Seismic damage assessment of Quebec stone masonry buildings based on macro-elements modelling

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ABSTRACT

Strong earthquakes generally lead to significant economic and social damage emphasizing the importance of seismic assessment of existing buildings and definition of mitigation measures. Old unreinforced masonry (URM) structures were primarily designed as gravity load systems and are known to be among the most vulnerable to earthquakes. Evaluation of the lateral resistance of those URM structures is a key element in predicting damage for seismic risk studies and defining strengthening strategies. However, the response of these buildings to seismic loads is non-linear, due to the progressive evolution of cracks in the mortar joints or the masonry blocks. This increases the difficulty in developing a coherent analytical model. Solutions were proposed to overtake this issue including sophisticated finite element models and simplified macro-element model based on idealization of the building as an equivalent frame. The latter solution represents an appropriate option for the evaluation of the seismic force-deformation capacity curves of several buildings with reasonable computational effort. These curves can then be compared to displacement threshold of different damage states to develop fragility functions representing the probability of damage given multiple levels of seismic intensity. The objective of this study is to develop seismic fragility functions for damage assessment of typical two storeys unreinforced stone masonry buildings located in the historical sector of Old Quebec City. Pushover analyses, using a macro-element model implemented in the software 3-Muri©, were conducted to derive the capacity curves of selected prototype buildings. Mechanical and geometric parameters were varied to obtain the median and dispersion in the capacity curve. Fragility functions were then generated using threshold displacement values, related to four damage states, taken from literature experimental data. The developed fragility functions are intended for use in regional scale damage assessment of earthquake scenarios.

Keywords: Masonry, Stone, Seismic Vulnerability, Macro Elements.

INTRODUCTION

Eastern Canada has a large stock of old unreinforced masonry (URM) buildings with architectural heritage value. Worldwide post-earthquake damage surveys showed that URM buildings are typically associated with the highest proportion of damage [1-5]. The evaluation of their seismic resistance plays therefore a key role in damage predictions for risk studies. It is also a concern for Architects and Engineers involved in defining rehabilitation and preservation strategies for those old URM load-bearing wall structures. Improving the evaluation of damage assessment of URM buildings requires better knowledge of their mechanical characteristics, lateral capacity and fragility [6]. Fragility is defined as the probability of reaching a given damage state for a given seismic intensity measure [7]. Fragility functions are defined from damage observations or structural analysis to obtain the response of the structure for increasing levels of ground motion intensity [8].

The response of URM buildings to seismic excitation is non-linear, due to the progressive evolution of cracks in the mortar joints or the masonry blocks. This increases the difficulty in developing a coherent analytical model. Detailed finite element models are used in modelling brick-mortar interface and evaluation the nonlinear response of wall elements. Simplified macro-element model based on idealization of the building as an equivalent frame, represents, however, a more reasonable computational effort while giving an appropriate option for the evaluation of the seismic force-deformation capacity curves of several buildings [9]. Macro-element modelling consists of identifying different nonlinear masonry elements according to the geometry of the walls and openings.

The purpose of this paper is to develop seismic fragility functions, based on macro-element analysis, for damage assessment of typical two storeys unreinforced stone masonry buildings located in the historical sector of Old Quebec City. The first step was to define prototype buildings representative of existing building inventory. Representative material properties for stone, mortar and masonry assembly are taken from recent experimental tests results [10]. Non-linear static analyses were carried out using the equivalent frame modelling approach. The analyses were carried out using the 3-Muri© software[11]. Capacity curves for those buildings were defined for a range of values for mechanical and geometric parameters to evaluate the median and dispersion in the capacity. Fragility functions were generated using threshold displacement values, related to four damage states, determined from structural analysis. At the end, fragility curves are used to predict damage for the studied building in Quebec for an hypothetical earthquake compatible with the NBCC 2015 [12] design spectra with a probability of 2% in 50 years.

METHODOLOGY AND THEORETICAL BACKGROUND

Prototype building

The prototype building used in this study is representative of a typical stone masonry building in the historical sector of Old Québec where 14% of the buildings are stone masonry. The inventory methodology and the information used for the structural characterization of these buildings can be found in [13]. Figure 1 shows the most common typology of stone masonry building in the area that was selected as a prototype.

