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SEISMIC ASSESSMENT OF TYPICAL UNREINFORCED MASONRY BUILDINGS USING NON-LINEAR TIME HISTORY ANALYSIS

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ABSTRACT: Unreinforced Masonry (URM) buildings are vulnerable to damage during strong earthquakes. Seismic assessment of URM buildings is essential for seismic loss estimation and implementation of seismic risk mitigation strategies. While there have been previous assessments of URM buildings in seismically active regions of the world, the assessment of buildings in Canada, with specific focus on the building inventory in Ottawa has been sparse. The existing Canadian practice is limited to rapid seismic screening of buildings, with occasional analysis of single structures. A detailed building inventory has been compiled for Ottawa recently by Sawada et al. (2014) who included data for over 50,000 buildings. This database was used in the current investigation to classify URM buildings into two different categories; low-rise and mid-rise buildings. The seismic vulnerability of representative buildings from each category was assessed by conducting non-linear time history analyses. The analyses were carried using software that incorporates incremental dynamic analysis and applied element method, thereby effectively modelling both in-plane and out-of-plane behaviour of masonry walls. Non-linear time-history analyses were conducted with the aim of developing seismic fragility curves for representative buildings. The fragilities reflect the effects of year of construction, and were developed by scaling synthetic earthquake.

1. Introduction

Past earthquakes have shown that unreinforced masonry structures are highly vulnerable to strong ground motions. This has once again become clear after the 2011 Christchurch Earthquake in New Zealand, which resulted in a devastation caused by extensive damage to URM buildings. In eastern Ontario and western Quebec, some significant earthquakes have occurred in the last century, notably: Val-des-Bois in 2010; Ste-Agathe-des-Monts in 1996 and 1997; Cornwall in 1944; and Temiscaming in 1935. Despite the frequency of seismic activity, there has not been a major earthquake in the region which could be recorded and compared to observed damage. As a result, seismic engineers are left with probabilistic tools to assess structures and to prevent possible damage.

Seismic assessment is a tool whereby it can be used both for loss estimation after an earthquake as well as helping authorities to dispatch help where it is most needed. It can also be used as a risk mitigation tool: once it is known that a structure is susceptible to significant damage, it is easier to justify its seismic rehabilitation.

In Canada, various studies have tried to meet the need for loss estimation of unreinforced masonry. Karbassi (2010) developed fragility curves for early 20th century industrial structures. This proved to be a great step; yet, the amount of industrial URM structures is quite limited and therefore not representative of the building stock. Abo-El-Ezz et al. (2013) is another example of work done on URM structures. In this study, the authors focused on stone masonry, which is not one of the common construction materials used in slightly more recent construction in eastern Canada. Therefore, this still meant limited use of the fragility curves. Elsabbagh (2013) worked with structures in Ottawa by using fuzzy logic and engineering sense to estimate damageability of structures due to various parameters. This was another good step in the right direction, but it is based on user judgement and input and hence may be viewed as having subjectivity.

The present study aims to define statistically significant fragility curves that can be applicable to most of the URM stock in the city of Ottawa. In order to do this, the authors consulted a large building inventory collected in Ottawa. This allowed the classification of structures based on a limited set of parameters and therefore the ability to generate fragility curves that give lower and upper boundaries for various URM buildings situated in the area. The steps required to do this include: selection of appropriate ground motions representative of the area's seismicity; defining a damage measure, which establishes a link between the ground motion and agreed upon performance levels; and the selection of a proper evaluation method to obtain sufficient information to generate probabilistic functions. This paper presents an approach to clarify the steps to be undertaken for seismic assessment of unreinforced masonry buildings in the National Capital Region.

2. Building Inventory

An important part of performing seismic assessment for a region is to determine representative structures of the various building categories present. Sawada et al. (2014) developed a geographic information system inventory of structures in the city of Ottawa, which at the time of writing contains just over 50,000 structures. This database was used to identify typical URM structures present in Ottawa. Structures were classified by building type according to the HAZUS-MH classification system. As a result, this study could focus on unreinforced masonry bearing wall structures, labeled URML and URMM for low-rise and mid-rise respectively. These URM structures formed 4% of the overall database.

