13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2907

STRUCTURAL CHARACTERISTICS OF HISTORICAL BUIDLINGS IN OLD MONTREAL

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SUMMARY

This paper presents a review of the typical structural characteristics of a group of buildings in the historic Old Montreal district. First, a review of the existing procedures for the evaluation of the seismic vulnerability of group of buildings based on the European and North American experiences is carried out. In second, a comprehensive inventory of the buildings and their structural characteristics is presented on the basis of the construction period and their typology. The dominant type of structures are the unreinforced masonry bearing walls structures, the moment-resisting frame structures and the mixed structures with masonry self-supporting exterior walls and interior steel or wood framing. A summary of the characteristics of those structures is presented in the paper.

INTRODUCTION

Eastern Canada is located in a stable continental region within the North American Plate, and consequently, has a relatively low rate of earthquake activity. Nevertheless, large and damaging earthquakes have occurred in the past and will inevitably occur in the future. The Charlevoix Seismic Zone, located some 100 km downstream from Quebec City, is the most seismically active region of eastern Canada. This zone has been subjected to five earthquakes of magnitude 6 or larger: in 1663 (Mag. 7); 1791 (Mag. 6); 1860 (Mag. 6); 1870 (Mag. 6 1/2); and 1925 (magnitude MS 6.2 ± 0.3). The Western Quebec Seismic Zone, which encloses the Ottawa Valley from Montreal to Témiscamingue was the site of at least three significant earthquakes in the past. In 1732, an earthquake estimated at 5,8 on the Richter scale shook Montreal, causing significant damage. In 1935, the area of Témiscamingue was shaken by an earthquake of magnitude 6,2, and in 1944, an earthquake of magnitude 5,6 located between Cornwall (Ontario) and Massena, N.Y., caused damage evaluated to two million dollars at the time. Occasionally, the area was also shaken by weaker earthquakes felt by the local population. 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

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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[4].

Although these events are rare, compared to the seismic activity in Western Canada or in California, their economic and social effects cannot be neglected. Reduction of potential damage caused by earthquakes requires relevant remedial measures that can be adequately defined by a damage and loss assessment for different earthquake scenarios. It is, therefore, of interest to define the seismic risk associated to cities such as Montreal and Quebec, both of which are densely populated. The seismic risk is the convolution of the *seismic hazard*, *vulnerability* and *exposure*. This paper focuses on the *vulnerability* of existing buildings in the area of Old Montreal, with specific references to the structural characteristics of these buildings. A comprehensive inventory of the buildings and their structural characteristics is presented. This characterization will serve two objectives. The first, to compare the observed structural characteristics with the descriptive typology of the different classes of buildings used in the seismic evaluation approaches proposed by the Canadian National Research Council [1, 2]. The second objective is to identify the most appropriate method of evaluation of the seismic vulnerability for that population of buildings.

METHODS OF EVALUATION OF THE SEISMIC VULNERABILITY

The vulnerability of a building is the evaluation of the damages it will suffer for different earthquake intensities. It is commonly expressed by functions or 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, observation of damages to steel and concrete buildings was used by Whitman et al. [3] to develop vulnerability matrices. In 1992, Coburn & Spence [4] 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 population.

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 [5] 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 opinion. 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 [6].

In all these approaches, all the buildings are classified into a few typological classes each defined as the ensemble of buildings that have some common characteristic, for instance materials, building technology, morphology, age of construction, etc. Thus, it assumes 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

[4] http://www.seismo.nrcan.gc.ca/

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, Augusti and Ciampoli [7].

