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CASE STUDY OF SEISMIC LOAD REDUCTION FACTORS FOR EQUIVALENT SEISMIC LOADS FOR LOW AND MID-RISE BUILDINGS

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ABSTRACT

The current study assesses the seismic response of four buildings in various seismic regions in Canada. The provisions of the 2010 National Building Code of Canada (NBCC) are strictly followed related to the loading and analysis of various buildings used in the study. The study uses different mid-rise buildings as case studies. The studied buildings have different plan view geometry, such as Rectangular, Semi L-Shape and L-Shape building. The buildings are analyzed for different seismic locations in Canada including, London, Toronto, Montreal and Victoria. These locations are chosen to simulate low, moderate and high seismic areas in Canada. Three-dimensional finite element models of the buildings are developed using the commercial finite element software package ETABS. The lateral force resisting system of the buildings consists of concrete shear walls aligned in both principle directions. The code provisions are strictly followed. The fundamental periods obtained from 2010 NBCC equations and finite element analysis are compared. Consequently, a comparison between the seismic base shear values obtained for the different fundamental period is conducted. The study reveals that the fundamental period obtained from 2010 NBCC can be overestimated for low storey buildings when compared to periods obtained using finite element analyses. In addition, the finite element analyses shows that the building fundamental period differs in the principle axes while the 2010 NBCC only provides a definite fundamental period equation to be used for the seismic analyses of a building. Such a difference in building fundamental periods leads to different base shear values along the principle axes of the building.

Keywords: Fundamental Period, Seismic, NBCC, Finite element, Equivalent static approach, Ductility reduction factors, Over-strength reduction factors

1. INTRODUCTION

Extensive research had been carried out for the development of seismic design guidelines for buildings in Canada. The National Building Code of Canada (NBCC) evolved over the years to incorporate several major improvements. The 2005 NBCC introduced numerous equations to calculate building's fundamental period for different types of lateral load resisting structure systems. The uniform hazard spectrum (UHS) approach was adopted for calculating site-specific response spectral acceleration and it was incorporated in the design base shear calculations (Heidebrecht, 2003). In addition, the 2005 NBCC introduced two force modification factors, R_d and R_o. The ductility related factor R_d, represents the structure's overall ductility. The over-strength related factor R_o, accounts for the reserve of strength inhibited by the structures that were traditionally designed for factored resistances.

Mitchell et al. (2010) compared the use of reduction factors for various seismic regions in Canada and compared the factored base shear values for two storey and ten storey concrete shear wall structures in

Montreal and Vancouver. The study concluded that the key parameters that influence the factored seismic base shears include: site seismicity, load factors, foundation conditions, determination of fundamental period, structural systems, and the corresponding reinforcement design and detailing requirements. The study also concluded that low-period structures designed according to older versions of the NBCC can be vulnerable to seismic activity.

Hamada and El Damatty, (2013) studied two irregular low and high-rise L-shaped buildings according to 2005 NBCC and 2010 NBCC. The study determined that the low-rise building's base shear obtained from the response spectrum analyses were 23% higher than the values calculated using the equivalent static approach as the code equations neglect the contribution of higher modes. For high-rise buildings, the study revealed that the effect of the higher modes recommended by 2005 NBCC is conservative and the shear force calculated by the static approach can be overestimated. Following the study, Hamada and El Damatty, (2016) studied the effect of modeling the concrete slabs as rigid and semi-rigid diaphragms on the seismic behavior of the two buildings. They found that base shear forces for rigid diaphragms were 13% and 9% higher than using semi-rigid diaphragms for low and high-rise buildings. The study also concluded that cracked effective inertia of the concrete slabs directly affects the natural frequency of the building.

Gilles et al. (2011) studied the factors affecting the estimation of building period and the empirical 2005 and 2010 NBCC equations for estimating the natural period of buildings. The study compared the natural periods calculated with the NBCC equations with periods measured from actual buildings. The study showed an inaccuracy in the NBCC empirical equations to calculate the natural period of the buildings. The authors outlined various parameters like soil stiffness, lateral stiffness and modelling skills which can lead to inaccurate building periods.

Gilles & McClure, (2012) compared the field measured natural periods for twenty seven Reinforced Concrete Shear Wall buildings in Montreal, Canada with the period equation given in the 2010 NBCC for shear wall buildings. The study concluded that the equation to estimate the period in accordance with the 2010 NBCC is inaccurate. Instead, an altered equation is proposed by the authors to calculate the natural period of the buildings. The equation was proven to vary linearly along the building height and significantly fits the measured periods of concrete shear wall buildings.