Among the variables used to describe each structure, the following were studied to identify the characteristics of a typical URM structure in Ottawa: i) year of construction, ii) number of stories, iii) plan irregularities and iv) vertical irregularities. This information was obtained by trained personnel who conducted on-site assessment to confirm proper evaluation.

2.1. Year of Construction

The year of construction was obtained from municipal databases or, where information was lacking, educated guesses based on the construction practices of different eras. This parameter is important as it directly relates to the construction quality and mechanical properties of materials used. Older construction often had lower standards and have been subject to weathering for a long period of time. As a result, spalling of mortar is evident on many of these old URM structures. Moreover, the minimum mandatory strength of materials has increased over the years. Among the URM structures in the database, 82% were built before 1945 and 97% before 1970.

2.2. Number of Storeys

The number of storeys plays an important role on response to earthquakes. As can be seen in Figure 1, 96% of the buildings were found to be less than four storeys high.

2.3. Plan Irregularities

Plan irregularities can give insight to the vulnerability of certain portions of a structure. The variables include detailed torsional irregularities and re-entrant corners. These were labeled using a scale in ascending degree of severity, as: i) not applicable, ii) negligible, iii) low, iv) moderate, v) high and vi) very high. For re-entrant corners, 66% of structures were found to have no irregularity while 91% were of low severity or less. On the other hand, 93% of the same structures were found not to have any torsional irregularity.

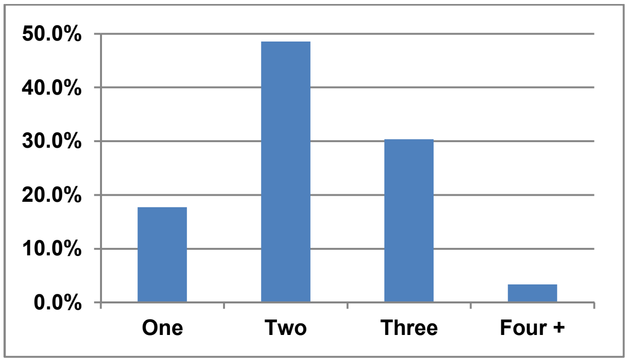


Figure 1 – Percentage of URM buildings with number of storeys

2.4. Vertical Irregularities

Vertical irregularities can be a source of considerable damage in a structure, and sometimes lead to complete collapse. The parameters considered to identify vertical irregularities include, soft storeys, weak storeys and the storey height. 93% of structures were found to be without any soft storey while 98% did not present any weak storeys. The URM buildings that have the same storey height formed 96% of those in the inventory.

2.5. Visual Information

Once the URM variables from the database were analyzed, visual information was collected using Google Earth and on-site visits. This gave insight on information not available in the database, such as geometric dimensions, arrangements of openings and bearing wall slenderness.

3. Methodology

In order to conduct seismic assessment, one has to define the parameters that are critical for establishing a probabilistic estimate of damage. Based on the information given in Section 2, representative URM structures were selected to cover most of the building stock in Ottawa. The information collected also included additional structural characteristics. In addition, seismic accelerograms of the region, as well as a method for measuring damage were selected. Finally, the parameters were brought together using incremental dynamic analysis to generate fragility curves.

3.1. Representative URM Structures

The 50,000 structures included in the inventory showed that most URM structures were regular in shape, with little plan and vertical irregularities. As a result, rectangular shapes were selected to represent the building stock. It was judged unnecessary to include irregularities for the small percentage of structures not meeting this criteria, as the irregular buildings differed greatly from one another. It would not be feasible to perform seismic assessment of all the irregular structures, unless a specific structure did require one.

3.1.1. Categories

One low-rise and one mid-rise structure were selected. A 2-storey structure was selected to represent low-rise URM buildings due to its prevalence (nearly 50% of all URM). It also happens to be conservative compared to single storey structures as was shown by Barrantes (2012), though both single-storey and two-storey URM buildings behave similarly. For the mid-rise structure, a 3-storey structure was selected given that it is the second most prevalent number of storeys in the inventory. At the time of writing, analysis of the low-rise structure had only just begun. As a result, it will not be discussed further in this paper.

