Seismic Risk Assessment of Existing Buildings in Old Quebec City, Canada

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SUMMARY:
This paper presents the results of a seismic risk assessment study of the Old Quebec City, Canada, for 1220 existing buildings, mainly pre-code unreinforced brick and stone masonry. Vulnerability modelling included a set of successive analytical development of capacity curves; displacement-based fragility functions; and vulnerability functions of the mean damage factor defined as repair to replacement cost ratio. These functions were conditioned to a structure-independent hazard intensity measure (IM), e.g. spectral acceleration. The distribution of the potential damage was evaluated for a scenario event of magnitude 6.2 at distance 15 km (M6.2R15). The results show that approximately 35% of the stone masonry buildings and 17% of the brick masonry buildings would suffer damage. A sensitivity analysis conducted to investigate the impact of uncertainties in the vulnerability modelling, showed that the damage estimates are significantly affected by the uncertainty in the ground shaking followed closely by the displacement based capacity and fragility curves.

Keywords: Seismic risk assessment, vulnerability, fragility functions, masonry buildings.

1. INTRODUCTION

The physical damage, social and economic losses incurred during the past destructive earthquakes emphasize the need to reasonable prediction of potential risk in seismic prone areas. A standard definition of seismic risk considers a combination of the seismic hazard, exposure, and vulnerability. The seismic hazard is a measure of the probability of a given intensity of earthquake shaking at the studied location over a given time period; exposure refers to elements at risk, i.e, built environment in that area; and vulnerability introduces the susceptibility to earthquake impacts, generally defined by the potential for damage and economic loss as result of intensity of seismic loading. Key element in the vulnerability modelling is the capacity of a building to sustain loads and displacements due to seismic shaking. Physical damage is generally represented through a set of fragility functions assigned to given damage state (Coburn and Spence, 2002), whereas economic losses are given by vulnerability functions (Porter, 2009). The outputs of vulnerability modelling are estimates of the potential physical damage and direct economic losses. Indirect damage, indirect economic losses and social losses, which should also be considered in the mitigation strategy, were not considered in this study.

The objective of this paper is to document the developed procedure and results of vulnerability modelling study of existing buildings in the Old Quebec City, Canada. The study was motivated by the presence of numerous historic masonry buildings with unique heritage value and the need to evaluate their behaviour under potential earthquake conditions. The assessment was performed for a scenario M6.2R15 event which corresponds to a probability of roughly 2% in 50 years (Adams and Halchuk, 2003). Inventory of 1220 existing buildings was conducted according to the material type (e.g. wood, concrete, stone masonry), height (e.g. low-rise, mid-rise), and design level (e.g. pre-code, recent code). The procedure applied analytically developed functions specific to the existing building types: (1) capacity curves describing the nonlinear structural behaviour; (2) displacement-based fragility functions representing the probability of exceeding specified damage state under various levels of displacement response; and (3) vulnerability functions of the mean damage factor (MDF) defined as the repair to replacement cost ratio (Porter, 2009). The analytical functions were conditioned to a structure-independent hazard IM, e.g. spectral acceleration at a particular period. The resulting distribution of damage for the selected seismic scenario is presented. At the end, a sensitivity analysis is conducted to investigate the impact of uncertainties in vulnerability modelling on the estimated damage for stone masonry buildings that represents high heritage value.

2. RISK ASSESSMENT FRAMEWORK AND INPUT MODELS

The analytical seismic risk assessment framework for existing buildings requires three input models (Porter, 2009): (1) buildings inventory model of existing buildings types and classification of buildings according to construction material, height and design level, (2) seismic hazard model using a ground-motion prediction equation compatible to the seismotectonic settings at the study region to estimate shaking intensity in terms of structure-independent IM (e.g. spectral acceleration at a particular period), and (3) vulnerability model represented as seismic hazard compatible vulnerability and fragility functions in terms of structure-independent IM. The output is the estimated damage magnitude, its distribution and repair cost ratio.

