SEISMIC RISK ASSESSMENT OF UNREINFORCED MASONRY BUILDINGS IN QUÉBEC

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ABSTRACT

During the 1988 magnitude 5.9 (M_w) Saguenay Earthquake, most of the damages were observed to unreinforced masonry structures even in Québec City and Montréal, located more than 340 km from the epicenter. Recent earthquakes, such as the Canterbury earthquake, have emphasized the need for pre-disaster seismic risk assessment of existing unreinforced masonry. This paper presents a review of observed typical damages to unreinforced masonry from past earthquakes in the province of Québec and an inventory and structural characterisation of existing typical unreinforced stone masonry structures. This characterisation was used to develop fragility functions for typical stone masonry buildings for quantitative assessment of earthquake risk at regional scale. It also presents the results of the seismic vulnerability assessment of 1220 buildings, mainly pre-code unreinforced brick and stone masonry, in Old Québec City, a UNESCO heritage city. Results for a scenario event of magnitude 6.2 at distance 15 km (M6.2R15) indicate that approximately 39% of the stone masonry buildings and 33% of the brick masonry buildings would suffer various levels of damage.

KEYWORDS: unreinforced masonry, stone, seismic risk, uncertainties.

INTRODUCTION

The seismic hazard in the province of Québec is generally defined as moderate with the exception of the high seismicity Charlevoix region. Although large urban centres like Montréal and Québec City are faced with moderate earthquake hazard, the global seismic risk is increased in the older sectors characterized by an important concentration of buildings constructed prior to the introduction of seismic design prescriptions. Unreinforced masonry buildings represent a significant portion among those pre-code constructions [1, 2]. Many historic buildings in the Old Québec City and Old Montréal are made of stone masonry and represent immeasurable architectural and cultural heritage. Built to resist gravity loads only, these buildings generally offer poor resistance to lateral seismic loads. Damage to stone masonry buildings from past earthquakes can be attributed to: (i) inadequate structural integrity due to the lack of connection between stone masonry structural walls and wooden floors and roofs, and (ii) inadequate structural resistance which results in typical shear cracking and disintegration of stone walls and their partial or total collapse [3]. The high seismic risk related to stone masonry buildings is even more aggravated due to their location in densely populated urban centers in a way that the consequences of failure of these structures tend to be severe with regards to human casualties, heritage damage and economic losses [4].

This paper presents a summary of observed damages to unreinforced masonry structures in the province of Québec and a description of the architectural and structural characteristics of masonry buildings with a focus on stone masonry. This information was used to develop fragility functions for stone masonry buildings in Old Québec City with a view to assessing potential earthquake damages to buildings in this UNESCO heritage city for different scenario events. The present study is part of the joint research project between the ETS Montréal and Natural Resources Canada on the development and implementation of tools for quantitative assessment of earthquake risk at regional scale.

PAST DAMAGES TO MASONRY STRUCTURES IN QUÉBEC

Damage to masonry structures in Québec should be analysed considering the historical seismicity and the evolution of masonry construction in the province. The largest reported earthquake is the 1663 Charlevoix-Kamouraska with an estimated magnitude of 7. More recent earthquake events with magnitudes ranging between 5.0 and 6.5 have also caused damage to structures. Table 1 presents a summary of the most significant earthquakes and reported damages to unreinforced masonry structures between 1663 and 2010 in the province [5, 6, 7, **Error! Reference source not found.**8].

Table 1: Reported damages to unreinforced masonry structures in the province of Québec

Year	Magnitude M_w (*Estimate)	Region	Reported damages to unreinforced masonry structures and elements
1663	7*	Charlevoix-Kamouraska	Non structural damages to churches / Collapse of chimneys
1732	5.8*	Montréal	Bending of bell towers / Light damages to houses / Failure of chimneys
1791	6*	Charlevoix-Kamouraska	Damages to 3 churches
1860	6*		Failure of one bell tower and wall cracking
1870	6.5*		Severe damages to 2 churches : Collapse of portal and part of the vault, cracking of walls
1925	6.2		Collapse of one church (out of plane failure of lateral walls and roof collapse) / Severe damages to 2 churches : Falling of blocks of bell tower, out of plane failure of unreinforced walls, shear cracking, / Collapse of chimneys / Severe damages to masonry houses
1935	6.1	Témiscamingue	Damages to 80% of chimneys and masonry walls
1988	5.9	Saguenay	In plane shear failure of unreinforced masonry walls an infill and cracking at opening corners / Out of plane failure of unattached partition walls and masonry claddings / Damage to churches (out of plane failure of facade) / Cracking of foundation masonry blocks / Damage to chimneys
2010	5.0	Val des Bois	Damages to chimneys and out of plane failure of a church gable

