Assessment of Structural Systems of Residential Buildings with Unreinforced Masonry Walls in Montreal

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ABSTRACT

Buildings with unreinforced masonry bearing walls (URM buildings) are seismically vulnerable, providing insufficient resistance to lateral forces, as demonstrated by major earthquakes worldwide. Evaluating the seismic vulnerability and performance of these buildings is crucial in earthquake-prone regions with a high concentration of URM buildings. In Montreal, which experiences moderate to high seismicity, a considerable proportion of residential buildings include URM bearing walls, most constructed between 1850 and 1950. These buildings were typically made using a variety of materials, including natural stone, concrete, and clay, or were built with mixed structural systems combining masonry and wood elements. The popularity of these construction methods varied over time, making it important to assess the structural capacity and fragility performance of these buildings to understand regional-scale seismic risk in Montreal. Seismic risk assessment involves integrating regional hazard data, building inventories, and vulnerability analyses. This paper reviews the existing literature to define the characteristics of mixed structural systems in Montreal, focusing on trends in URM building construction over time. It examines how past studies have addressed these buildings in inventories, response analyses, or fragility functions, identifies gaps in current research, and outlines key resources to simplify and enhance the regional-scale seismic risk assessments of the city.

KEYWORDS

Unreinforced masonry bearing wall buildings, Plexes, mixed structural systems, regional seismic risk assessment, residential buildings.

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INTRODUCTION

Past studies and earthquake events have highlighted the vulnerability of buildings with unreinforced masonry bearing walls (URM buildings) worldwide against earthquakes. As a case in point, in 2003, the city of Bam in Iran, where 90% of the residential buildings were URM buildings made of mud brick, suffered catastrophic damage when a magnitude Mw=6.5 earthquake struck and 80% of the city was destroyed [1]. Similarly, during the 2023 earthquakes with Mw=7.7 and Mw=7.6 in Turkey, URM buildings suffered extensive damage and collapse. These buildings accounted for a significant portion of the rural building stock in the affected provinces and were constructed using materials like stone, briquette, and mud brick [2].

As well, in Canada, URM buildings are widely used and available in the form of both reinforced and unreinforced bearing walls. According to the literature, most reinforced masonry buildings have been used in industrial and commercial buildings. However, URM buildings were more common in residential buildings in both Eastern and Western Canada [3]. With a focus on Eastern Canada, Montreal, as a populated city with moderate to high seismicity, contains plenty of residential buildings with masonry elements built using natural stone, concrete, or clay, with or without wood elements, constructed between 1850 and 1950. Before 1850, most URM buildings were constructed using stone masonry, with brick masonry used less frequently. No seismic design specified in modern codes (low-code, moderate-code, high-code) was applied in their construction, and they can be classified as pre-code buildings. Therefore, given their lack of compliance with seismic codes, their vulnerability to earthquakes, and their prevalence, the seismic evaluation of these buildings should be prioritized.

In general, two aspects of seismic response evaluation of URM buildings have been investigated in Eastern Canada. The first aspect involves numerical modelling and depending on the level of complexity and detail considered, these models can be categorized as macro, meso, or micro, each offering a tailored approach for testing and analyzing [4]. The second aspect, however, focuses on applying available guidelines and documents to facilitate seismic risk assessments and estimate potential losses, whether direct economic losses or social impacts, arising from seismic events. Examples include information provided by Hazus, FEMA guidelines, and their Canadian counterparts, such as the NRC Seismic Risk Screening Tool (NRC-SQST) [3], [5], [6], [7], [8]. Both approaches to seismic response evaluation have their respective advantages and disadvantages. The first approach, which relies on numerical modelling to estimate the seismic response of URM elements, typically produces building-specific or element-specific results. While this method provides higher precision, it may be less suited for regional-scale assessments or for capturing the diverse characteristics of buildings across an entire city. Moreover, numerical modelling often demands significant time and involves extensive comparisons due to uncertainties in input parameters, along with verification of test results. Several numerical models have focused on individual URM elements, whereas seismic evaluation of buildings requires the capacity of the entire structure, which can demand significant time. For instance, using distinct element modelling, a full-scale analysis of a URM tower required nearly three months of computational effort [9]. On the other hand, the second approach, which involves applying existing guidelines and documents, provides the ability to address problems within a limited timeframe and offers the capability to provide approximate estimates of event outcomes at the city level or, on a larger scale, across an entire province. However, it may not necessarily account for the specific capacities and unique characteristics of URM buildings in a city like Montreal, such as plexes, since these buildings have region-specific characteristics that may not be included in existing seismic assessment guidelines. In Hazus (and its complementary documents) and NRC-SQST, the primary methodology for obtaining the seismic responses of buildings is the Capacity Spectrum Method (CSM), in which the studied buildings are simplified into single-degree-of-freedom systems [8], [10]. Although this is an approximate method for obtaining building responses, it can still provide reasonable estimates of the inelastic response of buildings [11].