Figure 1: stone masonry building typology in Old Quebec City

The building was constructed during the 18th and mid-19th century. The massive front and rear walls have regular windows and door openings on both side of the building. Lateral firewalls and front and rear walls have the same thickness varying from 40 to 60 cm. The typical story height varies from 2.75m to 3.35m. The peripheral walls ensure the lateral stability of the building in both directions[6].

Material properties were taken from an experimental program carried out on stone masonry representative of traditional unreinforced masonry walls made of limestone from St-Marc-des-Carrières in Quebec [10]. The wall section is typically composed of limestone blocks joined with hydraulic lime and cement mortar. Experimental results included: compression strength of stone and mortar, compression and joint shear sliding strength of the stone-mortar assembly and diagonal shear strength of stone masonry wall specimens.

Macro-element modelling

The selected software to carry out the structural analyses is 3-Muri ©, a commercial version of the research software Tremuri [14], developed specifically for the analysis of unreinforced masonry buildings. It provides static and nonlinear dynamic analysis, based on the equivalent frame method, for the simulation of possible deformations and failure using macro-elements. Each macro-element represents a part of the structure defined by simple geometry, i.e. a wall, a panel or a column. It has a degree of freedom to simulate bending / crushing and shear failure modes [11]. In the case of a simple wall, the macro element is represented as shown in Figure 2.

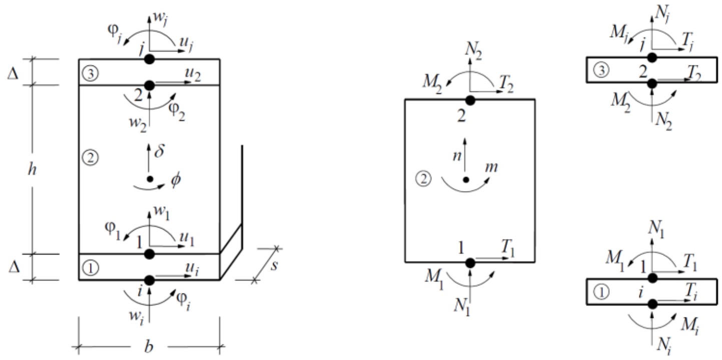

Figure 2:Kinematic model for the macro-element in 3-Muri © [11]

Each element is composed of three layers: a lower layer, a central part and a top layer. The two edge layers (top and bottom) are marked with a concentration of bending moments and axial forces while the central part is characterized by shear forces concentration [11]. The main advantage of this method is the reduced computational time compared to finite element method. This method allows creating a simplified model of the building and computes its capacity by simulating the failure modes of the macro-element.

Vulnerability analysis framework

The output of vulnerability analysis is a set of fragility and vulnerability curves. The former gives the probability of reaching a damage or limit state for a given intensity measure IM, such as the spectral displacement or acceleration, and the latter gives the economic loss in terms of the mean damage factor (MDF) defined as the repair to replacement cost ratio for a given IM. Figure 3 summarizes the process of the vulnerability framework used in this study to generate fragility and vulnerability curves. The definition of the fragility curves is characterized by the uncertainty in input parameters such as: the uncertainties in seismic demand and capacity of inventory due to the variation of the geometry and material properties, uncertainty in the definition of damage state, etc. [15]. The uncertainty in each input parameter is taken into consideration to evaluate the damage and estimate the following standard deviations: β_T the variability in the threshold of a damage state from the damage model; β_C the variability in capacity model and β_D the variability in the demand model.