In the current study, seismic analyses for four different concrete shear wall buildings is conducted. The equivalent static approach is used to obtain the seismic behavior of the buildings. All the seismic provisions according to 2010 NBCC are followed with the objective of studying the effect of building height, building plan view geometry, and building's location on the seismic response of the buildings. The study compared the fundamental periods from finite element (FE) analyses to the ones obtained from the 2010 NBCC fundamental period equations. Consequently, the seismic base shear obtained for fundamental periods from 2010 NBCC and FE analyses are compared.

2. ANALYSIS LOADS

2.1 GRAVITY LOADS

Gravity loads are calculated in accordance with the 2010 NBCC. The gravity loads include the building self-weight, super imposed dead loads, live loads, mechanical loads, and snow loads.

2.2 SEISMIC LOADS

Seismic loads are calculated in accordance with the provisions of Part 4 of the 2010 NBCC. The location of the buildings are taken as London, Toronto, Montreal, and Victoria. These locations are chosen to represent low, moderate, and high seismic locations in Canada. Soil Class D is chosen for the different sites. The velocity and acceleration soil factors and the site specific 5% damped spectral response acceleration values $S_a(T)$ are calculated as specified the 2010 NBCC. More details regarding the seismic loads calculations and application to the studied buildings are provided by Hamada and El Damatty (2013) and Hamada and El Damatty (2016)

3. CASE STUDIES AND ANALYSES MODELS

The mid-rise buildings used in the current study have different plan view geometry, such as Rectangular (Building A & D), semi L-shape (Building B) and L-shape building (Building C). The plan views of these buildings are shown in Figures 1-4. The applied lateral loads, such as seismic and wind loads, are resisted through a series of concrete shear walls located along the principle axes of the buildings as shown in Figures 1-4. The gravity loads are supported by the same concrete shear walls, and some localized concrete beam-column systems. The floors are two-way concrete slabs and are assumed to act as rigid diaphragms. The three-dimensional elastic FE models are developed using the commercial software ETABS V.15. Shell elements are used to model the concrete shear walls and two-way slabs. The out-of-plane stiffness of the floor slabs are significantly reduced to minimize their effect on the overall lateral stiffness. Three-dimensional frame elements are used to model the beams and columns. All the concrete beams are analyzed as simply supported beams and are expected to have a minimum effect on the buildings' lateral stiffness. In order to account for the effective stiffness of the cracked concrete sections, recommended effective cross-section inertias by the CSA A23.3-04 clause 21.2.5.2 and table 21.1 are used. Modal analysis is conducted to calculate the fundamental period of the buildings. The building mass was defined as recommended by the NBCC, and lumped at each floor level. Mesh sensitivity analyses are conducted and a recommended shell element mesh size of 1m x1m is used in the current study. Based on the 2010 NBCC seismic requirements, the equivalent static approach is used to study the seismic behavior of the buildings. The number of storeys of each building are gradually increased from three to fifteen storeys. The effect of both the buildings' mass and height on fundamental period and seismic base shear of each building is studied. The buildings' fundamental period calculated using FE analyses, is compared with the recommended 2010 NBCC values. The variation of the fundamental period with height is investigated. The variation of the buildings' fundamental period along both orthogonal directions is assessed. The corresponding base shear for the different fundamental periods is consequently compared.

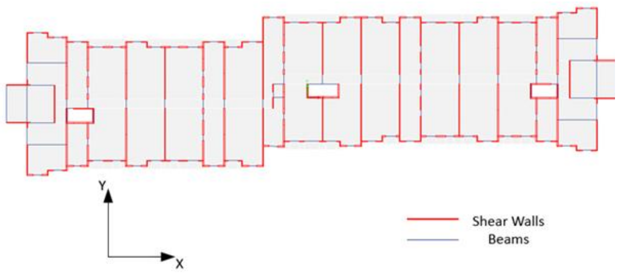


Figure 1: Schematic Plan View of Building A (Combined Rectangular Building)

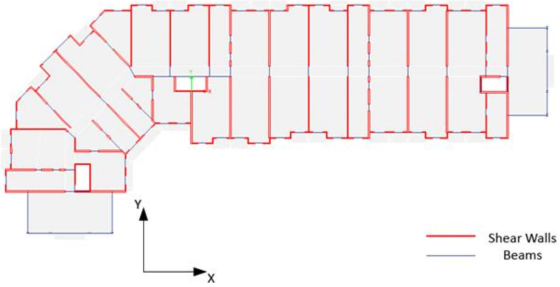


Figure 2: Schematic Plan View of Building B (Semi L-Shaped Building)