Vulnerability modelling of a typical building type can be conducted based on: observed damage from major earthquakes for which adequate records of the seismic motion are available (empirical method); expert opinion; analytical methods involving simplified mathematical models of structural response of a building or a type of buildings; time-domain numerical modelling of structural response; and by a combination of any of these methods (Porter 2009). In the absence of earthquake damage patterns or sufficient data, analytical methods are often preferred. In such case essential input components of the vulnerability assessment are the capacity curves and seismic hazard compatible fragility and vulnerability functions. Capacity curves describe the nonlinear structural behaviour and are generally obtained from pushover analysis as a relationship between top displacement and lateral load capacity (FEMA356, 2000). Fragility function define the probability of exceedence of a given physical damage state, e.g., slight, moderate, extensive and complete (Coburn and Spence, 2002). Fragility functions are usually given as lognormal distribution functions of a seismic IM, e.g., spectral acceleration at a given period (Sa). They can also be conditioned on a structural specific IM, e.g., inelastic spectral displacement, defined as displacement based fragility functions. Finally, vulnerability functions represent a relationship between seismic IM and expected mean loss of a specific building type, e.g. loss measured in terms of the costs to repair damage or MDF (Porter, 2009).

The conducted vulnerability modelling was inspired by the procedure employed in Hazus, the well known loss estimation methodology developed by US Federal Emergency Management Agency - FEMA (FEMA, 2003). The capacity curves and the displacement based fragility functions were previously defined by Abo-El-Ezz et al. (2011). The vulnerability modelling procedure is graphically presented in Fig 2.1.

For a given building type, the vulnerability modelling starts with the development of response spectra defined by structure-independent IM, Sa0.3s and Sa1.0s. The structural analysis is conducted in the spectral acceleration vs. spectral displacement (Sa-Sd) domain. The structural response is evaluated using the capacity spectrum method (CSM) (Mahaney *et al.*, 1993; ATC 40, 1996). In the CSM, the performance point is obtained based on the assumption that the nonlinear response of the system can be modelled as a linear equivalent single degree of freedom with increased period and effective damping which are both functions of the ductility demand (i.e. displacement demand over the yield displacement). In order to avoid computationally costly iterations for the structural displacement response, i.e. the performance point, the CSM procedure was amended according to the suggestions proposed by Porter (2009). In the amended CSM shown in Fig 2.1.a, the performance point for the considered earthquake magnitude-distance scenario is determined on the capacity curve in the Sa-Sd domain. The corresponding effective damping is calculated from the ductility-damping relationships (ATC-40, 1996), as shown in Fig 2.1.a. The associated values of the structure-independent IMs of the site-soil response spectrum (Sa0.3s for 5% damping), are obtained using the spectral reduction factor relationship that correlates the performance point Sa with effective damping to the Sa0.3s with 5% damping.

The second step continues from the performance point forward into the set of previously developed displacement based fragility functions (Abo-El-Ezz et al., 2011), to determine the probability of damage states (Fig 2.1.b). The obtained probabilities were ranked provided the computed IM (hollow dots on (Fig 2.1.c). Finally, integration of the loss conditioned on the probability of being in each damage state was conducted to determine the MDF at the considered IM (indicated with hollow dots in Fig 2.1.c). The CDF, central value in a range of damage factors, used to predict the MDF was assumed to be: 2% of the building structural system replacement cost for slight structural damage, 10% for moderate damage, 50% for extensive damage, and 100% for complete damage (Kircher et al., 1997). The same distribution of repair costs by damage state is also applied in the Hazus methodology (FEMA, 2003).

To establish a complete set of fragility and vulnerability functions in terms of the structure-independent IMs, the procedure was repeated for gradually increasing intensity levels, i.e., increasing demand response spectra (Fig 2.1.a). These actually represent the possible magnitude-distance combinations which can occur at a given location. The computed probabilistic damage states and mean damage factor were arranged in tabular format for respective structure-independent IM. The data were then fitted using MatLAB software to provide suitable hazard compatible seismic fragility and vulnerability functions defined as lognormal cumulative probability functions with proper mean and standard deviation. More details of the computation procedure can be found in Porter (2009) and Abo-El-Ezz et al. (2012). The above procedure revealed to be a powerful tool for conducting rapid vulnerability assessment before or immediately after a strong earthquake event.