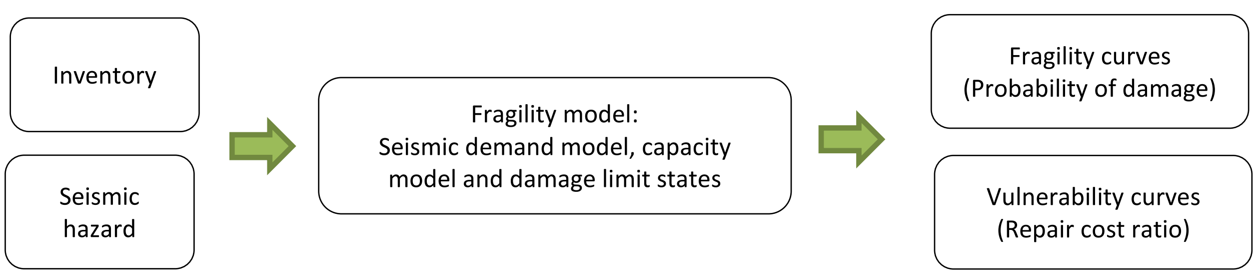

Figure 3: Process of analytical fragility and vulnerability modelling

CASE STUDY: STONE MASONRY BUILDING IN OLD QUEBEC CITY

Building modelling

The 3-dimentional modelling of the building starts by defining the geometry, specifying the floors and assigning vertical gravity loads. In a stone masonry building, gravity loads from the floors are supported by load bearing walls. In the equivalent frame method, the wall is modelled as a nonlinear frame element [16]. A typical floor is made of wood joists resting on the peripheral walls, and is considered as a planar orthotropic stiffening element. Figure 4 shows the numerical model of the prototype building. The discretization of the facade element (longitudinal X-direction), with the opening details and the macro-elements and the lateral firewall discretization (transversal Y-direction) are represented in Figure 4b and 4c, respectively.

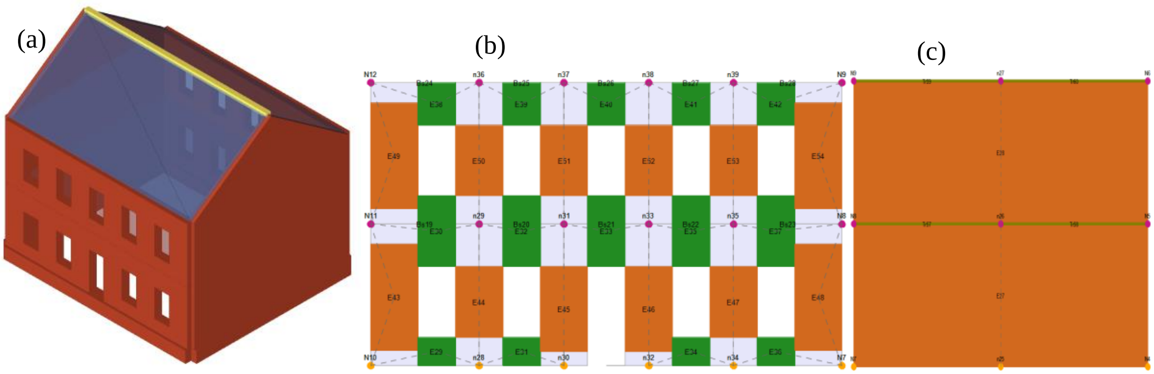

Figure 4:Numerical model of the selected building generated with 3-Muri© software: (a) 3-dimentionel modelling of the building, (b) Discretization of the facade element and (c) Discretization of the lateral firewall

A parametric study of the model is performed to select the mechanical properties. They are derived from experimental research work on limestone URM [10]. Average mechanical properties are presented in Table 1. Values for drift limits at which the analysis terminates are taken from Eurocode 8 [17].

Table 1:Stone masonry material properties [10]

Parameter		**Value**
E'_m	Modulus of elasticity	2823 MPa
G'_m	Shear modulus	487MPa
f'_m	Masonry compression strength	33 MPa
f'_j	Compressive strength of mortar	3.3 MPa
f'_b	Compressive strength of unit	100 MPa
f'_{td}	Masonry shear strength corresponding to diagonal cracking	0.37 MPa
c, f_{vm0}	Characteristic initial shear strength at zero compression	0.56 MPa
μ	coefficient of friction	0.85
w	Specific weight (kN/m^3)	22
δ_s	Shear ultimate drift ratio	0.4 %
δ_f	Rocking ultimate drift ratio	0.8 %

Pushover analysis

The non-linear static pushover analyses, performed with 3-Muri, adopt the Eurocode 6 [18] relations for the evaluation of bending/crushing and shear failure modes and based on the ultimate drift limits of URM walls. An equivalent elastic-perfectly plastic equivalent single degree of freedom “SDOF” model is defined from the corresponding capacity curve [16]. The pushover analyses of the prototype model in X and Y directions are shown in Figure 5, along with the idealized bilinear capacity curve corresponding to the mechanical parameters defined in Table 1. The capacity curve in the longitudinal X-direction simulates the massive front wall with several openings. In the transversal Y-direction, it simulates the lateral firewall.