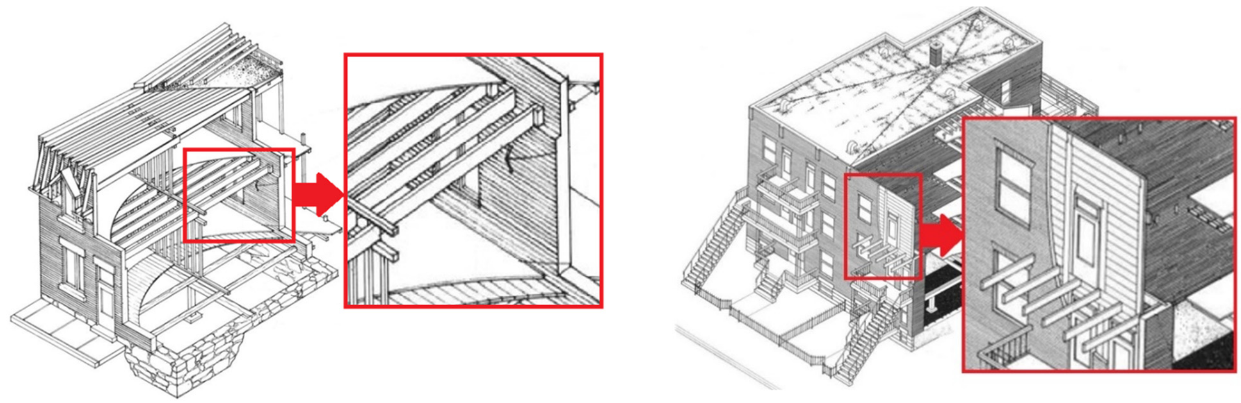
Considering the aforementioned aspects, the application of the available guidelines for regional-scale seismic risk assessment is particularly noteworthy. However, its implementation requires the development of capacity curves and fragility functions tailored to specific building classifications within the region. In Montreal, the building stock is categorized into three primary groups: single-family dwellings, plexes, and apartment buildings [12]. Among them, plexes are small, superposed flats that stand out due to their unique, region-specific characteristics, making them a distinctive feature of the city. These buildings typically have URM bearing walls and may also incorporate wooden elements, either as framing in floors and roofs or as part of the wall structure [13]. In this study, the primary objective is to develop a comprehensive understanding of plexes with mixed structural systems (URM-W) of URM and wood elements, one of the common residential building types in Montreal. To this end, the study reviews existing literature that highlights their defining characteristics and periods of construction, complemented by inventory results derived from open-access data sets that may be associated with these plexes. Additionally, relevant studies and guidelines that provide insights into their seismic capacity or fragility are analyzed to identify research gaps and propose directions for future investigation.

CHARACTERISTICS OF URM BUILDINGS IN MONTREAL

Before 1850 in Montreal, residential buildings were typically constructed as single-family houses, using wood or solid URM materials, comprising stone blocks and brick. According to Montreal's census of 1825, 45% of samples in this census were stone masonry buildings, a negligible part of samples were brick and the rest belonged to wood buildings, which shows that almost an even use of both stone masonry and wood at that time [12]. However, after this period, the prevalence of URM buildings in the residential sector increased. This shift was prompted by a series of devastating fires in the 1850s, which destroyed approximately 20% of the dwellings in the city. In response, new regulations mandated the use of non-combustible materials in construction, leading to the widespread adoption of firewalls made of solid stone and brick as safer alternatives to wood [14]. Simultaneously, between the 1850s and 1870s, the population of Montreal increased by over two times. This period marked the fastest rate of growth in the observed timeline, reflecting rapid urbanization and expansion in the city. The population increase created a higher demand for housing [15]. In response, the growing demand led to the construction of more affordable housing, such as plexes, while single-family houses were built in more affluent areas [12].

