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CASE STUDY OF SEISMIC LOAD REDUCTION FACTORS ON EQUIVALENT EARTHQUAKE LOADS FOR HIGH-RISE BUILDINGS

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Abstract: The design of the lateral load resisting system of high-rise buildings is mainly affected by the level of the wind and seismic loads. An economical design can be achieved when both lateral loads are approximately equal or close to each other. This can be achieved through changing the ductility demand. In the current study, three high-rise reinforced concrete shear wall buildings with different ductility levels and geometry, located in Toronto, Calgary, Montreal, and Vancouver, are used. The study focused on 20 to 60 storeys buildings with height range from 58.1 to 180 m. These cities represent low, moderate, and high seismic regions in Canada. The wind and seismic load provisions provided by the National Building Code of Canada (NBCC) are strictly followed for all buildings in each city. Three-dimensional finite element models of all buildings are developed and verified. The seismic forces are calculated using the equivalent static approach and the response spectrum analysis. Static and dynamic wind procedures are used to calculate the wind loads. The base shear forces, and base overturning moments of two selected shear walls for each building are calculated. By changing the level of ductility demand of each building, recommendations are made for each city to achieve closer wind and seismic loads. The study shows that the ductile design for reinforced concrete shear walls is the optimum system for designing the high-rise buildings in high seismic regions such as in Vancouver. In Montreal, wind loads and ductile structures (R_d R_o = 5.6) approximately have the same loading level on buildings with 30 storeys and above. The study shows that the moderately ductile shear wall systems could economically be accepted for high-rise buildings located in Toronto up to 40 stories, while wind loads govern the lateral load combinations in higher buildings. It is also found that conventional seismic procedure provides loads that are less than wind loads for 30 storeys buildings and above in Calgary.

1 INTRODUCTION

As per the National Building Code of Canada, buildings, any structural members and connections should be designed to have enough capacity to resist all kind of loads including gravity and lateral loads such as seismic and wind loads during their service life. The NBCC specifies the required design provisions for calculating the lateral loads for specific location, structural system, geometry, construction material, and building height. The most used seismic load calculation methods are the equivalent static approach and the response spectrum analysis. In some location in Canada, applying only the equivalent static approach is enough. However, the response spectrum analysis which accounts for higher mode of structures may lead to better results of the internal load distributions (Hamada and El Damatty 2013). The ductility-related (R_d) and over-strength-related (R_o) factors were introduced first time by NBCC 2005 for determining of the minimum lateral earthquake design force (V) at the base of the structure in the equivalent static force approach. The R_d addresses to the ability of energy dissipation in structures. The R_o accounts for the ability of reserve strength in the structural members (Mitchell et. al. 2003). The higher value of R_d represents the higher level of inelastic behavior of the structures. Thus, the specified detailing and requirements according to the Canadian Standard Association (CSA) building codes should be applied in the seismic designing procedure corresponding to the selected level of ductility to avoid any collapse in members during severe excitations. Satisfying those detailing and requirements may be more expensive than applying the conventional seismic design procedure in case if the building, especially the high-rise one, is located in a low seismic region. In consequence, the selection of appropriate level of ductility for the high-rise buildings matching their seismic regions plays an important role in the cost efficiency factor.

The high-rise buildings are more sensitive to the wind loads. Research shows that the effects of across-wind (*L*) and torsional (*M*) actions on the high-rise buildings would considerably be higher than to the along-wind (*D*) action due to wake induced by vortex shedding (Solari 2017). Furthermore, meeting the requirement for serviceability and habitability is the other key factor when designing the high-rise buildings as they experience the large displacement in the higher floors due to the wind loads (Solari 2017). Three different procedures for determining the design wind load of a building are indicated in NBCC: The Static Procedure, Dynamic Procedure, and Experimental Procedure. The Dynamic approach is recommended to use for designing the tall buildings or slender structures. However, only the last method considers the upwind obstructions, vortex shedding or aerodynamic instability effects.