Typological classification is also used in score assignment approaches. These generally consist of a rapid screening procedure with the objective to classify the seismic vulnerability of one building among a group of buildings with similar characteristics. The result of the evaluation is an index of performance or a vulnerability index that indicates the necessity for a more detailed structural analysis. In Canada, the rapid screening of potential hazardous buildings procedure is described in the "Manual for Screening of Buildings for Seismic Investigation", IRC-CNRC [1]. The computation of the final "priority index" considers the seismicity, the soil, the type of structure, its irregularities and the dangers associated with non-structural elements. This index is primarily an indication of the deviation from the seismic requirements of 1990, but can constitute a representation of the seismic risk of the building relative to a population of similar buildings. A rapid screening procedure with score assignments is also used in United States. It was initially described in the report ATC-21 [8] and then in the documents FEMA-154 and FEMA-155, [9, 10]. Other examples of score assignment procedures are those developed in Swizerland by the Swiss Federal Office for Water and Geology [11], or in Italy, known as the GNDT[5] method [12]. Although the score assignment approach has the advantage of giving a simple measure of vulnerability to each building in a statistical sense, it should be verified that equal values of the index correspond actually to the same vulnerability from a probabilistic view. The use of score assignment procedures to evaluate the seismic vulnerability of a group of buildings requires including damage probability matrices or functions. This was done by McCormack [13] who used the rapid screening procedure of the ATC-21 along with the damage probability matrices of the ATC-13 to assess the seismic vulnerability of the city of Portland, Oregon.

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. [14] or Lang [15]), the latter having the advantage of considering the non-linear displacement capacity and is applicable to a relatively large number of buildings.

The approach for the evaluation of the seismic vulnerability of the existing buildings in Old Montreal should be adapted to the available data and the structural characteristics of the buildings. It is, therefore, necessary to proceed to a comprehensive inventory of the buildings in this area.

[5] National Group of Defense against Earthquakes

GEOGRAPHICAL AND HISTORICAL BACKGROUND OF OLD MONTREAL

The Old Montreal district is located on the banks of the St-Lawrence River, limited to the north by St-Antoine St., to the east by Berri St. and to the west by McGill St. (See Figure 1). Its territory covers approximately 0,6 km^2 and includes the old fortified city of the 18^{th} century.

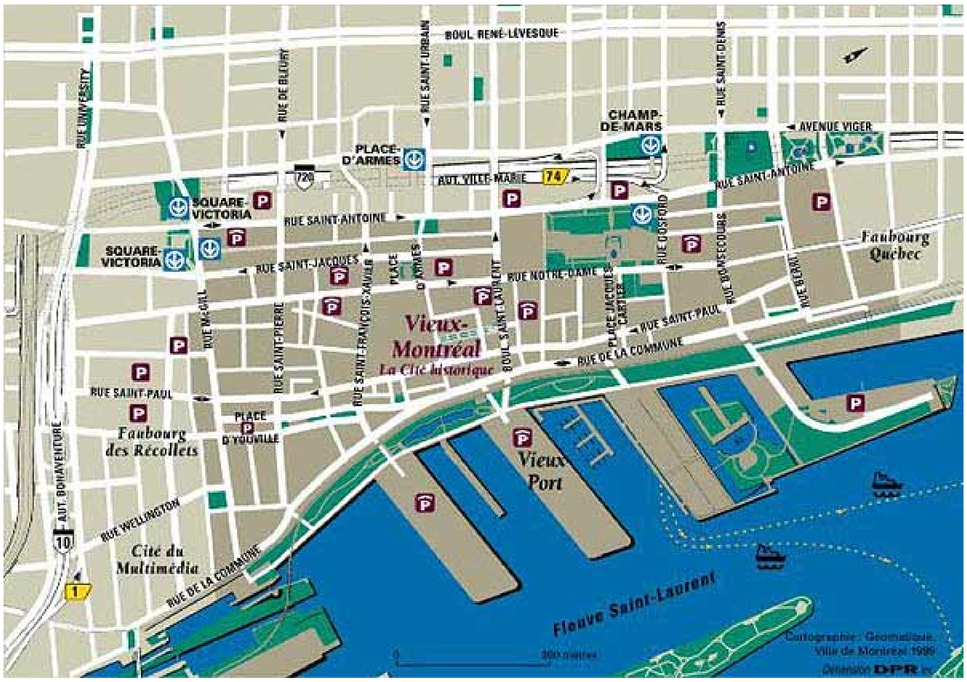


FIGURE 1: Localization of the Old Montreal

Montreal was founded on May 1642 by a group of French settlers on a tip of land that is now part of Old Montreal. This little 17th-century French settlement, initially baptized Ville-Marie, would grow and change quickly forging its architectural and structural evolution. The site of Old Montreal would become a fortified town in the beginning of the 18th century, to protect what resembled a little provincial French town, with convents and chapels, and private hotels. The great fire of 1721 would destroy more than 130 wood buildings leading to new rules governing construction and imposing masonry and light wood roof framing inside the fortified city.