The most important damages were observed in the Charlevoix-Kamouraska region which experienced several significant earthquakes between 1791 and 1925. Damages due to the 1988 magnitude 5.9 Saguenay earthquake were thoroughly reported and studied [6, 7, 9]. Damages to unreinforced masonry were observed from near the epicenter to as far as Montréal Nord, 350 km away. Overall, earthquakes in the province of Québec have caused damages to unreinforced masonry walls, chimneys and churches (out of plane failure of facades, side walls or gables and damage to bell towers). The relatively often observed seismic risk related to churches, mainly stone masonry constructions, is due to their ubiquitous presence: there are churches in every town and Montréal itself is named "La ville aux cent clochers", the city with one hundred bell towers! Chimney is also a very common component of buildings that suffers damage. It should be noted that following the major fires of 1682 and 1720 in Québec and Montréal respectively, the Intendant Dupuy of New France declared illegal any wood construction inside city walls (Ordonnance Dupuy of 1727). As the residential stone masonry constructions inside cities did not started before 1730th, chimneys were the only masonry element that could be potentially damaged by an earthquake, as observed during the 1663 and 1730 earthquakes.

Fortunately, to this day no earthquake has ever caused significant damage in a large urban center. However, the seismic hazard combined with the vulnerability of unreinforced masonry structures to earthquakes makes the seismic risk an indisputable reality not to be ignored. The first necessary step in developing seismic retrofitting and preparation of pre-disaster mitigation plans for urban centers is seismic risk assessment of the existing assets including unreinforced masonry buildings.

ARCHITECTURAL AND STRUCTURAL CHARACTERISATION

With a view to studying the seismic vulnerability of typical unreinforced masonry buildings in Québec, architectural and structural characterisation has been performed for the 19th century industrial brick buildings, pre-1960 reinforced concrete frames with unreinforced masonry infill, stone masonry churches, and stone masonry residential buildings in Old Montréal and in Old Québec sectors [1, 2, 10, 11].

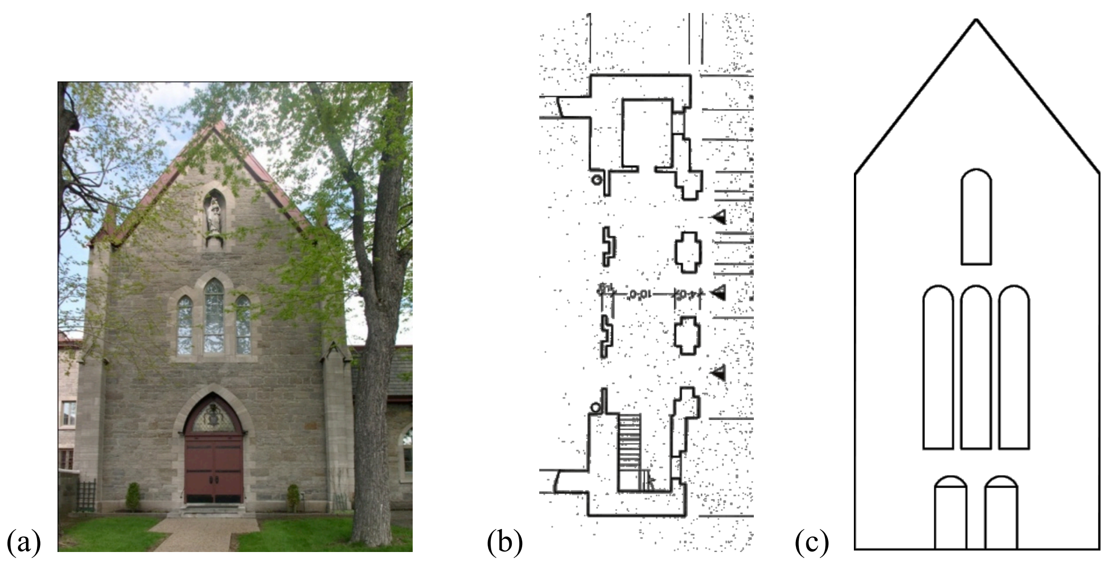

Figure 1: Baillargé church: a) Single aisle; b) Floor plan of the facade; c) Facade typology