More than 90 percent of high-rise building projects in Canada are in Greater Toronto, Calgary, Montreal, and Metro Vancouver (CTBUH 2018). Toronto and Calgary can be categorized as low-seismic areas, Montreal as a moderate-seismic area, and Vancouver as a high-seismic area. The first aim of this paper is to determine a ductility level for the Seismic Force Resisting Systems (SFRS) in high-rise buildings at different seismic areas in Canada, and as a result will lead to the most economic structural design. The second objective is to conclude that whether the wind loads are comparable with the seismic loads for different building heights, at different seismic hazard areas.

2 DESCRIPTION

2.1 Geometry and Structural System

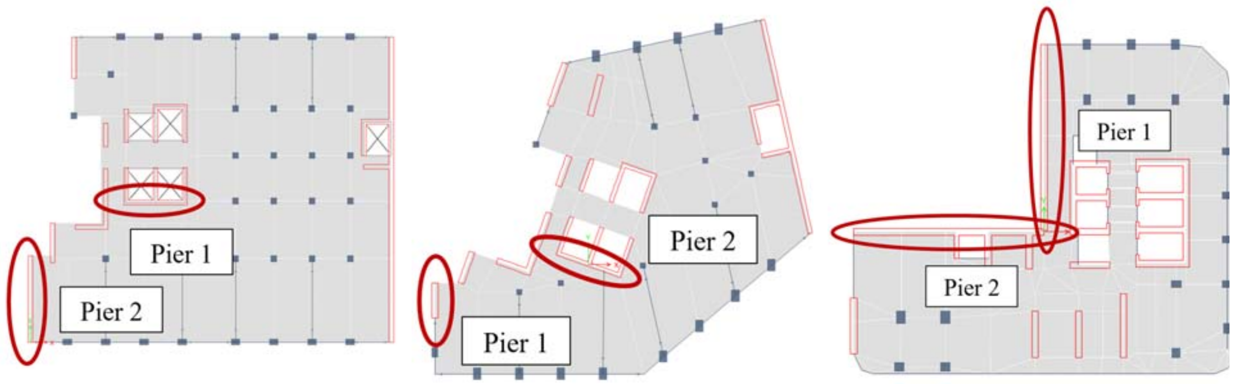
Three different kinds of buildings are selected as the case studies for this paper to achieve the noted objectives. Each building is studied for five different numbers of storeys ranging from 20 to 60 storeys with intervals of typical ten floors. The combination of both concrete shear walls and moment resistance frames (a dual system) is assumed as the type of SFRS for all case studies in the current study.

1. Case study 1: Regular (Square) shape. The typical floor height is 3m. The twenty storeys building has 60 m height and the sixty storeys one has 180 m total height.
2. Case study 2: Irregular (Pentagon) shape. The bottom three floors of this building have 3, 5.76, and 4.27 m height respectively, and other typical floors have 2.65 m height. The minimum and maximum height is 58.1 m and 164.1 m respectively. These floor heights are matching a replica existing building.
3. Case study 3: Special (L-Shape) case. The height of the first floor is 7.5m, three floors above have typical 5.5 m height, and other typical floors have 2.7 m height. The total height of twenty storeys building is 67.2 m and in sixty storeys one is 175.2 m. These floor heights are matching a replica existing building.

2.2 Finite Element Modelling and loadings

The three-dimensional linear finite element models are developed for the three buildings using the commercial software ETABS. The Modeling, assumptions, and analysis procedures are briefly explained as the follows. It is assumed that the normal concrete with modulus of elasticity, *E* equals to 28460 MPa is used. The columns and beams are modeled using frame elements. Shell element is used to model the shear walls and slabs. It is assumed that each floor is acting as a rigid diaphragm and the moment of inertia of the structural components in both directions are reduced based on CSA-A23.3-14 provisions. More details regarding the three-dimensional finite element models are provided by (Hamada and El Damatty 2013; Hamada and El Damatty 2016). The typical loadings including dead, superimposed dead, live, and snow, earthquake, and wind loads are based on recommended values by industry and according to the

NBCC provisions. The following paragraphs describe the seismic and wind loadings assumption in this paper.



a) b) c)