Throughout the whole first half of the 19th century, the old fortified town remained the residential and business district of the local bourgeoisie. The fortifications were demolished in 1801-1817, and Montreal, with its growing "sea port" would be the political and economic hub of Upper and Lower Canada. At the same time, the old city changed shape, and new architectural styles and infrastructures appeared. From the 1850s to the 1870s, the city was transformed into an industrialized metropolis. Great expanses of earlier architecture disappeared as huge multipurpose commercial buildings serving as warehouse-salesrooms sprang up. The industrial revolution brought to Old Montreal the construction of new headquarters for banks and insurance companies, the City Hall, etc…

In 1925, although the economic growth of Montreal would flourish outside the old city center, the latter remained the financial, legal and administrative center of Montreal. After the Second World War, property developers turned their attention to the new downtown, neglecting Old Montreal. In 1964, Old Montreal was declared an historic district.

INVENTORY OF THE BUILDINGS

Methodology

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,
- Web sites of La Société de développement de Montréal [16] and Héritage Montréal [17],
- Books on the architectural history of Montreal by Auger [18], Forget [19], Pinard [20], Lessard [21] and Michaud [22].

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. A summary of these characteristics is given hereafter.

Typological classification

As mentioned previously, 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 typological classification described in the Canadian rapid screening procedure for score assignments 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 select number of buildings will allow ascertaining its applicability. Table 1 gives the 15 types of building classes distributed among four general groups of structures according to their material: wood, steel, concrete and masonry.

Table 1: Typological classification

Type of structure	Description
Wood structures	Light wood frame Wood posts and beams
Steel frame	Light metal buildings Moment-resisting frame Braced steel frame Steel frame with concrete shear walls Steel frame with unreinforced masonry infill walls
Concrete	Concrete moment-resisting frame building Concrete shear-wall building Concrete frame with unreinforced masonry infill walls Precast concrete frame building Tilt-up buildings
Masonry	Reinforced masonry building with wood or metal floor and roof Reinforced masonry building with concrete diaphragm Unreinforced masonry bearing-wall building

Results of the inventory

Results of the inventory are presented in Figures 2 to 5. Figure 2 presents the classification of the buildings according to basic parameters such as the year of construction, the number of storeys, the use and the type of structure. 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. One of the pie charts in Figure 2 also gives the actual use of the buildings with predominance in commercial, offices and services. It should be noted that the uses have changed over the years, often from residential to commercial or from industrial and commercial, as warehouses and stores, to residential and offices.

