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CHARACTERIZATION OF THE LATERAL CAPACITY OF UNREINFORCED MASONRY RESIDENTIAL BUILDINGS IN MONTREAL FOR SEISMIC RISK STUDY

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Abstract: In Montreal Island 14% of the existing residential building stock is identified as unreinforced masonry structures (URM). These buildings were built between 1860 and 1915 in the central sectors of Montreal and have URM bearing walls and interior wood framing. This type of residential building presents several differences with the URM building class defined in the Canadian or American version of Hazus software used for seismic risk assessment studies. This paper has two objectives: (1) to propose a structural and dynamic characterization of those URM residential buildings, and (2) to evaluate their lateral capacity. Structural characterization was conducted through visual inspections of buildings undergoing renovation and through a literature review on the history of residential construction and architecture in Montreal. It consists of information on construction materials, the composition and dimensions of the roof, walls, floors and foundations, as well as details on connections between elements. Ambient vibration measurements were used to obtain the fundamental periods, mode shapes and damping of the structures. The collected data were used to develop a macro-element model based on idealization of the building as an equivalent frame. Modal and pushover analyses were conducted using the software 3-Muri© to derive the capacity curve of two prototype buildings, with a mansard roof and with a regular flat roof. An additional model with a row of 6 buildings was also analyzed. First results indicate the influence of the roof system on the lateral response and the increase in rigidity for buildings part of a row of houses.

1 INTRODUCTION

Recent studies from industry, government and universities recognize the potential for damaging earthquakes in Eastern Canada and particularly in large urban centres such as Montreal where the density of buildings and population increases the seismic risk (Yu et al. 2016, BAC 2013, Adams and Halchulk 2004). Settled in the 17th century, central sectors of Montreal have large populations of buildings constructed prior to the introduction of seismic provisions. A recent study on the seismic risk for residential buildings in Montreal showed that 14 % of about 300 000 inventoried buildings are unreinforced masonry (URM) (Chouinard et al. 2017, Youance and Nollet 2017). This study carried out by McGill University and

École de technologie supérieure in a partnership with Ministère de la Sécurité publique du Québec and Direction de la sécurité civile de la Ville de Montréal, also indicated that these buildings would sustain moderate to complete damage for an earthquake scenario with a magnitude M5.8 in the centre of the Island. This is in agreement with worldwide post-earthquake damage surveys showing that URM buildings are typically associated with the highest proportion of damage (Ingham and Griffith 2011, Klingner 2006, Park et al. 2009).

Most of URM residential buildings are located in the oldest central sectors of Montreal. No specific capacity or fragility data is available for those buildings and damage assessment is therefore carried out using data for URM building class as defined in the American software HazUS© (Fema 2012). Previous studies have shown that variation in building capacity and fragility models could lead to uncertainties that propagate along the computation process of seismic risk assessment resulting in significant deviations in damage distribution between models (Abo El Ezz et al. 2014 and 2015, Tyagunov 2014). The evaluation of the lateral resistance of URM buildings plays therefore a key role in improving damage assessment in seismic risk studies. It should rely on better knowledge of their mechanical and structural characteristics (Abo El Ezz 2013). Response of URM structures to seismic excitation is non-linear due to the progressive evolution of cracks in the mortar joints or the masonry blocks. This increases the difficulty in developing a coherent analytical model. Simplified macro-element model based on idealization of the building as an equivalent frame represents an interesting alternative to detail finite element models, with reasonable computational effort while giving an appropriate option for the evaluation of the seismic force-deformation capacity curve (Caliò et al. 2012).

This paper has two objectives. The first objective is to provide information about the materials, structural systems and dynamic characteristics of URM residential buildings in Montreal. These buildings have external bricks bearing walls and interior wood framing supported on the façade and rear walls or the lateral firewalls. The second objective is to evaluate the lateral resistance of a typical building using a 3-D model with representative material properties for bricks, mortar and masonry assembly taken from recent experimental tests results. Modelling used macro-element from the equivalent frame approach and non-linear static analyses were carried out with the 3-Muri© software (S.T.A. Data 2018, Lagomarsino et al. 2013).