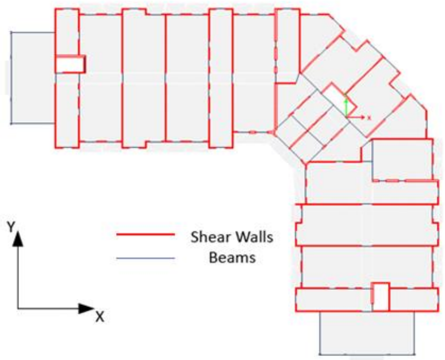


Figure 3: Schematic Plan View of Building C (L-Shaped Building)

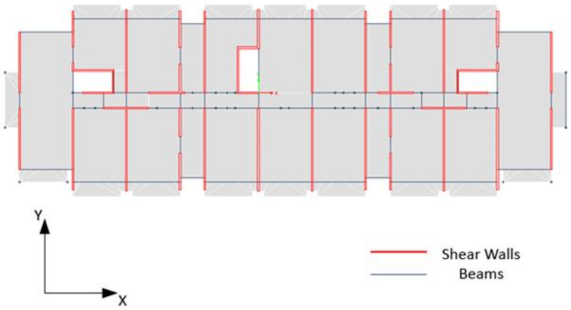


Figure 4: Schematic Plan View of Building D (Rectangular Building)

4. DISCUSSION AND RESULTS

The discussion and results section is divided into two main sections. Section 4.1 investigates the variation of building fundamental period with increase building height and mass. In addition, Section 4.1 studies the variation of the buildings' fundamental periods along the two principle directions. Section 4.2 compares the seismic base shear values based on the 2010 NBCC fundamental period and the FE analyses. The results are shown for Building's A, B, C, and D. The 2010 NBCC seismic provisions are strictly followed for all the buildings.

4.1 FUNDAMENTAL PERIOD COMPARISON

Figures 5 - 8 show the variation of Buildings' A, B, C and D fundamental periods T(a), T(x) and T(y) along the building height, where; T(a) is the 2010 NBCC building fundamental period at a certain building height; T(x) is the building's FE analysis fundamental period in the X-direction; and T(y) is the same building's FE analysis fundamental period in the Y-direction for the same height. T(a) is calculated using 2010 NBCC clause 4.1.8.11 (3c). Clause 4.1.8.11 (3c (iii)) limits the maximum allowable period for shear wall buildings as twice T(a). This upper limit for buildings' natural periods is also plotted in figures 5-8.

For Building A, and as shown in Figure 5, T(y) value remains lower than the 2010 NBCC recommended fundamental period and the 2010 NBCC upper limit for fundamental period for the different building heights. For three storey building, T(x) remains lower than T(a) but for six storeys and above, T(x) exceeds the 2010 NBCC recommended value but remains lower than the 2010 NBCC upper limit for concrete shear wall structures. Such results are expected based on Building A structure system shown in Figure 1, where significant number of shear walls are located along the Y direction of the building and very few in the X-direction. The period of the structure is inversely proportional to the square root of overall stiffness which results in a higher period in X direction. Both T(x) and T(y) remain lower than the 2010 NBCC fundamental period upper limit recommended by (Clause 4.1.8.11 (3c)). As the number of storeys increase, the total height increases which affects the fundamental periods of the structure. As shown in Figure 5, T(x) and T(y) increase with the increase of the building height but not in a linear manner as recommended in the literature.

The results for Building B are shown in Figure 6. Building B results follow a similar trend as Building A. T(x) and T(y) remain lower than the 2010 NBCC upper limit. For Building C, the results are shown in Figure 7. The lateral stiffness in both directions are quite comparable and hence building C fundamental periods are almost equal in X and Y directions. The periods in both X and Y directions remain lower than the 2010 NBCC upper limit for concrete shear wall structures. The results for Building D are shown in Figure 8. Building D fundamental periods in Y direction remain lower than the 2010 NBCC upper limit while the period in X direction exceed the 2010 NBCC upper limit.

As shown in Figures 5 to 9, in general the studied buildings' fundamental period obtained using FE analyses are lower than the ones obtained using 2010 NBCC equations. The lower FE obtained fundamental period results in a higher seismic base shear than the base shear obtained based on the 2010 NBCC provisions. The 2010 NBCC provisions do not consider the variation of the lateral stiffness of the building in the principle axes, and provides a single fundamental period value that is based on the total building height.