Among the inventoried 2750 religious buildings in Québec, 714 are stone masonry built before 1945 and 108 are located on the Montréal Island. Exterior walls are made of stone, interior structure is build of wood or steel, whereas bell towers could be either in wood or in masonry. The seismic vulnerability of these buildings can be evaluated by considering their main components as independent: the facades, the side walls and the bell tower. This approach by macro-elements is valid for relatively simple architecture [12]. This is the case for most Québec churches that could be described by one of the five following architectural types: des Récollets (before 1760), Baillargé (1790-1820), Conefroy (from 1800), Néo-roman (1880-1930) and “Façade Porche” with a bell tower in facade (1890-1950). Each of these architectural types has typical facade geometry, floor plan and its masonry quality is related to the period of construction. Figure 1 illustrates a typical Baillargé church with a single aisle, and shows the floor plan and geometry of its facade. A study of the macro-elements facade and bell tower has shown that the Baillargé type is the most vulnerable to seismic shaking [11]. This is due mostly to the slenderness of its facade, while the potential damage to bell tower is highly related to the frequency content of the earthquake.

Residential and commercial stone masonry buildings constitute an important part of Old Montréal and Old Québec building inventories. In Old Montréal, unreinforced masonry buildings are estimated to represent 44% of the building stock, while this ratio goes up to 76% in Old Québec (with 14% of stone masonry) (see Figure 6). A detailed inventory of over 16 412 buildings in downtown Québec City indicates that more than 27% of the buildings built before 1950 are made of unreinforced masonry (brick or stone) [13]. Besides field survey, the inventory consisted in reviewing architectural reports and theses, historic documents [14, 15] and archives (www.banq.qc.ca). The configuration of the stone masonry buildings has gradually evolved since the beginning of the colony. The three dominant types of stone masonry buildings shown in Figure 2 have been selected among the typologies reported by Vallières [14] and were used as structural prototypes for the remaining part of the study.

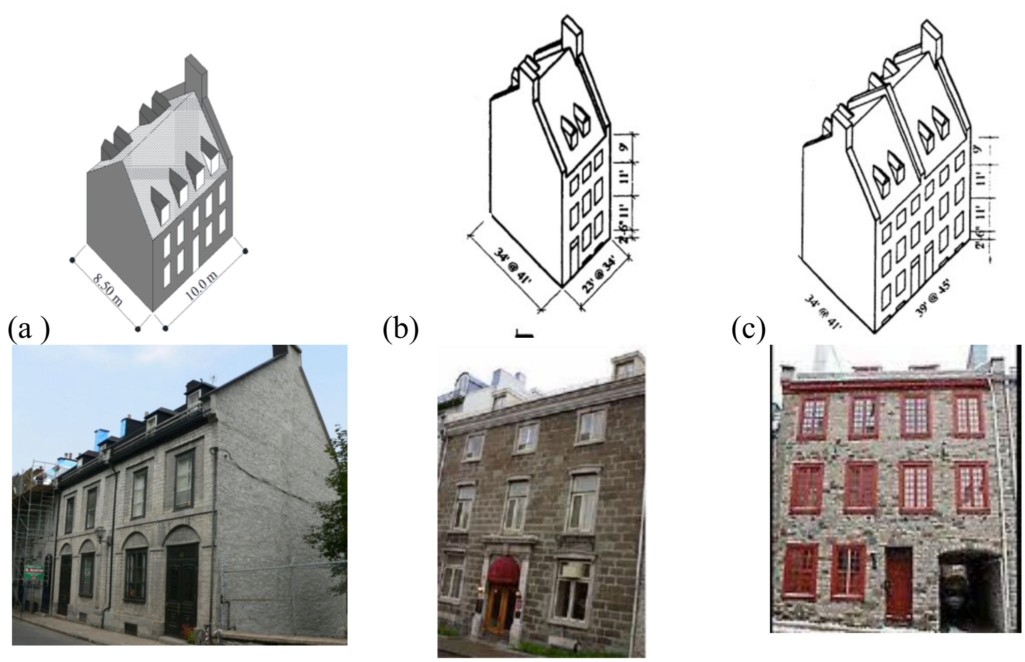

Figure 2: Typical stone masonry buildings: a) 1760-1800; b) 1800-1830; c) 1830-1850

