Seismic vulnerability study of historical buildings in Old Montreal: overview and perspectives

M.-J. Nollet, O. Chaallal & K. Lefebvre
Department of Construction Engineering, University of Quebec, École de technologie supérieure, Montreal, Canada

Abstract

This paper presents a review of the vulnerability evaluation methods available to study a group of buildings in the historic Old Montreal district based on their structural characterisation. The seismic vulnerability of structures is one of the key elements, along with the seismic hazard, site effect, value and exposure, to determine the seismic risk associated to a group of buildings. The city of Montreal, in Eastern Canada, has an effective seismic zone of 3 and 4, respectively, which is qualified as moderate to high seismicity on a scale of 0 to 6. Therefore, there is a need to develop tools to evaluate the seismic vulnerability of existing constructed facilities. Montreal historic buildings constitute an important and valuable segment of these facilities. A comprehensive inventory of Old Montreal buildings and their structural characteristics led to the identification of the dominant types of structure: unreinforced masonry bearing wall structures and moment-resisting frame structures with infill masonry walls. A review of the existing procedures for the evaluation of the seismic vulnerability of groups of buildings based on the European and North American experiences was carried out and procedures based on structural typology are considered as the most appropriate for this group of buildings along with the development of simplified models to obtain vulnerability functions.
Keywords: seismic vulnerability, seismic risk, historical building, unreinforced masonry.

1 Introduction

The seismic risk in urban area is obtained by the combination of the *seismic hazard* of the area, and the *vulnerability* and *exposure* of the constructed facilities including the site effects related to the soil conditions. In moderate seismicity regions, the seismic risk can be significant when site effects include problems of liquefaction or acceleration amplification, or when buildings are highly vulnerable. This can be the case for historical sectors of North American cities, such as Montreal or Quebec City in the Province of Quebec (Canada), where most of existing buildings have been constructed prior to the introduction of seismic codes. The objective of this paper is to review the available methods of evaluation of the seismic vulnerability of a group of buildings, to identify the most appropriate method for the population of buildings in the area of Old Montreal. A comprehensive inventory of the buildings and their structural characteristics is first presented and compared with the descriptive typology of the different classes of buildings proposed by the Canadian National Research Council. Two potential methods for the evaluation of the vulnerability of unreinforced masonry structures typical of Old Montreal are also presented.

2 Seismicity of the Province of Quebec (Canada)

Eastern Canada is located in a stable continental region within the North American Plate. The macroseismic zones of the Province of Quebec, the Charlevoix Seismic Zone, located some 100 km downstream from Quebec City, is the most seismically active region of eastern Canada. The Western Quebec Seismic Zone, which encloses the Ottawa Valley from Montreal to Témiscamingue is also relatively active. Large and damaging earthquakes have occurred in the past and will inevitably occur in the future. Damages mainly occurred to unreinforced masonry buildings [1]. More recently, in November 1988, an earthquake of magnitude 6 occurred in the Saguenay region causing tens of millions of dollars in damage. It was the largest earthquake in eastern North America since 1935. Some damages were observed as far as Montreal, 350 km from the epicenter. In November 1994, an earthquake of magnitude 5.2, centered a few kilometres West of Quebec city, was felt over a wide area of southern Quebec, eastern Ontario and the Northern New England states. Although these events are rare, compared to the seismic activity in Western Canada or in California, their economic and social effects cannot be neglected.

3 Inventory of the buildings in Old Montreal

3.1 Geographical and historical background of Old Montreal

The Old Montreal district is located on the banks of the St-Lawrence River. Its territory covers approximately 0.6 km^2 and includes the old fortified city of the 18th century. Montreal was founded on May 1642 by a group of French settlers on a tip of land that is now part of Old Montreal. From the 17th-century French settlement, Montreal became, in the first half of the 19th century, a residential and business district of the local bourgeoisie. From the 1850s to the 1870s, the city was transformed into an industrialized metropolis. These changes have forged Montreal's architectural and structural evolution. In the former fortifications sector, we find convents, chapels, and private hotels of the 17th and 18th century, headquarters for banks and insurance companies from the industrial revolution as well as huge multipurpose commercial buildings serving as warehouse-salesrooms. In 1964, Old Montreal was declared an historic district.

