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Structural characterization of residential buildings in Montreal with mixed structural systems for seismic risk studies.

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ABSTRACT

The abstract should contain a summary of the paper, including motivation, objectives, methodology and main results. The abstract cannot exceed 300 words.

Keywords: 5 keywords separated by commas.

INTRODUCTION

A recent seismic risk inventory of existing residential building stock in Montreal Island showed that wood frame structures constitute 83% of the total number of buildings followed by unreinforced masonry (URM) buildings with 14%. Several of those buildings built between 1860 and 1950 in the central sectors of Montreal have mixed structural systems consisting of unreinforced masonry walls and wood framing. This type of residential structure is not specifically considered in the building classification defined in neither the Canadian nor American version of Hazus software used for seismic risk assessment studies. The main objective of this paper is to provide information about the materials, structural systems and dynamic characteristics of these buildings. Two different types of structures are studied. URM-B1 has URM external bearing walls and interior wood framing supported on the façades or the lateral firewalls. In URM-B2 the façade walls are made of timber planks that may support the floor system. 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 material, 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. Ambient vibration measurements were used for the dynamic characterization of the buildings. Data was analyzed to obtain the fundamental periods, mode shapes and damping of the structures using the Enhanced Frequency Domaine Decomposition method (EFDD) and the Frequency Domain Decomposition method (FDD). Measurements were also conducted on site, to obtain the ground frequency resonance using the horizontal over vertical spectral ratio method (HVSR). The collected data will be used to develop and calibrate models for the evaluation of the lateral resistance and fragility analysis of these buildings.

Keywords: URM, Residential Buildings, Stacked wood planks, Ambient Vibrations, HSRV

INTRODUCTION

Historical records indicate that the Montreal area is a region of moderate seismic activity. Since 1663, only 7 historical events have been reported with a maximum intensity greater than VIII on Modified Mercalli Scale, or greater than an estimated magnitude M_w 5.8 [1][2][3][4]. 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 [5][6][7]. Montreal is the second most populous metropolitan centre in Canada with more than 1.9 million inhabitants (2016 census). Initially settled in the 17th century, a large proportion of buildings was built prior to the introduction of modern seismic design codes. In addition, a significant portion of the city was built on soft soil deposits known to amplify seismic waves [8]. The National Building Code of Canada specifies a horizontal PGA of 0.379 g with a probability of exceedances of 2% in 50 years [9]. It is in this context that a first seismic risk analysis for residential buildings in Montreal was 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 [12].

Results showed that more than 83% of about 300 000 inventoried residential buildings are wood frame structures and 14 % are unreinforced masonry (URM) buildings [13]. For an earthquake scenario with a magnitude M5.8 in the centre of the Island, about 27% of the wood buildings and 67% of the URM buildings would sustain moderate to complete damage. Associated economic losses represent 55% and 37%, of the total loss to residential buildings. In the oldest sectors of Montreal, several buildings constructed between 1860 and 1950 are mixed structural systems consisting of unreinforced masonry walls and wood framing. They represent almost 46% of the approximate 70 000 residential buildings in the central sectors of Montreal. However, no specific fragility data are available for those buildings. Therefore, seismic risk studies carried out with HazCan [10] (the Canadian version of the seismic risk assessment software HazUS [11] adapted to the seismological Canadian context) use fragility data defined for light wood frame structures (W1) or URM buildings as available in HazUS . Previous studies have shown that variation in building capacity and fragility could lead to uncertainties that propagate along the computation process of seismic risk assessment [14][15].

The main objective of this paper is to provide information about the materials, structural systems and dynamic characteristics of two types of buildings known to have mixed structural systems consisting of unreinforced masonry walls and wood framing. The first type, URM-B1, has URM external bearing walls and interior wood framing supported on the façades or the lateral firewalls. In the second type, URM-B2, the façade and rear walls are made of timber planks that may support the floor system.

METHODOLOGY

The structural characterization 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 buildings of the two types, URM-B1 and URM-B2. A total 14 buildings were visually inspected, 4 URM-B1 and 10 URM-B2. 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 characterisation was carried out by ambient vibration measurements (AVM) recorded using four high resolution tromographs (Tromino©). AVM were taken in 3 URM-B1 buildings and 5 URM-B2 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). AVM were also conducted on the site of 5 buildings to obtain the frequency of resonance of the soil using the horizontal over vertical spectral ratio method (HVSR).