Figure 1: Typical Plan View of Case Studies a) Square b) Pentagon c) L-shape

Soil Class (*C*) is always considered as a benchmark for comparison of buildings under seismic loads. However, Soil Class (*D*) is used for calculating the modification factors of the Uniform Hazard Spectrum (UHS) data for each seismic region in the current study as a continuation of previous studies done by authors for these buildings. It is noted that the User's Guide-NBCC 2015 Structural Commentaries recommend that the lower value of R_dR_o product in determining the seismic loads should be used (NRCC 2015). Therefore, the product of R_dR_o corresponding to the reinforced concrete shear walls is used for ductile, moderate ductile, and conventional buildings (Table 1). According to NBCC 2015 clause 4.1.8.7, the equivalent static approach can be used in any case where $I_E F_a S_a(0.2) < 0.35$ such as Toronto and Calgary regardless of structural configuration and height. Thus, both the static approach and linear dynamic response spectrum analyses are performed for buildings to calculate the maximum seismic forces on the buildings. Also, the effects of accidental torsional moments are considered in both analysis procedures. The direction of seismic load action and the following considerations are assumed based on the NBCC provisions (100% of the prescribed earthquake loads applied in one direction plus 30% in the perpendicular direction).

The static wind procedure is used to calculate the wind load on buildings less than 60 m height. The dynamic wind procedure is used for the buildings with height equal to or greater than 60 m. The fundamental period used for determining the dynamic wind loads is calculated in each direction, for each building height, using the developed 3D model. The exposure and gust effect factors are calculated based on the assumption of open terrain and the critical damping ratio of 2% for buildings. The pressure coefficient which accounts for the effects of aerodynamic shape of the building are assumed as +0.8 in windward and -0.5 in leeward direction for all case studies. However, it is recommended that wind tunnel modelling should be performed for determining pressure coefficients for irregular shape buildings (NRCC 2015). For considering the critical buildings' responses, the direction of both seismic and wind loadings varies from 0 to 360 degrees with an increment of 15 degrees (Hamada and El Damatty 2013).

Table 1: Ductility and Over-Strength Related Modification Factors

Type of SFRS	R_d	R_o
Ductile shear walls	3.5	1.6
Moderately ductile shear walls	2.0	1.4
Conventional construction shear walls	1.5	1.3

2.3 Research Methodology

In the current study, three high-rise reinforced concrete shear wall buildings with different ductility levels and geometry, located in Toronto, Calgary, Montreal, and Vancouver, are used. These cities represent low, moderate, and high seismic regions in Canada. Figure 2 shows the flow chart of the conducted analyses in the current study. The wind and seismic loads are calculated based on the location of buildings. The total number of 180 finite element models are developed. The results of fundamental lateral period, base shear forces, and internal forces from the numerical models are examined based on the following steps:

