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EFFECT OF TORSION AND NON-STRUCTURAL COMPONENTS ON SEISMIC FLOORS ACCELERATIONS: A CASE STUDY BUILDING IN MONTREAL

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Abstract: The seismic design of acceleration sensitive non-structural components (NSCs) requires the computation of accelerations at the building floor levels on which they are installed. It was shown in recent studies that these accelerations depend on the building dynamic properties that are in turn affected by the presence of NSCs. Unlike regular buildings, very few studies focused on the seismic behavior of NSCs located in irregular buildings. In this paper, the effect of non-structural components on seismic floor acceleration amplification (FAA) was assessed in a torsionally irregular 6-story building named "maison des étudiants" (MDE) and located on the campus of the École de technologie supérieure (ETS) in Montreal. FAAs were computed by performing seismic simulations on two calibrated building models implemented in the Finite Element Software (ETABS) and subjected to 12 earthquakes calibrated to match Montreal's uniform hazard spectrum. The two models were calibrated using ambient vibration measurements performed at two construction stages: bare-frame without NSCs and full-frame with NSCs including masonry walls, curtain walls and secondary beams. The results show that the computed FAAs corresponding to both construction stages are higher than the FAAs prescribed by the National Building Code of Canada (NBCC) for NSCs attached to the periphery of the irregular building. In addition, less FAAs were observed at the full-frame stage when compared to the bare-frame stage

Keywords: Non-structural components, torsion, floor acceleration amplification, uniform hazard spectrum

1 INTRODUCTION

Non-structural components (NSCs) of a building, known in Canada as operational and functional components (OFCs), are the elements that are not part of the gravity and lateral force resistance systems but are subjected to seismic floor accelerations and displacements when an earthquake occurs (CSA 2014, Qu et al. 2014). Engineering demand parameters in the form of seismic floor accelerations can be correlated to structural and non-structural damage as has been shown in many past earthquakes (Tinawi et al. 1990, Mckevitt et al. 1995, Filiatrault et al. 2001, Filiatrault and Sullivan 2014, FEMA 2015).

In Canada, the seismic design of NSCs is done according to an empirical equation prescribed in the national building code of Canada (NBCC) (CNRC 2015) and the CSA S832 standard "Seismic risk reduction of operational and functional components (OFCs) of building" (CSA 2014). This equation is mainly targeted to regular buildings where floor acceleration amplification (FAA) calculated as the ratio between the peak floor acceleration (PFA) and the peak ground acceleration (PGA) is assumed to vary linearly along the building height with a maximum value of three at the rooftop. However, several parameters such as the influence of higher modes of the building, the effects of torsion and the dynamic interaction between structural system and NSCs are actually ignored (Singh et al. 2006, Aldeka et al. 2014, Asgarian and McClure 2014, Qu et al. 2014, Asgarian and Mcclure 2017).

Nowadays, advanced construction techniques and architectural innovations make it increasingly possible to build more complex buildings that often have structural irregularities and thus subjected to torsion (Aldeka et al. 2014). Unlike regular buildings, very few studies focused on the seismic behavior of NSCs located in irregular buildings. Aldeka et al. (2014) computed the dynamic response of NSCs in 9 finite element building models with torsional irregularity and found that: 1- NSCs attached to the flexible parts of rigid floors, i.e. at their periphery, are subjected to higher accelerations than those located at the center of rigidity (CR), 2- NSCs attached to the flexible parts of taller buildings are more affected by torsion than those attached to the flexible parts of shorter buildings. Moreover, Qu et al. (2014) concluded that accelerations at the periphery of the floors can be 60% higher than the accelerations prescribed by the equation of the ASCE / SEI 7 standard (ASCE 2016) that proposes a FAA profile similar to that found in NBCC.