Figure 1: Duplexes, triplexes, and fiveplexes [12], [16]

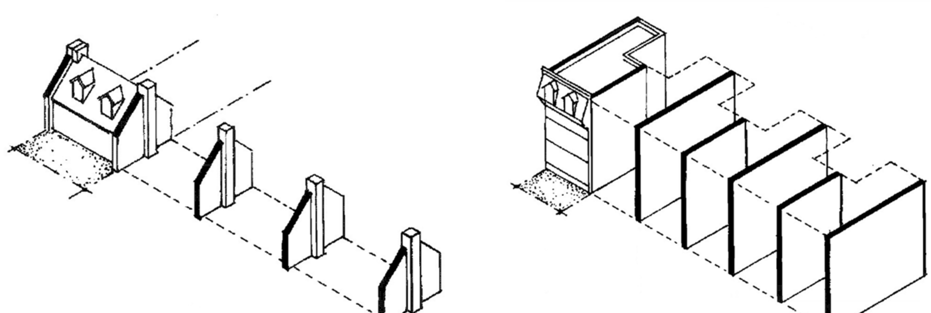
Plexes were typically built as duplexes—multi-family dwellings with two separate units on each floor—which began appearing in 1866, or as triplexes—three-storey multi-family townhouses with one unit per floor—which emerged in 1890 in Montreal. Additionally, triplexes could be expanded to fourplexes, fiveplexes, or sixplexes if two units were constructed on each floor, as shown in Fig. 1 [16]. Based on the literature, two common types of URM-W are found in Montreal. The first type features interior wood frames supported by exterior URM bearing walls and also firewalls, which were mainly constructed before 1915 [13]. The second type includes horizontal timber plank walls between vertical wooden posts in the façade and rear walls, with a brick veneer to protect the wood from moisture; in the opposite direction, URM walls also function as firewalls. Both types of buildings usually exist in the form of row housing or as aggregates with shared party walls. One example of each URM-W building type is illustrated in Fig. 2 (a) and (b). Further information on the typical floor plans, geometry properties, and other architectural characteristics can be found in past studies [13], [16], [17].



(a) **(b)**

Figure 2: (a) First type of URM-W buildings with wood frames and URM bearing walls; (b) Second type of URM-W buildings with timber plank walls [16]

The purpose of URM firewalls was to provide separation between residential dwellings, preventing the spread of fire from one unit to adjacent ones. Fig. 3 illustrates the arrangement of firewalls in row housing, positioned perpendicular to the façade. This form of attached dwellings, with firewalls on two orientations, also helped improve conditions during harsh weather and contributed to material and energy savings.

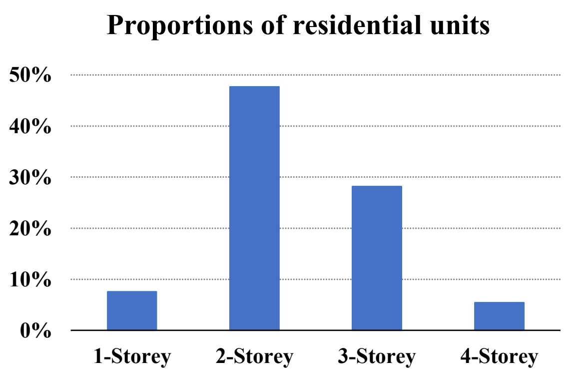


(a) **(b)**

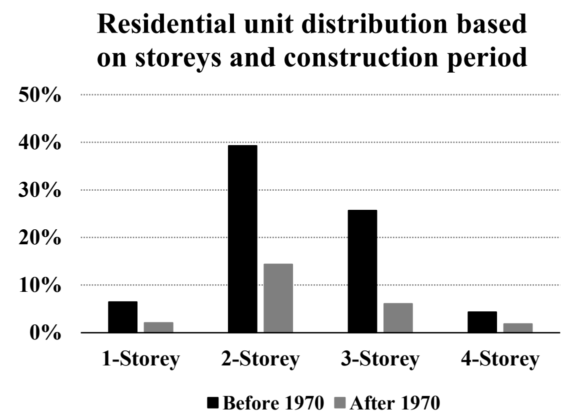
Figure 3: General configuration of firewalls in row housing: (a) Early firewalls constructed with stone; (b) Shared walls (or *mitoyen* walls) constructed with bricks [18]

Available Inventory Data Sets

As of the date of this study, no open-access resources are available that specify the structural systems of residential buildings in Montreal. However, an open-access sampled data set provided by the Montreal Property Assessment of Units offers information on the number of residential units categorized by the number of storeys and year of construction. As shown in Fig. 4(a), 89% of residential units are in buildings with fewer than five storeys, including 8% in one-storey buildings, 48% in two-storey buildings, 28% in three-storey buildings, and 5% in four-storey buildings [19]. It is important to note that the sampled data set includes incomplete entries, which have been excluded from the statistics; as a result, these statistics do not reflect the actual total number of residential units in the Statistics Canada database but represent 63% of the total units. Furthermore, Fig. 4(b) provides insight into the construction periods of these residential units, showing that the majority were built before 1970, particularly in two-storey and three-storey buildings. This concentration of residential units in low-rise buildings highlights the role of plexes, such as duplexes and triplexes. These buildings form a notable portion of the residential units, reflecting the city's historical and architectural character and their presence underscores the need to consider them in housing policies and urban development strategies.