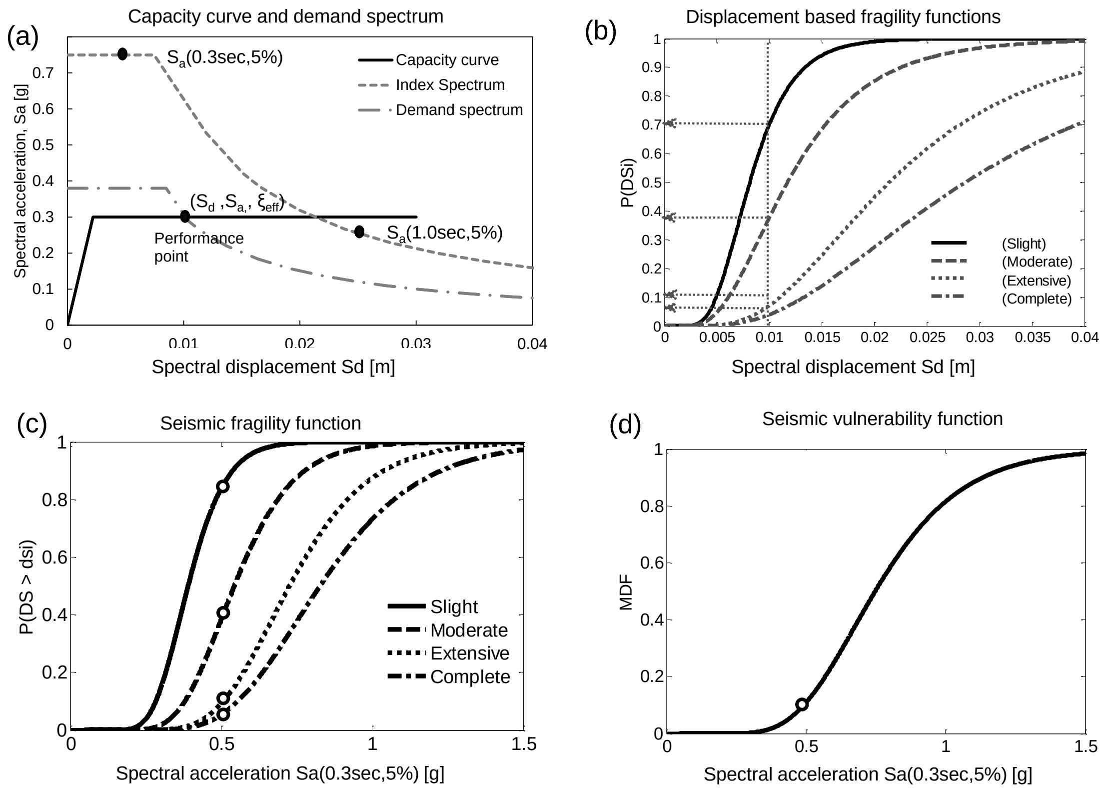

Figure 2.1. Illustration of the vulnerability modelling procedure (a) definition of the performance point; (b) estimation of the probability of damage states; (c) conversion of the fragility functions against spectral acceleration; d) development of the vulnerability function in terms of MDF.

3. CASE STUDY

3.1. Inventory

The building inventory was compiled by a combination of data from the municipal database of the City of Quebec and from the field survey of 1220 buildings. The inventoried buildings were classified according to: (1) construction material, e.g. wood, steel, concrete, stone masonry; (2) structural system, e.g. frame or wall structure; (3) seismic design code level, e.g. pre-code for building not seismically designed (before 1970) and mid-code for buildings designed according to seismic provisions (after 1970 and before 1990); (4) height, e.g. low-rise with 1 to 3 stories, mid-rise with 4 to 7 stories. This classification scheme corresponds to that employed by the Hazus methodology (FEMA, 2003).

Examination of the inventory given in Table 3.1. reveals that the dominant building types are the pre-code unreinforced brick masonry (62%) and stone masonry buildings (14%) as shown in Fig 3.1. Moreover, 91% of existing buildings were built before 1970. Although, the first seismic design provisions were first introduced in the 1941 National Building Code edition they evolved considerably over the years and most buildings constructed prior to 1970 are considered as pre-code buildings, especially unreinforced masonry.

Table 3.1. Distribution of building classes within the study area. Buildings types and heights were selected according to the Hazus methodology (FEMA, 2003)

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

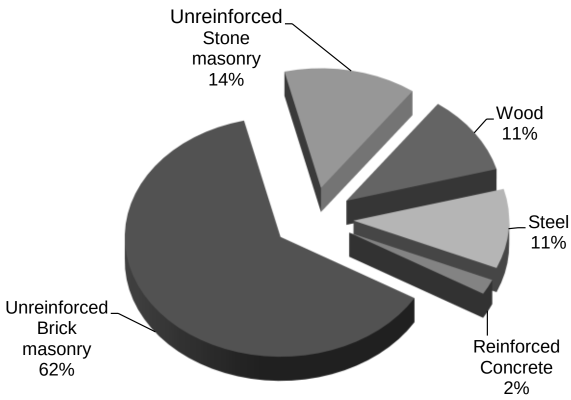

Figure 3.1. Distribution of buildings according to construction material.