Moreover, it was shown in recent studies that the dynamic properties of a building are affected by the presence of NSCs such as masonry infill walls, curtain walls, secondary beams and façades (Su et al. 2005, Li et al. 2011, Asgarian and McClure 2014, Orumiyehei et al. 2017, Bonne 2018). In fact, Li et al. (2011) found that infill walls can increase rigidity by almost 60%, while Su et al. (2005) found that the ratio between the stiffness of the full-frame including external and internal walls, and secondary beams and that of the bare-frame varies between 4 and 11.1. Asgarian and McClure (2014) studied the influence of infill walls on the dynamic properties and floor spectra of a hospital building by using AVMs and finite element modeling and they found that infill walls resulted in reducing the building period by about 66%, while increasing the floor accelerations experienced by NSCs and reducing the drift demand. Orumiyehei et al. (2017) studied the effect of infill walls on the seismic response of 5 regular and 1 irregular reinforced concrete (RC) buildings and found an increase in PFAs by adding infill walls due to increased building stiffness. Perrone and Filiatrault (2018) studied the influence of masonry walls on FAAs and floor response spectra (FRS) by performing non-linear time-history analyses on 10 RC moment-resisting frame buildings and concluded that the presence of infill walls results in an increase of floor accelerations and spectral accelerations.

In this paper, a numerical study was carried out to evaluate the effects of torsion and NSCs on the seismic floor acceleration amplification in elastic buildings. To this end, FAAs were determined in a torsionally irregular case study building named “maison des étudiants” (MDE) and located on the campus of “École de technologie supérieure” (ETS) in Montreal. Time-history analyses were performed on two calibrated 3-D finite element models representing the building at two construction stages: bare-frame without NSCs and full-frame with NSCs including masonry walls, curtain walls and secondary beams. These models were implemented in the finite element software (ETABS) and calibrated using ambient vibration measurements performed in a previous study by Bonne (2018).

2 Description of the MDE case study building

The studied building named “Maison des étudiants” (MDE) is a 28 m six-story irregular building made of concrete and steel. It has two basement levels, local businesses on the first floor, offices and classrooms on the upper floors. The roof houses a mechanical room, and an extension of elevators and stairs. The lateral load resisting system consists of reinforced concrete frames, concrete core walls in the form of elevator shafts and shear walls (Bonne 2018). The building has a torsional irregularity because there is a shift between the center of mass (CM) and the CR at all floors. Figure 1 shows 3-D views of MDE at the bare- frame and full-frame stages and Figure 2 shows a plan view of the ground floor.

(a) (b)

Figure 1: Isometric views of the MDE building a) at bare-frame stage; b) at full-frame stage (Bonne 2018)

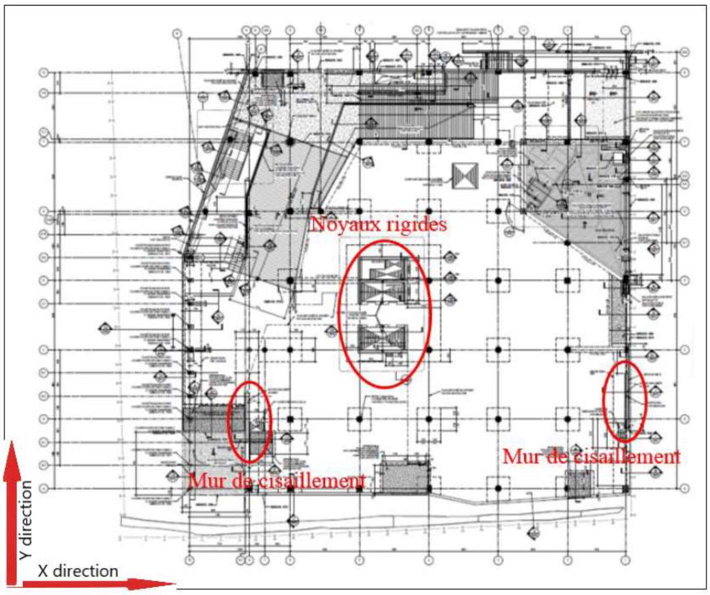


Figure 2: Plan view of the ground floor (Bonne 2018)

3 Numerical study

3.1 3-D Finite element models of the MDE

In a recent study, Bonne (2018) used ambient vibration measurements (AVMs) carried at the bare-frame and the full-frame stages of the building to extract the dynamic properties of the building using Artemis (SVIBS 2011). The bare-frame of the MDE was then modeled in ETABS by including only the structural elements such as concrete core, shear walls, columns, beams and floor slabs. NCSs consisting of masonry infills walls, curtain walls and secondary beams were modeled and added to the bare-frame model to generate the full-frame model and NSCs consisting of mechanical and electrical systems, ceilings and partitions were added as mass only. The two numerical models were calibrated using the measured dynamic properties obtained from AVMs. It should be mentioned that the masonry walls were added to the bare-frame model at the ground level for calibration purposes only because these walls were already installed when AVMs were performed for the bare-frame (Bonne 2018); therefore, these walls were then removed from the bare-frame model when analyzing it. The modal analysis of the two frames using FEM shows that the first 2 modes are flexural-torsional, while the third mode is torsional and the fourth and fifth modes behave as lateral modes in both directions (Table 1).