3.2 Methodology of the inventory

The inventory of the buildings in Old Montreal was realized by a walking survey of the streets, and consultation of documents and structural drawings. Among the different sources of information, the following have been used: evaluation roles of the city, data bank of the City Buildings Service, structural drawings from city archives, government archives and religious congregation archives, and books on the architectural history of Montreal [2, 3, 4].

Eighty-nine buildings, all constructed before 1929, were identified and classified according to their year of construction, structural type, use and number of storeys. For each of the most represented class of buildings, typical buildings were characterized in detail using drawings, pictures and interior inspection when possible. Typological classification is used in many approaches to assess the seismic vulnerability of a group of buildings. Generally defined for the population of buildings under study it is sometimes used at a larger scale. The Canadian typological classification is based on the descriptions given in the report ATC-21 of the Applied Technology Council of California. Therefore, a direct application of this classification to the population of the buildings in Old Montreal could be questionable. Nevertheless, each building was assigned to one of the classes of the Canadian typological classification system and a detailed study of the structural characteristics of a selected number of buildings will allow ascertaining its applicability.

3.3 Results of the inventory

Forty-four percent (44%) of the buildings are unreinforced masonry bearing-walls, 40% are steel frame structures with or without unreinforced masonry infill walls, and the remaining 16% is equally shared between wood and concrete constructions. Sixty-three percent (63%) of the buildings have less than 5 storeys, 30% have 6 to 10 storeys, while 7% have more than 10 storeys.

When regrouped according to their year of construction, three periods of construction can be identified: (i) the pre-industrial period, from 1684 to 1859, with 34% of the buildings, (ii) the industrial period, from 1860 to 1913, during which 54% of the buildings were constructed, and (iii) the beginning of the 20th century, from 1914 to 1929, with 12% of buildings. The relations between the period of construction, the number of storeys, and the type of structures are illustrated in Figures 1 to 3.

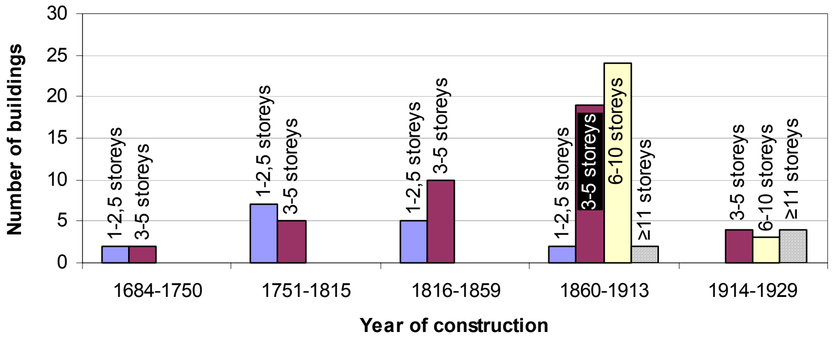

Figure 1: Number of storeys versus year of construction.

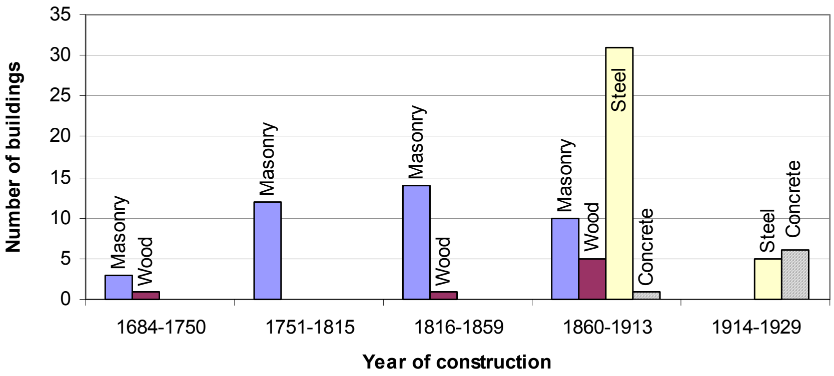

Figure 2: Type of structure versus year of construction.