3.1.2. Effects of Age

Given the variability in the age of building stock, it is impossible to consider all possible variations. As a result, lower and upper bound values were selected for mechanical properties of materials based on literature review. The work of Lefebvre (2004), who conducted a review of URM properties in the 20th century for eastern Canada, was indispensable in determining the lower end of masonry strength that corresponds to the start of the 20th century construction. On the other hand, structures built in the 1970s or later may not have undergone serious degradation and therefore may still be the same as used currently in the masonry industry. In this instance, the minimum specified strength by the Design of Masonry Structures S304.1-04 as well as the work of Drysdale and Hamid (2005) defined the upper boundary.

3.1.3. Effects of Openings

The presence of openings, doors or windows, has a significant effect on the failure mechanism of URM structures. For this reason, each structure is asymmetrical. In one direction, the amount of openings is significant – leading to a low ratio of rigidity compared to a whole bearing wall – while the other direction has few openings. Depending on structures, a conservative estimate can be taken by considering the orthogonal wall direction with the most openings.

3.2. Seismic Intensity

Despite the high seismic potential activity in eastern Canada, there has not been a large number of recorded accelerograms to perform statistically significant seismic assessment. As a result, synthetic accelerograms were deemed a suitable replacement; the works of Atkinson and Beresnev (1998) and Atkinson (2009) granted records easily matching the uniform hazard spectra (UHS) by following the selection procedure proposed in the latter work for ground motions of soil class C. The period of URM structures is typically no more than 0.4 or 0.5s (Mouyannou et al., 2014; Ingham and Griffith, 2011; Pantazopoulou, 2013) which means that the target spectrum would be in the lower end of the period range considered in UHS. 20 accelerograms were selected, based on the following criteria: near-fault or far-fault and magnitude 6.0 or 7.0. This permits the comparison of the effects of seismicity, while maintaining good fidelity with seismic activity near Ottawa. The average scaled spectrum compared to the UHS for Ottawa can be seen in Figure 2.

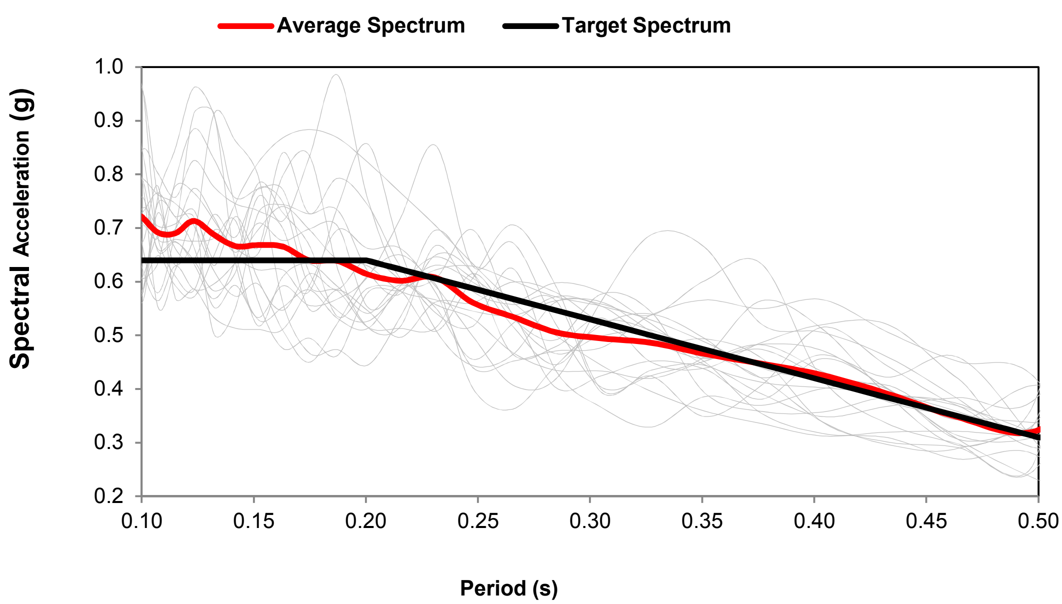


Figure 2 – Scaled Accelerograms for Ottawa UHS

Ground motion intensity will be primarily measured as a function of spectral acceleration due to the fact that the selection criterion of the ground motions was done by comparing the standard deviation of the target spectrum to the spectral acceleration of the record. Since the data is available, peak ground acceleration will also be used as an intensity measure in order to see if any correlation can be found.