2 METHODOLOGY

2.1 Structural Characterization of URM buildings

The structural characterization of URM residential buildings, called URM-B1, was conducted through visual inspections of typical buildings undergoing renovation or rehabilitation work, and through a literature review on the history of residential construction and architecture in Montreal. The latter was used to identify sectors of Montreal with the highest density of URM-B1 buildings. A total 4 buildings were visually inspected. The structural characterization includes information on construction materials, the composition and dimensions of the roof, walls, floors and foundations, as well as details on connections between elements and between the wood and masonry systems.

The dynamic characterization was carried out by ambient vibration measurements (AVM) recorded using four high resolution tromographs (Tromino©). AVM were taken in 3 buildings to define the fundamental periods, mode shapes and damping of the structures. Data were analyzed by the Enhanced Frequency Domaine Decomposition method (EFDD) and the Frequency Domain Decomposition method (FDD).

2.2 Evaluation of the Lateral Capacity

A prototype building was defined from the geometry and structural characteristics information gathered in the previous step. Material properties were taken from an experimental program carried out on brick masonry representative of traditional unreinforced masonry walls (Touraille 2019, Touraille et al. 2019). The wall section is typically composed of moulded clay brick joined with hydraulic lime and cement mortar. Experimental results included: compression strength of brick and mortar, compression and joint shear sliding strength of the brick-mortar assembly and diagonal shear strength of brick masonry wall specimens.

The selected software to carry out the structural analyses is 3-Muri © (S.T.A. Data 2018), a commercial version of the research software Tremuri (Lagomarsino et al. 2013), developed specifically for the analysis of unreinforced masonry buildings. It provides static and nonlinear dynamic analysis, based on the equivalent frame method, for the simulation of possible deformations and failure using macro-elements. Each macro-element represents a part of the structure defined by simple geometry, i.e. a wall, a panel or a column. It has a degree of freedom to simulate bending / crushing and shear failure modes. This method allows creating a simplified model of the building and computes its capacity by simulating the failure modes of the macro-element.

3 CHARACTERIZATION OF URM-B1 BUILDINGS

At the end of the 18th century working-class neighbourhoods appeared around the historical Old Montreal. Those areas were built without any urbanization planning mostly using wood as the main construction material for houses. Unfortunately, the great fire of 1852 destroyed a large part of those districts (SIM 2018). After this dramatic event, the City of Montreal adopted legislation to prevent fire propagation by requiring construction of building in masonry. It was at that time that URM-B1 houses started to be constructed (Auger et Roquet 1999).

3.1 Structural Characterization

Most of URM-B1 buildings were built between 1860 and 1915 and are generally located in the south part of the island of Montreal in the districts of Ville-Marie, South West and Plateau Mont-Royal. They are prevalent in Westmount and Outremont districts, both formally distinct towns with strict regulations requiring masonry construction for residential houses. The location of URM-B1 buildings is shown in Figure 1. The colours on the map indicate the direction of the floor support system: 1) on common URM firewalls, 2) on façades and rear URM walls or 3) unknown.

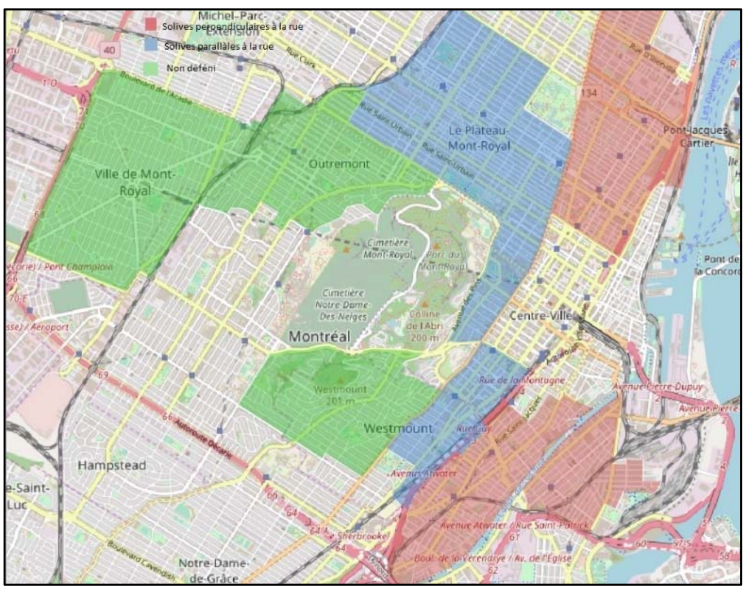
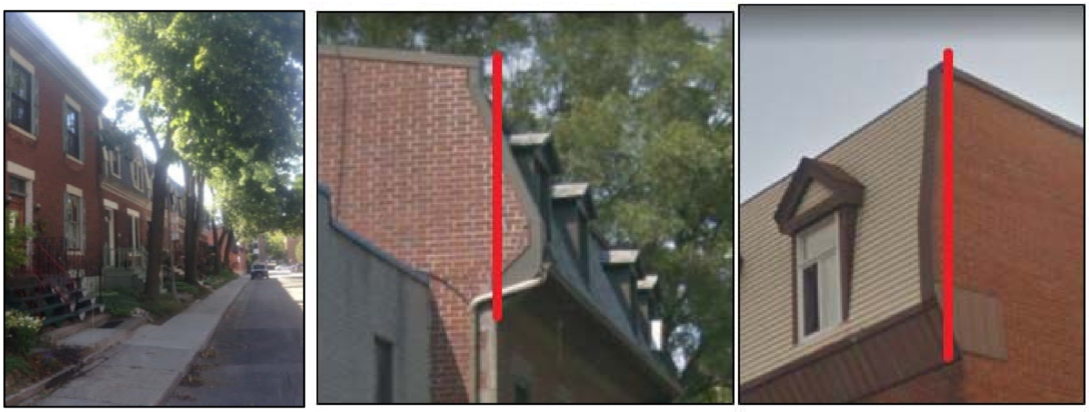