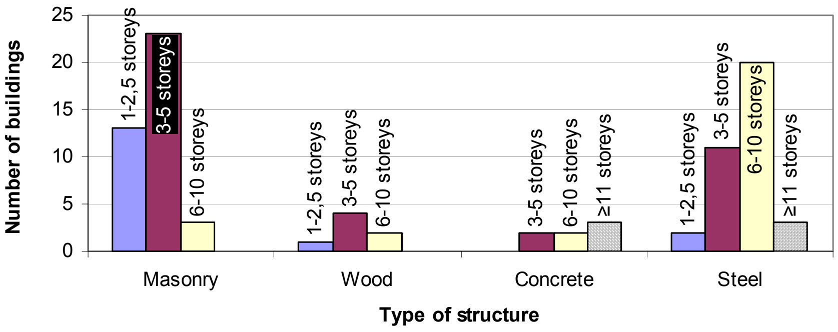

Figure 3: Number of storeys versus type of structure.

Figures 1 and 2 clearly show that the buildings of the pre-industrial period have less than 5 storeys and 29 out of 31 buildings are unreinforced masonry structures. It can be assumed that most of these were constructed according to the rules governing construction during the French Regime and imposing exterior masonry bearing walls, fire protection walls between adjacent buildings and massive wood carpentry for the interior of the structure. The industrial revolution is dominated by the construction of steel structures, most of them with 6 to 10 storeys as shown on Figure 3. Construction of buildings with more than 10 storeys would only be permitted by a municipal regulation in 1924. Structures with over 10 storeys and constructed prior to that date have undergone major modifications in recent years. In Figure 3, it is also possible to observe that a few buildings identified as masonry and wood are 6 to 10 storeys high. These buildings have generally mixed structures with exterior masonry self supporting walls and an interior steel structure. The wood structures are 7-storeys high and are identified as post-and-beam structures.

3.4 Structural characteristics of most common typology

Identification of the structural characteristics allows one to associate to a building a typological class. A closer look to the most common structural types of buildings in the Old Montreal, unreinforced masonry which represents 44% of the building population, shows several differences with the Canadian typological classification such as : (1) the period of construction between 1684 and 1913 compare to 1860-1940, (2) four unreinforced masonry bearing walls composed of rubble stone or ashlar stone, (3) wall thickness up to 1,5 m, (4) adjacent walls are fire protection walls, (5) several chimneys, and (6) narrow openings (windows and doors). Figure 4 shows an exterior picture of a typical URM house constructed before 1860.

Figure 4: Typical URM building.

4 Review of the vulnerability evaluation methods

In most approaches to the evaluation of the seismic vulnerability of a group of buildings, buildings are classified into a few typological classes. Each class is defined as the ensemble of buildings that have some common characteristics, for instance materials, building technology, morphology, age of construction, etc. Thus, these approaches assume that many buildings (each class) have the same vulnerability, described in probabilistic terms. The applicability of the vulnerability functions defined in this manner, to a group of buildings, requires that their characteristics fit the description of the typological class in which they are assigned. Preferably, the typology of the buildings should be defined for each region according to the construction techniques and materials used.

The vulnerability of a building is the evaluation of the damage it will suffer given the earthquake intensity. It is commonly expressed in terms of matrices obtained from observation of damaged buildings in earthquake-struck areas or by simulation using numerical or analytical models of the buildings. Following the San Fernando earthquake of 1971, Whitman et al. [5] developed vulnerability matrices from observations of damage on steel and concrete buildings. In 1992, Coburn and Spence [6] used data from several earthquake damage studies to develop vulnerability functions for different types of buildings with five damage levels. The definition of these relationships between damage and earthquake intensity on the basis of observed vulnerability requires a substantial quantity of data and is, strictly speaking, only valid for the area of the city used in the definition or for regions of similar building populations.