3.3. Damage Measure

A performance-based approach was selected to represent the general damage level of the structures. The performance levels defined in ASCE 41-13 (2013) have been adopted. These performance levels are: i) immediate occupancy (IO), ii) life safety (LS) and iii) collapse prevention (CP). Depending on the structure and its collapse mechanism, various indices are proposed. For the mid-rise structure, it was found that star-stepped cracks around the openings would govern the failure mechanism. This is typical of shear failures and CP levels have been suggested to occur around inter-storey drift levels of 0.4% (Priestley et al., 2004). This was later confirmed by observing drift of local elements around openings. The inter-storey drift levels closely matched those of the piers near these openings. The performance levels for in-plane piers and walls are shown in Table 1 with symbols defined in Figure 3.

Table 1 – Performance Levels as Governed by Percentage Drift Levels

Acceptance Criteria			
	Immediate Occupancy (%)	Life Safety (%)	Collapse Prevention (%)
Piers	0.1	$0.3h_{eff}/L$	$0.4h_{eff}/L$
Inter-storey	0.1	0.3	0.4

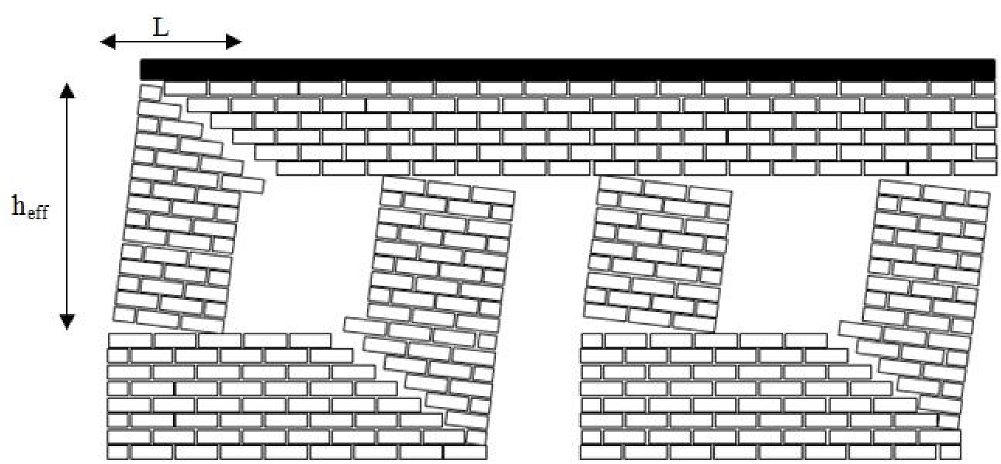


Figure 3: Observed Behaviour and Pier Characteristics

3.4. Incremental Dynamic Analysis and Damage Probability

Incremental dynamic analysis (IDA) was used to generate the complete spectrum of damage ranges for the mid-rise URM. This involves scaling the 20 ground motions previously selected to various degrees in order to generate an IDA curve in each case. This curve gives invaluable information on the structure's performance during an earthquake and allows the user to pinpoint the performance levels as a function of ground motion intensity. The general guidelines proposed by Vamvatsikos and Cornell (2002) were used to perform the IDA, most notably the hunt and fill algorithm.

It further gives some clarification on the capacity of the structure to resist a particular ground excitation. In some cases, it was noticed that the structure was able to reach neither the selected interstorey drift levels nor local drifts specified in Table 1 prior to collapse. Conversely, some ground motions allowed the structure to attain drift levels significantly beyond those specified in Table 1 without exhibiting collapse. When either of these situations presented itself, the IDA curve became a necessary tool to determine the performance levels. For example in the IDA curve shown in Figure 4, immediate occupancy performance level was selected to occur at the appearance of minor cracking, as an indication of the onset of nonlinearity. Life safety limit was assumed to be reached when extensive cracking began to appear as indicated by the point beyond which the curve started to flatten significantly. Collapse prevention point was assumed to be reached at a point where the slope of the curve became less than 20% of the initial elastic tangent, as suggested by Vamvatsikos and Cornell (2002). For this specific accelerogram, the life safety and collapse prevention performance level damage indicators are significantly higher than those proposed earlier as included in Table 1.