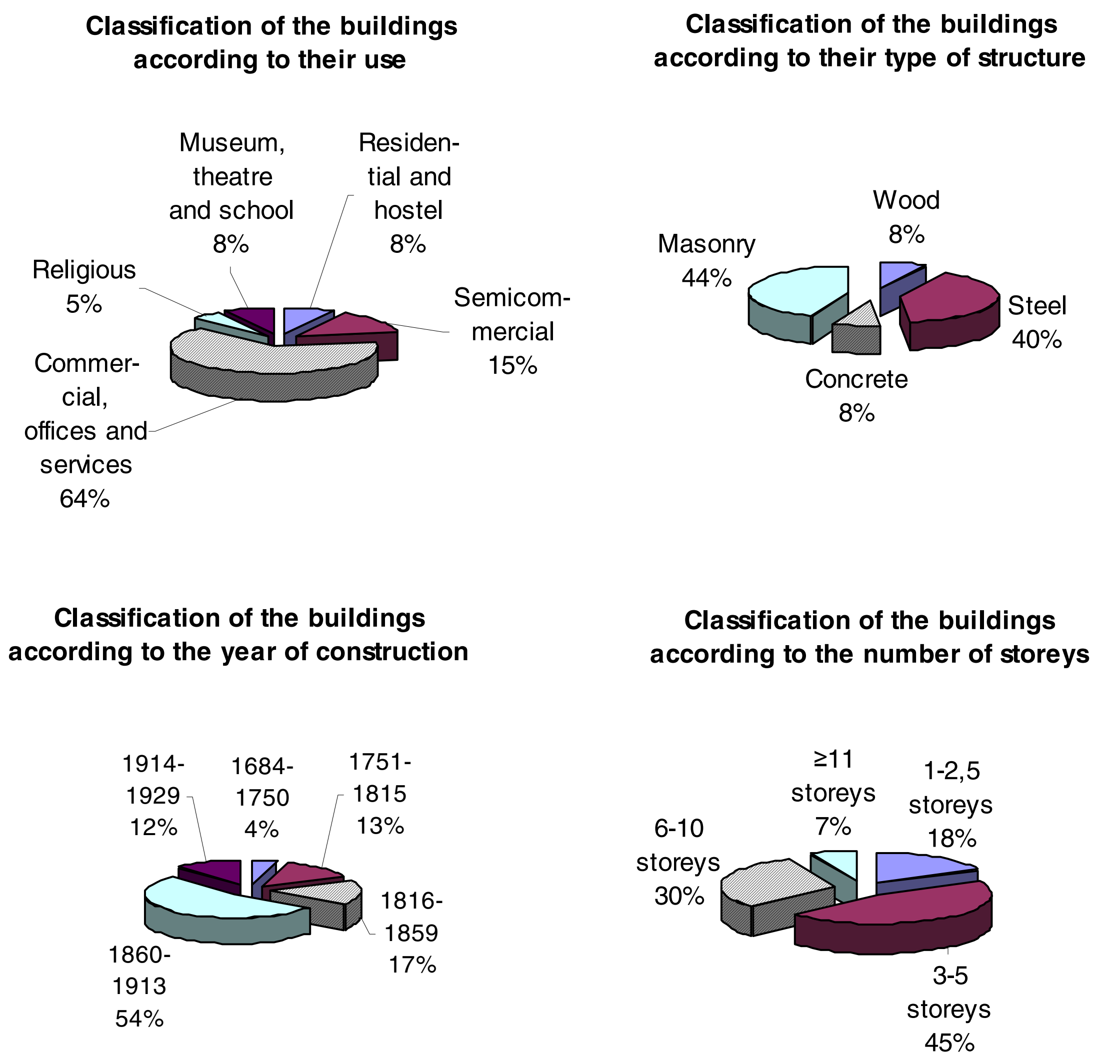


Figure 2: Classification of the buildings according to the use, type of structure, year of construction and number of storeys

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 20^{th} 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 well represented in Figures 3 to 5.

Figure 3: Number of buildings according to the number of storeys and the year of construction

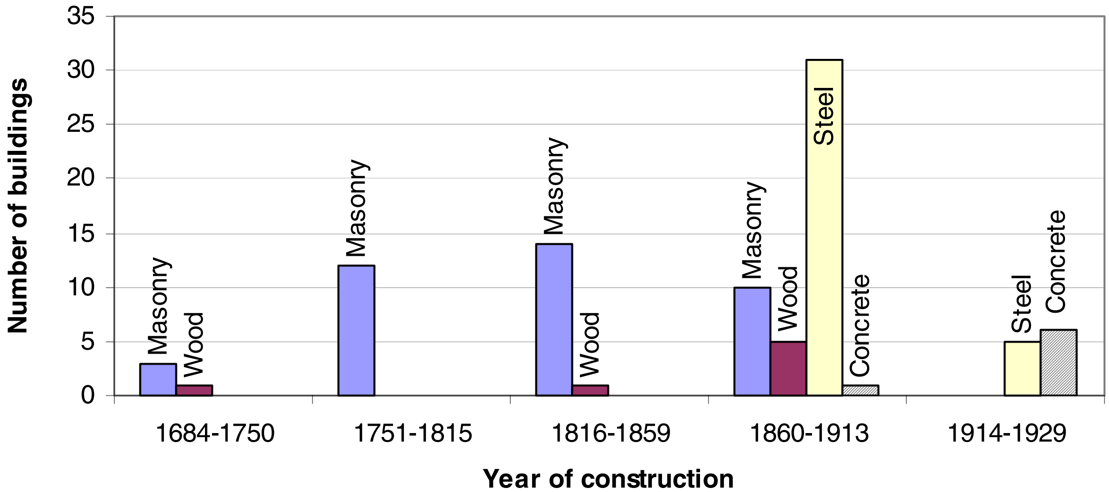


Figure 4: Number of buildings according to the type of structure and the year of construction