3.2. Seismic Hazard

One of the important steps in evaluating the seismic risk for any region is to assess the seismic hazard and identify the events of interest. In this study, the seismic hazard was defined with scenario of M6.2 at a distance 15km (M6.2R15) selected to match the National Building Code of Canada probability level of 2%/50 years (NBCC, 2010). Atkinson and Boore (2006)-AB06 ground motion prediction equation was used to develop the response spectra for the selected scenario. The ground motion parameters retained for the vulnerability modelling were the spectral accelerations at 0.3s and 1.0s, as IMs representative for short and long period buildings (FEMA, 2003). For site class B (rock), the predominant soil type in Old Quebec City, the Sa(0.3s)=0.38g and Sa(1.0s)=0.07g (Fig 3.2.).

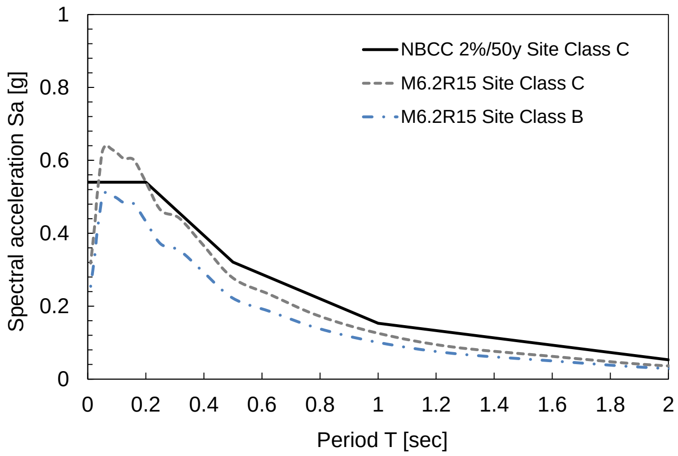

Figure 3.2. Response spectra for the selected M6.2R15 scenario on site class C (very dense soil and soft rock) and B (rock), and the NBCC 2%/50 years uniform hazard spectrum for Quebec City for site-class C.

3.3. Vulnerability Model

Due to similar construction practices in Canada and in United States, capacity curves and displacement based fragility functions available in the Hazus technical manual (FEMA, 2003) were employed for the vulnerability modelling of the building types listed in Table 1.1. with the exception of stone masonry. For stone masonry buildings, which are not explicitly considered by Hazus, capacity curves and fragility functions were those generated by Abo-El-Ezz et al. (2011) and are presented in

Fig 2.1.a and Fig 2.1.b, respectively. Fig 3.3.a and Fig 3.3.b show 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 higher damage potential for the same IM. The procedure depicted in Fig 2.1. was then applied to obtain the vulnerability functions shown in Fig 3.4. The standard repair costs (e.g., 100%, 50%, 10% and 2%) were used (Kircher et al., 1997; FEMA, 2003).