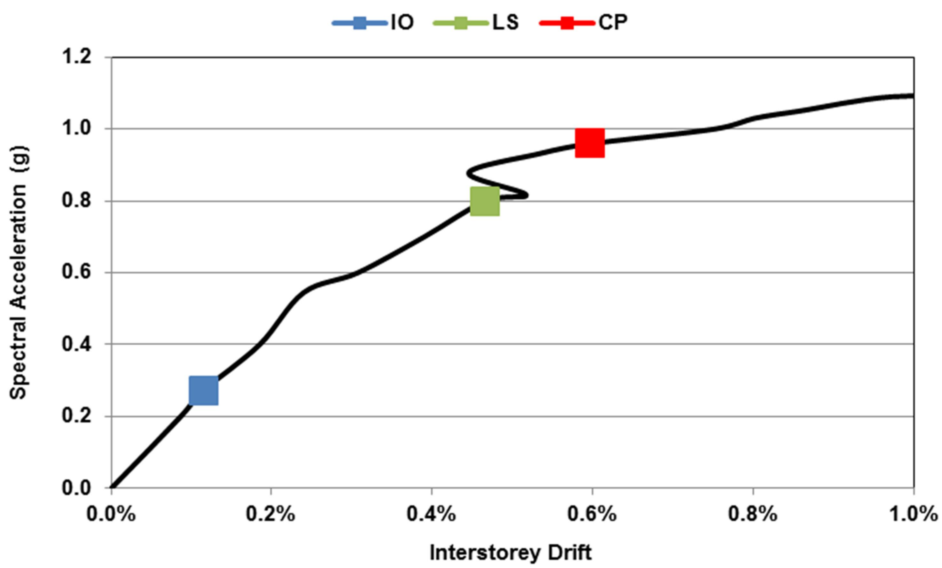


Figure 4 – IDA curve for ground motion #1

In general, the designated damage measures for performance levels were representative of the structure's behaviour as shown in the multiple records IDA curves depicted in Figure 5. While some variability can be observed, we note that immediate occupancy level is consistently well defined by all the IDA curves as the onset of initial cracking (departure from linear elastic portion) at about the same interstorey drift level, which has been adopted and used in Table 1.

The next step in the seismic assessment is to define a probabilistic damage function, which relates performance levels to ground motion intensity. The well-known concept of fragility curves was judged to be the most suitable for this task. The fragility curve can be established by using Eq. 1.

$$F(X) = P(d > D) = \phi\left[\frac{\ln(X)-\ln(\mu)}{\ln(\sigma)}\right] \qquad (1)$$

Where, F represents the fragility curve; X is the ground motion intensity (spectral or peak ground acceleration); P is the probability of exceedance of a given performance level; d is the observed damage level (inter-storey drift); D is the threshold for the selected performance level; ϕ is the cumulative normal density function; $\ln(\mu)$ is the median of logarithmic intensity measure and $\ln(\sigma)$ is the standard deviation of the same logarithmic intensity measure.