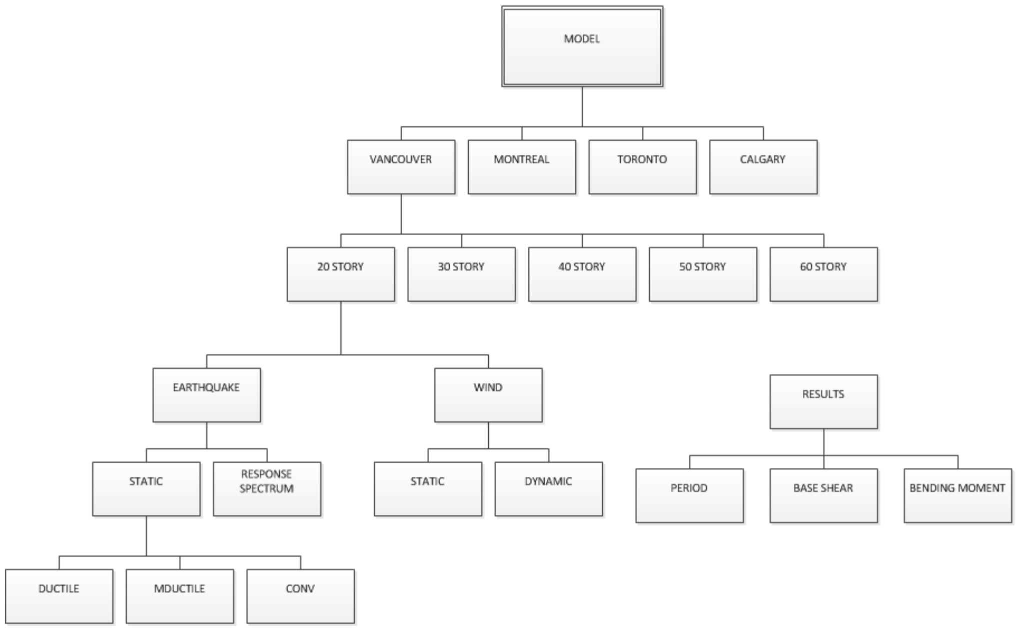


Figure 2: The Research Methodology

1. The calculation of the fundamental lateral period is the most important characteristics of building in both seismic and wind design. NBCC 2015 clause 4.1.8.1 (7) suggests series of empirical equations for determining the fundamental lateral period of buildings regarding their structural system. For an instance, $T = 0.05(h_n)^{3/4}$ recommend for shear walls and other structures. The numerical model calculates the natural period and allocates it to corresponding principal direction based on the mass participating ratio for each mode. The calculated natural period from the numerical model may exceed the recommended NBCC 2015 period. Accordingly, the numerical model of the lateral base shear force is less than the calculated values from NBCC. On the other hand, the numerical fundamental period may be less than the recommended value by the code which leads to higher seismic forces. According to clause 4.1.8.11 (3d), the calculation of (T) for the seismic load shall not be taken 2 times greater than the determined value based on the equation above for shear walls.

2. After successfully identifying natural period to calculate the seismic and wind loads, the primary comparison factor would be the base shear forces. First, the design earthquake and wind base shear forces are calculated. The scaling factors for dynamic seismic analyses are derived. Then, the force variations along the height of buildings with different ductility and over-strength related reduction factors are compared.

3. The geometry of new tall buildings may not be symmetric due to architectural considerations. Consequently, structural engineers find it hard to locate the lateral resisting structural system in a symmetric orthogonal layout. Two different shear walls are selected for each building as shown in Figure 1. Then, the bending moment at the base level of these shear walls are compared for the different cases.

3 RESULTS AND DISCUSSION

3.1 Fundamental Lateral Period

As discussed above, The NBCC presents series of empirical equations for determining the fundamental lateral period based on the building's height. This calculation is unique and does not account for shape of building in any direction and the lateral load resisting system orientations. The different stiffness characteristics in each direction of the building will result in different fundamental lateral period. Figures 3 and 4 show the fundamental lateral period in (*X*) and (*Y*) direction for each case study. The numerical model calculations are based on the Modal Analyses. As shown in Figures 3 and 4, the directional fundamental period calculated by the numerical model meets the NBCC requirements and in other cases it is obligated to use the Upper limit of the NBCC. In order to provide meaningful comparison and limit the variables, it was not necessary to change the presented buildings' design for different heights. The directional fundamental period might change with the change of the design but based on previous results the values still are higher than the NBCC upper limit.

The literature shows that the actual response of building and code prediction may be different in the initial stage of calculation. However, it will reach to the same pattern after an intense earthquake shaking by increasing damping and stiffness degradation (Mihaylov and El Naggar 2014). Also, the critical period of building in cross-wind direction should be calculated to design for vortex shedding and instabilities. This period shifting occurrence may significantly affect the cross-wind resonance, especially when the actual critical period for vortex shedding is in the range of calculated fundamental period in seismic design.

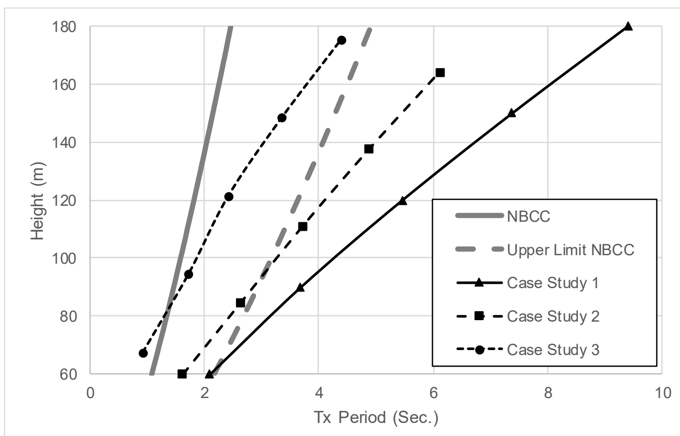


Figure 3: The Fundamental Lateral Period in (*X*) Direction Compared with NBCC Code