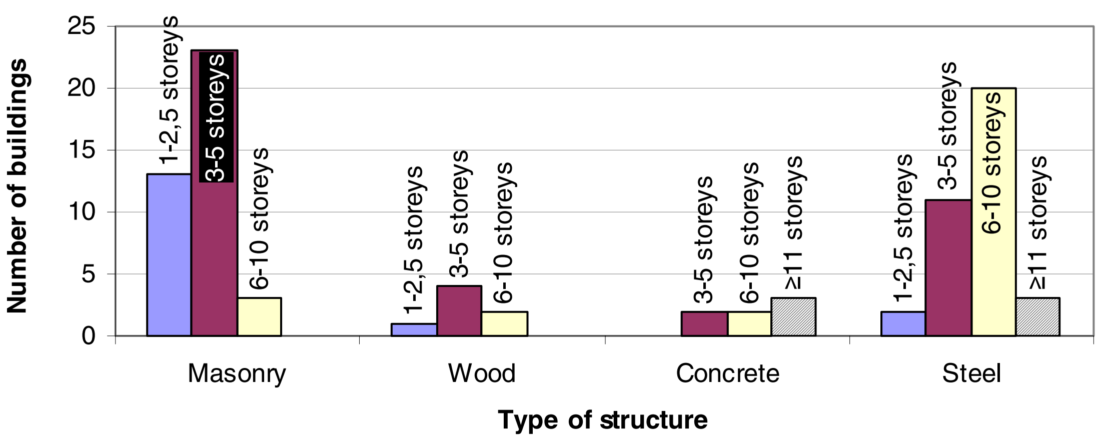
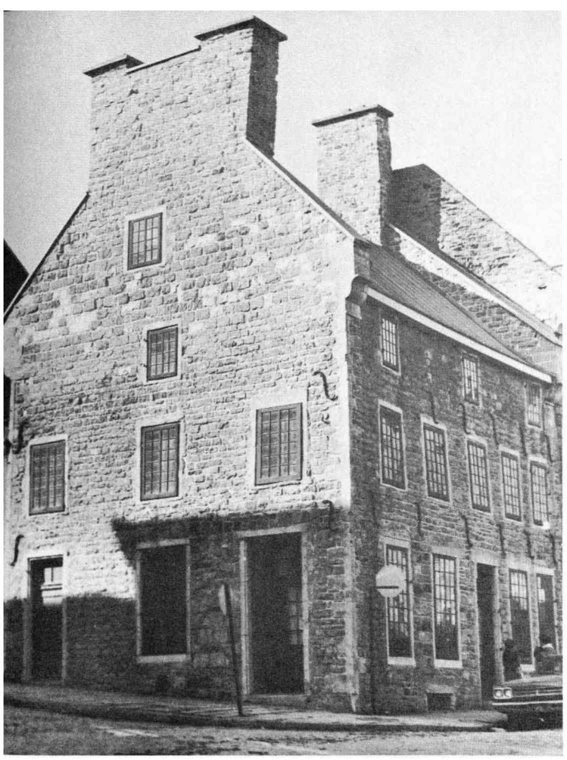


Figure 5: Number of buildings according to the number of storeys and the type of structure