These building types were constructed during the 18th and mid-19th century. The façade walls are relatively thick, ranging from 0.4 to 0.6m, sometimes up to 1.5m at the base, and have regular narrow window and door openings on both sides of the building. One to three storeys high, their typical storey height ranges from 2.75m to 3.35m. Lateral fire walls were also constructed with the same thickness as the façade walls. The typical floor is made of wood resting on the façade walls with a light roof frame. The buildings' lateral resistance is provided by the thick perimeter walls (façade and fire walls) in both directions. Masonry is made of limestone or sandstone with lime mortar. Unfortunately, no information related to stone masonry material properties specific to Québec City buildings have been found in the literature so far.

DAMAGE ASSESSMENT OF STONE MASONRY IN OLD QUÉBEC CITY

In order to assess probable damages for stone masonry buildings shown in Figure 2, hazard compatible seismic fragility functions were developed from analytical methods. A seismic fragility curve defines the probability of physical damage, or damage state *DSi* (e.g. *DS1*: slight, *DS2*: moderate, *DS3*: extensive or *DS4*: complete) in terms of a given seismic intensity measure, IM. The main components of the fragility analysis procedure are the capacity curves and the displacement based fragility curves.

Capacity curves describe the nonlinear structural behaviour as a relationship between top displacement and lateral load capacity. The capacity curves for stone masonry buildings were previously developed from series of analyses on an equivalent single degree of freedom system (ESDOF) for 1, 2 and 3 storeys buildings [2]. Five values of shear strength (f_t) were considered: (i) 0.30MPa, (ii) 0.18MPa, (iii) 0.12MPa, (iv) 0.06MPa, (v) 0.03MPa. Figure 3 shows the resulting capacity curves for the 2 storeys building prototype along with the capacity curves developed for simple stone masonry building implemented in the European Earthquake Loss Estimation Routine (ELER) [16] and for pre-code unreinforced brick masonry typology in Hazus, the well known loss estimation methodology developed by US Federal Emergency Management Agency (FEMA) [17]. Note that these curves cannot be directly compared because of the different assumptions in material or geometrical characteristics, information and tools that were used in the development process. This fact emphasises the need of critical use of the existing risk assessment tools and obtained results.

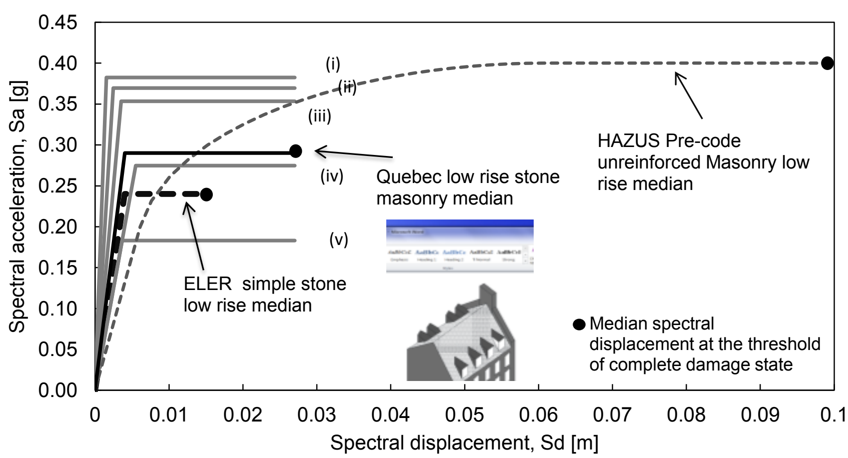

Figure 3: Capacity curves for typical 2 storeys buildings

The probabilistic displacement based fragility curves were developed based on inter-storey drift ratios at the threshold of each damage state from experimental data of stone masonry walls under cyclic loading [18]. These drift threshold values were then converted to spectral displacement for an ESDOF model of the building. Figure 4a presents the fragility functions for the 2-storeys stone masonry building. They represent lognormal cumulative probability distributions for different damage states *DSi* in terms of spectral displacement S_d. To illustrate the application of these curves, damage state probabilities were obtained for a spectral displacement demand S_d = 0.01m as shown in Figure 4a. For the given spectral displacement demand, discrete damage state probabilities were evaluated as the difference of the cumulative probabilities of reaching or exceeding successive damage states. The computed final damage state probabilities are shown in Figure 4b and compared to the respective damage probabilities obtained applying displacement fragility curves defined in Hazus and ELER.