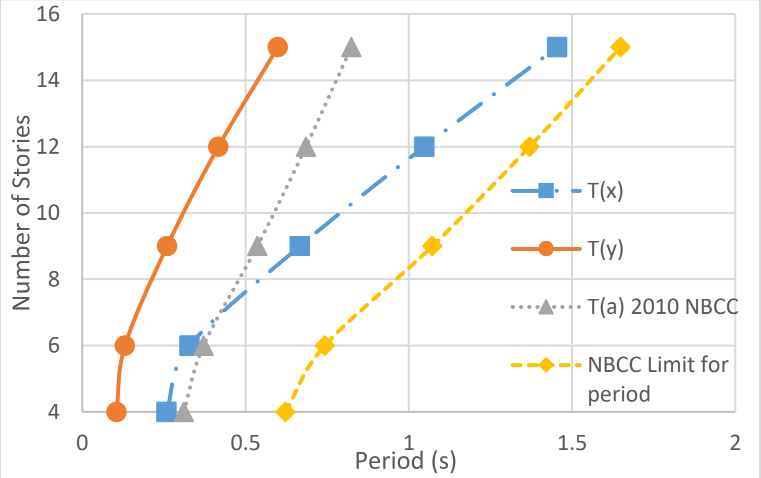


Figure 5: Variation of Fundamental Period along building height for Building A

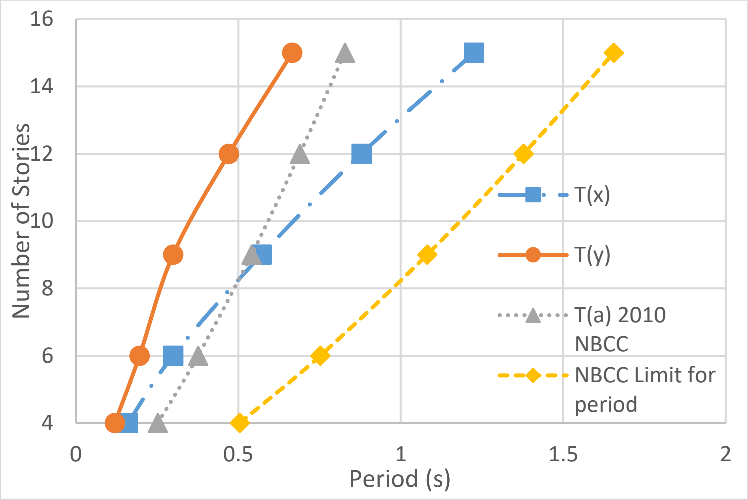


Figure 6: Variation of Fundamental Period along building height for Building B

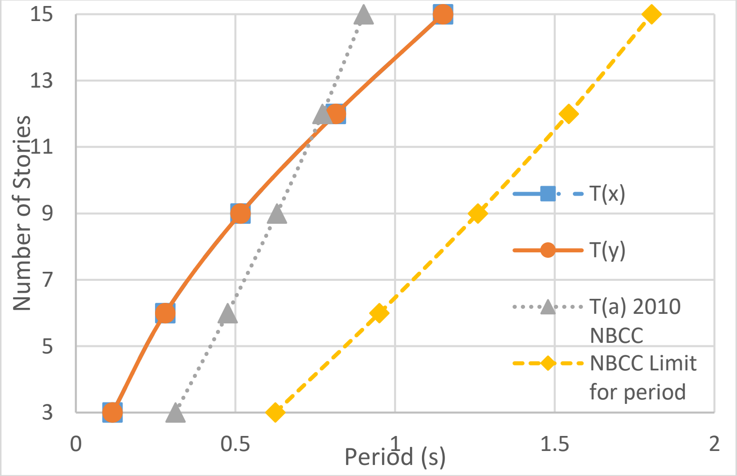


Figure 7: Variation of Fundamental Period along building height for Building C

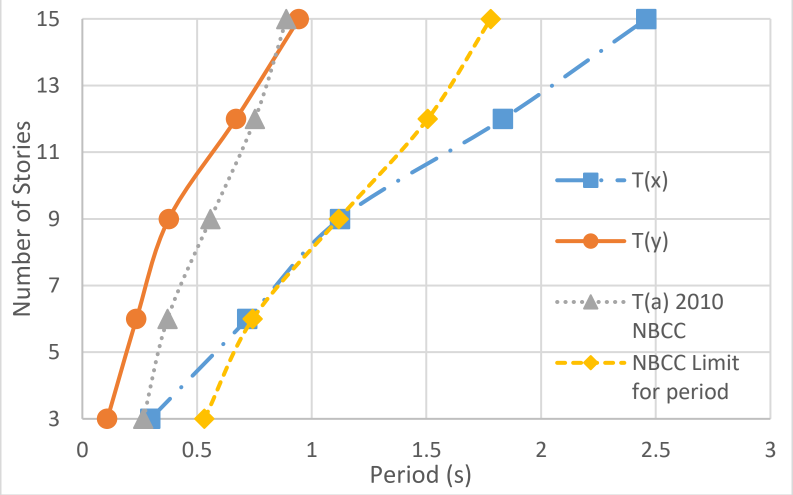


Figure 8: Variation of Fundamental Period along building height for Building D

4.2 SEISMIC BASE SHEAR COMPARISON

Figures 9-12 show the variation of the seismic base shear with the building height for Buildings A, B, C and D, respectively. For each building, the results are presented for London, Toronto, Montreal, and Victoria. The 2010 NBCC equivalent static approach is used to calculate the buildings' base shear, more details are provided by Hamada and El Damatty (2013).

