GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7450

Methodology for rapid assessment of seismic damage to buildings in Canadian settings

A. Abo-El-Ezz, M.J. Nollet, M. Nastev

2014

Natural Resources Canada Ressources naturelles Canada

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7450

Methodology for rapid assessment of seismic damage to buildings in Canadian settings

A. Abo-El-Ezz[1], M.J. Nollet[1], and M. Nastev[2]

[1] École de technologie supérieure, Montréal

[2] Geological Survey of Canada, Ottawa

2014

doi:10.4095/293874

Recommended citation
Abo-El-Ezz, A., Nollet, M.J., and Nastev, M., 2014. Methodology for rapid assessment of seismic damage to buildings in Canadian settings; Geological Survey Canada, Open File 7450, 41 p. doi:10.4095/293874

Abstract

A framework for rapid risk assessment is proposed considering local inventory of the building stock, definition of the seismic hazard and evaluation of the respective structural vulnerabilities. Structural vulnerability represents the central component of the framework and is based on the concept of fragility functions which combine the intensity of the seismic motion to the expected damage for a given structural type. This report documents the development of a rapid procedure for the seismic risk assessment of buildings. The procedure was first developed using the structural characteristics of the existing buildings in Old Quebec City with an emphasis to historic stone masonry buildings. Still it can be applied to existing or planned buildings of any structural type incorporating respective: (1) capacity curves which characterize the nonlinear behaviour of a building (exposure); (2) displacement fragility curves which represent the probability of exceedance of specified damage state under various levels of structural response (vulnerability); and (3) site specific response spectra used to estimate the structural demand for a series of earthquake magnitude-distance combinations (hazard).

A modified approach to the capacity spectrum method is proposed for evaluation of the expected damage as opposed to the usual iterative procedure for the displacement response, e.g., the one implemented in the well-known U.S. Federal Emergency Management Agency – FEMA's Hazus software. The developed methodology revealed to be a powerful tool for rapid assessment of seismic risk of a single building type or a regional risk assessment as it significantly reduces the computation time. It was validated through seismic damage assessment of 1220 buildings in Old Quebec City for a scenario event of M6.2 and distance 15km. The results were compared to those obtained by applying the Hazus software for the same input parameters (capacity curves and displacement based fragility functions) and showed negligible differences.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

List of abbreviations

ATC	Applied technology council
C1L	Concrete moment frame low rise
CSM	Capacity spectrum method
DCM	Displacement coefficient method
DS	Damage state
ESDOF	Equivalent single degree of freedom
GMPE	Ground motion prediction equation
HAZUS	Hazards United States loss estimation method
IM	Intensity measure
PGA	Peak ground acceleration
S1L	Steel moment frame low rise
S2L	Steel braced frames low rise
S5L	Steel frames with URM infill low rise
URM	Unreinforced masonry
URMB	Unreinforced brick masonry
URMS	Unreinforced stone masonry
W1L	Wood light frame low rise
UHS	Uniform hazard spectrum
NBCC	National building code of Canada

METHODOLOGY FOR RAPID ASSESSMENT OF SEISMIC DAMAGE TO BUILDINGS IN CANADIAN SETTINGS

1. INTRODUCTION

Physical damage and social and economic losses observed during the past destructive earthquakes worldwide emphasize the need to reasonably predict the potential risks in seismic ally-prone areas. A standard definition of seismic risk considers the combination of the seismic hazard, exposure, and respective vulnerability, where: the seismic hazard represents a measure of the probability of a given shaking intensity at the studied location over a given time period; exposure refers to the assets 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 a result of the intensity of seismic loading. A key element in the vulnerability modelling is the capacity of a building to sustain loads and displacements due to seismic shaking. Physical damage is typically 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, 2002). The outputs of vulnerability modelling are estimates of the potential physical damage and direct economic losses.

This report documents the development of a rapid procedure for the seismic risk assessment of buildings. The procedure was first developed using the structural characteristics of the existing buildings in Old Quebec City with an emphasis on historic stone masonry buildings. It can also be applied to existing or planned buildings of any structural type incorporating respective: (1) capacity curves which characterize the nonlinear behaviour of a building (exposure); (2) displacement fragility curves which represent the probability of exceedence of specified damage state under various levels of structural response (vulnerability); and (3) site-specific response spectra used to estimate the structural demand for a series of earthquake magnitude-distance combinations (hazard). A modified approach to the capacity spectrum method is proposed for evaluation of the expected damage as opposed to the usual iterative procedure for the displacement response, e.g., the one implemented in the well known U.S. Federal Emergency Management Agency – FEMA's Hazus software (FEMA, 2012). The developed methodology is validated through seismic damage assessment of 1220 buildings in Old Quebec City and the results are compared to those obtained by applying the Hazus software for the same input parameters.

2. OVERVIEW OF THE PROPOSED METHODOLOGY

The analytical seismic damage assessment framework, illustrated in Figure 1, requires three input models: (1) characterization of the existing or planned building(s) according to the structural type, construction material, height and design level; (2) definition of the seismic hazard to estimate the potential shaking intensity in terms of structure-independent intensity measure - IM (e.g. spectral acceleration at a particular period); and (3) vulnerability modelling represented with seismic hazard compatible fragility functions in terms of the structure-independent IM. The damage estimates are given in terms of probability of exceedence of the prescribed damage states.

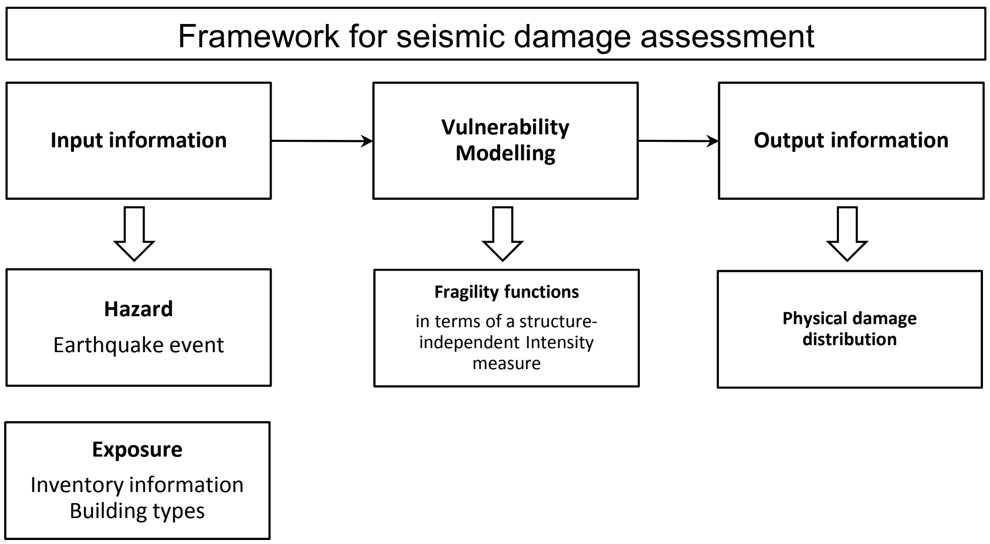


Figure 1 Framework for seismic damage assessment.

The vulnerability of a typical building type can be assessed based on: observed damage from the past earthquakes with adequate records of the seismic motion (empirical method); experts' opinion; analytical methods involving simplified mathematical models of structural response of a building or a type of buildings; sophisticated time-domain numerical modelling of structural response; and by a combination of any of these methods (Porter 2002). In the absence of observed 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 fragility 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). On the other hand, fragility functions 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 ($S_a(T)$). They can also be conditioned on a structural specific IM, e.g., inelastic spectral displacement (S_d), defined as displacement based fragility functions.

The vulnerability modelling procedure developed in this study is inspired by the procedure employed in Hazus (FEMA, 2012) and is graphically presented in Figure 2. It starts with the development of response spectra defined by structure-independent IMs, Sa(0.3sec) and Sa(1.0sec), referred to as Sa0.3 and Sa1.0 in the following text. For a given building type, the structural analysis is conducted in the spectral acceleration vs. spectral displacement (Sa-Sd) domain. The response of the building to a given response spectra is defined by a performance point (Sd-Sa), corresponding to the intersection of the capacity curve and demand spectrum (over-damped spectrum) (Figure 2a). The performance point is generally 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, both related to the ductility demand (i.e. displacement demand over the yield displacement). Hazus applies the CSM for structural analysis and capacity and displacement fragility curves for damage analysis (Figure 2b). It starts from the demand spectrum given Sa0.3 and Sa1.0 for 5% damping, calculating forward the performance point with Sd and Sa for respective effective damping. The performance point is then used to estimate the probability of the damage states from displacement fragility curves. This requires iterations that could be computationally costly for a large portfolio of buildings or a probabilistic risk assessment. Moreover, the Hazus procedure does not offer seismic fragility functions in a tabular or graphical form plotted against a structure-independent intensity measure IM. It is thus difficult to correlate the predicted damage to a structure-independent IM. In order to overcome these difficulties, the proposed methodology provides a non-iterative solution to the CSM and predefined fragility functions in terms of a structure-independent IM, which greatly reduces the computational demands.

In the proposed vulnerability modelling procedure the CSM was amended according to the suggestions made by Porter (2009), Figure 2.a. It starts with a given value for the structural response Sd, calculating the respective Sa for the performance point on the capacity curve in the Sa-Sd domain. The corresponding effective damping is then calculated from the ductility-damping relationships (ATC-40, 1996). The associated values of the structure-independent IMs of the site-soil-adjusted idealized demand (input) response spectrum (Sa0.3 and Sa1.0 for 5% damping), are obtained next using the spectral reduction factor relationship between the performance point Sa with the effective damping and the Sa0.3 and Sa1.0 with 5% damping.

The second step continues forward from the performance point into the set of previously developed displacement based fragility functions (Abo-El-Ezz et al., 2011) to determine the probability of damage states (Figure 2.b). The obtained probabilities are ranked with respect to the computed IM (indicated with hollow dots in Figure 2.c).