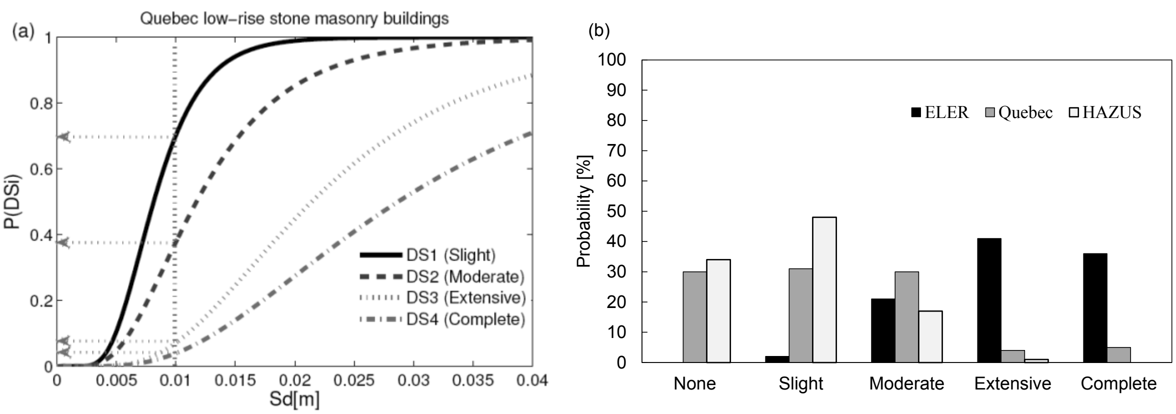

Figure 4: Damage state probabilities: (a) Fragility curves for 2 storeys stone masonry buildings, (b) Damage distributions.

Damage estimates indicate that slight to moderate damage will be the most probable damage to stone masonry buildings. Slight damage is defined as drift threshold corresponding to first flexural cracking of the ESDOF model of the building. As expected, Hazus shows highest probability of no to slight damage due to the higher deformation capacity assumed for brick masonry, whereas the highest probabilities of extensive and complete damage are predicted with ELER due to the assumed lower deformation capacity.

SEISMIC RISK ASSESSMENT OF BUILDINGS IN OLD QUÉBEC CITY

To perform a seismic risk assessment study of buildings in Old Québec City seismic hazard compatible fragility functions were developed in terms of spectral acceleration S_a*(0.3sec, 5%)*, a structure-independent seismic IM. The capacity and displacement fragility curves are convolved with response spectra scaled at increasing levels of seismic intensity as illustrated in Figure 5.