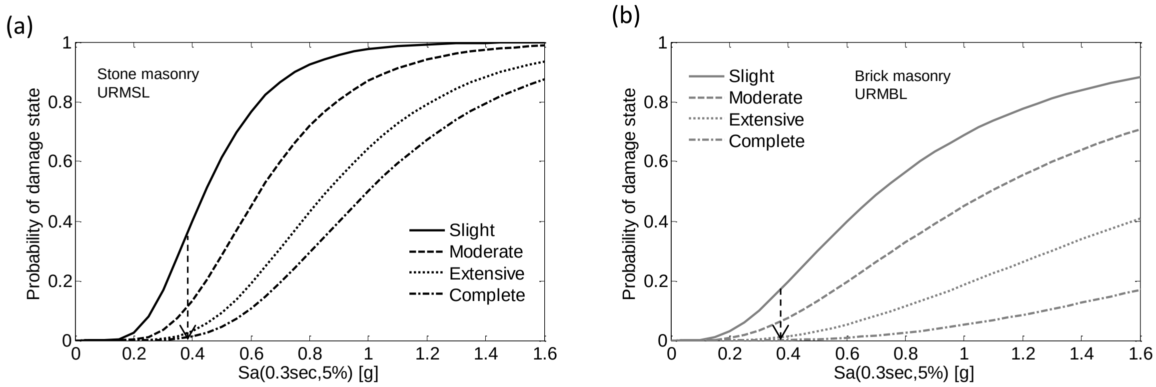

Figure 3.3. Fragility functions for (a) stone masonry buildings, and (b) brick masonry buildings. The dotted arrow shows the IM for the selected scenario M6.2R15.

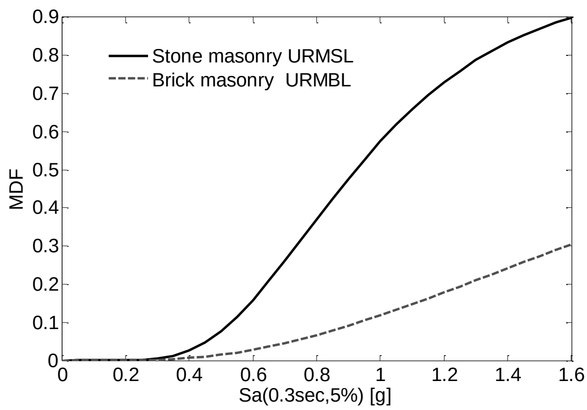

Figure 3.4. Seismic vulnerability functions for stone and brick masonry buildings.

4. RESULTS

The potential damage for the considered M6.2R15 scenario is given in Fig 4.1.a. The total number of buildings that will be subjected to certain degree of damage is 202, or 16%. Out of 1220 buildings, only two buildings, stone masonry buildings, will suffer complete damage. A summary of the proportion of buildings by construction material type and damage states is shown Fig 4.1.b. Predictably, most of the expected damage will occur in the pre-code stone and brick masonry buildings. Approximately 35% of the stone masonry buildings (59 buildings out of 168) and 17% of the brick masonry buildings (130 buildings out of 765) will suffer certain damage. The highest structural repair cost is expected for stone masonry and brick masonry buildings, with MDF of 1.8% and 0.9%, respectively.

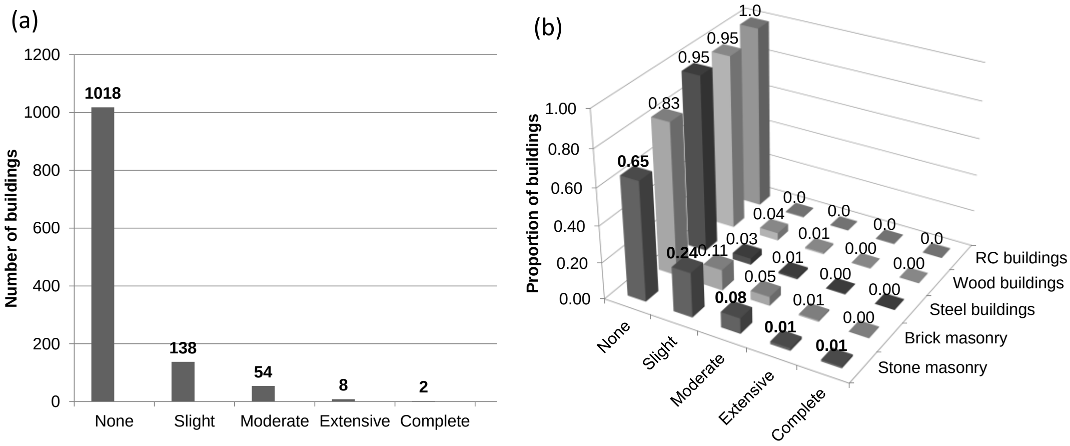

Figure 4.1. a) Total number of buildings in each damage state, b) proportion of buildings by construction material type in each damage state for a scenario event M6.2R15.