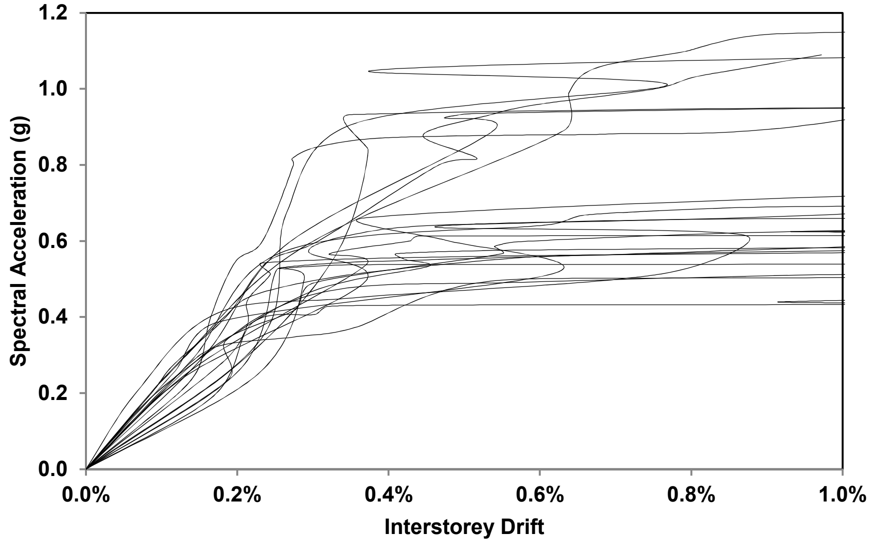


Figure 5 – Multiple Records IDA curves

3.5. Structure Modeling

The structure was modelled using applied element software "Extreme Loading® for Structures" by Applied Science International. This software was selected for its ease of modelling masonry, and more specifically the ability of its elements to simulate rigid masonry blocks without having to input data to simulate cracking in masonry prisms. This has become possible because the elements are connected to each other by means of springs, which carry normal and shear forces. Furthermore, connectivity between the elements meeting at a corner was easily made by means of these springs. This ensures that out-of-plane walls contribute to the required stiffness of in-plane walls. A sample model of the mid-rise structure can be seen in Figure 6. An external module using the freeware scripting language AutoIt v3 was written and compiled by the authors to handle the incremental dynamic analysis portion of the analysis. This greatly simplified the analysis process and made it possible to handle thousands of simulations with relative ease.

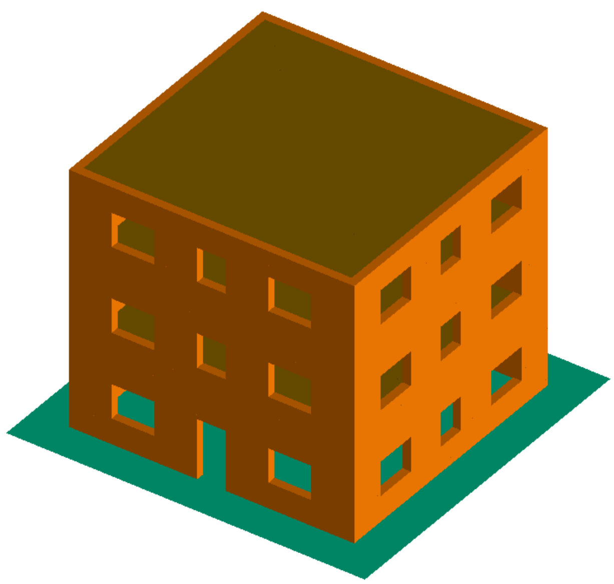
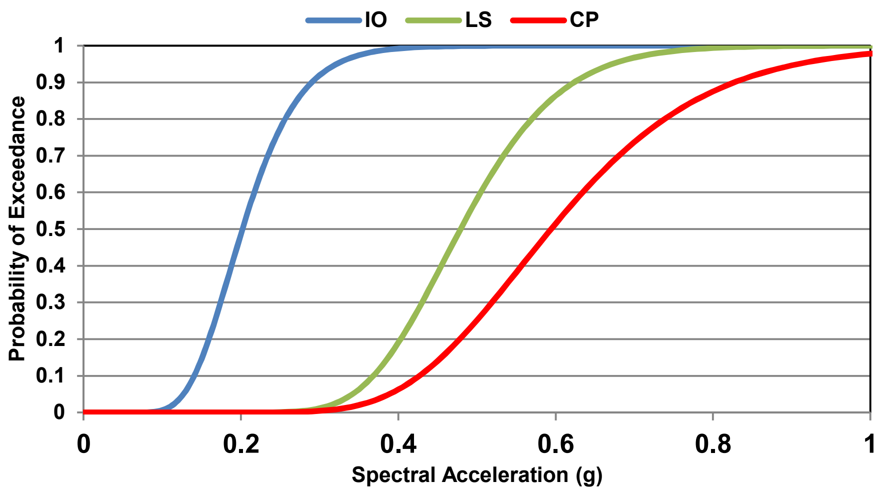