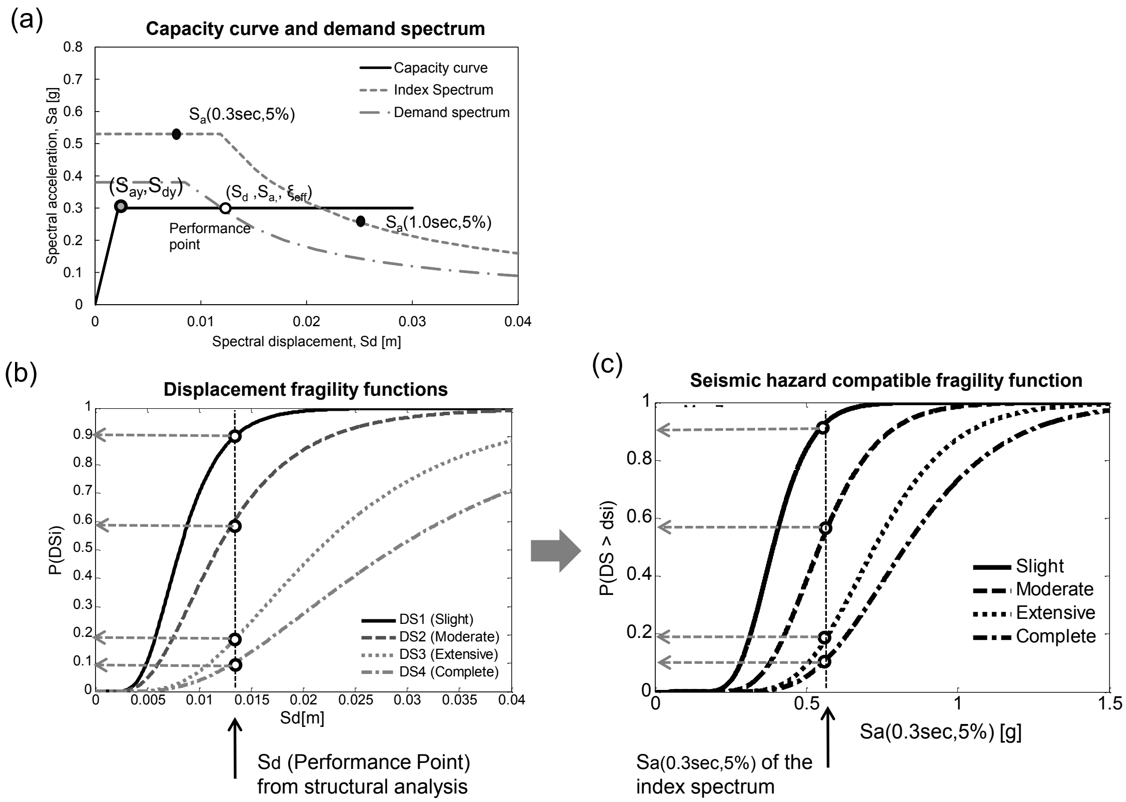

Figure 5: Fragility analysis of Québec stone masonry buildings: (a) Capacity curve and demand spectrum; (b) Estimation of the probability of damage states from displacement fragility functions; (c) Conversion of the fragility functions against spectral acceleration.

This approach uses idealized response spectra defined by IM, $S_a(0.3sec)$ and $S_a(1.0sec)$, using ground motion prediction equation representative for the seismic settings in Eastern Canada [19]. The structural analysis is conducted in the spectral acceleration vs. spectral displacement (S_a-S_d) domain. The response is evaluated using the widely used nonlinear static procedure capacity spectrum method (CSM) (Figure 5a). In the CSM, the performance point (S_d, S_a, ξ_{eff}) is obtained based on the assumption that the nonlinear response of the system can be modelled as a linear ESDOF with increased period and effective damping, both related to the ductility demand. The probability of damage states, for a given building type and considered magnitude-distance scenario, is determined from the performance point into the set of previously developed displacement based fragility curves (Figure 5b). The obtained probabilities are then ranked with respect to the corresponding IM (indicated with hollow dots in Figure 5c). To establish a complete set of fragility functions in terms of the seismic IMs, the procedure is repeated for gradually increasing intensity levels, i.e., increasing demand spectra. The reader is referred to [20] for more details.

The above procedure was used to conduct a rapid risk assessment of some 1220 existing buildings in the Old Québec City, mainly pre-code unreinforced brick and stone masonry. The distribution of the potential damage was evaluated for a scenario M6.2R15 event which roughly corresponds to a probability of exceedance of 2% in 50 years. Table 2 gives the result of the inventoried buildings classified according to: (1) construction material; (2) structural system; (3)

seismic design code level (pre-code for building not seismically designed and mid-code for buildings designed according to moderate seismic provisions); (4) height. The inventory analysis reveals that the dominant building types are the pre-code unreinforced brick masonry (62%) and stone masonry buildings (14%) as shown in Figure 6. Moreover, 70% of the existing buildings were built before the introduction of seismic provisions in building codes (before 1950), while 91% were built before 1970 considered as a reference year in terms of seismic code requirements.