HISTORICAL CONTEXT

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 with houses made of wood. Unfortunately, the great fire of 1852 destroyed a large part of those districts **Erreur ! Source du renvoi introuvable.**. 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 [17]. This type of construction was expensive because bricks were imported from Europe. The use of stacked timber planks called "carré de madrier" for the façade and rear walls, covered by a brick veneer (URM-B2) allowed cheaper constructions while still respecting the objective of the legislation. This explains why there are more URM-B2 houses than URM-B1 in Montreal. In both cases, URM-B1 and URM-B2 houses are generally part of a row of buildings, two or three stories high, with individual units separated by a common unreinforced brick firewall. Timber planks construction for residential buildings was very common until the middle of the 20th century in most districts of Montreal. Its use continued until the 1970s in districts belonging to the former city of Montreal owing to fire regulations that forbid the use of light wood framing.

STRUCTURAL CHARACTERIZATION

Buildings URM-B1

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.

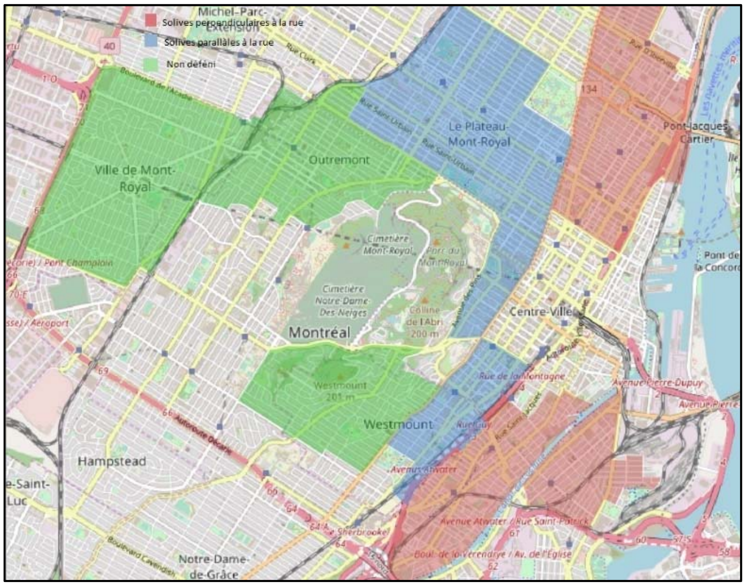
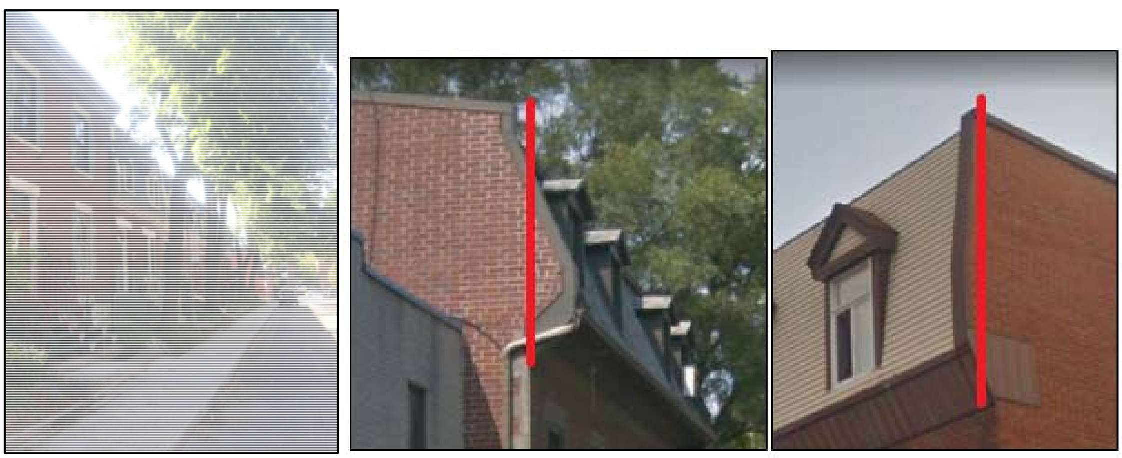


Figure 1: Location of URM-B1 buildings (Internal wood framing supported by URM firewalls (Blue), by façade and rear URM walls (Red) or unknown (Green).

The most common URM-B1 building is a single-family house of two storeys, part of a row of buildings as shown in Figure 2 (a). Story height varies between 6 m and 7 m.