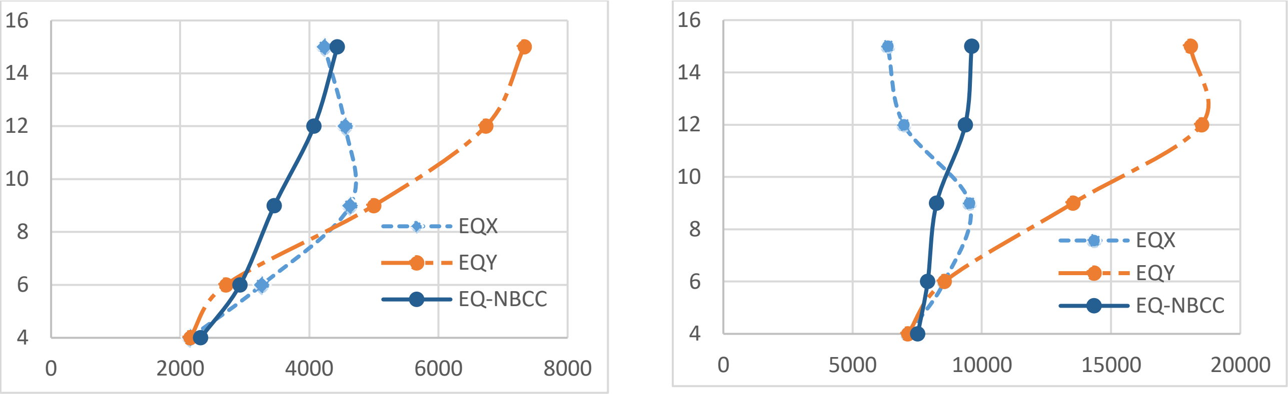
As shown in Figure 9, the building base shear in the X-direction increase with the increase of the building height. As the number of storeys are increased, the total mass of the building is increased and results in a higher fundamental period. The increase in the total mass of the building is directly related to the increase of buildings' seismic base shear. However, the increase in the fundamental period results in lower base shear values. Accordingly, when building A storeys are increased from 4 to 6, the building mass changes by 21% while the spectral acceleration decreases by 10%. Similar trend is observed from 6 to 9 storeys. However, when the storeys are increased further from 9 to 12, the building mass increases by 36% while the spectral acceleration decreases by 41% and accordingly the base shear is significantly reduced. A similar trend is observed for the increase from 12 to 15 storeys.

As shown in Figure 9 for the Y direction, the period of the structure increases gradually but doesn't increase as much to go into the downward trough of the design spectral acceleration graph. Consequently, the seismic base shear in the Y direction increases with the increase in the number of storeys.

Figures 10 (a) to (d) outline the variation of seismic base shear calculated for Building B for London, Toronto, Montreal, and Victoria. The results are shown for different building heights, 4 to 15 storeys. Similar findings were observed for both Building A and Building B. The curve obtained for seismic base shear for different number of storeys follows a bell shaped curve for both X and Y direction, with curve peaks located at different building heights.

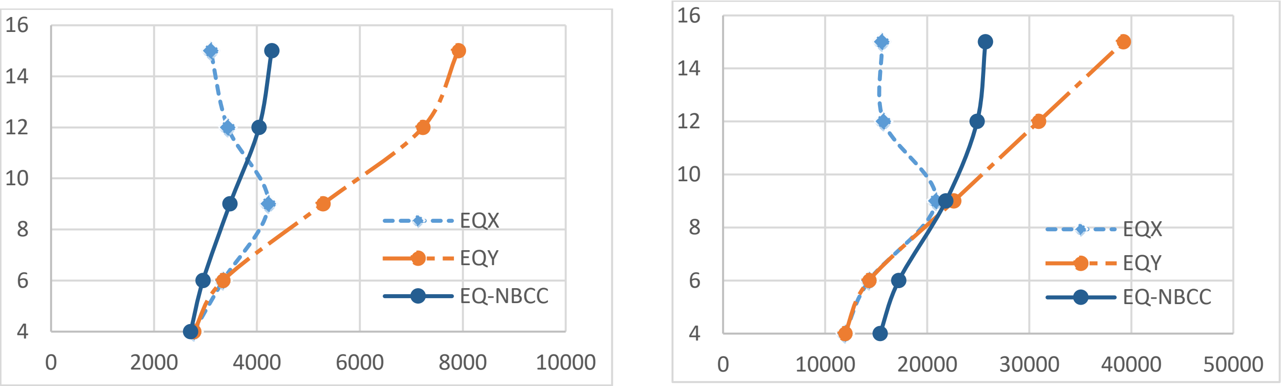
Figures 11 (a) to (d) outline the variation of seismic base shear calculated for Building C for London, Toronto, Montreal, and Victoria. The results are shown for different building heights, 3 to 15 storeys. For Building C, the seismic base shear obtained in both directions is equal as the T(x) and (T(y) are the same. The lateral force resisting system, i.e. the number of shear walls, are the same in both directions which results in comparable stiffness in X and Y direction. As shown in Figure 7, the period for the building is same in X and Y direction at different building heights. Similar to Buildings A and B, the curve obtained for seismic base shear for different number of storeys follows a bell shaped curve for both X and Y directions.