Figure 1: Location of URM-B1 buildings (Internal wood framing supported by URM firewalls (Blue), by façade and rear URM walls (Red) or unknown (Green).

The most common URM-B1 building is a single-family house of two or three storeys, part of a row of buildings with individual units separated by a common unreinforced brick firewall as shown in Figure 2(a). Story height varies between 6 m and 7 m.



(a) (b) (c)

Figure 2: Typical URM-B1 houses: (a) in Westmount, (b) with real mansard roof, (c) with false mansard roof.

URM-B1 houses have many structural and architectural aspects in common. Mansard roof is one of the major common architectural elements of those houses. The oldest versions have real mansard roof, recognizable by the position of the pivot point of the roof offset from the front wall line, has shown in Figure 2 (b). The real mansard is a structural weakness due to the horizontal thrust on the front wall that can create instability. The false mansard is a decorative element added on flat roofs with no structural purpose. It is recognizable by the position of the pivot point of the roof aligned with the front wall line (Figure 2 (c)).

The URM walls are composed of two to three rows of moulded clay bricks bonded by lime or cement-lime mortar, with thickness decreasing at higher floor levels. Foundation is made of stones and is 24 inches thick. In older buildings, the main beam element supporting the first floor is made of a tree trunk, 10'' in diameter, embedded at its extremities in the URM walls on a bearing length of 4'' to 6''. The width of the house has an influence on the spanning direction of the floor joists. Houses with a width between 5 and 6 metres have joists spanning parallel to the street, supported by the URM firewalls. This is more common for older houses built before 1880. Houses with a width between 6 and 15 metres have their joists spanning perpendicular to the street and are supported by the façade and rear URM walls. All joists are embedded in the URM walls on a bearing length of approximately 3 inches, see Figure 3 (a). One interesting feature of these buildings is the use of half-timber work, a method in which URM firewalls are constructed of timber frames and the spaces between the structural members are filled with bricks. This French-style construction technique (Auger and Roquet 1999) is illustrated in Figure 3 (b).

(a) (b)

Figure 3: Features URM-B1 houses: (a) floor joists embedded in URM firewalls (b) half-timber encased in URM firewall.

Even though there was no building code at the time, construction practices were relatively uniform and most buildings are very similar. The inspections made it possible to conclude on the recurrence of certain structural elements. Wood planks of three by eleven inches were used in all constructions for floor joists and as built-up beams for the first floor system in more recent buildings. When required, internal bearing walls were made with wood stud 3''x3'' @ 12'' c/c. Wood decking is made of planks, 4'' to 8'' width and 1'' in thickness.

3.2 Dynamic Characterization

Three buildings were tested by ambient vibration measurements (AVM) all part of a row of buildings. All were rectangular 2-storey buildings with a depth of 10 to 12 m and width between 5.66 to 6.35m, spanning direction of the floor system being parallel to the street.