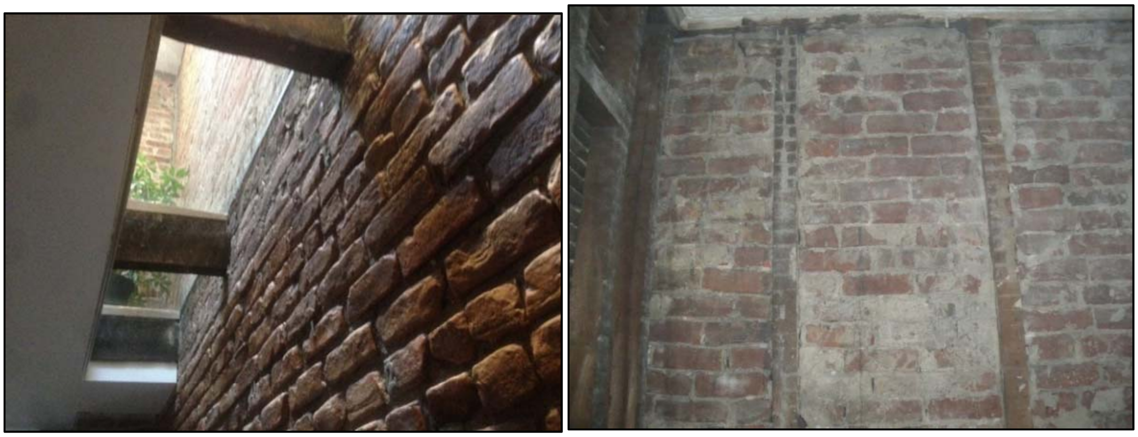
(a) (b) (c)

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, as shown in Figure 2 (c).

The bearings walls are composed of two to three rows of bricks, with thickness decreasing at higher floor levels. Foundation is made of stones and are 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 meters 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 meters 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 f timber frames and the spaces between the structural members are filled brick. This French-style construction technique [17] is illustrated in Figure 3 (b).

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 studs 3''x3'' @ 12'' c/c. Wood decking is made of planks, 4'' to 8'' width and 1'' thick.



(a) (b)

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

Buildings URM-B2

Buildings with timber plank walls were the most popular type of construction due to their lowest cost. URM-B2 buildings are therefore common in more neighbourhoods than URM-B1 buildings. As shown in Figure 4, it is possible to find them in many districts developed before 1950 in Montreal. The colours on the map indicate the direction of the floor framing system. Between 1865 and 1880, joists were perpendicular to the street and were supported by the timber planks façade and rear walls (in red on the map). Buildings with joists parallel to the street and supported by the common firewalls were built in two different periods, between 1875 and 1900 (in red on the map) and after 1900 (in red on the map).

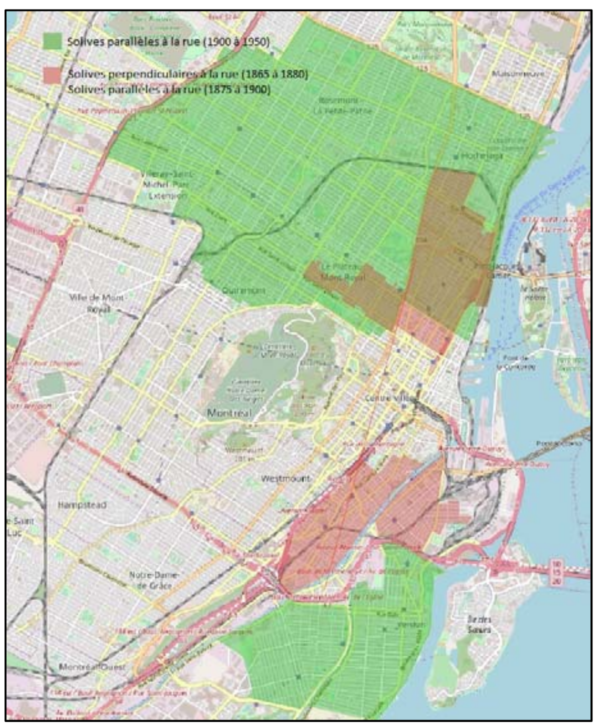
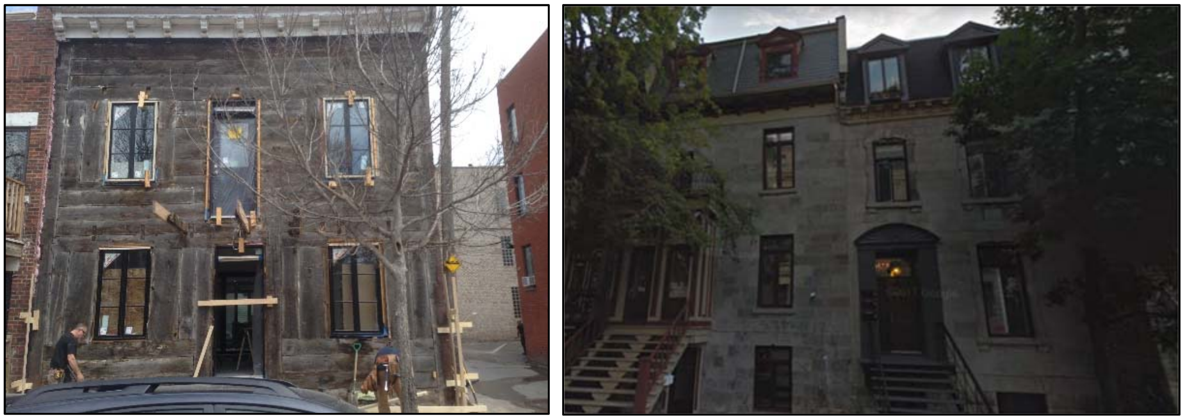