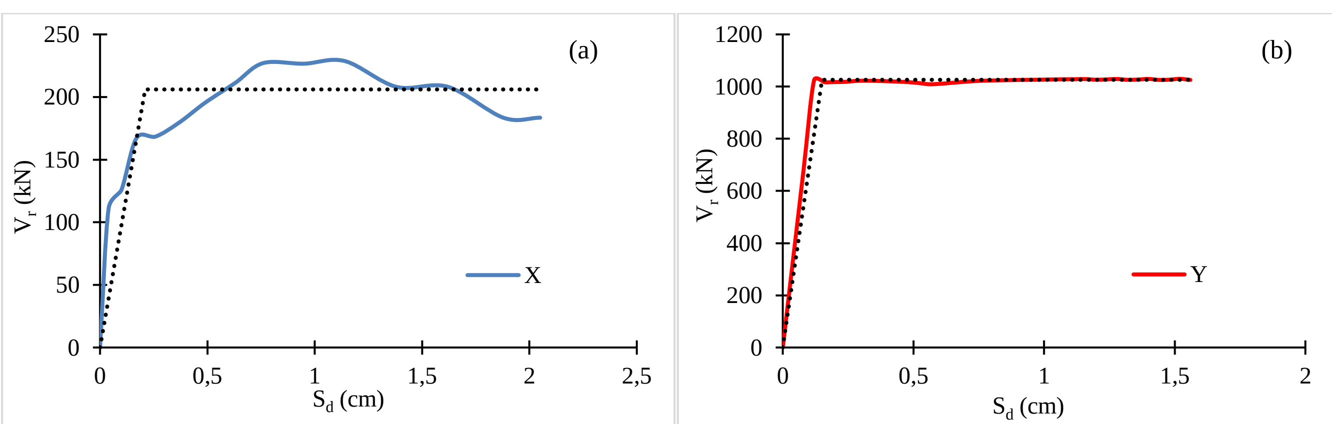

Figure 5: Capacity curves of the stone masonry building: (a) in X direction, (a) in Y direction

As shown the Figure 5, the maximum capacity in longitudinal X-direction reached 206 kN which is almost five times smaller than the capacity in the transversal Y-direction, which is 1026 kN. The front walls have regular windows and door opening, which explains the reduction in the lateral resistance of building compared to the massive firewall with no opening.

Parametric analysis of the capacity curves

In order to simulate the variability in the mechanical characteristics of the stone masonry buildings, non-linear static analyses were carried out for 20 structural models of the same building using variable mechanical parameters. Table 2 presents the different values considered for the masonry compression strength, the modulus of elasticity, the shear modulus, the shear strength for diagonal cracking and the specific weight of the stone masonry. Besides the experimental data on material mechanical properties for this URM stone building from [10], no other experimental data are available and limit values for mechanical parameters were selected based on recommendations from the literature for similar material.

Table 2: Variable mechanical parameters

Parameter		Value
E'_m	Modulus of elasticity (MPa)	2823 MPa to 5500 MPa
G'_m	Shear modulus (MPa)	487 MPa to 1375 MPa
f'_m	Masonry compression strength (MPa)	30 MPa to 40 MPa
w	Specific weight (kN/m^3)	20 kN/m^3 to 24 kN/m^3
f'_{td}	Masonry shear strength corresponding to diagonal cracking	0.25 MPa to 0.56 MPa

The median capacity curve in Figure 6 represents the median response of the 20 structural models with variable mechanical parameters. The median lateral resistance of the building in the X-direction is 296 kN with standard deviation of 110 kN, which is approximately 1,5 larger than for the prototype building previously analysed. The variability in the material mechanical properties has a significant influence on the capacity of the building. For example, the increase in specific weight of the stone masonry increases the structure mass and consequently the resistance to the lateral loading.

The ESDOF of the median capacity curve is defined by a median equivalent first mode period of vibration of 0.19sec, an equivalent elastic stiffness of the system of 219 635 kN/m and an ultimate displacement of 1.37cm. Results of these analyses will be used to estimate the variability in the capacity model, β_C.