To establish a complete set of fragility functions in terms of the structure-independent IMs, the procedure is repeated for gradually increasing intensity levels, i.e., increasing demand response spectra (Figure 2.a). The computed probabilistic damage states are arranged in tabular format for respective structure-independent IM. The data is then fitted with lognormal cumulative probability functions with proper mean and standard deviation to provide suitable hazard compatible seismic fragility functions. More details of the computation procedure are presented in the next section. The above procedure revealed to be a powerful tool for conducting rapid damage assessment before or immediately after a strong earthquake event.

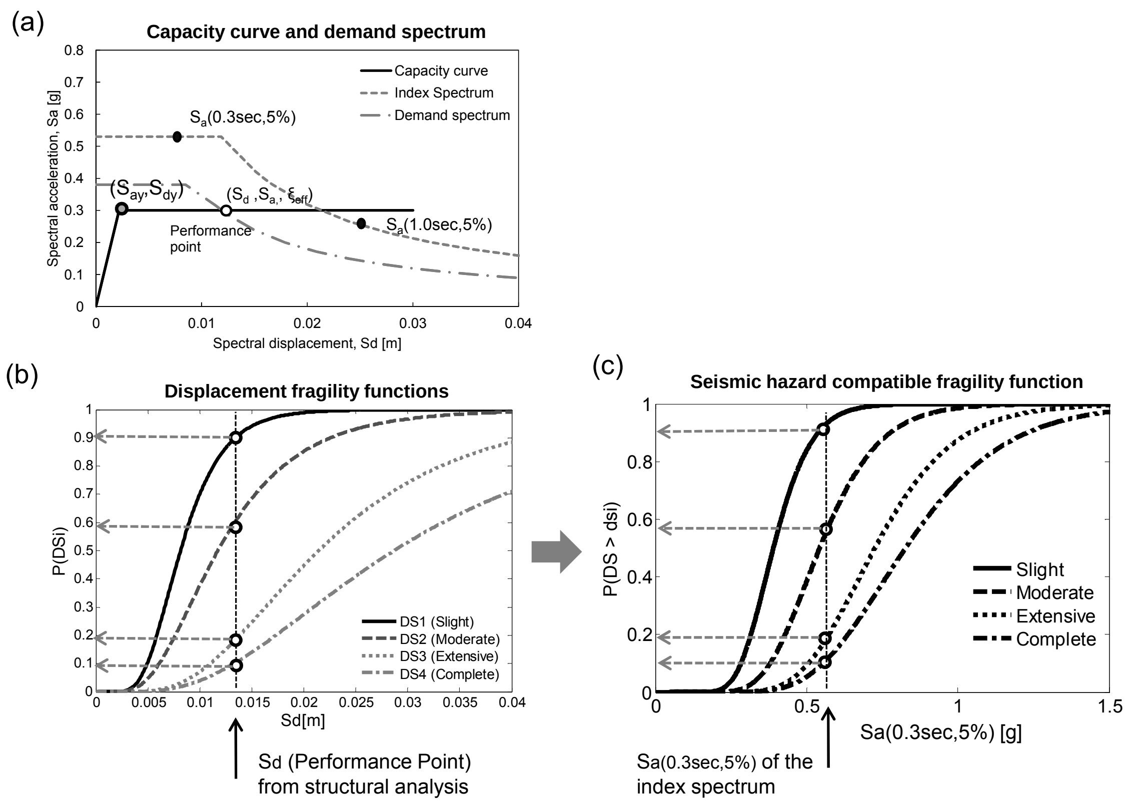


Figure 2 : Illustration of the vulnerability modelling procedure (a) definition of the performance point; (b) estimation of the probability of damage states; (c) conversion of the fragility functions against spectral acceleration.

3. STEP-BY-STEP COMPUTATION

In this section, the detailed computations for the methodology of development seismic hazard compatible fragility functions are presented. The standard CSM procedure to determine the structural displacement response (i.e., the performance point), is amended according to the suggestions by Porter (2009). A simple spreadsheet calculation algorithm was written using MS Excel. The structure of the algorithm is shown in Figure 3.

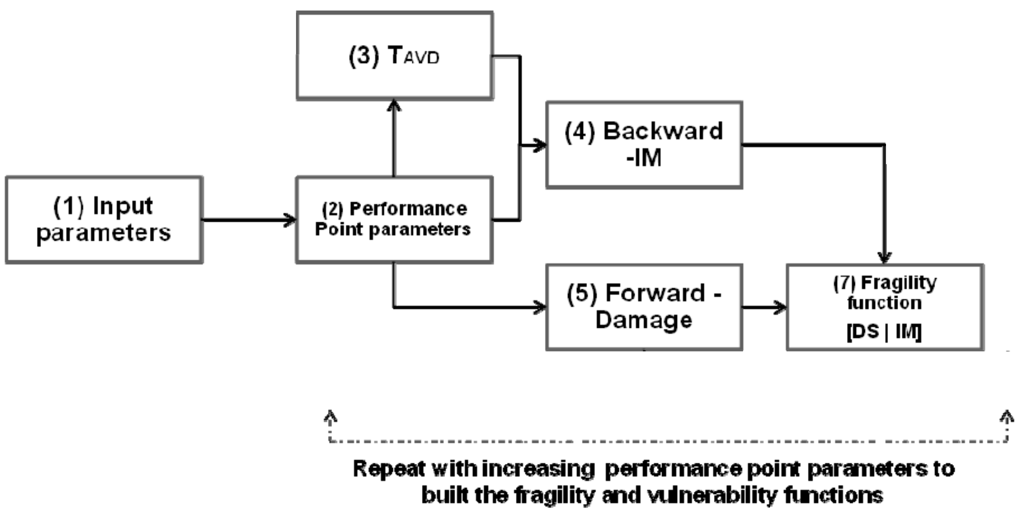


Figure 3: Algorithm structure in MS Excel for the development of seismic hazard compatible fragility and vulnerability functions.

3.1. Step-1: input parameters

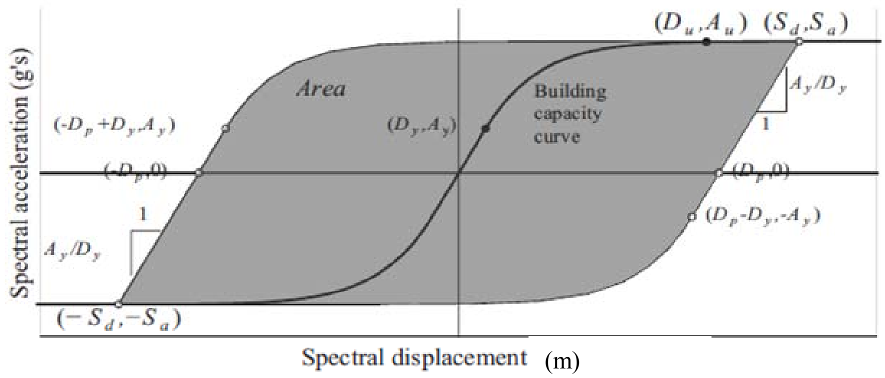
For each building type, the required input parameters are summarized in Table 1. The input parameters include: (1) capacity curve parameters, (2) displacement based fragility functions parameters, and (3) seismic parameters. These parameters could be obtained from specific structural and damage analysis of the structural types considered in the studied region. If building structural types could be adequately represented by structural types defined in Hazus, it is possible to use the corresponding predefined parameters given in Hazus Technical manual. The seismic hazard is defined from a suitable ground motion prediction equation (GMPE) that takes into account the magnitude, distance and site-class parameters. Atkinson and Boore (2006) GMPE was applied in this procedure which is compatible with eastern Canadian seismic settings.

Table 1 : Input parameters

Capacity Curve parameters:	Yield Displacement D_y(m)
	Yield Acceleration A_y (g)
	Ultimate Displacement D_u (m)
	Ultimate Acceleration A_u (g)
	Elastic damping ratio ξ_e
	Degradation factor κ
Displacement Fragility Functions parameters:	Slight damage median λ_1 (m)
	Slight damage log-Standard deviation β_1
	Moderate damage median λ_2 (m)
	Moderate damage log-Standard deviation β_2
	Extensive damage median λ_3 (m)
	Extensive damage log-Standard deviation β_3
	Complete damage median λ_4 (m)
	Complete damage log-Standard deviation β_4
Seismic setting parameters:	A ground motion prediction equation (GMPE).
	Site class : A (Hard rock), B(Rock), C(Very Dense soils), D(Stiff soils), E(Soft soils)
	Magnitude (M)
	Distance, R (km)

3.2. Step-2: performance point parameters:

This is the central step of the procedure from which calculations are carried out backward to evaluate the structure-independent intensity measure IM and then forward to damage and loss analysis. The performance point is defined as the intersection of the capacity curve and the demand spectrum (over-damped spectrum) with known values of (S_d ,S_a, T, ξ_{eff}). T denotes the effective period at the performance point. The procedure starts with assuming a value for S_d, then calculating S_a of the performance point from the capacity curve, and calculating the effective damping and period, as illustrated in Figure 4.



Calculate S_a

$$S_a = S_d A_y / D_y \qquad S_d < D_y$$

$$= A_0 + b\sqrt{1 - \frac{(S_d - D_u)^2}{a^2}} \qquad D_y \le S_d < D_u$$

$$= A_u \qquad D_u \le S_d$$

$$b = \frac{D_y (A_y - A_u)^2 - (D_y - D_u) A_y (A_y - A_u)}{(D_y - D_u) A_y - 2 D_y (A - A_u)}$$

$$a = \sqrt{\frac{-D_y (A_y - A_u) b^2}{A_y (A_y - A_u + b)}}$$

$$A_0 = A_u - b$$

↓

Calculate ξ_{eff}

$$\xi_{eff} = \xi_e + k\left(\frac{Area}{2\pi S_d S_a}\right)$$

$$Area = 4 S_a \left(S_d - \frac{S_a}{A_y / D_y}\right)$$

↓

Calculate T

$$T = 2\pi \sqrt{\frac{S_d}{S_a \cdot g}}$$

Figure 4 : Calculations of the performance point parameters (Porter, 2009).