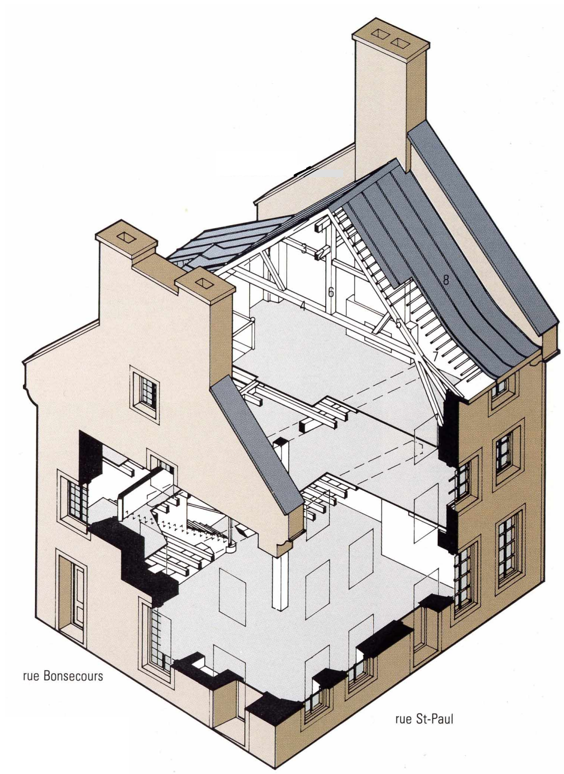
Figures 3 and 4 clearly show that the buildings of the pre-industrial period have less than 5 storeys and 29 out of 31 buildings are unreinforced masonry structures. It can be assumed that most of these were constructed according to the rules governing construction during the French Regime and imposing 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 5. 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 5, 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 a mixed structure 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.

EXAMPLES OF STRUCTURAL CHARACTERISTICS

Among the dominant type of structures 44% were identified as unreinforced masonry. The Maison du Calvet, constructed in 1770 on St-Paul Street is an example. Figures 6a and 6b show an exterior picture of the house and an artistic view of the interior, respectively. The typical characteristics are four unreinforced masonry bearing walls, with one protection fire wall. Several chimneys can be observed in the side walls, an illustration of the adaptation to the climatic conditions of the region. The number of openings in the bearing masonry walls, on the façade and on the side wall is typical. The roof is a wood truss supported on the façade walls with straight wood sheathing and a metal covering. The floor span system is composed of joists and beams supported in part by the side walls and by a wood posts. The beams are integrated in the masonry walls with steel rods anchored on the façade by decorative elements. This detail is sometimes replaced by a simple pin or completely absent.



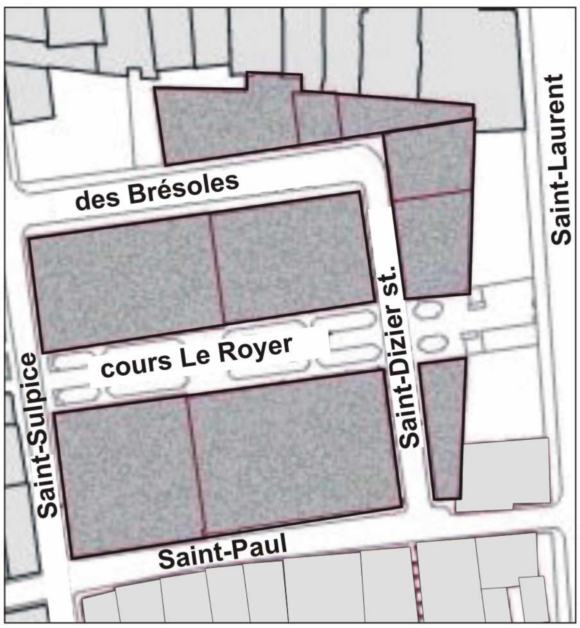
(a) Outside view from Lessard [16]