Figures 12 (a) to (d) outline the variation of seismic base shear calculated for Building D for London, Toronto, Montreal, and Victoria. Similar trends are observed for Building D and the variation of the base shear with different building heights follows a similar trajectory to the previous buildings.



a) London, ON

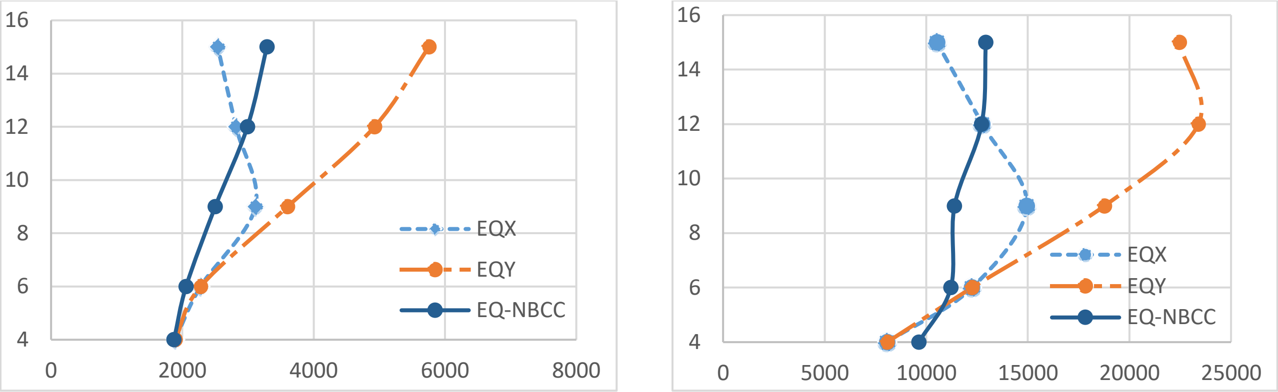
c) Montreal, QC



b) Toronto, ON

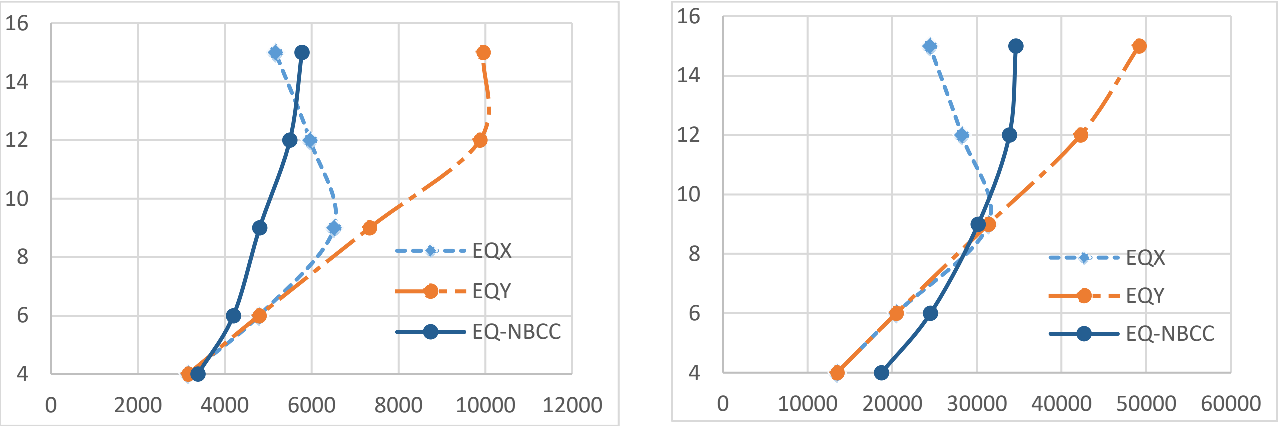
d) Victoria, BC

Figure 9: Variation of seismic base shear with number of storeys for Building A (Number of storeys (x-axis) V/S Base Shear (kN) (y-axis))