3.3. Step-3: Evaluation of T_{AVD}

T_{AVD} is the period at the intersection of the constant-acceleration and constant-velocity portions of the demand spectrum that correspond to the performance point computed in step-2. The value of T_{AVD} is used to decide whether the performance point falls on the constant acceleration portion or the constant velocity portion of the demand spectrum. Figure 5 illustrates the procedure to calculate T_{AVD} for a given magnitude, distance, site class, and effective damping ratio.

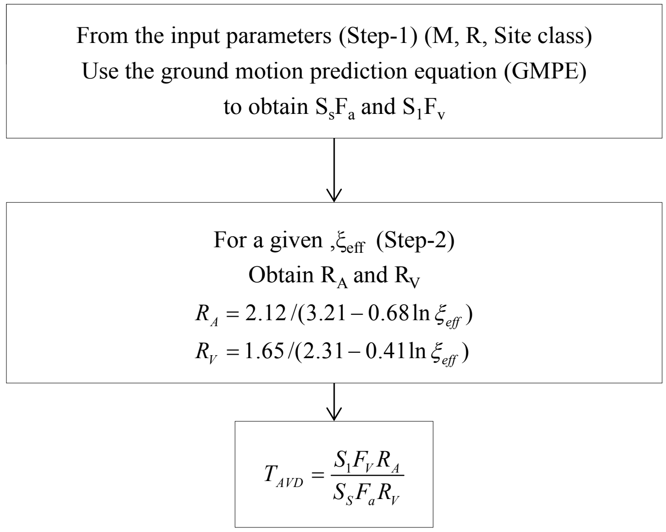


Figure 5 : Calculations of the T_{AVD}.

The ground motion prediction equation - GMPE is used to determine the site specific 5% damped elastic response spectrum defined by the control point S_sF_a = (Sa0.3,5%) and S_1F_v = (Sa1.0,5%) for given M and R. S_s and S_1 are the site class B accelerations for the constant acceleration and velocity portions of the spectrum, respectively. S_sF_a is the soil-site adjusted spectral acceleration for 5% damping at 0.3sec and S_1F_v is the site-class adjusted spectral acceleration for 5% damping at 1.0sec. F_a and F_v are the site-class amplification factors other than the site-class B for constant-acceleration portion and constant-velocity portion of the spectrum, respectively (Table 2). R_A and R_V are the damping reduction factor for damping ratios more than 5% for constant-acceleration portion and constant-velocity portion of the spectrum, respectively. It should be noted that the NBCC (2010) applies equivalent amplification factors to those used by FEMA (2012), but with site-class C as a reference site category.

Table 2 : Site amplification factors (FEMA, 2012)

	Site class				
	A	B	C	D	E
S_s (g)	F_a				
<0.25	0.8	1.0	1.2	1.6	2.5
0.5	0.8	1.0	1.2	1.4	1.7
0.75	0.8	1.0	1.1	1.2	1.2
1.0	0.8	1.0	1.0	1.1	0.9
>1.25	0.8	1.0	1.0	1.0	0.8
S_1 (g)	F_v				
<0.1	0.8	1.0	1.7	2.4	3.5
0.2	0.8	1.0	1.6	2.0	3.2
0.3	0.8	1.0	1.5	1.8	2.8
0.4	0.8	1.0	1.4	1.6	2.4
>0.5	0.8	1.0	1.3	1.5	2.0

3.4. Step-4: Backward IM

In the previous step, an estimate of T_{AVD} for a given combination of magnitude, distance, site-class and damping ratio was obtained. In this step, backward calculation is conducted from the performance point to the parameters of the input spectrum. It is desirable to infer the "control points" of the index spectrum given a point on the demand spectrum (the performance point), magnitude, distance, and site-class. Control points here mean S_sF_a = (Sa0.3,5%) and S_1F_v = (Sa1.0,5%) of the index spectrum. The values of the control points depend on the fact whether the performance point falls on the constant acceleration portion ($T < T_{AVD}$) or the constant velocity portion of the demand spectrum ($T > T_{AVD}$). Figure 6 illustrates the backward calculations. This step was proposed by Porter (2009) to avoid the iterative procedure in the evaluation of the performance point in the standard CSM in ATC-40.

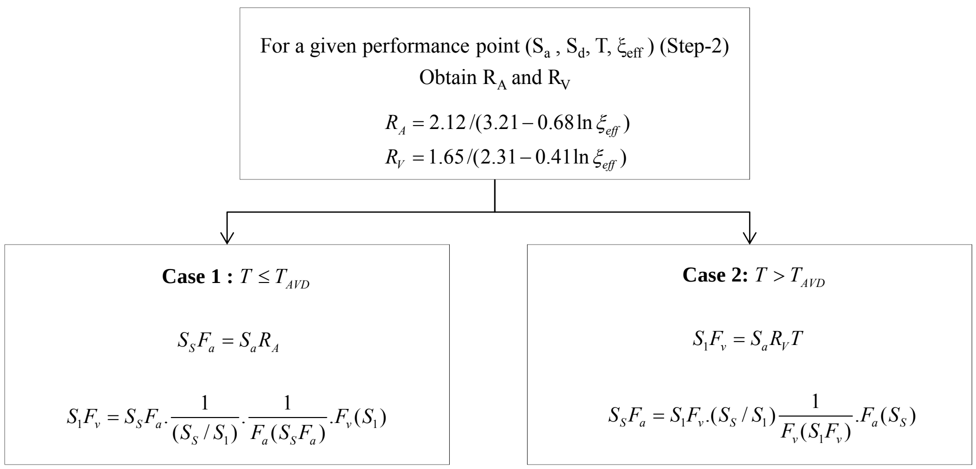


Figure 6 : Calculations of the control points of the index spectrum.

The ratio of S_S / S_1 is the spectral acceleration response factor derived in step-3 for the T_{AVD} of site class B and 5% damping; $F_a(S_S)$ and $F_v(S_1)$ are the site amplification factors given in Table 2. ($S_S F_a$) is the site amplification factor F_a expressed as a function $S_S F_a$ (Table 3), and $F_v(S_1 F_v)$ is the site amplification factor F_v expressed as a function $S_1 F_v$ (Table 4). These factors provide conversions from site-amplified shaking to rock shaking.

Table 3 : Inferring F_a from $S_S F_a$ and site class (Porter, 2009)

Site class	$S_S F_a$ (g)						
	0.1	0.2	0.4	0.6	0.8	1	1.25
A	0.8	0.8	0.8	0.8	0.8	0.8	0.8
B	1	1	1	1	1	1	1
C	1.2	1.2	1.2	1.2	1.11	1	1
D	1.6	1.6	1.6	1.47	1.3	1.15	1
E	2.5	2.5	2.5	2.5	1.88	0.9	0.9

Table 4 : Inferring F_v from $S_1 F_v$ and site class (Porter, 2009)

Site class	$S_1 F_v$ (g)						
	0.1	0.2	0.4	0.6	0.8	1	1.2
A	0.8	0.8	0.8	0.8	0.8	0.8	0.8
B	1	1	1	1	1	1	1
C	1.7	1.68	1.54	1.36	1.3	1.3	1.3
D	2.4	2.4	2	1.68	1.5	1.5	1.5
E	3.5	3.5	3.45	3.24	2.88	2.4	2.4

3.5. Step-5: Forward damage:

In this step, the procedure goes forward from the performance point (step-2) into a set of displacement based fragility functions to determine the probability of damage state. The obtained probabilities are tabulated conditioned to the computed IM obtained from step-4. This is illustrated in Figure 7.

For a given performance point (S_a , S_d, T, ξ_{eff}) (Step-2)

$$P\left[DS = ds \mid S_d = x\right] = 1 - \Phi\left(\frac{\ln\left[x/\lambda_1\right]}{\beta_1}\right) \qquad ds=0$$

$$= \Phi\left(\frac{\ln\left[x/\lambda_{ds}\right]}{\beta_{ds}}\right) - \Phi\left(\frac{\ln\left[x/\lambda_{ds+1}\right]}{\beta_{ds+1}}\right) \qquad 1 \le ds \le 3$$

$$= \Phi\left(\frac{\ln\left[x/\lambda_4\right]}{\beta_4}\right) \qquad d=4$$

Figure 7 : Calculations of damage states probabilities for a given performance point.

Where $P\left[DS = ds \mid S_d = x\right]$ denotes the probability of structural damage state ds given that S_d takes on some particular value x, and Φ denotes the cumulative standard normal distribution. The parameters λ_{ds} , β_{ds} denote, respectively, the median and logarithmic standard deviation values of the fragility function to resist damage state *ds* from 0 as no damage, 1 as slight damage, 2 as moderate damage, 3 as extensive damage and 4 as complete damage.

3.6. Step-6: Hazard compatible fragility functions

To establish the fragility functions in terms of structure-independent IMs, the procedure is repeated for increasing values of the performance points (step-2). The computed probabilistic damage states are then fitted to provide suitable hazard compatible seismic fragility (Figure 8) as a lognormal cumulative distribution functions.

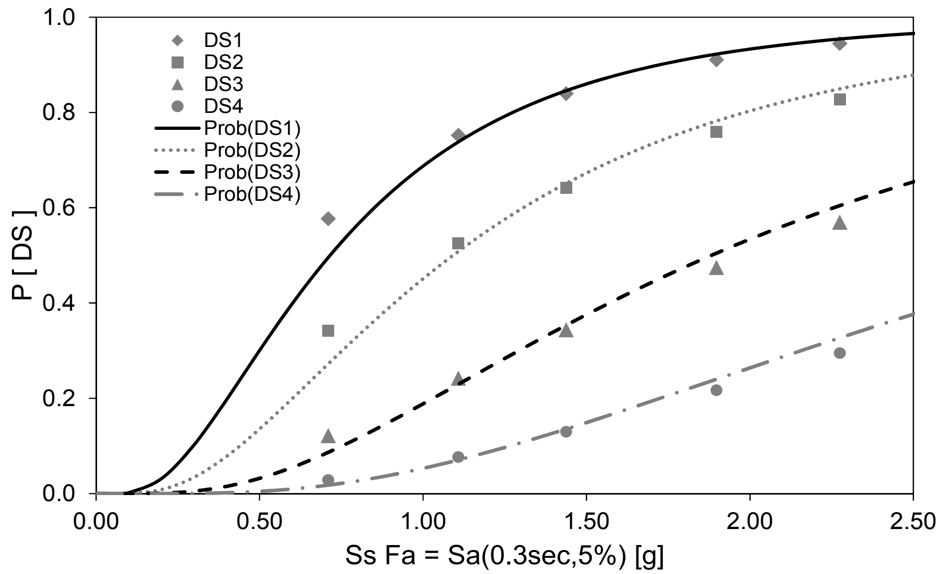


Figure 8 : Illustration of the fitted lognormal distribution for the hazard compatible fragility functions for URM brick buildings.