(a)



(b)

Figure 4: Statistics on the proportions of (a) residential units, and (b) residential unit distribution by storeys and construction period according to sampled data sets in Montreal [19]

Seismic Assessment of URM-W Buildings: Available Resources and Needs

The existence of plexes in Montreal emphasizes the necessity of including these buildings in the seismic assessment of the city, which should be defined in terms of inventory, exclusive seismic capacity, and specific fragility functions as pre-code buildings. As mentioned, these unique building types, constructed with URM-W, are often houses of two to six multifamily residential units. As a result, a major earthquake could displace multiple households, emphasizing the need for an inventory that captures both the number of buildings and the residential units they contain, as this represents the first critical aspect that needs to be addressed. Such a detailed inventory is essential for assessing the potential scale of dislocation and population displacement. Despite the importance of these structures, as mentioned, open-access data sets for residential buildings in Montreal lack detailed information about their structural systems. Existing studies often rely on information related to occupancy or limited surveys that represent only a small subset of the city's buildings [20]. However, most URM-W buildings were constructed using a few well-defined techniques tied to specific historical periods. This presents an opportunity to develop a systematic and standardized framework for classifying the buildings based on their number of storeys and years of construction, utilizing distinct historical construction trends in Montreal.

Another critical aspect necessary for the seismic assessment of URM-W buildings is the lateral seismic capacity and fragility functions of these buildings. To date, two notable studies conducted by Kraiem et al. (2019 and 2022) have investigated URM-W buildings in Montreal. One study focused on three URM-W systems at the building scale, integrating URM bearing walls with wood elements in the floor and roof. These systems were numerically modelled, and their capacity curves were developed for two orthogonal directions. The modelling details were based on visual inspections, and the results accounted for factors such as row housing configurations and variations in roof systems [21]. Also, in another study, the lateral resistance of a traditional timber plank wall was numerically modelled and investigated [17]. Among existing resources, key guidelines and documents are available for estimation of seismic capacity curves of URM and wood light frame (W1) buildings and developing fragility curves, including Hazus (2024), Hazus AEBM (2009), FEMA-BCA (2023), NRC-SQST (2020), and FEMA-P155 (2015) [3], [8], [22], [23], [24]. However, as mentioned in the previous section, the capacity curves for buildings with only URM bearing walls or only W1 components may not necessarily capture the behaviour of URM-W buildings [17]. The presence of both URM walls and wood elements, either as timber plank walls or wood frames, can provide additional seismic resistance to the buildings. Therefore, more research is needed to quantify the seismic performance of URM-W buildings as a hybrid system using numerical modelling, experimental investigations, and the consideration of the contributions of the wall force-deformation behaviour of each material to the total seismic resistance [25].

In this case, reasonable simplifications based on available studies on the seismic assessment of hybrid structural systems can be applied. In the absence of specific studies on these building types in Montreal, similar research with shared concepts can provide valuable insights for selecting capacity parameters from available resources for preliminary risk assessment. Past studies have been reviewed on seismic behaviour and vulnerability of aggregate buildings of masonry or mixed structural systems with masonry façade walls featuring openings, solid masonry walls in the perpendicular direction, and reinforced concrete or wooden beams [26], [27], [28]. A similar structural condition exists for URM-W buildings in Montreal as row or aggregate buildings. Through nonlinear static and dynamic analyses, these studies highlighted those façades and their materials play a key role in determining seismic strength and damage patterns. Based on this, for URM-W buildings with URM façades (the first type), seismic capacity parameters and fragility functions from key guidelines (e.g., Hazus and NRC-SQST) specific to URM may capture their seismic behaviour. Conversely, for those with wood façades (e.g., timber planks, the second type), W1 parameters from the same sources may approximate their seismic performance. Adopting this approach in the absence of detailed numerical and experimental simulations specific to Montreal buildings can provide a first-order estimation of the seismic capacity of these classes of buildings for preliminary regional-scale risk assessment.

CONCLUSION

Seismic evaluation and regional-scale seismic risk assessment rely on several key factors: building inventory, local construction practices, seismic capacity curves, and the application of fragility functions to assess building damage and performance. This study focuses on residential plexes in Montreal, classified as URM-W buildings, which incorporate both URM and wood elements, were constructed before 1970, and usually contain two or more units. The study provides background information on these buildings and their characteristics, along with open-access sampled datasets detailing the statistical distribution of residential units by the number of storeys and year of construction. The study highlights gaps in existing frameworks, underscores the need to classify these buildings separately, and discusses available resources for deriving seismic capacity and fragility functions.

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