Figure 4: Location of URM-B2 buildings

Timber plank walls are typically made of stacked white pine planks with a cross-section of three by eleven inches covered by one layer of brick veneer. Figure 5 (a) shows a typical timber plank wall where the brick veneer that was traditionally anchored by four inches nails is being replaced and fixed with new corrugated masonry anchors. House in Figure 5 (b) is typical of URM-B2 built between 1865 and 1880, with typical width between 6.5 to 8.5 metres. In these buildings, the 3'' x 11'' joists are encased in the full thickness of the timber plank walls, i.e 3''. Other structural details for the foundation, roof and floor system are similar to those of URM-B1 houses.



(a) (b)

Figure 5: Typical URM-B2 houses: (a) timber plank wall, (b) 1865-1880 with floor system supported on the timber plank wall.

The oldest version of URM-B2 with spans parallel to the street (1875 to 1900) has a carriage entrance that provides access to the backyard. This element introduces a structural weakness to the building since the common brick firewall is located at mid span of this entrance (Figure 6 (a)). Between 1900 and 1950, the most common URM-B2 declination is a two to three storeys apartment building. The exterior staircase in front of the house is the main architectural distinctive element as shown in Figure 6 (b).

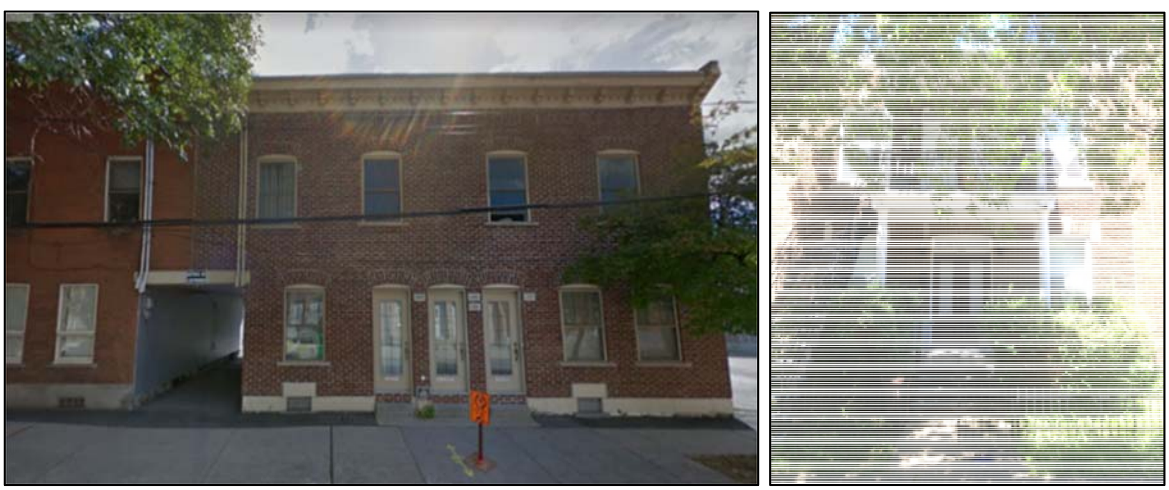


Figure 6 : Typical URM-B2 houses with spanning direction of the floor parallel to the street: (a) with carriage entrance located in South-West of Montreal, (b) with front staircase in Rosemont Petite-Patrie.

These buildings have similar construction characteristics. The joists are parallel to the street and are supported by common URM firewalls, which have a thickness of 16'' in the case of 1875-1880 buildings, and sometimes only 8'' in more recent buildings. Other structural details of the foundation, roof and floor system are similar to those of URM-B1 houses except for the introduction of concrete foundations around 1920. In that case, the joists were used to support the concrete scaffolding and thereby were encased in the concrete wall.