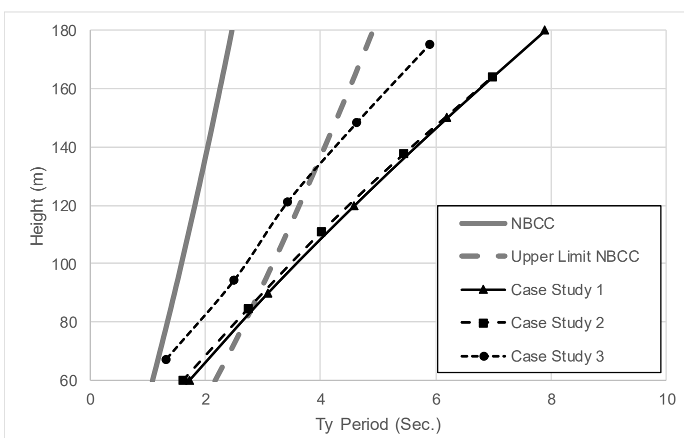
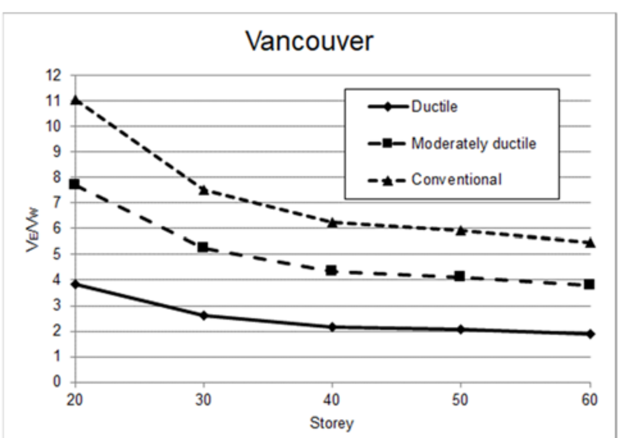


Figure 4: The Fundamental Lateral Period in (*Y*) Direction Compared with NBCC Code

3.2 Ductility level for the Seismic Force Resisting Systems

The comparison between the seismic and wind forces is presented in this section. The maximum total base shear forces (*V*) of the building and the maximum base bending moments (*M*) of the selected shear walls regarding the different ductility levels and seismic regions are calculated. The peak response of both static and dynamic seismic analyses are compared with the maximum values for wind loads. The normalized seismic to wind peak response in terms of base shear (V_E/V_W) and base overturning moment (M_E/M_W) for each case study is derived. The average of these normalized values for all case studies with the same number of storeys are shown in Figures 5 to 8. As shown in Figures 5 to 8, the (*Y*) axes represent a seismic to wind peak response and the (*X*) axes represent the number of stories. The following discussion elaborates more about the ductility level and comparison between seismic and wind loads for each city:

1. In Vancouver, the average minimum ratio of the inelastic earthquake to wind for base shear (*V*) and bending moment (*M*) reaches to 2 and 1.5 respectively (Figure 5). Accordingly, the wind loads are not significant for the structural design of tall buildings in Vancouver or high seismic areas. However, it would be important for designing of the secondary members and claddings. Thus, the selection of ductile system is recommended as the best economic option for high-rise building in high seismic regions.
2. The base shear and internal force comparison in Montreal reveals that both wind and earthquake loads are approximately equal for 30 storeys buildings and above (Figure 6). The seismic design can be carried out based on ductile system but the wind load combination may govern in designing the external or torsional sensitive members.
3. For Toronto, as shown in Figure 7, the base shear force ratio proves that the wind load is twice bigger than inelastic earthquake load with R_dR_o equal to 5.6 for 30 storeys buildings and above. Therefore, using ductile details and requirements may not be proper for the structural design of high-rise buildings in this region. Also, the moderately ductile base shear force gets close to the wind base shear when the number of the story reaches to 60. However, the wind bending moment results prove that the conventional seismic design is the most economical for designing a building with more than 40 storeys in Toronto.
4. The earthquake and wind loads comparison for Calgary disclose that the wind loads should be certainly selected as the dominated lateral design loads for 30 storeys buildings and above (Figure 8). In other words, even the conventional seismic loads may not be governing the load case for design. Accordingly, the aerodynamic effect of wind loads plays an important role for structural design due to the shape of building.



