFRS elements designed with accidental torsion applied by displacing the CM (T_{acc} = CM ± 0.05b) for torsionally regular buildings or by adding the static torque for torsionally irregular buildings. As was the case for the SFRS design forces in Figure 8, μ/μ_{ref} for buildings with $\Omega = 0.75$ and $\Omega = 1.00$ display a discontinuity at $e_{CR}/b = 0.04$ for $\Omega = 0.75$ and $e_{CR}/b = 0.15$ for $\Omega = 1.0$. For these values of Ω and e_{CR}/b, the buildings shift from being torsionally regular ($B \leq 1.7$) to torsionally irregular according to NBCC. Therefore, the accidental torsion design method changes from displacing the CM to adding the effects of a static torque. There is no discontinuity in μ/μ_{ref} for buildings with $\Omega = 1.25$ because all structures are torsionally regular for the range of e_{CR}/b considered in the study. In general, the ductility demand ratio μ/μ_{ref} is relatively unaffected by the ductility reduction factor R_d. Applying accidental torsion with the static torque yields $\mu/\mu_{ref} \leq 1$ for all cases considered except when e_{CR}/b is greater than 0.27 for $\Omega = 0.75$ and $\Omega = 1.0$ for $R_d = 3.0$. This is also the case for $\Omega = 0.75$ when $R_d = 5.0$. When $\Omega = 1.25$, B is smaller than 1.7 for all e_{CR}/b values considered and accidental torsion was accounted for by displacing the CM. For these structures, the ductility demand ratio μ/μ_{ref} exceeds 1.0 to reach maximum values of 1.12 and 1.10 for R_d = 3.0 and 5.0, respectively. For these structures with $\Omega = 1.25$, it is observed that there is no increase in the ductility demand when using $T_{acc} = \pm F_x(0.1b)$ to account for accidental torsion in design. In the context of this paper, it must be noted that values μ/μ_{ref} greater than 1.0 do not mean inadequate seismic performance and possibility of collapse. The results obtained herein only indicates that suggests that including accidental torsion by displacing the CM by ± 0.05b for torsionally regular buildings, as permitted in NBCC 2015, may result in structures experiencing higher inelastic displacement demands. Further studies are needed to evaluate the possible consequences of this higher ductility demand on the probability of collapse.

CONCLUSIONS

The objective of this paper was to define the effect of applying the design method specified in NBCC 2015 for accidental torsion on the design forces for the SFRS elements and ductility demand considering nonlinear behaviour. Three building torsional conditions were considered: (i) torsionally irregular according to NBCC ($B > 1.7$), (ii) torsionally neutral (B=1.7) and torsionally regular ($B \leq 1.7$). In general, design forces obtained by including accidental torsion as a static torque of $\pm F_x(0.1b)$ are larger than those resulting from displacing the CM from the CG by 0.05b. However, for torsionally neutral and torsionally regular buildings, both design approaches for accidental torsion produced similar SFRS element design forces. This agrees with NBCC 2015 design philosophy because it only allows to optionally model accidental torsion by moving the CM if the building is torsionally regular.

The response parameter used to investigate nonlinear behaviour was the normalized ductility demand μ/μ_{ref}. The ductility μ is the SFRS element ductility demand for buildings designed with consideration of accidental torsion and analyzed using nonlinear models in which the CM was displaced by 0.05b to introduce accidental torsion condition. The ductility μ_{ref} is the SFRS element ductility demand for buildings designed and analyzed without consideration for accidental torsion. The design method for accidental torsion was said to be adequate when the computed ratio μ/μ_{ref} was equal to or less than 1.0. For all structures considered, using the static torque in design resulted in acceptable ductility with $\mu/\mu_{ref} \leq 1$ except for structures designed with R_d = 3.0 cases when the normalized accidental eccentricity e_{CR}/b was higher than 0.27. When permitted in the 2015 NBCC, including accidental torsion by displacing the CM resulted in excessive ductility demand with μ/μ_{ref} ratios reaching up to 1.12 and 1.1 for structures designed with R_d = 3.0 and 5.0, respectively. For these structures, further studies are needed to evaluate if such higher ductility demand can have an impact on the capacity against collapse. These studies should examine the capacity of other structural components such as edge columns to safely accommodate the larger displacements caused by the amplified torsional response.

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