5. SENSTIVITY ANALYSIS

Recent studies showed that among the many uncertainties encountered in the seismic risk assessment, the uncertainties related to vulnerability modelling contribute the most (Crowley et al., 2005). As most of the potential damage was concentrated in the stone masonry buildings, a sensitivity analysis was conducted to investigate the impact of the uncertainties on damage estimates of these buildings (Abo-El-Ezz et al., 2012). The M6.2R15 was considered as the base-case scenario. Seismic intensity, yield acceleration of the capacity curve, elastic damping ratio, degradation factor, displacement based fragility functions (median and standard deviation) and damage factors were considered as varying parameters. For each parameter a set of reasonable increments was considered, i.e. -25%, 0% (base case scenario), +25%. First, vulnerability functions were generated for the base-case scenario and then they were generated by varying only the studied parameter and keeping the remaining parameters constant. The sensitivity was determined comparing deviations from the base case scenario using tornado diagrams to illustrate the sensitivity of the resulting value (i.e. MDF in this case) against the considered input parameters. The absolute difference of the deviation from the base-case scenario (swing) was used as a measure of the sensitivity (Porter et al., 2002). In other words, the parameters that have larger swing are more influential.

The damage assessment sensitivity to different input parameters is presented in Fig 5.1. The central vertical line represents the MDF for the base case (1.8%). As expected, the predicted MDF is most sensitive to the ground shaking intensity. The uncertainty in the ground shaking is of both epistemic and random nature. This uncertainty can be quantified but only slightly reduced. The other parameters are characterized mainly with epistemic uncertainties that can eventually be reduced with increased knowledge. The MDF 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. The assumptions of the elastic damping, degradation factor and the damage factors assigned to each damage state have only moderate impact on the final MDFs.

It should be noted that all of the above structural parameters have notable impact on the results of the vulnerability modelling and show the importance of conducting region-specific vulnerability analysis in order to reduce the uncertainties. These results indicate that more attention should be given to the development of the displacement based fragility functions and capacity curves.

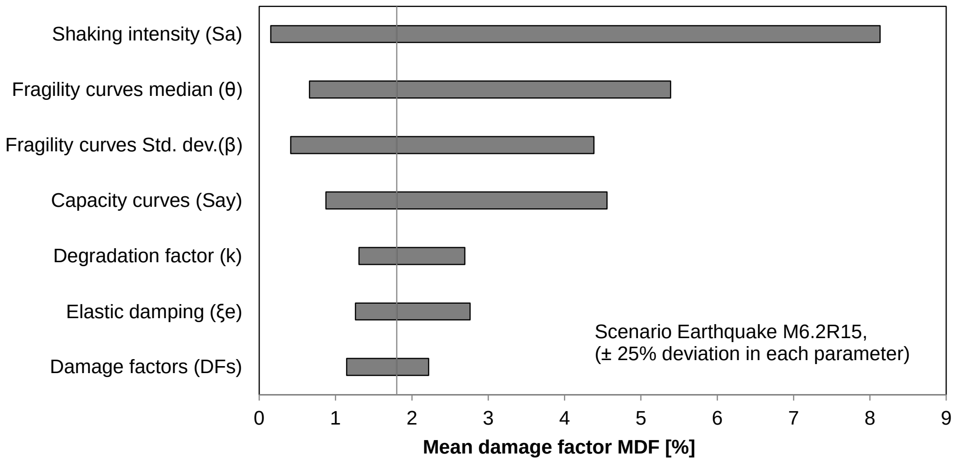

Figure 5.1. Variation of the predicted MDF for different input parameters in vulnerability analysis for stone masonry buildings.

6. CONCLUSIONS

Vulnerability modelling of existing buildings in Old Quebec City was completed. Many of the buildings were built before the introduction of seismic provisions, hence the need to predict their seismic performance. The assessment was performed for a scenario event of magnitude 6.2 at distance 15km corresponding to a probability of 2% in 50 years. The inventory consisted of 1220 buildings classified according to their material type (e.g. concrete, wood, stone masonry), height (e.g. low, medium), and design level (e.g. pre-code, recent code). The modelling procedure consisted of generation of a set of analytical capacity, fragility and vulnerability functions in terms of a structure-independent intensity measure with respect to the encountered building types. The study showed that most of the expected damage will be concentrated in the old brick and stone masonry buildings, with 17% and 35% of damaged buildings in the respective class. A sensitivity analysis conducted to investigate the impact of uncertainties in vulnerability modelling on the estimated damage for stone masonry buildings showed that the damage estimates are significantly affected by the uncertainties in the considered displacement based fragility and capacity curves. These results emphasize the need of particular attention in the development of region-specific fragility and capacity curves.

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