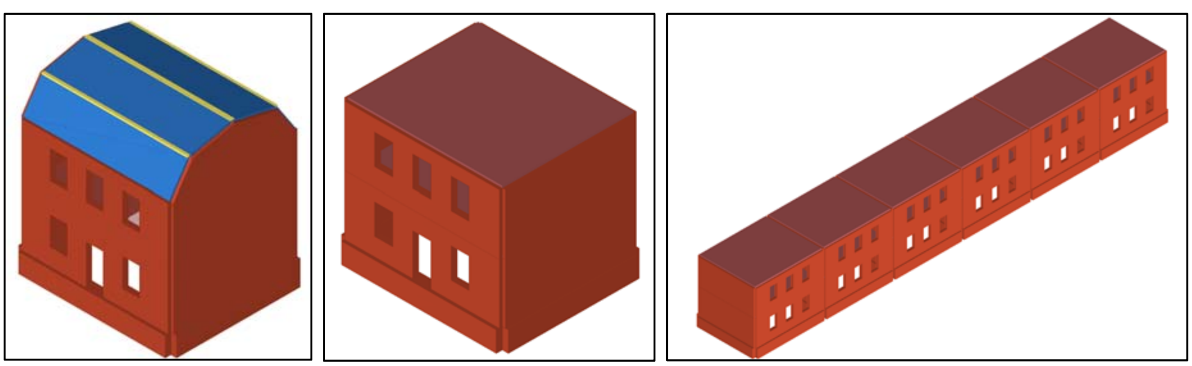
The fundamental periods obtained by EFDD and FDD methods vary between 0.128 to 0.153 second with an average of 0.14 second. These experimental periods are smaller than the fundamental period computed with the equation proposed by the NBCC 2015 ($0,05(h_n)^{3/4}$) (CNRC 2015). With an average building height h_n of 6 m, the natural period is estimated to be 0.19 sec. The first mode of vibration is a translational mode, in the Y-direction perpendicular to the street. As the buildings are regular in shape, there is no torsional mode. All buildings are part of a row of houses and are connected through the common URM firewalls, thereby creating a very rigid behaviour in the longitudinal X-direction. Damping values obtained from EFDD method were between 0.13 and 0.15%. These low damping values are more characteristic of ambient noise than the damping of 5% usually recommended by codes for large earthquakes.

Another AVM campaign is undergoing to obtain more data and to complete the dynamic characterization for isolated single-family houses, with different roof systems and different floor spanning directions.

4 EVALUATION OF THE LATERAL CAPACITY

4.1 Modelling of the Prototype Buildings

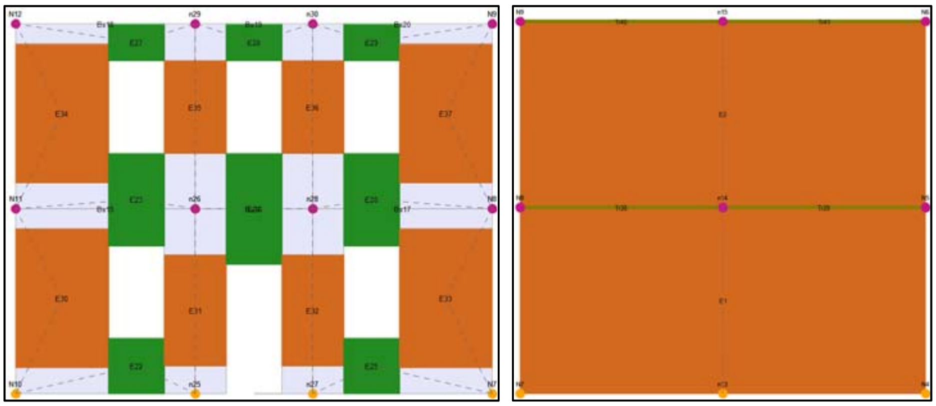
The analysis of the lateral capacity was carried out for three models of 2-storey buildings. The prototype building for model 1 is an isolated single family house with a mansard roof (Figure 4a), while the prototype building for model 2 in similar in dimensions but has a regular flat roof (Figure 4b). The third model represents a row of 6 houses of Prototype 2, that is with a flat roof (Figure 4c). Prototypes 1 and 2 have the following dimensions: (height=6 m, width= 7.7 m, depth = 6.5 m). The floor and roof systems are made of 6" x 1'' planks on 3''x11'' wood joists @ 16'' c/c simply supported by the URM lateral façade and rear walls. The mansard roof structural system is made of inclined 7''x5'' rafters and floor and ceiling joists. All the loads from the roof and floors are supported by the 30 cm façade and real walls while the lateral firewalls are 20 cm thick.