In the absence of data from past earthquakes, vulnerability functions can also be obtained from experts' opinions. In the Applied technology council's report ATC-13 [7] in 1985, damage probability matrices were derived for 78 classes of installations, 36 of which are buildings, based on the opinions of 58 experts. Although, the uncertainties related to the opinions of the experts are a drawback, this approach remained the reference for many earthquake assessment studies until the mid 1990's. The interactive software for risk assessment HAZUS® developed by the National Institute of Building Science in 1997 is also based on expert opinions. It allows to estimate the state of damage that would result from a given spectral displacement and acceleration. Another type of vulnerability function based on observed vulnerability, as well as expert opinion, is the use of the vulnerability of the buildings implied in the macroseismic scales, such as the EMS-98 [8].

The use of analytical models to develop vulnerability functions for the building population concerned is another approach for evaluating the seismic vulnerability of a group of buildings. This approach can be applied to areas where data from past earthquakes is not available. When structural characteristics of typical buildings are well known, it is then possible to analyze a limited number of buildings to obtain representative vulnerability functions that could be applied to a larger population of buildings in an earthquake risk scenarios study. These analyses can use static linear or non-linear procedures (D'Ayala et al. [9] or Lang [10]), the latter having the advantage of considering the non-linear displacement capacity and is applicable to a relatively large number of buildings.

5 Perspectives in the evaluation of the seismic vulnerability of the buildings in Old Montreal

5.1 Vulnerability functions

Considering the notable differences in the typology of the buildings in Old Montreal with the Canadian classification, available fragility curves developed for buildings in United States can not be used. One interesting avenue is the development of adapted vulnerability functions for the structural typologies identified. Vulnerability functions are obtained from the capacity curve of the structure, from a push-over analysis, and the seismic demand. Analytical models considering the most probable failure mode for each pier (section of wall between openings) have been used of the typical URM structures identified in Old Montreal. The resulting bilinear capacity curve is shown on Figure 5 and compared with HAZUS capacity curves for typical URM buildings. Damages levels can then be identified for different spectral acceleration. This procedure can also be applied to other typologies in the objective to obtain a fragility curve of the area in terms of probability of damages according to the spectral acceleration.

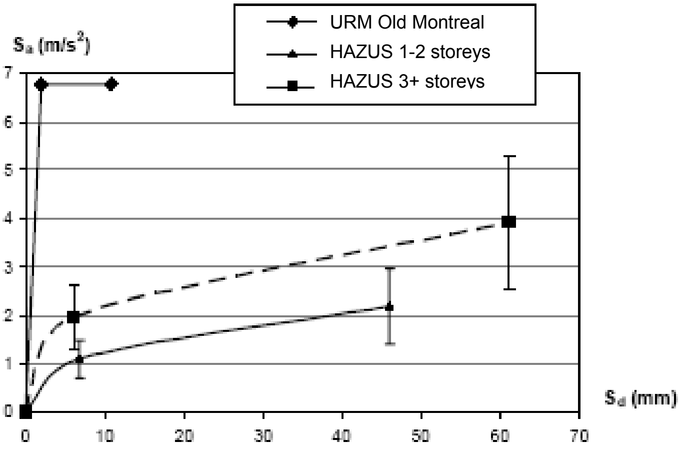

Figure 5: Bilinear capacity curve for the URM buildings in Old Montreal.

5.2 Damage probability matrices

The lack of data on the damages resulting from past earthquake in the region limits the application of methods based on damage probability matrices and intensity scales. However, several DPM have been developed over the years for the American typologies and have been used, with a certain success in Western Canada [11]. In Eastern Canada cities, although most of the building classes can be associated to existing American building class, this is not the case for historic district such as Old Montreal. European typological classification, however, offers several similarities between their unreinforced masonry typologies and the URM structures in Old Montreal as illustrated in Figure 6.