a) London, ON

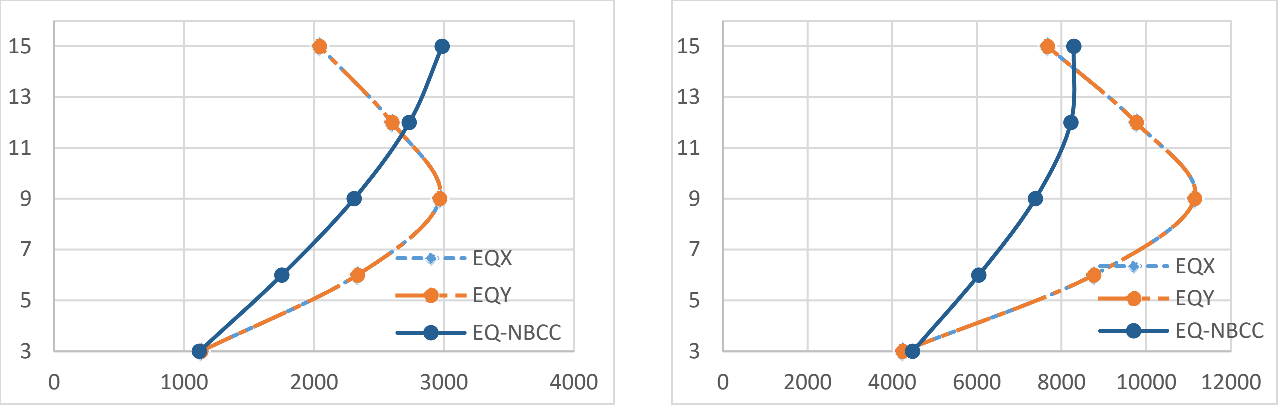
c) Montreal, QC



b) Toronto, ON

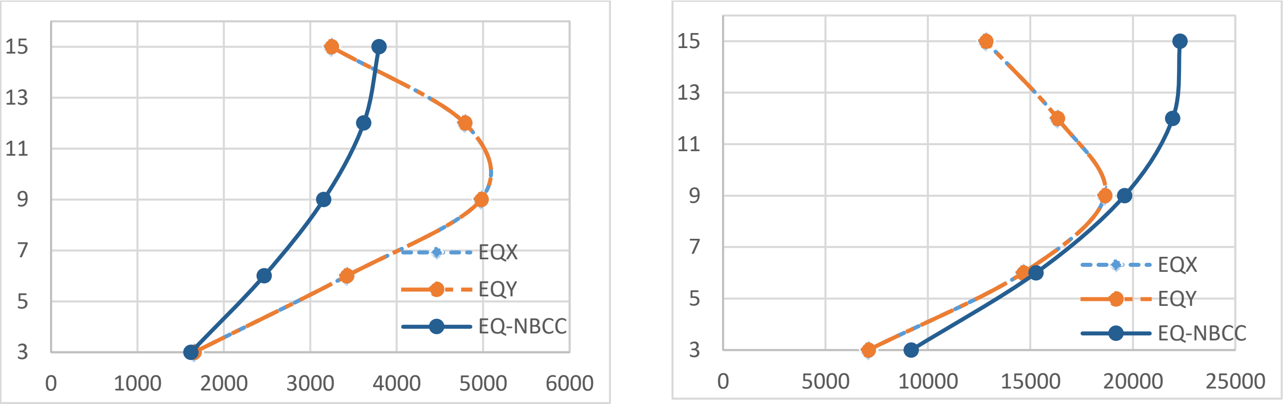
d) Victoria, BC

Figure 10: Variation of seismic base shear with number of storeys for Building B (Number of storeys (x-axis) V/S Base Shear (kN) (y-axis))