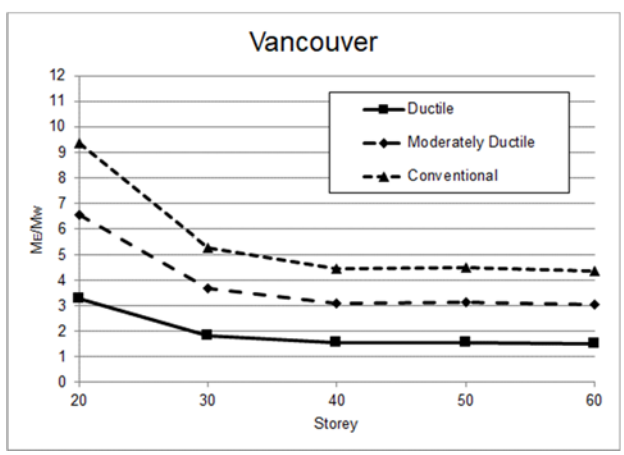


Figure 5: The Average of Earthquake to Wind Peak Response for Vancouver City

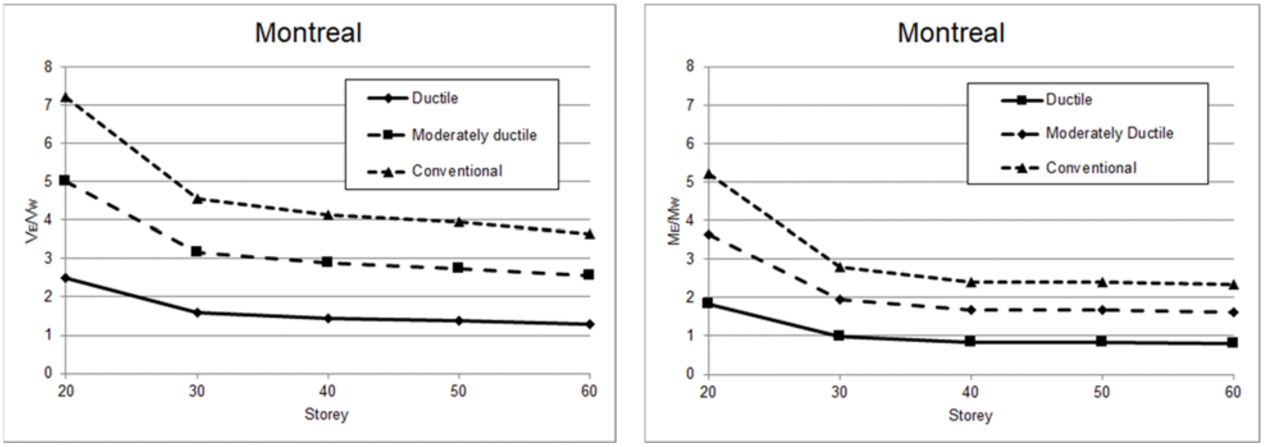


Figure 6: The Average of Earthquake to Wind Peak Response for Montreal City

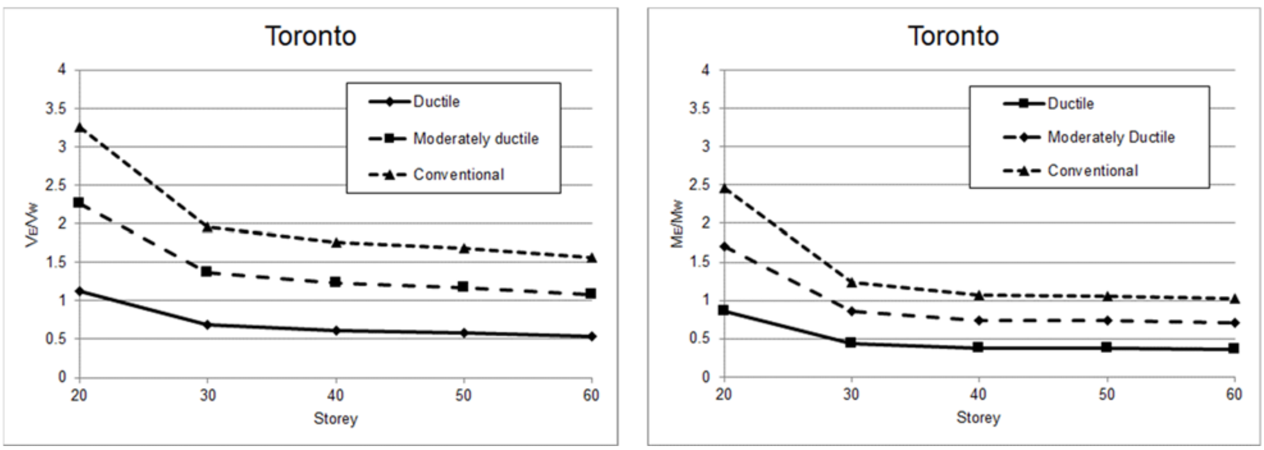


Figure 7: The Average of Earthquake to Wind Peak Response for Toronto City

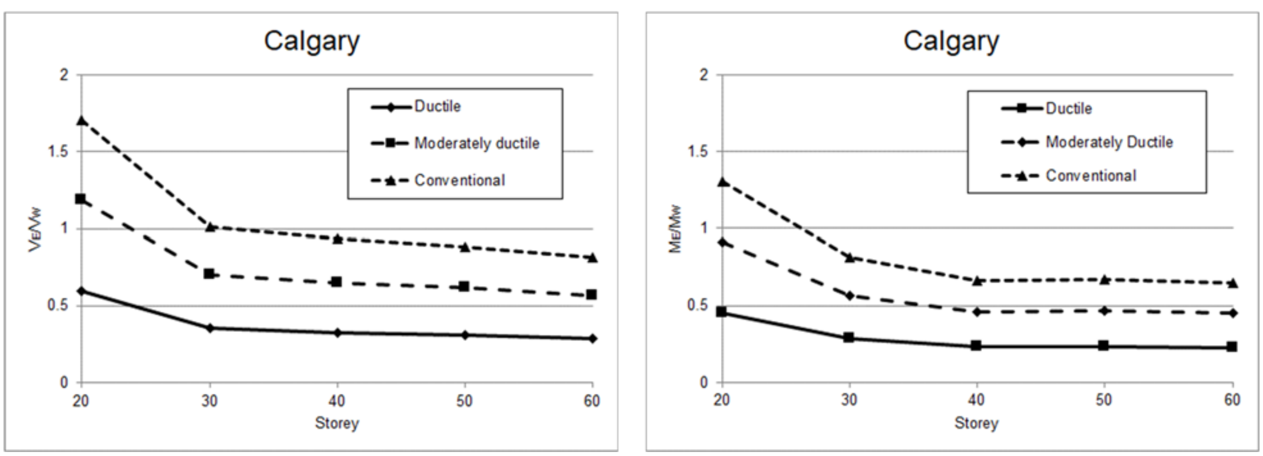


Figure 8: The Average of Earthquake to Wind Peak Response for Calgary City

4 CONCLUSION

The current paper investigates the NBCC seismic and wind loads provisions for structural analyses of three different high-rise buildings. Four cities, Vancouver, Montreal, Toronto, and Calgary, are chosen to represent the several seismic hazard levels in Canada. The following conclusions can be drawn:

- The fundamental lateral period of high-rise buildings can be varied in different directions which the empirical equation of the NBCC does not accounts for and gives only one value based on the height of the building and the lateral load structural system.
- The determination of an accurate fundamental period for each direction could be very critical in assessment of structural behavior under the wind loads.
- The ductile system is the best economical option for designing a high-rise building located in high- and moderate- seismic regions of Canada.
- The moderate ductility is the proposed structural system for seismic design of high-rise building located in Toronto region.
- The wind load is the dominated lateral load for designing high-rise buildings located in Calgary.
- The analyses show that for the ductility and over-strength factors (R_dR_o) equal to 1, the elastic seismic base shears are always higher than the wind base shears.

These results cannot be extrapolated for other buildings with different structural characteristic or located in other seismic regions in Canada without further research. The current study can be considered as the preliminary recommendations for the structural design of a high-rise building.

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