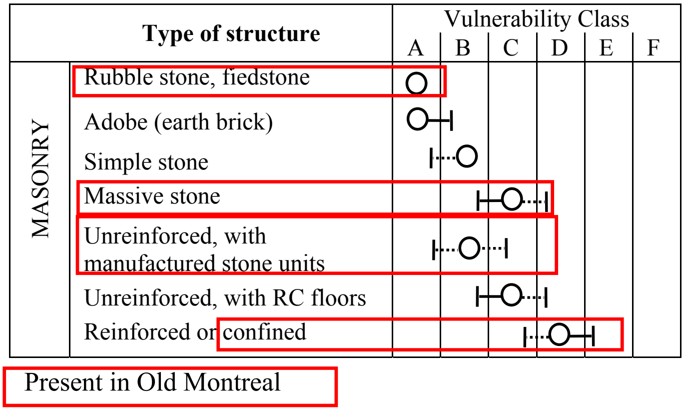

Figure 6: EMS masonry typology.

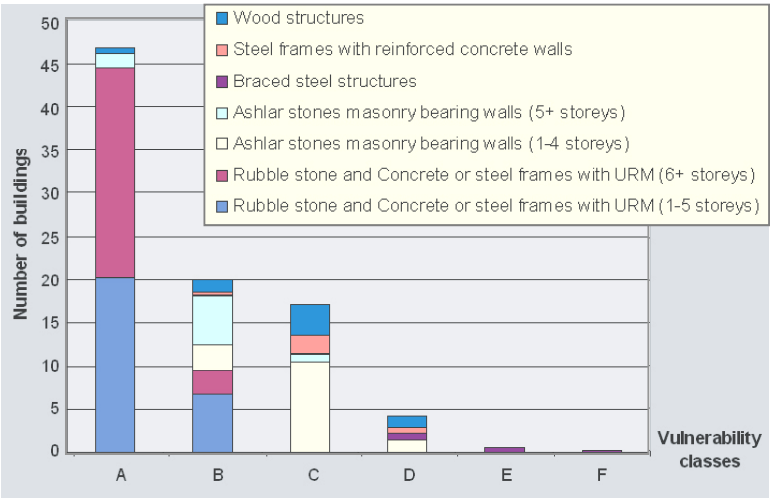

Figure 7: Distribution of buildings among the EMS vulnerability classes.

As an exploratory study, the EMS-98 methodology has been applied to the buildings of the Old Montreal. The vulnerability class has been identified from analytical models of the buildings for different degrees of damage, and the DPM of the EMS-98 have been used to develop fragility curves for the group of buildings. Figure 7 gives the distribution of buildings among the six vulnerability classes of the EMS, whereas Figure 8 shows the fragility curves obtained for the group of buildings studied.

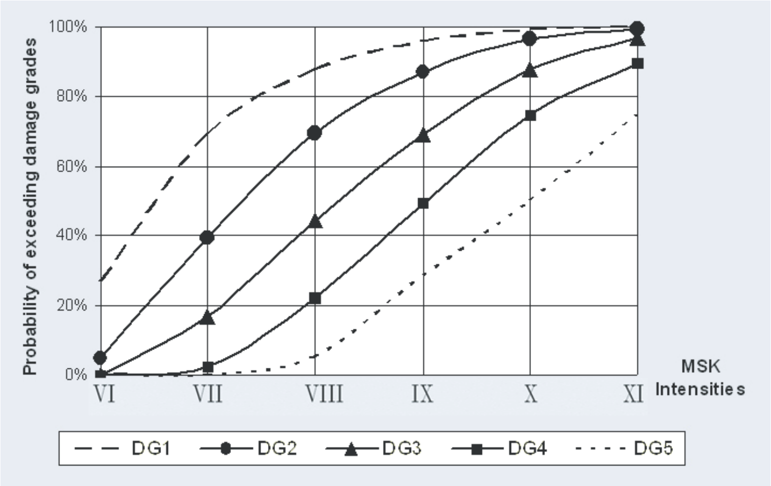

Figure 8: Fragility curves of the 89 buildings of the inventory.

6 Conclusion

The structural inventory of buildings in the historical district of Old Montreal identified the most dominant type of structures as unreinforced masonry bearing walls structures. Notable differences have been observed between the structural characteristics of those buildings and the North American typology. This confirmed the necessity to develop an adapted method of evaluation of the seismic vulnerability for historic areas in Quebec. Considering the absence of data from past earthquake, the most promising approach is the development of vulnerability curves from analytical models adapted to the structural and material characteristics of the structures.

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