Table 2: Old Québec city building inventory

Building type	Height	Number of buildings	Code level	
			Pre-code (before 1970)	Mid-code (after 1970)
W1L (wood light frame)	Low-rise	131	86	45
S1L (Steel Moment Frame)	Low-rise	32	20	12
S1M (Steel Moment Frame)	Mid-rise	12	12	-
S2L (Steel braced frames)	Low-rise	30	14	16
S2M (Steel braced frames)	Mid-rise	24	24	-
S5L (Steel frames with URM infill)	Low-rise	33	33	-
C1L (Concrete moment frame)	Mid-rise	25	0	25
URMBL (Unreinforced Brick masonry)	Low-rise	469	469	-
URMBM (Unreinforced Brick masonry)	Mid-rise	296	296	-
URMSL (Unreinforced stone masonry)	Low-rise	168	168	-
Total number		1220	1122	98

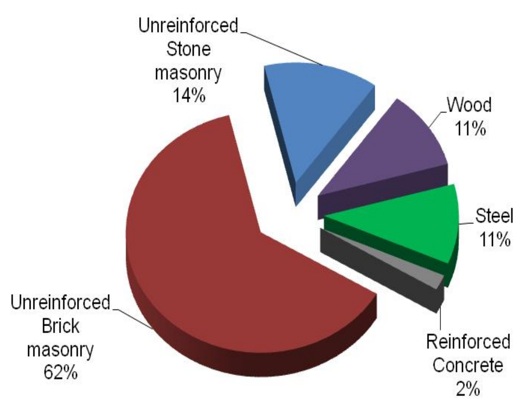

Figure 6: Buildings distribution according to construction material.

Due to similar construction practices in Canada and in the United States, capacity curves and displacement based fragility functions reported in the Hazus technical manual [17] were used for the vulnerability modeling for the building types listed in Table 2. For stone masonry buildings, which are not explicitly considered by Hazus, the applied capacity curves and fragility functions were generated in the present study. Figure 7 shows an example of the fragility functions for low-rise stone and brick masonry buildings, respectively. These fragility functions indicate that the stone masonry buildings are more vulnerable than brick masonry buildings, showing comparatively higher damage potential for the same IM.

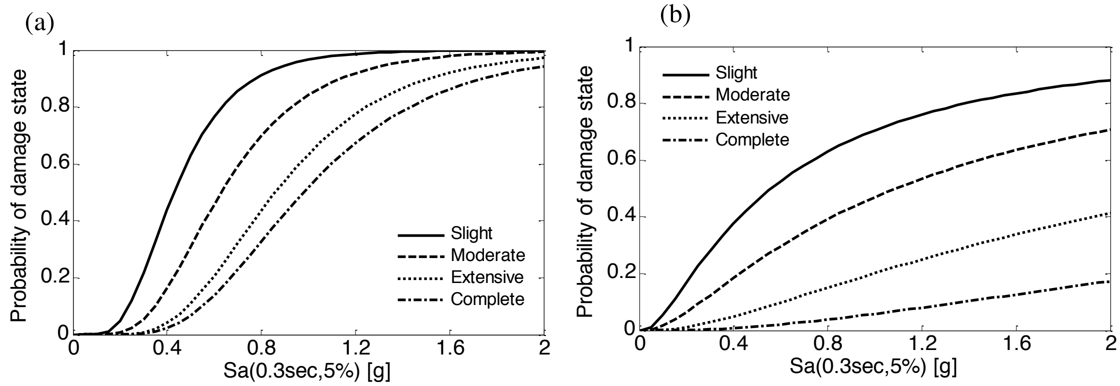

Figure 7: Fragility functions for: (a) Stone masonry, and (b) Brick masonry buildings.

The seismic hazard was defined with the M6.2R15 scenario selected to match the National Building Code of Canada probability level of 2%/50 years, see Figure 8a. The ground motion parameters retained for the vulnerability modelling were the spectral accelerations at 0.3sec and 1.0sec, as IMs representative for short and long period buildings. For site class B (rock), the predominant soil type in Old Québec City $S_a(0.3sec)=0.38g$ and $S_a(1.0s)=0.07g$. A summary of the proportion of buildings by construction material type and damage states for the considered M6.2R15 scenario is given in Figure 8b.