For future modelling of the buildings under study, it is important to consider the type of connections between the wood elements and the masonry walls. Although these connections appear visually embedded, they generally do not have lateral and vertical restraints. They are usually simply resting on the walls. The connections between the wooden elements and the timber planks offer more restraint. The joists or beams generally pass through the timber planks and are nailed to it, thus blocking lateral and vertical displacements.

AMBIENT VIBRATIONS MEASUREMENT ON BUILDINGS

Eight two storeys buildings have been tested by ambient vibration measurements. Seven are part of a row of buildings, three URM-B1 and four URM-B2, and one URM-B2 was an isolated single-family house. All were rectangular 2-storeys buildings with a depth of 10 to 12 m. Width of URM-B1 was between 5.66 to 6.35m with floor spanning direction parallel to the street. URM-B2 were larger, between 7.62 to 10.7 m, with floor spanning direction perpendicular to the street

The average fundamental periods obtained, by EFDD and FDD methods, for URM-B1 and URM-B2, are 0.14 sec and 0.09 sec, respectively. These experimental periods are smaller than the fundamental period computed with the equation proposed by the NBCC 2015 ($0{,}05(h_n)^{3/4}$) [9]. Using 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, 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 an infinitely rigid behavior in the longitudinal direction. The signals analysis shows a difference in rigidity between URM-B1 and URM-B2 buildings, the latter being more rigid. This could be explained by a greater structural integrity in the URM-B2 buildings with a higher contribution of all the different structural components to its rigidity. Damping values obtained from EFDD method were between 0.13 and 0.15% for URM-B1 and between 0.17% and 0.43% for URM-B2. Slightly higher damping for URM-B2 is explained by the presence of the timber plank walls. These low damping values are more characteristic of ambient noise than the damping of 5% usually recommended by codes for large earthquake.

One URM-B2 family house was also tested to evaluate the longitudinal fundamental period of an isolated building. Mode shapes were found along the two axes of the building. The average fundamental periods obtained, by EFDD and FDD methods, in transversal and longitudinal direction are, 0.135 sec and 0.18 sec, respectively. Transversal period is similar to the one measured in the case of row houses, while the longitudinal period is higher and closer to the 0.19 sec given by NBCC equation. These results confirm the hypothesis of the infinite rigidity created when buildings are part of a row and are connected to each other. Damping was 0.93% and 0.57%.

HSRV RATIO

Ambient vibration measurements were also conducted on site of 4 buildings, to obtain the frequency of resonance of the soil using the horizontal over vertical spectral ratio method (HVSR). The objective of these measurements is to confirm the seismic site category define from the microzonation map of Montreal Island [9]. At this stage of the study, first results show good agreement between the experimental data and microzonation information. Another campaign of measures is planned for summer 2019 and results will be used for the structural analysis of some buildings.

CONCLUSIONS

The objective of this study was to document the structural system and dynamic properties of two types of buildings frequently found in the oldest sectors of Montreal. These buildings were constructed between 1860 and 1950. They have a mixed structural systems consisting of unreinforced masonry walls and wood framing. The first type, URM-B1, has URM external bearing walls and interior wood framing supported on the façade and rear walls or on the lateral firewalls. In the second type, URM-B2, the façade and rear walls are made of timber planks that sometimes support the interior wood framing system.

Review of documentation revealed that URM-B2 are more frequent mainly because of their lower construction cost. Visual inspection of some typical buildings made it possible to establish a relationship between the floor spanning direction and the width of the facade of a building. Narrower buildings often have joists supported by the common URM firewalls while in larger buildings joists are usually supported by the façade and rear walls, URM or timber plank walls. Constructive details were observed 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 2-storeys buildings, URM-B1 and URM-B2 type and on an isolated single-family building of the URM-B2 type. The results showed that URM-B1 have a period of about 0.14 second, and URM-B2 buildings have a period of about 0.09, the latter being more rigid. In buildings part of a row of houses, no motion in the longitudinal direction was observed due to a great rigidity. In the single-family house of URM-B2 type, the fundamental period in transversal direction was 0.135 sec which is similar to the one obtained in row houses buildings, and was 0.18 sec in the longitudinal direction. All values are smaller than the period given by the NBCC 2015 equation. Another campaign of AMV on buildings and sites is planned for summer 2019. All collected data will be used to develop and calibrate models for the evaluation of the lateral resistance and fragility analysis of these buildings.

ACKNOWLEDGMENTS

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