Table 1: Mode shapes and associated periods of bare-frame and full-frame models of the MDE

Mode number	Shape	Periods (s)	
		Bare-frame	Full-frame
1	Flexural-torsional in X direction	0.644	0.58
2	Flexural-torsional in Y direction	0.518	0.508
3	Torsional	0.425	0.419
4	lateral in X direction	0.125	0.13
5	lateral in Y direction	0.117	0.125

As shown in Table 1, the presence of NSCs resulted in decrease of periods for the first three modes. The small variation of the periods between the bare-frame and the full-frame models (9.9% for the first mode) compared to the values found in other studies which is around 66% (Asgarian and McClure 2014, Perrone and Filiatrault 2018) could be attributed to the presence of masonry infill walls at the ground floor in both models as mentioned previously.

3.2 Selection and scaling of ground motions

Given the lack of recorded ground motions in eastern Canada, artificial ground motions are used as an alternative to historical ground motions for analysis purposes (Tremblay et al. 2015). However, artificial ground motions must be scaled to be compatible with the target uniform hazard spectrum (UHS) of the locality provided by the NBCC. Earthquake records used in this case study can be found on the website www.seismotoolbox.ca (Atkinson 2009). For eastern Canada, 4 scenarios are identified depending on the magnitude of the earthquake and its fault distance as shown in Table 2. Each scenario consists of 15 ground motion time histories with 2 horizontal components (longitudinal and transverse) and one vertical component, corresponding to a probability of exceedance of 2% in 50 years. In this study, only the horizontal floor accelerations are considered and seismic simulations were carried out by applying times histories in both orthogonal directions simultaneously. The calibration of ground motion time histories should be carried out according to one of the two methods prescribed in the NBCC 2015 commentary (CNRC 2015), where the calibration is conducted over a range of periods depending on the fundamental period of building. Method A consists of defining the target spectrum over the entire range of periods and method B is based on dividing the target spectrum to several spectra. Each division is spanned by each scenario period according to earthquake records characteristics (Tremblay et al. 2015). In this study, method B is used where the scaling is done by matching the magnitude 6 events with short periods and magnitude 7 events with long periods (Atkinson 2009). In each earthquake scenario, 3 ground motions were chosen by selecting earthquakes having the smallest standard deviations between their spectrum and the target spectrum.

Table 2: Used Scenarios of earthquake records in eastern Canada (Atkinson 2009)

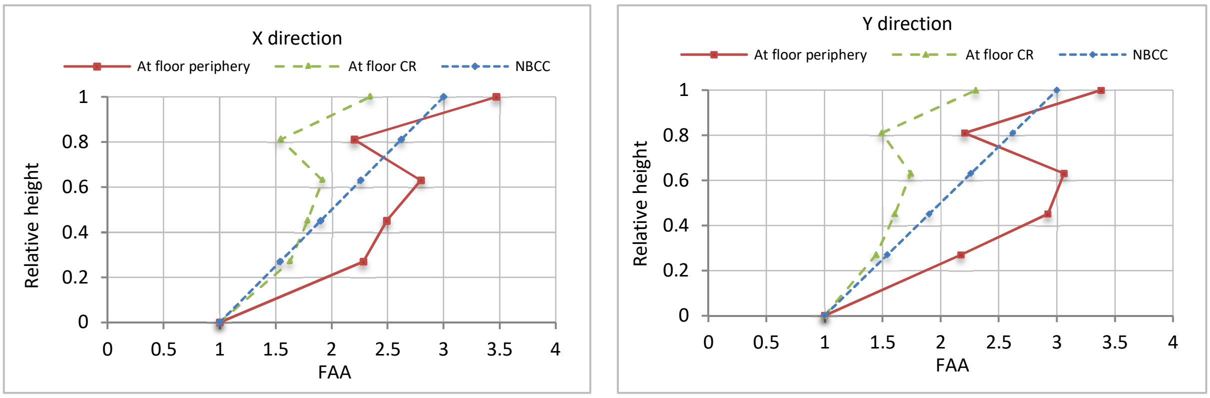
Magnitude	Fault distance (km)	Number of records used
6	15-20	3
6	20-30	3
7	15-25	3
7	50-100	3