4. VALIDATION STUDY

The above procedure was validated conducting a rapid damage assessment of existing buildings in Old Quebec City. The study was motivated by the presence of numerous historic masonry buildings with unique heritage value and the obvious need to evaluate their behaviour under potential earthquake scenarios. The assessment was performed for a hypothetical M6.2R15 event which corresponds roughly to the probability of exceedence of 2% in 50 years according to the National Building Code of Canada (NBCC, 2010; Adams and Halchuk, 2003). The input response spectrum for the selected scenario was developed using the ground motion prediction equation given by Atkinson and Boore (2006). The ground motion parameters retained for the damage assessment were the spectral accelerations Sa0.3=0.38g and Sa1.0=0.07g as representative IMs for the short and long period range for the predominant site class B (rock) in the study area. The building inventory was compiled by a combination of data from the Quebec City municipal database and a field survey of 1220 buildings (Nollet et al., 2012). The inventoried buildings were classified according to: (1) construction material: wood, steel, concrete, masonry; (2) structural system: frame or wall structure; (3) seismic design code level: pre-code, low-code, mid-code and high-code; (4) height: 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, 2012). The inventory results are given in Table 5.

Table 5 : Distribution of building types in Old Quebec City

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

Table 5 shows that the dominant building types are the pre-code unreinforced brick masonry (62%) and stone masonry buildings (14%). 91% of the existing buildings were built before 1970. The first seismic provisions were introduced in the 1953 edition of the National Building Code and ever since they have evolved considerably. However, most of the buildings constructed prior to 1970 are considered as pre-code buildings, in particular the unreinforced masonry buildings, whereas buildings built between 1970 and 1990 are considered as mid-code. In addition, due to the similar construction practices in Canada and in the United States, the capacity curves and displacement based fragility functions used for the vulnerability modelling of the building types listed in Table 5 are the same as those suggested in Hazus (FEMA, 2012). The only exception were the stone masonry buildings, not explicitly considered by Hazus, for which capacity curves and damage fragility functions were generated by Abo-El-Ezz et al. (2011). The resulting fragility functions in terms of structure-independent IM for all buildings types considered in this study are presented in Appendix-I.

The computed damage levels experienced by the 1220 buildings and separated by building construction for the considered M6.2R15 scenario are given in Figure 9 and 10. The total number of buildings that will be subject to certain degree of damage is 369, or roughly 30% of the buildings. Predictably, most of the expected damage is due to the poor performance of the pre-code stone and brick masonry buildings. Approximately 39% of the stone masonry buildings (65 buildings out of 168) and 33% of the brick masonry buildings (252 buildings out of 765) will suffer certain damage.

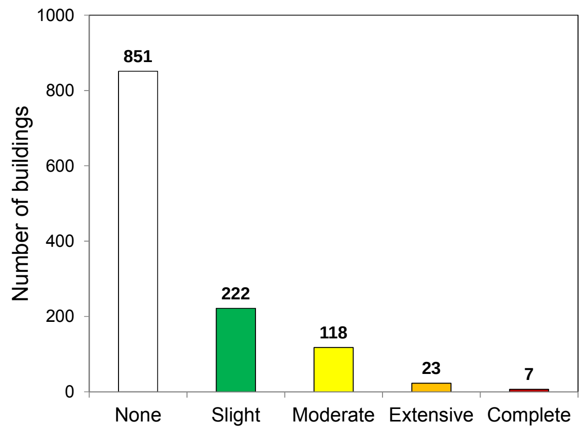


Figure 9 : Total number of buildings in each damage state for a scenario event M6.2R15.

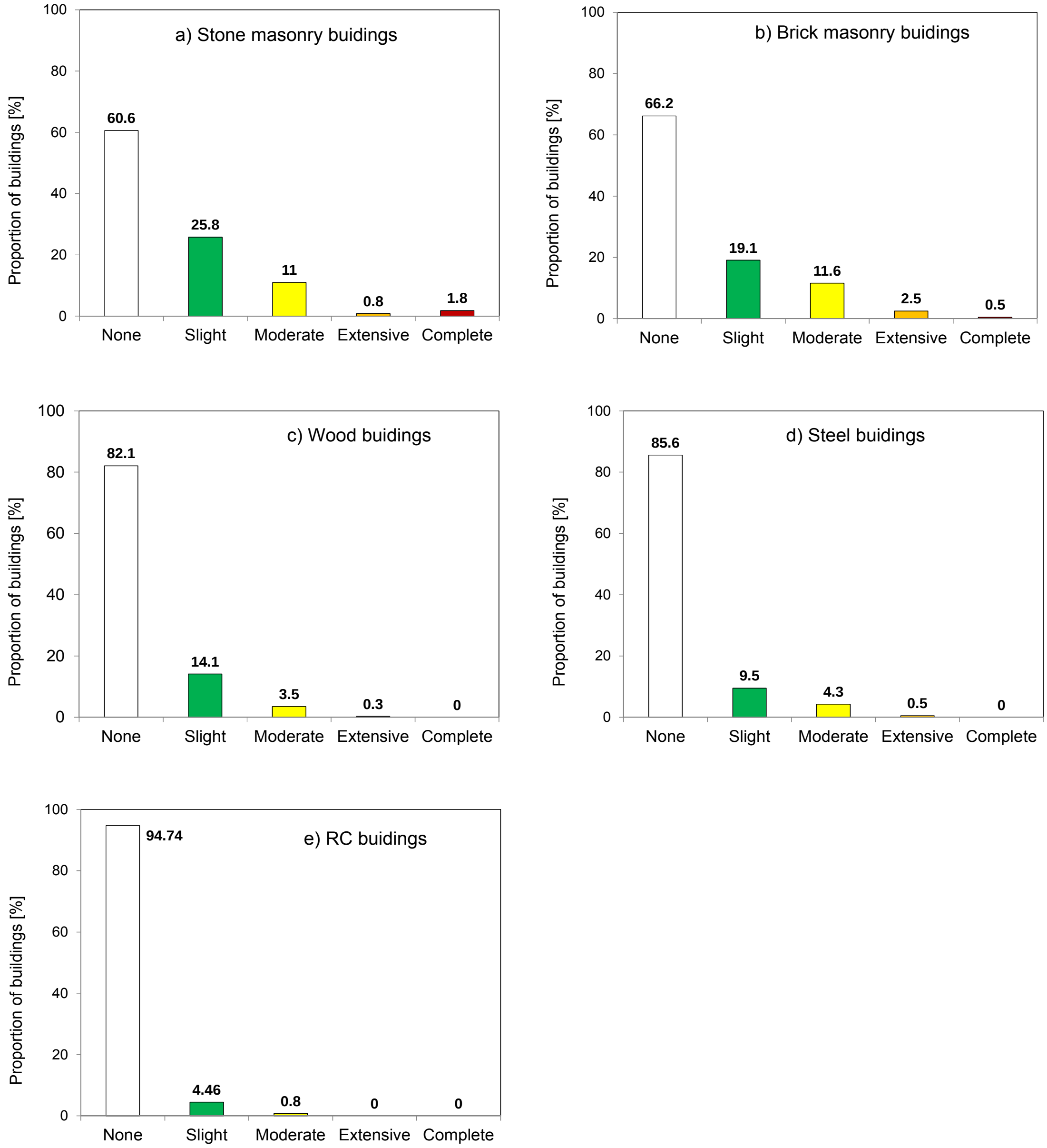


Figure 10 : Proportion of buildings by construction material type in each damage state for a scenario event M6.2R15.

5. COMPARISON WITH HAZUS

The obtained results were compared with damage estimates obtained with the Hazus software for the same structural and seismic settings. The comparison of probability of structural damage was conducted for the four building classes: pre-code unreinforced masonry low-rise buildings (URML_Precode), pre-code steel braced frame buildings (S2L_Precode), pre-code light wood frame buildings (W1L_Precode) and pre-code steel moment frame buildings (S1L_Precode). The comparison is presented in Table 6, which indicates almost identical results from both methods. More details on the comparison are given in Appendix-II.

Results obtained by one type of numerical modelling, according to the procedure developed in this study, are compared against results obtained with another type of simulations, with Hazus. In the absence of field observation records, this comparison confirms the validity of the developed procedure as, to ensure accurate risk assessments, the Hazus methodology has been subjected to extensive testing against actual damages during past earthquakes. Still the obtained results are sensitive to the assumed input parameters and uncertainties can result in considerable deviations (Abo-El-Ezz et al. 2012).

Table 6 : Comparison with damage assessments obtained with the Hazus software.

Probability of expected damage [%]	URMBL_Precode		S2L_Precode		W1L_Precode		S1L_Precode	
	This study	Hazus software	This study	Hazus software	This study	Hazus software	This study	Hazus software
None	64	66	86	87	79	79	89	84
Slight	19	18	9	9	16	16	8	13
Moderate	13	12	5	4	5	5	3	3
Extensive	4	3	0	0	0	0	0	0
Complete	1	1	0	0	0	0	0	0

6. CONCLUSIONS

A methodology was presented for rapid risk assessment in terms of seismic hazard compatible fragility functions conditioned to a structure-independent intensity measure IM, e.g., input spectral acceleration at a particular period for elastic 5% damping. The procedure combines (1) capacity curves which characterize the nonlinear behaviour of the existing buildings (exposure); (2) displacement fragility curves which represent the probability of exceedence of specified damage state under various levels of structural response (vulnerability); and (3) input response spectrum for the considered scenario used for the assessment of the structural demand imposed by the earthquake shaking (hazard). A modified capacity spectrum method is proposed for rapid evaluation of the potential damage to avoid the standard Hazus iterative procedure for obtaining the displacement response. Although it can be applied for a single building or a class of buildings, the developed methodology revealed particularly powerful for rapid regional-scale risk assessment as it significantly reduces the computation time and does not require a GIS platform as in the case of Hazus. Another advantage of the methodology is the flexibility to conduct a sensitivity study on the main input parameters that affects the damage assessment results.