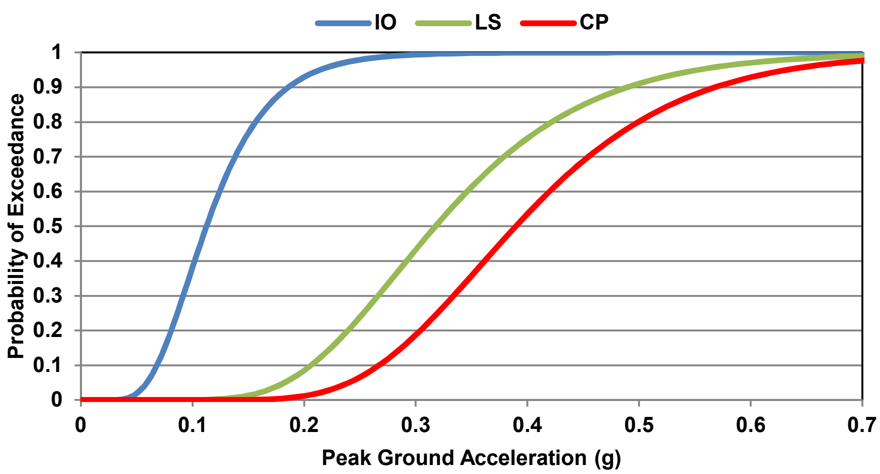
Figure 6 – Mid-rise model

4. Results and Discussion

Due to the large number of parameters that affect seismic vulnerability, the paper focuses on a single set of parameters for a structure constructed at the start of the 20th century with a large percentage of openings. The fragility curves based on spectral acceleration (SA) or peak ground acceleration (PGA) were developed and are shown in Figure 7.



(a)



(b)

Figure 7 – Fragility curves as a function of SA (above) and PGA (below)

One can see that the curves based on spectral acceleration show a smaller standard deviation than those based on peak ground acceleration. This is not surprising given the selection method previously described. The observed trend is also consistent with previous observations that indicate that the first mode response usually governs low-rise and some mid-rise structures. This observation was confirmed by the current analyses, which clearly showed that higher modes had very little impact on the structural response of URM buildings considered in the current study. Nonetheless, PGA remains to be a very useful measure for further analysis of data as will be demonstrated next.

The fragility curves for PGA, shown in Figure 7b, can be applied to the 2010 Val-des-Bois Earthquake that was felt strongly in Ottawa. One can see that the observed structural performance correlates well with the predicted damage state indicated by the fragility curves. Accordingly, the PGA of this earthquake was 0.04g and corresponds to 0.4% of structures to be subjected to immediate occupancy damage level, with the rest of the building stock remaining fully operational and intact. This is in agreement with the almost non-existent structural damage observed in the city of Ottawa.

Extending the above comparison to an earthquake with a probability of exceedance of 2% in 50 years hitting Ottawa, it can be extrapolated that 59% of older URM buildings would exceed the collapse prevention performance level, 91% exceeding life safety and 100% exceeding immediate occupancy. This comparison demonstrates potentially catastrophic consequences of a code level earthquake on a good portion of the existing URM stock in Ottawa.

5. Concluding Remarks

Seismic assessment of URM buildings in Ottawa was conducted using representative structures. A recently established inventory of existing buildings, in excess of 50,000, was used for this purpose. The building stock enabled the classification of URM buildings into two wide categories, as low-rise and medium-rise buildings, covering the majority of existing URM buildings in Ottawa. A three-storey mid-rise URM building was selected in the current phase of the investigation to construct fragility curves for selected performance levels. The fragility curves were established for spectral accelerations and peak ground accelerations. The results presented in the paper provide a useful tool for seismic risk assessment of URM buildings in Ottawa. Preliminary assessment of three-storey buildings indicate that the majority of these buildings would suffer serious damage when subjected to the NBCC 2010 code level earthquakes with 2% probability of exceedance in 50 years. Further research and expansion of the fragility curves are required for seismic risk assessment of URM buildings in Ottawa.

6. Acknowledgements

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