3.3 Effect of torsion on FAAs

In order to evaluate the influence of torsion on FAAs along the building height, FAAs were computed at the periphery of the floors where the effect of torsion is deemed significant (Qu et al. 2014) and compared to values computed at the center of rigidity (CR). Linear modal time history analysis was carried out considering a damping of 3% for all the modes of building as recommended by NBCC 2015 commentary for dynamic analyses (CNRC 2015). For each floor, the mean FAA is calculated by averaging the maximum FAAs corresponding to each of the 12 earthquakes described in Table 2. Sections 3.3.1 and 3.3.2 present respectively results obtained for bare-frame and full-frame as compared to FAA profile proposed in NBCC 2015 and calculated with the formula $\left(1+2\,\frac{h_x}{h_n}\right)$, where h_x is the height of the floor on which the component is installed and h_n is the total height of the building. It should be noted that the ratio $\frac{h_x}{h_n}$ represents the relative height.

3.3.1 Bare-frame

Figure 3 shows the maximum FAAs computed at the periphery and at the CR at all floor levels of bare-frame and the FAA profile proposed in the NBCC.



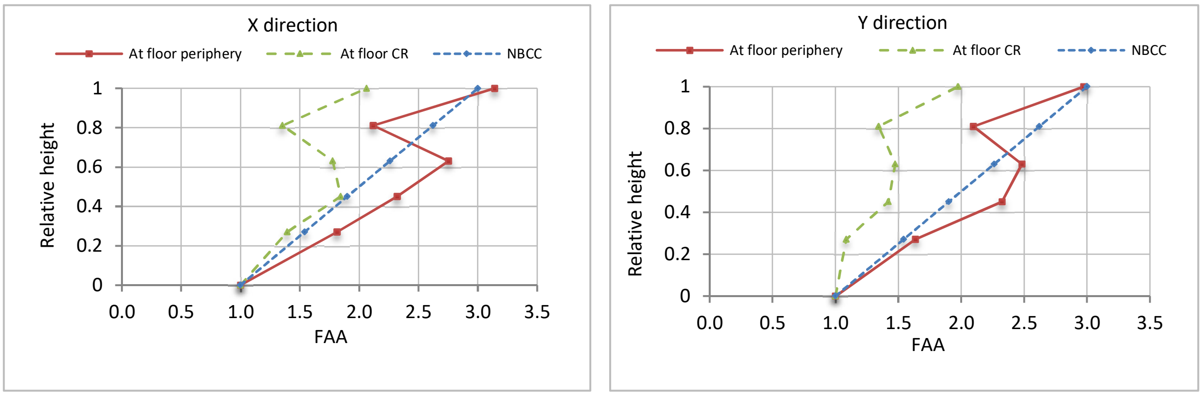
(a) (b)

Figure 3 Computed FAAs for bare-frame in: a) the X direction; b) the Y direction

We can note that the variation of FAAs are not linear as opposed the linear profile of FAAs proposed in the NBCC, where it is assumed to be dictated by the building first lateral mode of deformation. This nonlinear FAAs profile in the case of MDE can be attributed to the influence of higher modes; therefore, the floor amplification profile along the building is not always governed by the first mode, which is in agreement with findings from previous studies (Kehoe and Hachem 2003, Singh et al. 2006, Petrone et al. 2014, Azeem and Mohiuddin 2016). On average, the computed values of FAAs at the floor periphery are greater than the FAAs prescribed by the NBCC by 20.5% in the X direction and 25.4% in the Y direction with standard deviations of 21.2% and 24.5%, respectively. In addition, the computed FAAs at the periphery are higher than those computed at the CR by an average of 43.2% in the X direction and 60.5% in the Y direction with standard deviations of 3.3% and 15.1%, respectively. The obtained results in the X direction are close to those found by Aldeka et al. (2014) where the torsion amplifies accelerations by 42% on average, while the effect of torsion in the Y direction is more pronounced. In fact, the modal analysis of the bare-frame demonstrated that for the 3rd mode which is torsional, the ratio of mass participation in the X direction is 6.8% while it is 32.7% in the Y direction. Thus, the effect of torsion is more pronounced in the Y direction than it is in the X direction.