The methodology was validated through damage assessment of 1220 existing buildings in Old Quebec City for a scenario event of magnitude 6.2 at distance 15km, with probability of exceedence of roughly 2% in 50 years. The results show that most of the expected damage would be concentrated in the brick and stone masonry buildings, with as much as 33% and 39% of at least slightly damaged buildings in each class. A comprehensive comparison with respective damage assessments obtained with the well known FEMA's Hazus software gives very similar results.

LIST OF BIBLIOGRAPHICAL REFERENCES

Abo-El-Ezz A., Nollet M.J., Nastev M., 2012. Development of seismic hazard compatible vulnerability functions for stone masonry buildings, *Proceedings of the Canadian Society of Civil Engineering 3rd Structural Specialty Conference*, Edmonton, Canada.

Abo-El-Ezz.A, Nollet. M.J, Nastev.M. 2011. Analytical displacement-based seismic fragility analysis of stone masonry buildings. *3rd Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN2011)*, Corfu, Greece.

Abo-El-Ezz A., Nollet M.J, and Nastev M. 2013a. « Seismic fragility assessment of low-rise stone masonry buildings ». *Journal of Earthquake Engineering and Engineering Vibrations*, Vol.12 No.1, 2013;

Adams, J. and Halchuk, S. 2003. *Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada*. Open File no. 4459, Geological Survey of Canada, Ottawa, Canada.

ATC-40. 1996. *Seismic evaluation and retrofit of concrete buildings*, Vol. 1, Applied Technology Council, Redwood City, CA, USA.

Atkinson, G. M. and Boore, D. 2006. Earthquake ground-motion prediction equations for eastern North America, *Bulletin of the Seismological Society of America*, 96, 2181-2205.

Coburn, A. and Spence, R. 2002. *Earthquake protection*, *2nd edition*, J. Wiley, Chichester, England.

FEMA 356. 2000. *FEMA 356 Pre standard and Commentary for the Seismic Rehabilitation of Buildings*. United States Federal Emergency Management Agency, Washington, D.C., USA.

FEMA. 2012. *Hazus®-MH 2.1 – Earthquake Model Technical Manual*. Federal Emergency Management Agency, Washington, D.C, 718 p.

Mahaney,A; Paret, T.F; Kehoe,B.E. and Freeman. S.A. (1993). The Capacity Spectrum Method for Evaluating Structural Response during the Loma Prieta Earthquake. *Proceedings of the 1993 United States National Earthquake Conference*, Memphis, Tennessee. Vol. 2, 501-510.

NBCC (2010). National Building Code of Canada, National Research Council of Canada, Institute for Research in Construction, Ottawa, Canada.

Nollet M.J, Désilets C., Abo-El-Ezz A., Nastev M., (2012). *Approche méthodologique d'inventaire de bâtiments pour les études de risque sismique en milieu urbain*. Open File 7260, Geological Survey of Canada, Canada.

Porter, K.A., 2002. Seismic vulnerability. Chapter 21, *Handbook of Earthquake Engineering*, W.F. Chen and C.R. Scawthorn, eds., CRC Press, Boca Raton, FL

Porter, K. A., 2009. Cracking an open safe: HAZUS vulnerability functions in terms of structure-independent spectral acceleration, *Earthquake Spectra* 25, 361–378.

APPENDICES

APPENDIX-I: Structural and vulnerability parameters for buildings in Old Quebec City

Table-A I-1 Capacity curves input parameters (FEMA, 2012)

Building Type	D_y(m)	A_y (g)	D_u (m)	A_u (g)	ξ_e	κ
W1L-precode	0.006	0.2	0.110	0.6	15%	0.3
W1L-midcode	0.009	0.3	0.165	0.9	15%	0.6
S1L-precode	0.004	0.062	0.070	0.187	5%	0.2
S1L-midcode	0.008	0.125	0.140	0.375	5%	0.4
S1M-precode	0.011	0.039	0.135	0.117	5%	0.2
S2L-precode	0.004	0.1	0.048	0.2	5%	0.2
S2L-midcode	0.008	0.2	0.096	0.4	5%	0.4
S2M-precode	0.015	0.083	0.123	0.167	5%	0.2
S5L-precode	0.003	0.1	0.030	0.2	5%	0.2
C1M-midcode	0.015	0.104	0.176	0.312	7%	0.4
URML-precode	0.006	0.2	0.061	0.4	10%	0.2
URMM-precode	0.007	0.11	0.046	0.222	10%	0.2

Table-A I-2 Displacement fragility functions input parameters (FEMA, 2012)

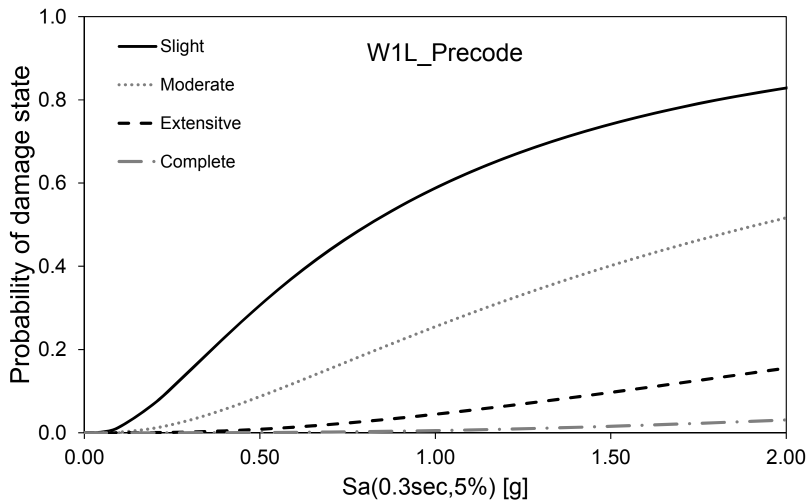
Building Type	S_d (m)							
	Slight		Moderate		Extensive		Complete	
	λ_1	β_1	λ_2	β_2	λ_3	β_3	λ_4	β_4
W1L-precode	0.010	1.01	0.025	1.05	0.078	1.07	0.192	1.06
W1L-midcode	0.013	0.84	0.032	0.86	0.098	0.89	0.240	1.04
S1L-precode	0.026	0.85	0.042	0.82	0.089	0.80	0.219	0.95
S1L-midcode	0.033	0.80	0.057	0.75	0.129	0.74	0.329	0.88
S1M-precode	0.044	0.70	0.070	0.75	0.148	0.81	0.366	0.98
S2L-precode	0.022	1.01	0.035	0.96	0.088	0.88	0.219	0.98
S2L-midcode	0.027	0.93	0.047	0.92	0.128	0.93	0.329	0.93
S2M-precode	0.037	0.73	0.058	0.75	0.146	0.80	0.366	0.98
S5L-precode	0.013	1.20	0.026	1.11	0.066	1.08	0.154	0.95
C1M-midcode	0.038	0.70	0.066	0.70	0.178	0.70	0.457	0.89
URML-precode	0.008	1.15	0.017	1.19	0.041	1.20	0.096	1.18
URMM-precode	0.013	0.99	0.026	0.97	0.064	0.90	0.149	0.88

Table-A I-3 Capacity curves for stone masonry buildings in Quebec (Abo-El-Ezz et al. 2013)

URM Stone	D_y(m)	A_y (g)	D_u (m)	A_u (g)	ξ_e	κ
	0.005	0.3	0.028	0.3	10%	0.2

Table-A I-4 Displacement fragility functions for stone masonry buildings in Quebec (Abo-El-Ezz et al. 2013)

Building Type	S_d (m)							
	Slight		Moderate		Extensive		Complete	
	λ_1	β_1	λ_2	β_2	λ_3	β_3	λ_4	β_4
URM Stone	0.005	0.53	0.012	0.61	0.021	0.61	0.028	0.67



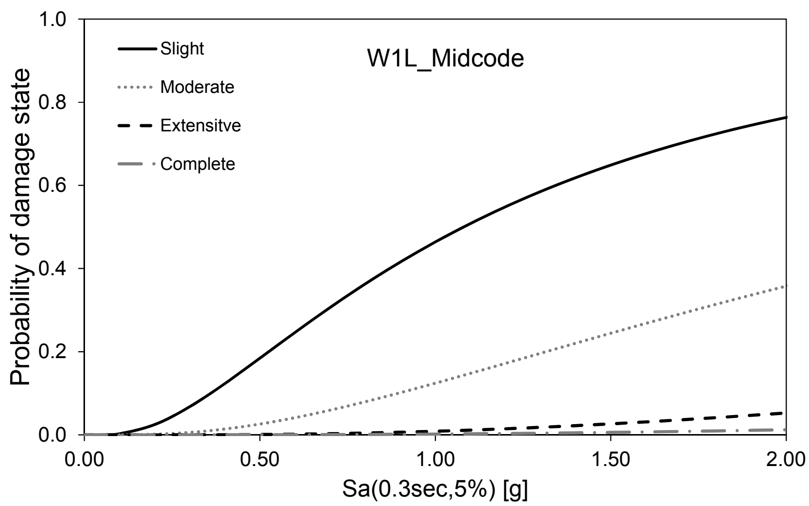


Figure-A I-1 Seismic hazard compatible fragility for building types in Old Quebec City.