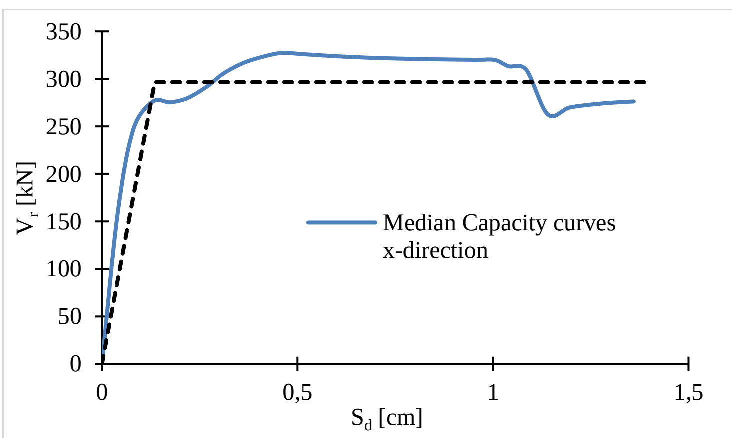

Figure 6: Median capacity curves of the prototype with variability in mechanical characteristics of the stone masonry

Fragility analysis

Fragility curves are usually given in the form of lognormal distribution of the probability of being in or exceeding a given damage state for a structural response parameter such as inelastic displacement demand or spectral acceleration. The damage state DS is determined from the capacity curve obtained from the analysis carried out with 3-Muri, using definitions recommended from the literature [19]. The median displacements for each damage state are determined on the capacity curve from the nature of the cracking: Slight damage "DS1" is characterized by flexural cracking, moderate damage "DS2" by shear cracking, extensive damage "DS3" by maximum shear strength and the complete damage "DS4" by ultimate deformation at 20% loss of strength. The conditional probability of being in or exceeding a particular damage state[20], DS, at a given spectral displacement S_d, is defined by:

$$P[DS|S_d] = \Phi\left[\frac{1}{\beta_{DS}}\ln\left(\frac{S_d}{\bar{S}_{d,DS}}\right)\right] \tag{1}$$

$$\beta_{DS} = \sqrt{CONV(\beta_C, \beta_D)^2 + \beta_T{}^2}$$

Where, Φ is the standard normal cumulative distribution function, $\bar{S}_{d,DS}$ is the median value of the spectral displacement at which the building reaches the threshold of damage state DS, β_{DS} is the standard derivation of spectral displacement for each damage state DS. The standard derivation β_{DS} is the contribution of three parameters: β_T is the variability in the threshold of a damage state from the damage model, $CONV(\beta_C, \beta_D)$ is the combination between β_C the variability in capacity model and β_D the variability in the demand model. Here, the $CONV(\beta_C, \beta_D)$ is obtained for a combination of the median capacity curves of Figure 6 with the response spectra of 8 scenarios (M6R10; M6R20; M6R30; M7R10; M7R20; M7R30; M7R40; M7R60) obtained with Atkinson and Boore ground motion prediction equation for Eastern north America [21]. In addition, β_T is determined from literature experimental data. Table 3 gives the resulting $\bar{S}_{d,DS}$ and β_{DS} for each damage state.

Table 3: Median and dispersion of the displacement based damage states for the prototype of building in Quebec City

	$\bar{S}_{d,DS}$ **[cm]**	β_{DS}
DS1[Slight]	0.09	0.74
DS2[Moderate]	0.57	0.8
DS3[Extensive]	0.9	0.81
DS4[Complete]	1.25	0.86