3.3.2 Full-frame

Figure 4 shows the maximum FAAs computed at the periphery and at the CR at all floor levels of full-frame and the FAA profile proposed in the NBCC.



(a) (b)

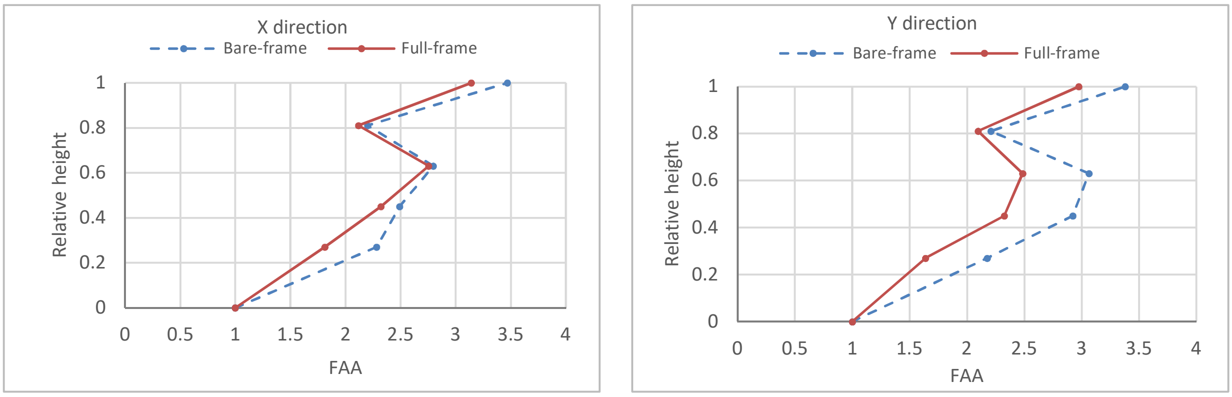
Figure 4 Computed FAAs for full-frame in: a) the X direction; b) the Y direction

It can be seen from Figure 4 that FAAs values at the periphery of the different floors are greater than those prescribed by the NBCC by an average 9.4% in the X direction and 3.5% in the Y direction, with standard deviations of 15.6% and 13.9%, respectively. Also, the computed values of FAAs at the periphery are higher than those at CR by an average of 43.9% in the X direction and 58% in the Y direction, with standard deviations of 13.2% and 7.1%, respectively. Similarly to the bare-frame, the effect of torsional mode on FAAs is more pronounced in the Y direction (23.3% mass participation ratio) compared to the X direction (7.41% mass participation ratio).

3.4 Effect of NSCs on FAAs

3.4.1 At the periphery

In order to evaluate the effect of NSCs, FAAs computed at the periphery of the bare-frame and the full-frame in both orthogonal directions were compared at all floor levels as shown in Figure 5.



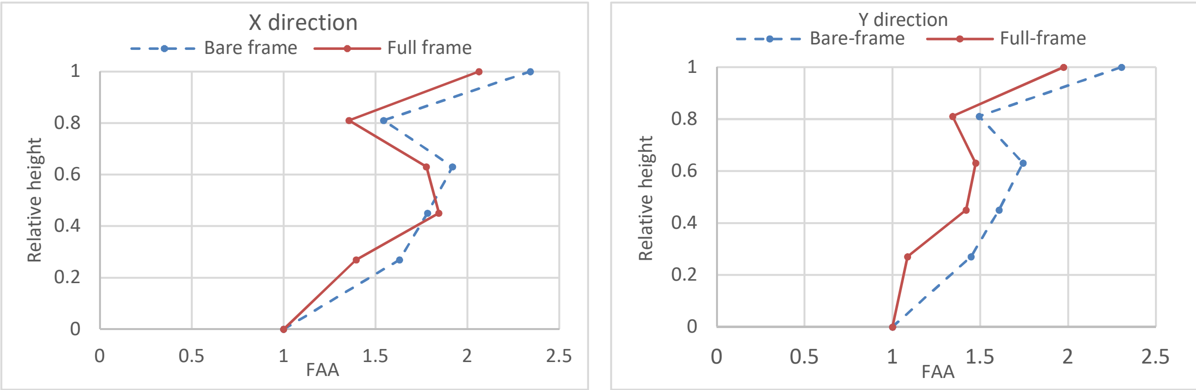
(a) (b)