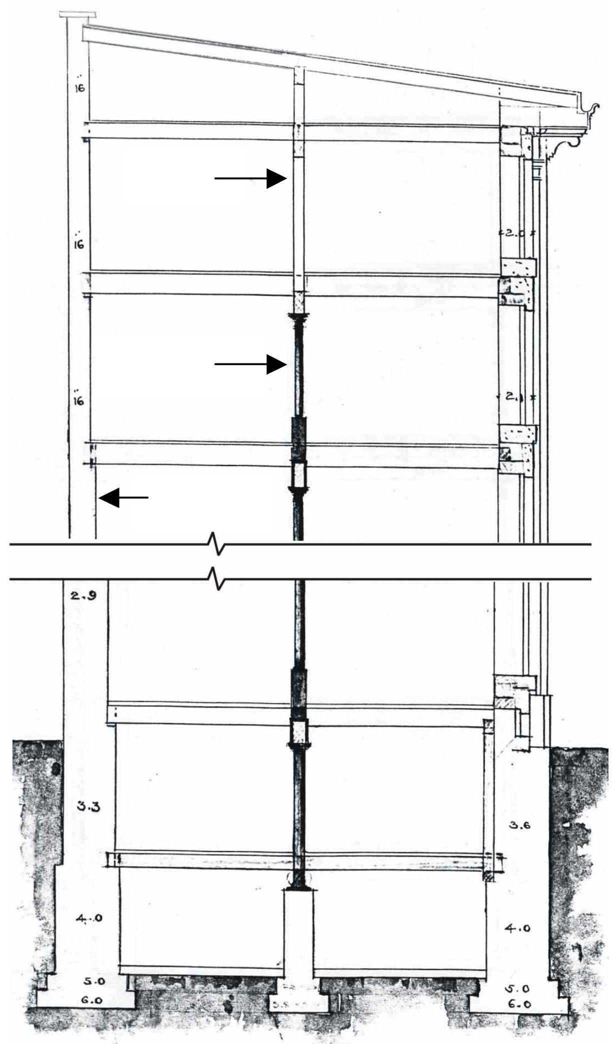
(b) Isometric view from Michaud [17]

Figure 6: La Maison du Calvet

Among the buildings constructed between 1860 and 1913, two types are dominant: steel moment-resisting frame structures of 6 to 10 storeys and mixed structures with masonry self-supporting exterior walls and interior steel or wood framing. Several warehouses and stores constructed by religious communities for commercial rental purposes are of this second category. One example is the five warehouses of Les Dames de l'Hôtel-Dieu (Figure 7a). These buildings of 5 to 7 storeys have a light wood truss roof system and a floor system composed of wood joists and beams. Almost all the loads of the roof and floors are carried by wood posts (12 in. × 12 in.) on the superior floors and by steel or cast iron columns on the lower floors, as illustrated by the example of Figure 7b. In one case all five floors have cast iron columns. The side walls are masonry self-supporting walls with, surprisingly, almost as many openings as the façade walls. Protection fire walls made of brick masonry are included in one direction to separate apartments.



(a) Localization of the warehouses



(b) Cross section from Mesnard [23]

Figure 7: Warehouses of Les Dames de l'Hôtel-Dieu

DISCUSSION

Among the interesting characteristics observed from this inventory is the significant number of unreinforced masonry bearing wall structures. Masonry structures are generally qualified among the most vulnerable types of structures. However, this vulnerability can vary significantly depending on the construction details. This condition is recognized by the European typological classification system by assigning to unreinforced masonry structures three ranges of vulnerability classes among a possibility of six. This variability in the vulnerability of the unreinforced masonry buildings is not reflected in the Canadian typological classification system. Other observations also deserve to be noted. The presence of protection fire walls between adjacent buildings indicates a coupling in the behavior of the structures, which needs to be addressed in the case of simplified or detailed analyses. The chimneys in these walls, as well as the numerous openings in the walls, contribute to the vulnerability of the buildings.

In general, the buildings of the industrial period can be easily assigned one of the typological classes of Table 1. However, the details of the mixed structures described earlier, such as the cast-iron posts with wood floor systems, the number of openings in the self-supporting walls, and the interior masonry walls used with wood structures make the typological classification of the buildings a complicated task.

CONCLUSIONS

A inventory of the buildings in Old Montreal was performed to bring forth their structural characteristics in view of selecting the most suitable method for evaluating of their seismic vulnerability. The dominant type of structures are the unreinforced masonry bearing walls structures, the moment-resisting frame structures and the mixed structures with masonry self-supporting exterior walls and interior steel or wood framing. The different types of structures observed imply significant variability in the vulnerability functions to be defined for the buildings. The typical characteristics outlined will further lead to the analysis of simplified models for the definitions of the buildings' vulnerability functions.

ACKNOWLEDGEMENTS

The authors wish to record their appreciation of the financial support for the research leading to this paper, by NSERC, the Natural Sciences and Engineering Research Council of Canada and by the École de technologie supérieure. They also wish to thank the City of Montreal and Les Soeurs Hospitalières de St-Joseph for giving them access to their data banks and their archives, respectively.