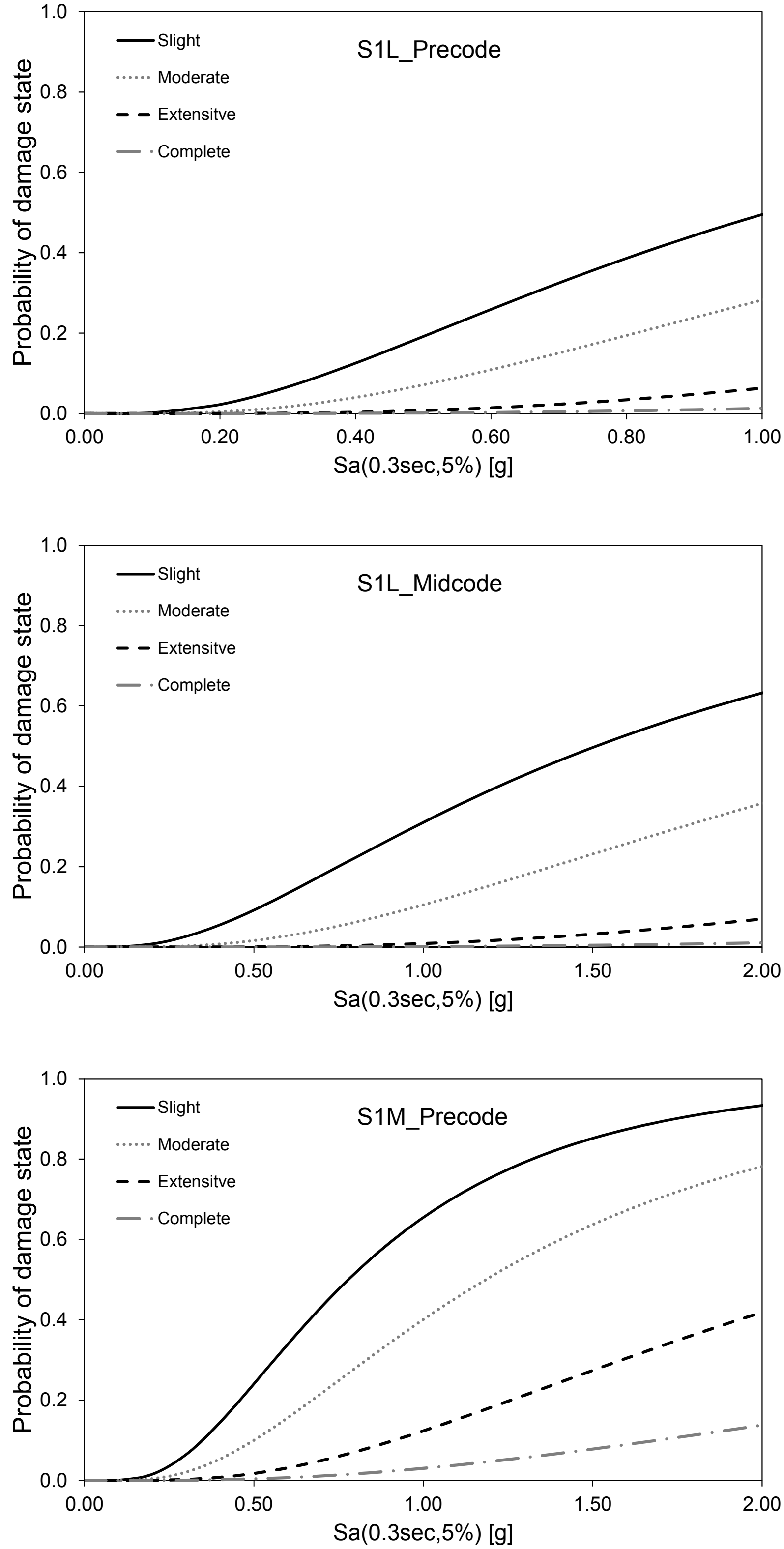
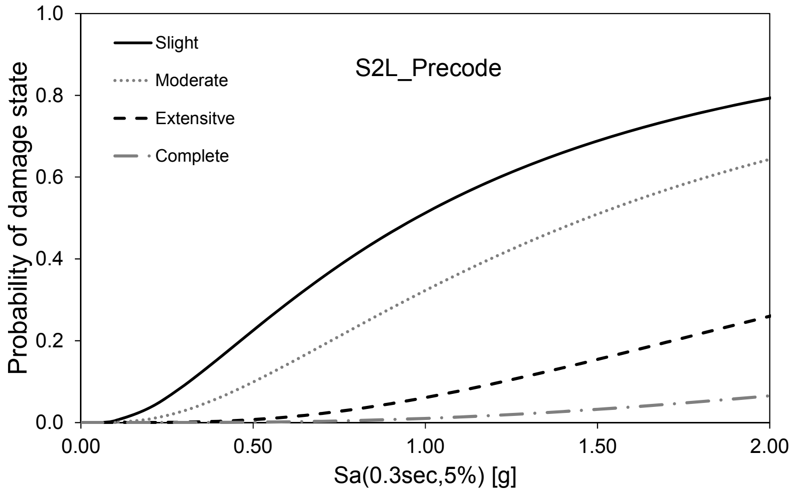
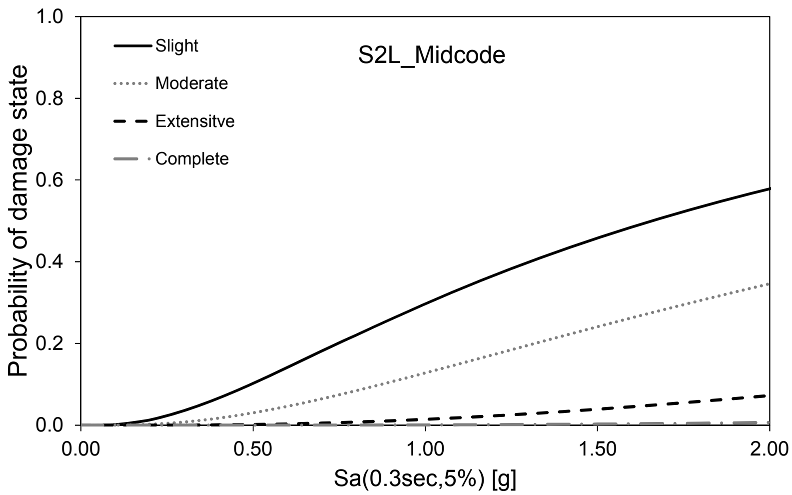


Figure-A I-1 Seismic hazard compatible fragility for building types in Old Quebec City (continued).





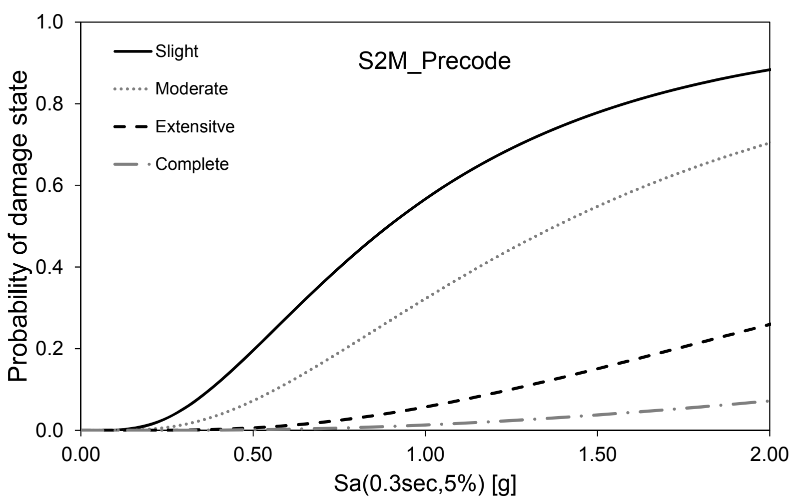
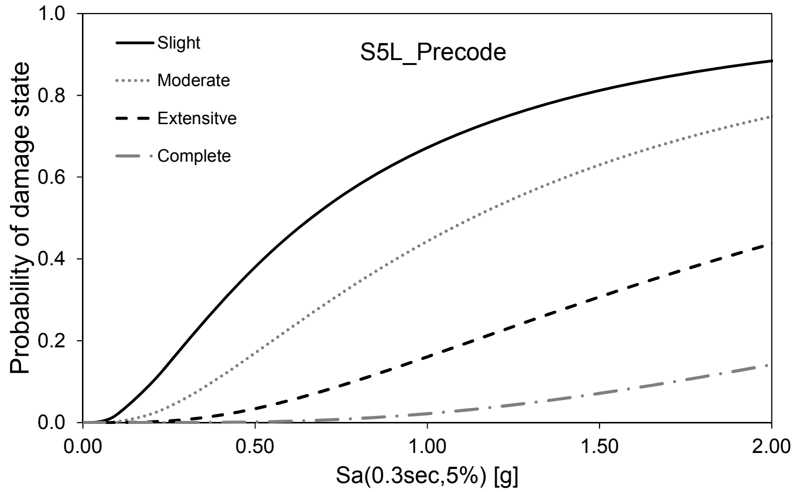
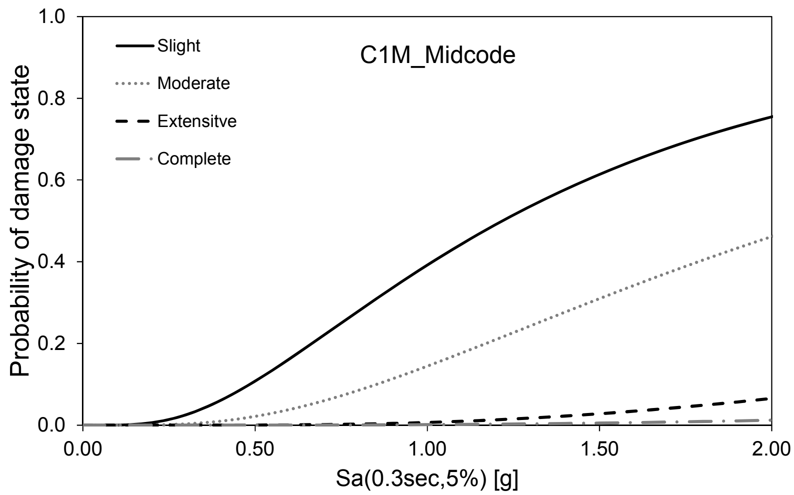


Figure-A I-1 Seismic hazard compatible fragility for building types in Old Quebec City (continued).