(a) (b) (c)

Figure 4: Prototype buildings: (a) Flat Mansard roof, (b) Flat regular roof, and (c) Row of 6 houses

In the equivalent frame method, the masonry walls are modelled as nonlinear frame elements (Lagomarsino et al. 2013) according to the geometry of the openings. Figure 5 shows the different numerical models of the prototypes: The discretization of the façade element (longitudinal X-direction) with the opening details and the macro-elements, and the discretization of the lateral firewall (transversal Y-direction) are represented in Figure 5a and 5b, respectively. The wood floors and ceilings are considered as a planar orthotropic stiffening element. The mansard roof rafters are modelled by inclined beam elements. Dead weight of the structure is considered through the specific weight of the wood and masonry elements.



(a) (b)

Figure 5: Numerical model of the selected building generated with 3-Muri© software: (a) discretization of the façade wall and (b) discretization of the lateral firewall.

No specific data on the mechanical properties were available. Therefore, mechanical properties were derived from experimental research work on URM assemblies and wallets made of manufactured moulded brick masonry typically used as replicas of traditional masonry in remediation projects. Weak cement-lime mortar was used to match the mechanical properties of the original traditional cement-lime mortar (Touraille 2019, Touraille et al. 2019). The average mechanical properties presented in Table 1 are used for the first series of analysis.

Table 1: Brick masonry material properties (Touraille 2019, Touraille et al. 2019)

Parameter		**Value**
E'_m	Modulus of elasticity	3.46 GPa
G'_m	Shear modulus	2.08GPa
f'_m	Masonry compression strength	14.5 MPa
f'_j	Compressive strength of mortar	5.87 MPa
f'_b	Compressive strength of unit	26.3 MPa
f'_{td}	Masonry shear strength corresponding to diagonal cracking	0.37 MPa
c, f_{vm0}	Characteristic initial shear strength at zero compression	0.56 MPa
μ	coefficient of friction	0.85
w	Specific weight (kN/m3)	19
δ_s	Shear ultimate drift ratio	0.4 %
δ_f	Rocking ultimate drift ratio	0.8 %

4.2 Modal analysis

Modal analysis of prototype buildings was carried out with 3-Muri software. Table 2 presents the fundamental periods T_x in the longitudinal X-direction (parallel to the façade and rear walls), T_y in the transversal Y-direction (parallel to the firewalls) and the natural period of the building for the three models (Figure 4). The natural period of the structure T is practically the same for the three models. Considering first the isolated buildings (Prototypes 1 & 2), the period in the transversal direction (Y) is smaller than in the longitudinal direction (X) because of the greater rigidity of the firewalls. In the longitudinal direction (X), the fundamental period T_x of the building with a mansard roof is larger than for the building with the regular flat roof, emphasizing the influence of the roof system on the rigidity of the structure.

Table 2: Fundamental period of vibration

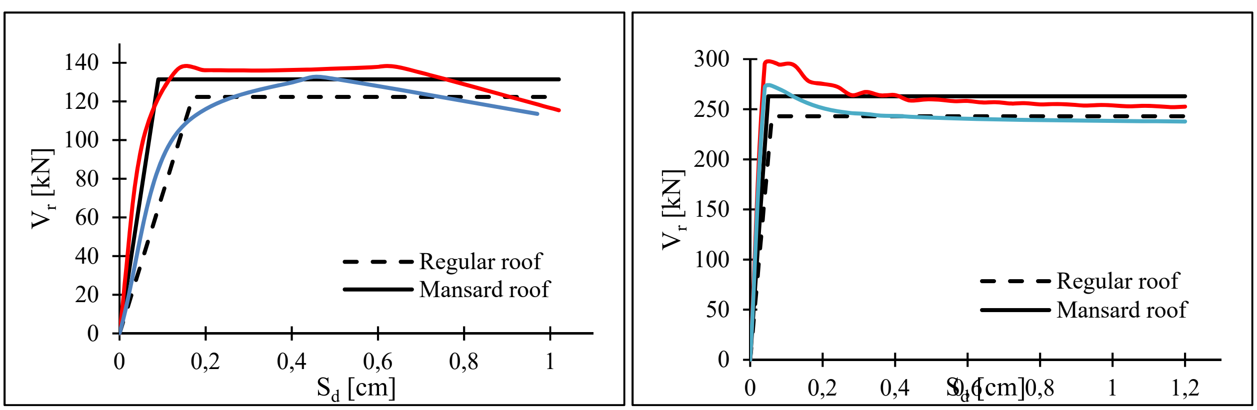
Model	T_x [sec]	T_y [sec]	T [sec]
Prototype 1 : Mansard roof	0.209	0.072	0.061
Prototype 2 : Flat roof	0.157	0.073	0.067
Prototype 3: Row of 6 houses (flat roof)	0.098	0.086	0.065