Figure 5: Comparison between FAAs at the periphery of bare-frame and full-frame in: a) the X direction; b) the Y direction

It can be observed from Figure 5 that computed values of FAAs of bare-frame are higher than those of full- frame, by an average of 8.4% in the X direction and 16.2% in the Y direction with standard deviations of 6.6% and 6.9% respectively. This result does not agree with previous studies (Asgarian and McClure 2014, Orumiyehei et al. 2017, Perrone and Filiatrault 2018) that dealt with irregular and regular buildings. It was shown in MDE case that considering NSCs in full-frame such as masonry walls, curtain walls and secondary beams increases the stiffness while mechanical equipment, partitions and furniture increases the mass compared to bare-frame structure (Bonne 2018). Thus, the response of structure is affected by both increased mass and stiffness due to different types of NSCs. It can also be noted that floor accelerations at the lower levels of the MDE are more influenced by the lateral modes, while those at the upper levels are more influenced by the torsional modes.

3.4.2 At the CR

FAAs computed at the CR of the bare-frame and the full-frame in both orthogonal directions were compared at all floor levels in order to evaluate the effect of NSCs as shown in Figure 6.



(a) (b)

Figure 6 Comparison between FAAs at the CR of bare-frame and full-frame in: a) the X direction; b) the Y direction

It can be seen from Figure 6 that FAAs at the CR of bare-frame are higher than those of full-frame by an average of 7.5% in the X direction and 15.3% in the Y direction with standard deviations of 7.2% and 5.2%, respectively. Therefore, the effect of NSCs is more pronounced in the Y direction, especially at the lower levels.

4 Conclusion

The mains objectives of this case study were to evaluate the effects of torsion and NSCs on FAAs in a torsionally irregular 6-story building located in the campus of “École de technologie supérieure” (ETS) in Montréal and named “maison des étudiants” (MDE). FAAs were computed at each floor by performing linear time-history analyses on two 3-D numerical models of the building that were calibrated through dynamic properties extracted from AVMs carried at two construction stages: bare-frame without NSCs and full-frame with NSCs consisting of masonry walls, curtain walls and secondary beams. Each building model was subjected to 12 earthquake records compatible with Montreal’s UHS.

The influence of torsion was assessed by comparing the average values of maximum FAAs corresponding to each record computed at the periphery of floors (with torsion) to those computed at the CR (without torsion). Results show that torsion leads to an increase in FAAs by 43 to 60% with a maximum standard deviation of 15.1%. In addition, the results show that FAA profile prescribed by NBCC underestimates the FAAs (with torsion) by up to 25.4% on average with a maximum standard deviation of 24.5% while it covers FAAs at the CR in almost all cases, which highlights that FAAs of CR are mainly affected by lateral modes.

On the other hand, the effect of NSCs was assessed by comparing average values of maximum FAAs computed at each floor periphery to those computed at CR of bare-frame and full-frame. It was found that FAAs values of bare-frame are higher than those of full-frame in both directions by 7.5 to 16.2%. These findings can be explained by the fact that while NSCs like masonry walls and curtain walls increase the building stiffness, other NSCs like mechanical systems, partitions and furniture increase only its mass.

It can be concluded from this study that FAA profile provided in NBCC underestimates FAAs in some cases, since the contribution of higher modes and the effect of torsion are not considered. Thus, further studies considering these parameters are recommended for the future revision of the NBCC FAA profile. In addition, more analyses should be performed in bare-frame and full-frame of regular and irregular buildings of different heights in order to deduce a general trend and quantify the effects of NSCs on FAAs profile.

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