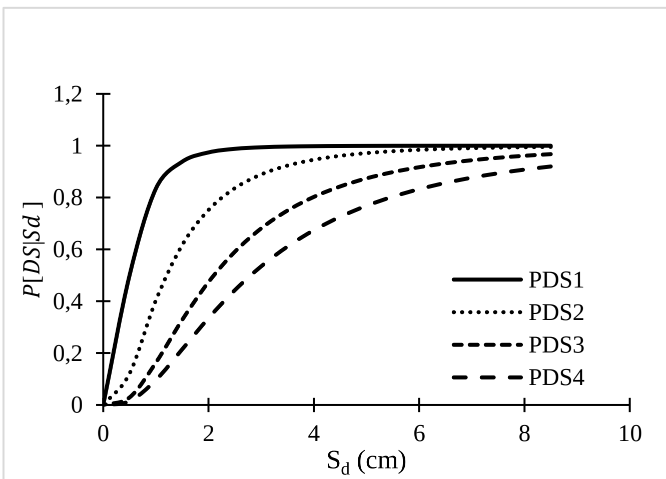

Figure 7: Fragility curves for the prototype stone masonry building

Damage distribution for Quebec City prototype building

The fragility curves in Figure 7 can be used to estimate damage distribution of the initial prototype building (basic case). The performance point on the capacity curve (Figure 5a) is calculated by the Capacity Spectrum Method "CSM" according to the procedure proposed in [22]. This method is based on the assumption that the nonlinear response of the system can be modelled as a linear ESDOF with an effective period and an effective damping [22]. The characteristic of ESDOF derived from the capacity curve of basic case are: effective masse m*=249 tons, modal participation factor Γ= 0.68 and the yield fundamental period of vibration T_y= 0.336sec. The performance point for the Quebec City, for 2% in 50 years uniform hazard spectrum, is given by: S_a[g]= 0.122; S_d=0.53cm; β_{eff}= 0.15%. The percentage of the damage for each damage state can be estimated from the fragility curves of Figure 7. The estimated damage indicates that 53% of buildings are expected to sustain some degree of damage, for this uniform hazard spectrum (Figure 8). On the other hand, 3.5% of buildings are expected to sustain extensive to complete damage. It should be noted that these results provides a first-order estimate of damage of a population of buildings and should not be used for building-by-building assessment.

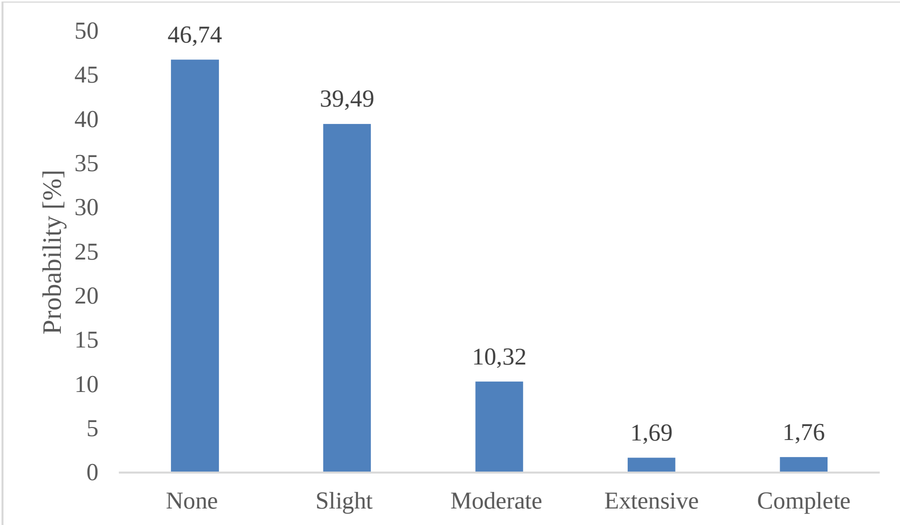

Figure 8: Damage states probabilities computed with fragility curve

CONCLUSIONS

Seismic vulnerability analysis of the existing masonry buildings is considered as a necessary first step towards the quantification of potential damage from future strong earthquake events. This paper presented a simplified method for the development of seismic fragility curves of unreinforced stone masonry buildings representative of historical buildings in Quebec City region. Pushover analyses, using a macro-element model implemented in the software tool 3-Muri©, were conducted to derive the capacity curves of a selected prototype building. Mechanical and geometric parameters were varied to obtain the median and dispersion in the capacity curve. Fragility curves were then generated using threshold displacement values, related to four damage states, taken from literature experimental data. The developed fragility curves where then used to quantify the probability of damage of an earthquake scenario corresponding to a 2% in 50 years hazard values. The study showed the potential benefits of the applied procedure in providing first-order estimate of seismic induced damage, which can help in emergency planning and mitigation scenarios at urban scale.

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