The modal analysis of the row of 6 houses shows a slight increase in the transversal direction (Y) compared to the model of an isolated building. This is mostly due to the fact that the firewalls are shared by adjacent buildings and therefore the ratio of rigidity and mass between the row of buildings and a single building is slightly different. The period remains smaller than the experimental average value of 0.14 sec obtained for row buildings. In the longitudinal direction (X) the period decreases by 38% from 0.157 sec for the isolated building to 0.098 sec for the row buildings indicating that the interaction between the buildings. To improve the calibration of the models, a second series of analysis will be performed with variations in the mechanical parameters to represent masonry of different levels of quality.

4.3 Pushover Analysis

The non-linear static pushover analyses, performed with 3-Muri, adopt the Eurocode 6 (Eurocode 2005a) relations for the evaluation of bending/crushing and shear failure modes and is based on the ultimate drift limits of URM walls. Values for drift limits, at which the analysis terminates, are taken from Eurocode 8 (Eurocode 2005b) and are given in Table 1.

The idealized bilinear capacity curve (corresponding to the mechanical parameters defined in Table 1) resulting from the pushover analyses of the prototype models in X and Y directions are shown in Figure 6 for the isolated buildings, Prototypes 1 and 2. An equivalent elastic-perfectly plastic, single degree of freedom “SDOF” model can then be defined from the capacity curve (Galasco et al. 2006). The SDOF is characterized by the strength V_r*, the modal participation factor Γ, the effective mass m*, the yield displacement d* and the fundamental period of vibration T*.



(a) (b)

Figure 6: Capacity curves of the URM-B1 prototype building: (a) in longitudinal X-direction, (a) in transversal Y-direction

As shown in Figure 6, the capacity of both prototype buildings in transversal Y-direction is almost twice that in the longitudinal X-direction. The façade and rear walls have regular windows and door openings, which explains the reduction in the lateral resistance of buildings compared to the massive firewalls with no opening. In the longitudinal X-direction, the capacity and the stiffness of the building with mansard roof, respectively 131kN and 1460 kN/cm, are greater than for the model with regular flat roof, 122 kN and 720 kN/cm. In the transversal Y-direction, the two prototypes have roughly the same stiffness, with a small difference in lateral resistance, 220 kN for regular roof and 238kN for mansard roof. Figure 7 shows the modes of rupture in the walls. Most macro-elements present a shear failure by diagonal tension. In the longitudinal wall, most damage to the second storey is by diagonal tension of the pillars. In the spandrels, defined on the basis of the vertical alignment and overlaps of openings, damage is by bending mode. In the lateral wall, the only damage is to the masonry elements in the first storey by shear failure and compression failure.