a) London, ON

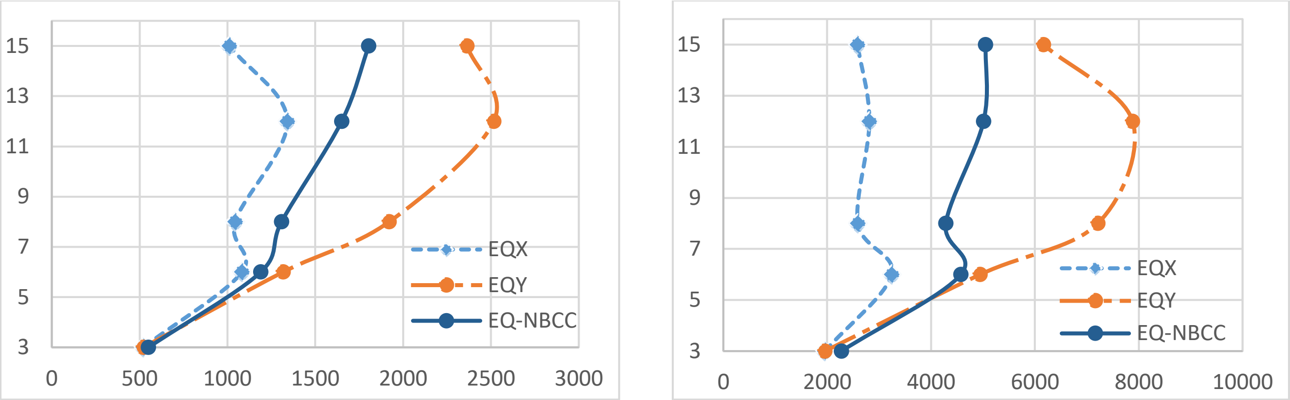
c) Montreal, QC



b) Toronto, ON

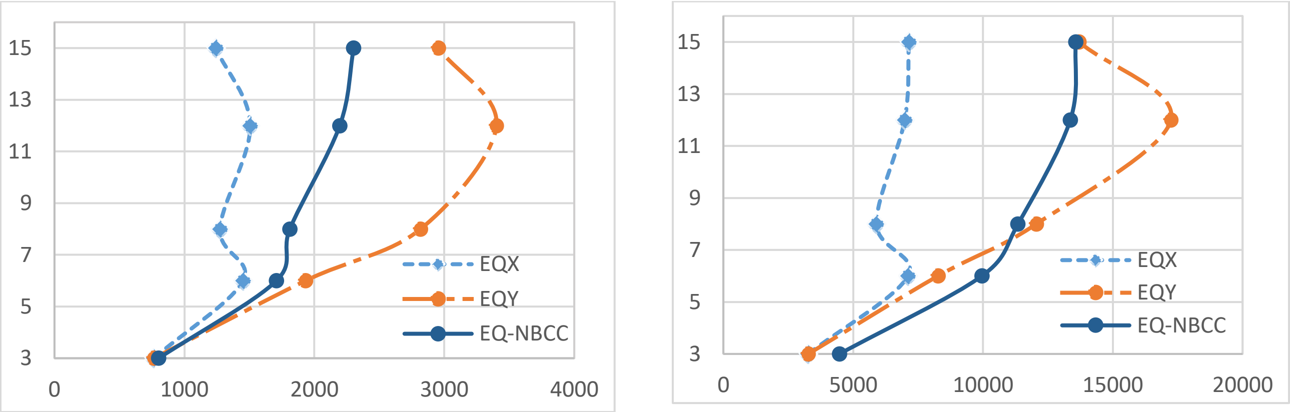
d) Victoria, BC

Figure 11: Variation of seismic base shear with number of storeys for Building C (Number of storeys (x-axis) V/S Base Shear (kN) (y-axis))



a) London, ON

c) Montreal, QC



b) Toronto, ON

d) Victoria, BC

Figure 12: Variation of seismic base shear with number of storeys for Building D (Number of storeys (x-axis) V/S Base Shear (kN) (y-axis))

5. CONCLUSIONS:

The current study assesses the seismic response of a number of buildings in four different seismic regions in Canada. The seismic provisions of the 2010 NBCC are followed. The study uses different mid-rise buildings having different plan view geometry, such as Rectangular, Semi L-Shape, and L-Shape buildings. Three-dimensional finite element models of the buildings are developed using the commercial finite-element software package ETABS. The fundamental periods obtained from 2010 NBCC equations and the finite element analyses are compared. The study compared the base shear values obtained from 2010 NBCC equivalent static method and the finite element analyses. The following conclusions can be drawn:

i. The 2010 NBCC fundamental period equation for shear wall buildings can over or under-estimate the buildings' fundamental period in comparison to the FE analyses. The current study shows that for some buildings, the natural periods obtained from the three-dimensional FE are significantly smaller in one or both of the principle axes of the building than those obtained from the 2010 NBCC provisions. This variation is mainly based on the layout of the lateral load resisting system in the principle directions of the buildings discussed in the current study. The 2010 NBCC seismic provisions can over-estimate the fundamental period for low and mid-rise buildings and underestimate the building's base shear.

ii. The normal impression is that an increase in the number of storeys increases the overall mass of the building which in-turn increases the seismic base shear of the structure. Despite that, an increase in the height and mass of the building increases the fundamental period, causing it to be located in the downward trough of the design spectral acceleration graph. Such condition leads to a significant decrease in the seismic base shear as shown in the results for some of the studied buildings.

iii. The current study shows that for all the studied buildings, the increase in building weight doesn't always results in increase in seismic base shear. These results cannot be extrapolated without further investigation of other buildings with different natural frequencies and different geometries.

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