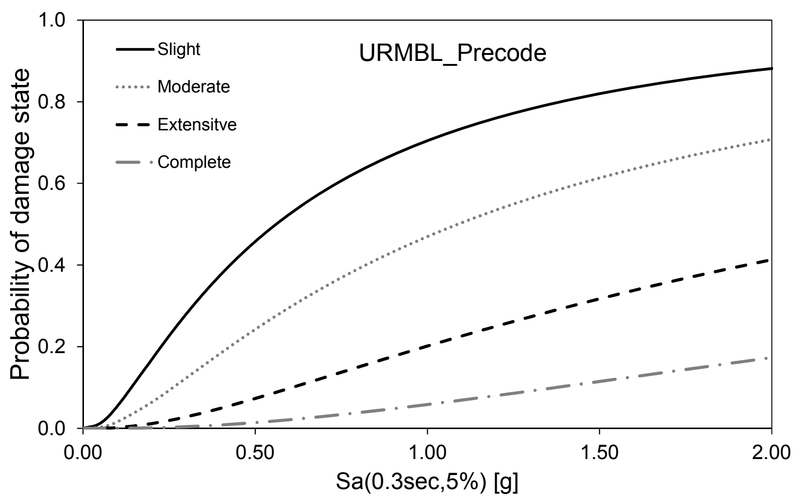
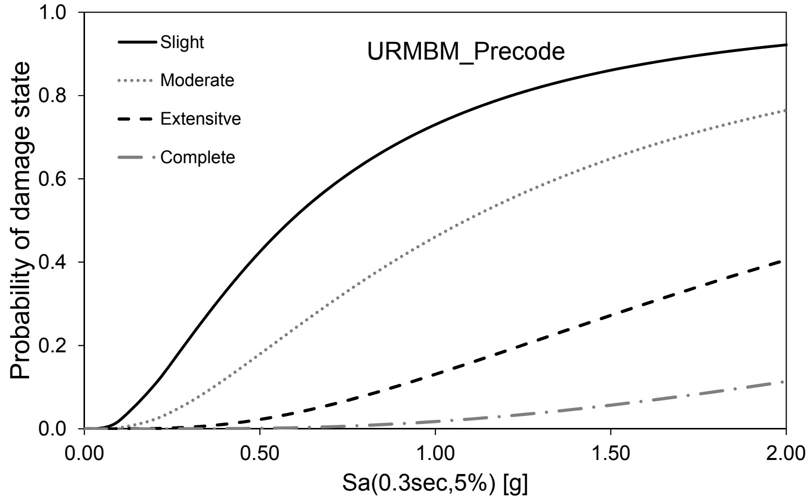


Figure-A I-1 Seismic hazard compatible fragility for building types in Old Quebec City (continued).



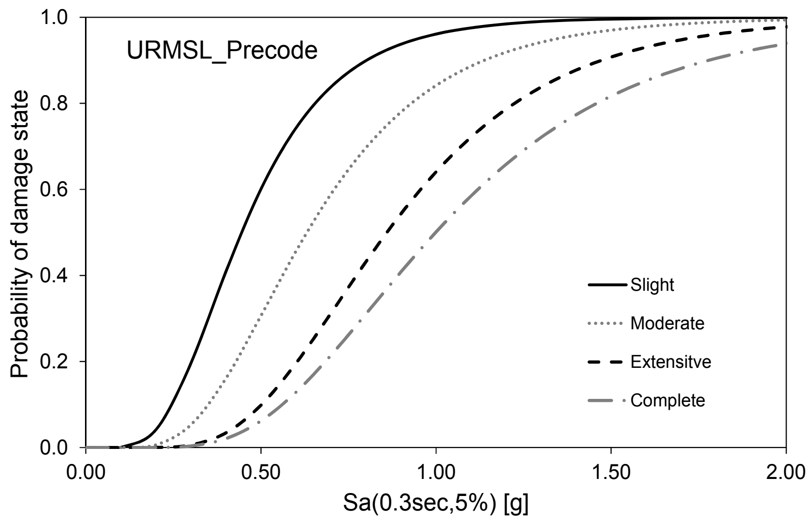
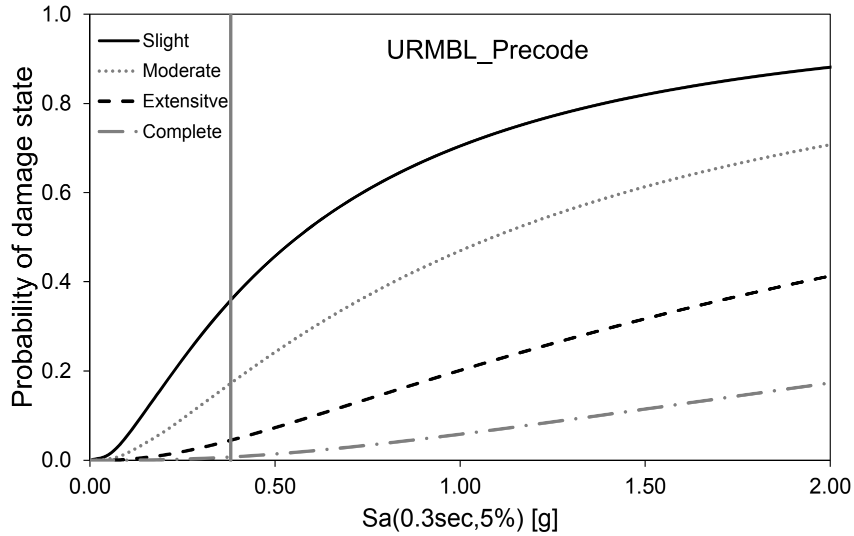


Figure-A I-1 Seismic hazard compatible fragility for building types in Old Quebec City (continued).

Appendix-II: Comparison against damage assessments with the Hazus software

The comparison of probability of structural damage is conducted for four building classes: URML_Precode, S2L_Precode, W1L_Precode and S1L_Precode. Figures A-II-1 to A-II-8 present the damage prediction using the procedure proposed in this study and the results from Hazus software for the considered seismic scenario of M6.2R15km.

(a)



(b)

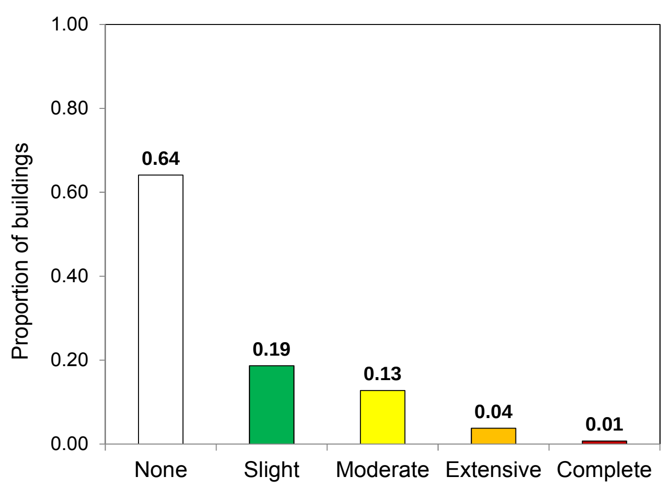


Figure-A II-1 Illustration of damage assessment using the procedure in this study: (a) fragility functions for URMBL-Precode building class and (b) the predicted damage proportions for Sa0.3=0.38g.

HAZUS AEBM- Individual Building Report

7/20/2012

Building Information

Id Number:	US000014
Building Name:	24041001085_4_RES1_URML
Address:	Address
Latitude / Longitude:	45.61/-71.32
Building Profile:	4_RES1_URML_PC

Ground Motion

SA @ 0.3 seconds (g) :	0.38
SA @ 1.0 seconds (g) :	0.07
PGA (g) :	1.00
Soil Type :	Very Dense Soil and Soft Rock

Building Intersection Points

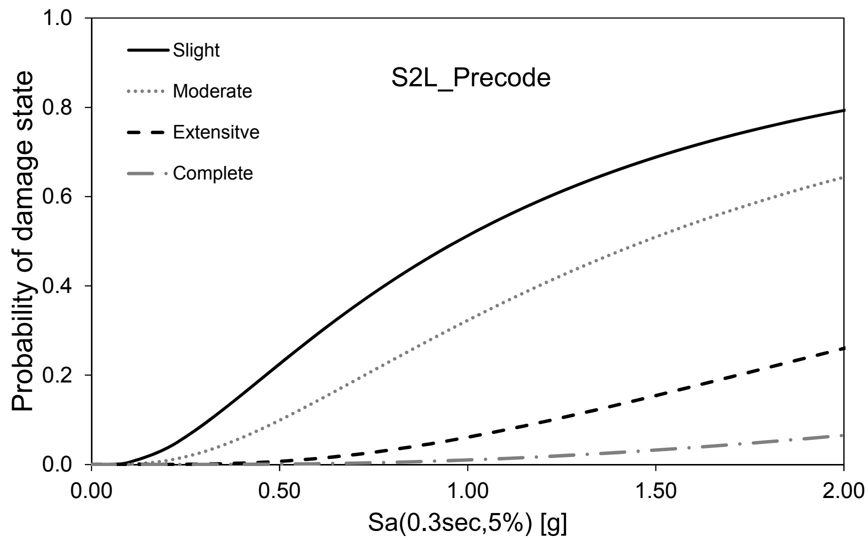
Displacement (in) :	0.20
Acceleration (g) :	0.58

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	66.0	79.0	6.0
Slight	18.0	12.0	22
Moderate	12.0	7.0	41
Extensive	3.0	1.0	25
Complete	1.0	1.0	6

Figure-A II-2 Hazus software damage prediction for Sa0.3=0.38g for the URML_Precode building class.