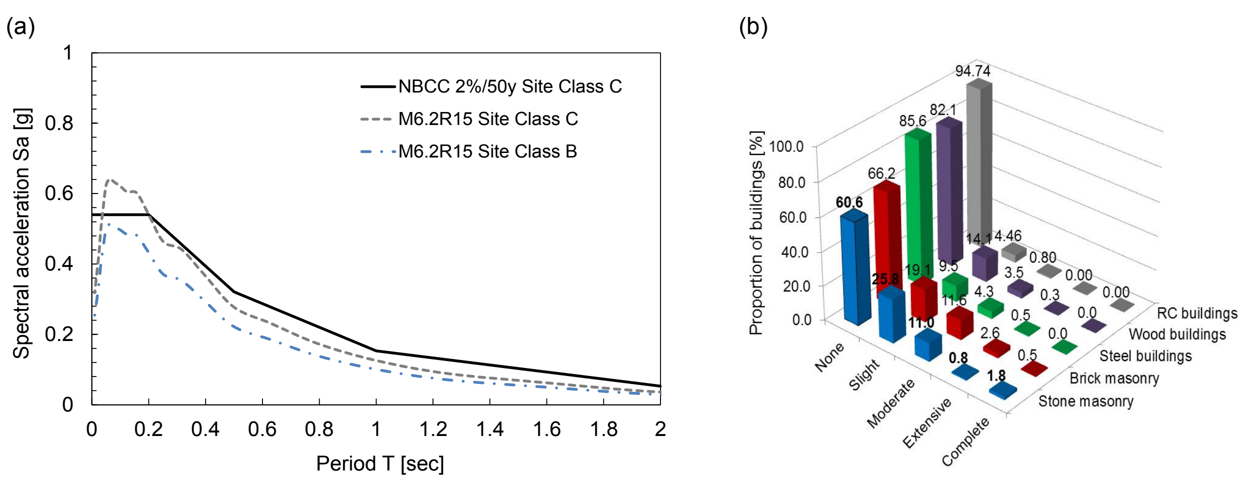

Figure 8: Earthquake M6.2R15 scenario: (a) Response spectra, (b) Proportion of buildings by construction material type in each damage state

The total number of buildings that will experience a certain degree of damage is 369, or 30%. Predictably, most of the expected damage will occur in the pre-code stone and brick masonry buildings. Approximately 39% of the stone masonry buildings (65 out of 168 buildings) and 33% of the brick masonry buildings (252 out of 765 buildings) will suffer various level of damage. It should be noted that for that earthquake scenario ($S_a(0.3sec)=0.38g$) the probability of slight and moderate damages is similar for those two building types, explaining the similarity in the damage distributions.

Other researches, have also investigated the sensitivity of the resulting damage estimation to the variation of the input parameters: structural parameters (capacity curves yield acceleration, elastic damping, degradation factors), damage parameters (displacement fragility functions median and standard deviation), and loss parameters (repair cost ratio). Results showed that the damage estimates are significantly affected by the uncertainty in the ground shaking, both epistemic and random nature. Result is also highly sensitive to the assumed median and standard deviation of the threshold values for the displacement based fragility functions, followed by the yield acceleration of the capacity curves. These parameters are characterized mainly with epistemic uncertainties that can eventually be reduced with increased knowledge.

CONCLUSION AND RESEARCH DEVELOPMENT

Masonry structures are present as monumental buildings such as churches and historical residential buildings mainly in old parts or major cities such as Montréal and Québec. Unreinforced brick masonry buildings are more frequent than unreinforced stone masonry buildings. This paper gives a review of occurred typical damages to unreinforced masonry during the past strong earthquakes in the province of Québec. The structural characterisation of stone masonry buildings contributed to the development of seismic vulnerability evaluation methods for those buildings. Focus was given to 1-3 storeys stone masonry structures for which capacity curves and displacement based fragility curves were generated. They were used as an input in a robust analytical procedure for the development of seismic hazard compatible fragility functions to estimate the structural damage to buildings for different earthquake magnitude-distance combinations. A scenario-based vulnerability assessment of 1220 buildings in Old Québec city was conducted for an M6.2R15 event corresponding to the probability of exceedence of 2% in 50 years. The results showed that most of the expected damage will be concentrated in the old brick and stone masonry buildings, with 33% and 39% of damaged buildings in the respective class. Future research will include consideration of out of plan behaviour in capacity analysis of stone masonry building and better definition of material properties and damage threshold values to reduce uncertainties in damage estimation.

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