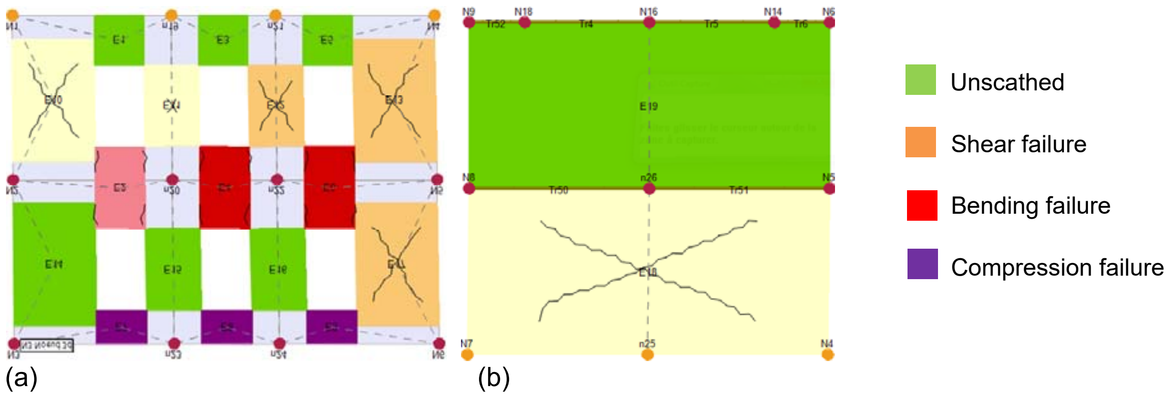


Figure 7: The modes of rupture of the URM-B1 prototype building: (a) in longitudinal X-direction, (a) in transversal Y-direction

Figure 8 presents the capacity curves of the row of 6 buildings (regular flat roof) in each direction. The row of 6 houses is composed by 7 walls with thickness 20 cm in Y-direction and 12 walls with thickness of 30 cm with openings in X-direction. The capacity of the row buildings in the longitudinal X-direction is greater than the capacity in the transversal Y-direction, that is 1440 kN versus 946 kN. In the Y-direction the capacity of the row of buildings is proportional to the capacity of individual firewalls, thereby confirming that the transversal capacity of those buildings can be estimated by considering the resistance of the individual walls. However, in the X-direction the capacity of the row of buildings is greater than the summation of the resistance of the isolated buildings. These first results indicate that the seismic vulnerability of buildings part of a row of buildings should be considered differently from isolated buildings.

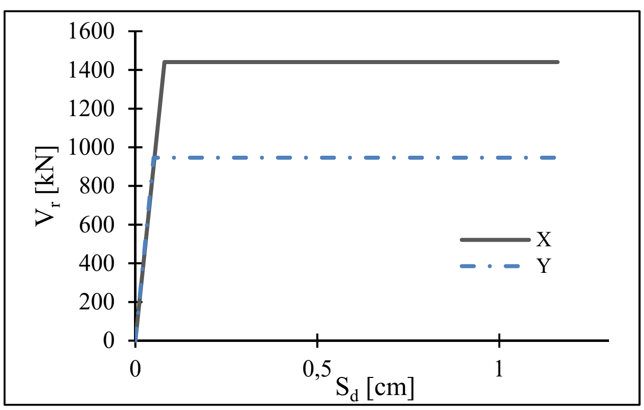


Figure *8*: Capacity curves of the row of 6 houses

5 CONCLUSION

The objective of this study was to document the structural system and dynamic properties of URM buildings frequently found in the oldest sectors of Montreal, constructed between 1860 and 1915, and to assess their lateral capacity. These buildings have unreinforced masonry external bearing walls and interior wood framing supported on the façade and rear walls or on the lateral firewalls. Visual inspection of some typical buildings made it possible to identify the constructive details such as the type of connections between the joists and the walls, thickness of walls and element dimensions. Ambient vibration measurements were carried out on four 2-storey buildings. The results showed that the period of these buildings is around 0.14 second, which is lower than the 0.19 second estimated with the NBCC equation. These buildings are part of a row of houses and no motion in the longitudinal direction was observed due to a great rigidity.

Collected data were then be used to develop a macro-element model to evaluate the lateral capacity of typical prototype buildings. Two prototypes of 2-storey buildings with a mansard roof and a flat roof were considered as well as a row of 6 flat roof buildings. Modal analysis shows the influence of the roof system on the longitudinal direction of the building, while the URM firewalls determine the response in the transversal direction. Pushover analyses, using the software tool 3-Muri©, were conducted to derive the capacity curves. Again, the influence of the roof system could be observed on the lateral capacity of isolated buildings in the longitudinal direction. Results also indicate that seismic vulnerability of buildings part of a row of buildings should be considered differently from isolated buildings. Another AVM campaign is undergoing to obtain more data and to complete the dynamic characterization for isolated single-family houses, with different roof systems and different floor spanning directions. To improve the calibration of the models, series of analysis will be performed with variations in the mechanical parameters to represent masonry of different levels of quality as well as the quality of the connection between the wood floor and the walls.

Acknowledgements

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