(a)



(b)

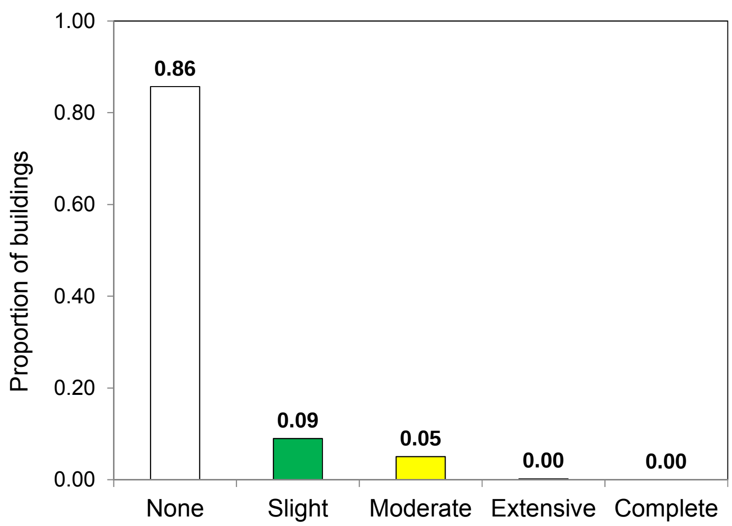


Figure-A II-3 Illustration of damage assessment using the procedure in this study: (a) fragility functions for S2L-Precode building class and (b) the predicted damage proportions for Sa0.3=0.38g.

HAZUS AEBM- Individual Building Report

7/20/2012

Building Information

Id Number: US000026

Building Name: 24041001085_7_RES1_S2L_F

Address: Address

Latitude / Longitude: 45.61/-71.32

Building Profile: 7_RES1_S2L_PC

Ground Motion

SA @ 0.3 seconds (g) : 0.38

SA @ 1.0 seconds (g) : 0.07

PGA (g) : 1.00

Soil Type : Very Dense Soil and Soft Rock

Building Intersection Points

Displacement (in) : 0.28

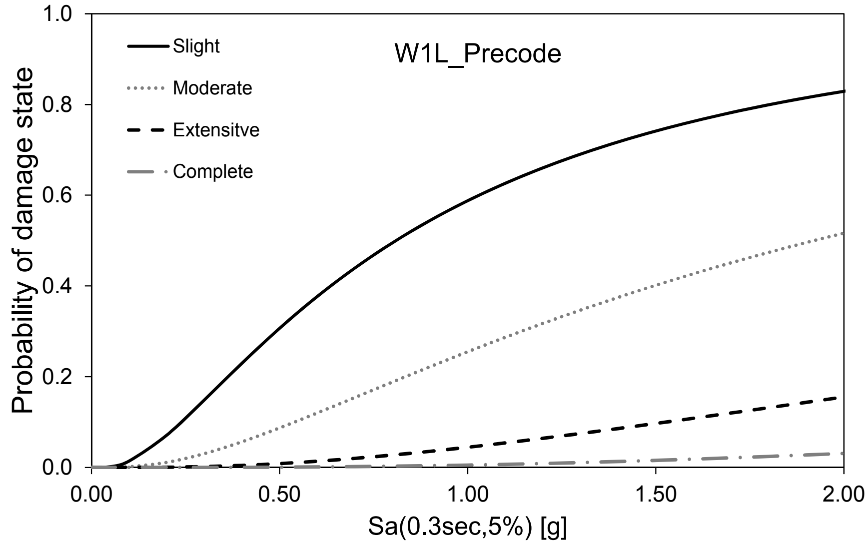
Acceleration (g) : 0.57

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	87.0	86.0	5.0
Slight	9.0	11.0	25
Moderate	5.0	3.0	39
Extensive	0.0	0.0	24
Complete	0.0	0.0	6

Figure-A II-4 Hazus software damage prediction for Sa0.3=0.38g for the S2L_Precode building class.

(a)



(b)

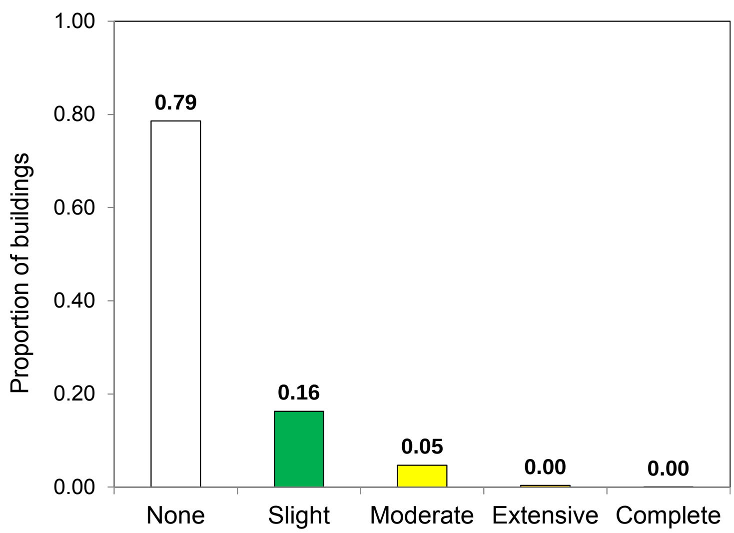


Figure-A II-5 Illustration of damage assessment using the procedure in this study: (a) fragility functions for W1L-Precode building class and (b) the predicted damage proportions for Sa0.3=0.38g.

HAZUS AEBM- Individual Building Report

7/20/2012

Building Information

Id Number: US000017

Building Name: 24041001085_5_RES1_W1_P(

Address: Address

Latitude / Longitude: 45.61/-71.32

Building Profile: 5_RES1_W1_PC

Ground Motion

SA @ 0.3 seconds (g) : 0.38

SA @ 1.0 seconds (g) : 0.07

PGA (g) : 1.00

Soil Type : Very Dense Soil and Soft Rock

Building Intersection Points

Displacement (in) : 0.17

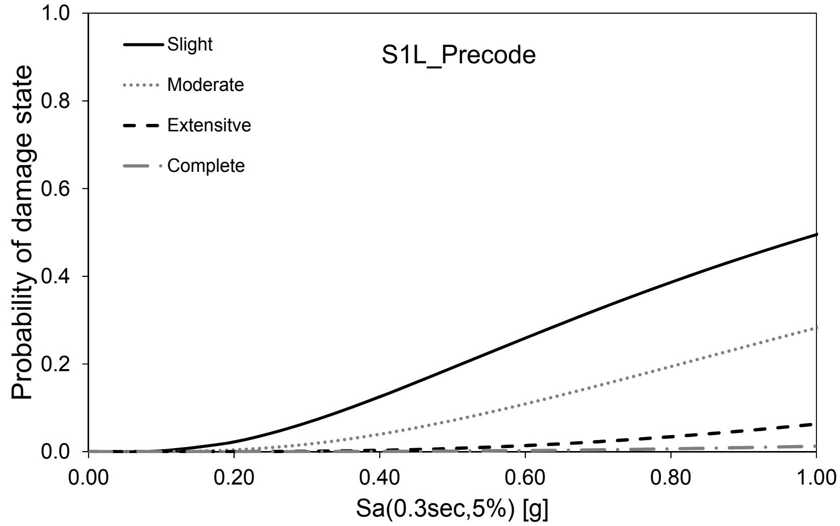
Acceleration (g) : 0.57

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	79.0	84.0	7.0
Slight	16.0	11.0	23
Moderate	4.0	5.0	39
Extensive	0.0	0.0	25
Complete	0.0	0.0	6

Figure-A II-6 Hazus software damage prediction for Sa0.3=0.38g for the W1L_Precode building class.

(a)



(b)

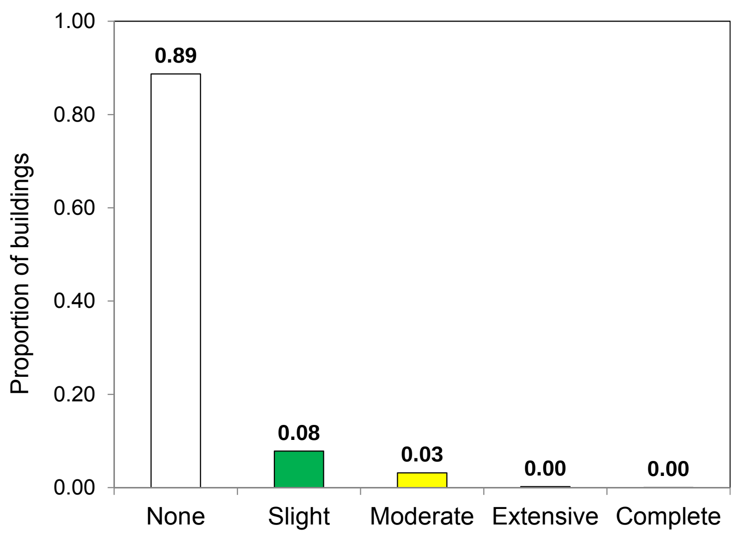


Figure-A II-7 Illustration of damage assessment using the procedure in this study: (a) fragility functions for S1L-Precode building class and (b) the predicted damage proportions for Sa0.3=0.38g.

HAZUS AEBM- Individual Building Report

7/20/2012

Building Information

Id Number: US000022

Building Name: 24041001085_6_RES1_S1L_F

Address: Address

Latitude / Longitude: 45.61/-71.32

Building Profile: 6_RES1_S1L_PC

Ground Motion

SA @ 0.3 seconds (g) : 0.38

SA @ 1.0 seconds (g) : 0.07

PGA (g) : 1.00

Soil Type : Very Dense Soil and Soft Rock

Building Intersection Points

Displacement (in) : 0.36

Acceleration (g) : 0.55

Building Damage

Damage State	Damage State Probabilities (%)		
	Structural	Non-Structural Drift	Non-Structural Acceleration
None	90.0	84.0	6.0
Slight	7.0	13.0	26
Moderate	3.0	3.0	39
Extensive	0.0	0.0	23
Complete	0.0	0.0	6

Figure-A II-8 Hazus software damage prediction for Sa0.3=0.38g for the S1L_Precode building class.