REFERENCES

1. IRC-CNRC. "Manuel de sélection des bâtiments en vue de leur évaluation sismique." Ottawa : Institut de recherche en construction - Conseil national de recherches du Canada, 1992.
2. IRC-CNRC. "Lignes directrices pour l'évaluation sismique des bâtiments existants." Ottawa : Institut de recherche en construction - Conseil national de recherches du Canada, 1992.
3. Whitman, R.V., J.W. Reed, and S.-T. Hong. "Earthquake damage probability matrices." Proceedings of the 5th World Conference on Earthquake Engineering, Rome, Italy. 1974: 2531-2540.
4. Coburn, A. and Spence, R. "Earthquake protection." 2nd Edition, Chichester: John Wiley & Sons, 2002.
5. ATC - Applied Technology Council. "ATC-13: Earthquake Damage Evaluation Data for California." Applied Technology Council: Redwood City, California, 1985.

6. Grünthal, G., Musson, R.M.W., Schwarz, J. and Stucchi, M. "European Macroseismic Scale 1998 (EMS-98)." Cahiers du Centre Européen de Géodynamique et de Séismologie. Luxembourg, 1998.
7. Augusti, G. and M. Ciampoli. "Heritage buildings and seismic reliability." Progress in Structural Engineering and Materials, 2000; 2: 225-237.
8. ATC - Applied Technology Council. "ATC-21: Rapid Visual Screening of Buildings for Potential Seismic Hazards". U.S. Federal Emergency Management Agency, 1988.
9. BSSC. "FEMA 154: 2nd Edition, Rapid Visual Screening of Buildings for Potential Seismic Hazards: a Handbook". developed by the Buildings Seismic Safety Council for the U.S. Federal Emergency Management Agency (report No. FEMA 154): Washington D.C., 2002.
10. BSSC. "FEMA 155: 2nd Edition, Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation." developed by the U.S. Buildings Seismic Safety Council for the Federal Emergency Management Agency (report No. FEMA 155): Washington D.C. 2002.
11. OFEG. "Appréciation de la sécurité parasismique des bâtiments existants – Principes et directives régissant la première phase." Office fédéral des eaux et de la géologie - Centrale de coordination pour la mitigation des séismes : Bienne, Suisse, 2003.
12. GNDT. "Rilevamento della vulnerabilita sismica degli edifici." Gruppo Nazionale per la Difensa dai Terremoti: Italy:2002.
13. McCormack, T.C. and F.N. Rad. "An Earthquake Loss Estimation Methodology for Buildings Based on ATC-13 and ATC-21." Earthquake Spectra 1997;13(4): 605-621.
14. D'Ayala, D., et al. "Earthquake loss estimation for Europe's historic town centres". Earthquake Spectra 1997. 13(4): 773-792.
15. Lang, K. "Seismic vulnerability of existing buildings." Ph.D. Thesis, Institute of Structural Engineering, Swiss Federal Institute of Technology (ÉPFZ): Zurich, 2002.
16. Société de développement de Montréal. "Website of Old Montreal." http://www.vieux.montreal.qc.ca/, 2002. (Consulted on September 2003).
17. Héritage Montréal. "Heritage Montreal." http://www.heritagemontreal.qc.ca/, 2002. (Consulted on September 2003).
18. Auger, J. "Mémoire de bâtisseurs du Québec : répertoire illustré de systèmes de construction du 18e siècle à nos jours." Montréal : Éditions du Méridien, 1998.
19. Forget, M. "Les gratte-ciel de Montréal." Montréal: Éditions du Méridien,1990.
20. Pinard, G. "Montréal, son histoire, son architecture." 6 tomes. Montréal: Éditions La Presse et du Méridien, 1987-1991.
21. Lessard, M. and Marquis, H. "Encyclopédie de la maison québécoise, 3 siècles d'habitations." Montréal: Éditions de l'Homme, 1972.
22. Michaud, J. "Vieux Montréal, Cité résidentielle." Montréal: Ville de Montréal et Ministère des Affaires culturelles du Québec, 1983.
23. Mesnard, A., "Plans des magasins sur la rue St-Dizier – section transversale". Montréal: Archives of Les Religieuses Hospitalières de Saint-Joseph, 1873.