The 11th Canadian Conference on Earthquake Engineering

Canadian Association for Earthquake Engineering

URM BEARING WALL BUILDING SEISMIC RISK IN VICTORIA, CANADA & BENEFIT-COST ANALYSIS FOR REHABILITATION

Brandon Paxton
Design Engineer, Read Jones Christoffersen Ltd., Victoria, BC, Canada
bpaxton@rjc.ca

Ken Elwood
Professor and MBIE Chair in Earthquake Engineering, University of Auckland, New Zealand
k.elwood@auckland.ac.nz

Jason Ingham
Professor, University of Auckland, New Zealand
j.ingham@auckland.ac.nz

Bret Lizundia
Principal, Rutherford + Chekene, San Francisco, CA, USA
blizundia@ruthchek.com

ABSTRACT: Despite their well-known seismic vulnerability, unreinforced masonry (URM) buildings continue to be a leading source of loss of life and property damage in earthquakes around the world. In the United States, some communities that have experienced losses first hand, such as San Francisco, California and Seattle, Washington have responded with public policy aimed at mitigating the risks associated with these buildings. In contrast, Victoria, British Columbia, Canada is an example of a community with substantial seismic hazard that has yet to experience a damaging earthquake and thus has not seen widespread interest in mitigating seismic risks. It is also a city with a substantial stock of clay brick URM bearing wall buildings, constructed around the turn of the 20th century, reasonably similar in form to those devastated by the 2010/2011 Canterbury earthquake sequence in New Zealand. To promote seismic upgrading of URM buildings in the region, a study was undertaken to perform benefit-cost analyses specifically for seismic rehabilitation in Victoria, considering its seismic hazard, building assets, pedestrian/occupant exposure, and local construction costs. The loss estimates are underpinned by building empirical motion-damage relationships based on observed damage in past earthquakes in California and New Zealand. Rehabilitation measures considered range from parapet bracing to full seismic upgrades consistent with local practices. Parapet bracing and other partial retrofits are shown to have favorable benefit-cost ratios and thus be strong candidate measures for risk mitigation programs. Full upgrades are shown to have less favorable benefit ratios. In all cases, reduced casualties represent a significant fraction of the benefits, which provides supporting evidence for cost-sharing among building owners and the public.

1. Introduction

Victoria lies in the Cascadia Subduction Zone which has the potential for crustal, subcrustal, and subduction earthquakes and, as a result, has one of the highest seismic hazards in Canada (NRC 2010). Despite this hazard Victoria has yet to experience shaking beyond MMI VI intensity since the middle of the 19th century (Lamontagne, et al. 2008), before URM building construction began in Victoria. Elsewhere in the world, seismic risk mitigation efforts have been implemented as part of political and emotional responses to earthquake losses. The intent of this study was to provide rational evidence for seismic risk mitigation efforts and to, hopefully, help avoid unnecessary losses in the future. While results focus on URM bearing wall buildings in Victoria, BC, the methodology could be adapted and applied to other locations and buildings. Note that the term "URM building" as used herein refers to clay brick URM bearing wall buildings with flexible timber diaphragms (similar to the model building type "URM" as described in FEMA (2006) and that all dollar figures herein represent third quarter 2014 Canadian dollars. Before proceeding with a discussion of the overall benefit-cost analysis (BCA), brief discussions are provided on the URM building stock in Victoria and the current status of URM seismic risk mitigation in Victoria compared to other regions facing similar risk.

2. URM Buildings in Victoria

Casual observation indicates that the vast majority of unreinforced masonry buildings in Victoria are clay brick bearing wall buildings with flexible timber diaphragms. Very few buildings except major churches are constructed from stone masonry and non-bearing wall buildings are also quite rare. Figure 1 shows typical clay brick bearing wall buildings in Victoria. In 1989, a city building official performed a complete survey of a significant portion of Victoria's downtown core (City of Victoria 1989) and identified 260 of 329 buildings in this area as being of URM construction (note: this includes all types of unreinforced masonry). Among these URM buildings, two-storey and three-storey buildings were found to be the most common (Figure 2, left) and the majority of buildings were constructed before 1920 (Figure 2, right). These buildings are relatively similar to those found on the west coast of the United States. They are also somewhat similar to those found in the Canterbury region of New Zealand, although there are some key differences (Paxton 2014).

Figure 1 – Typical URM Buildings in Victoria

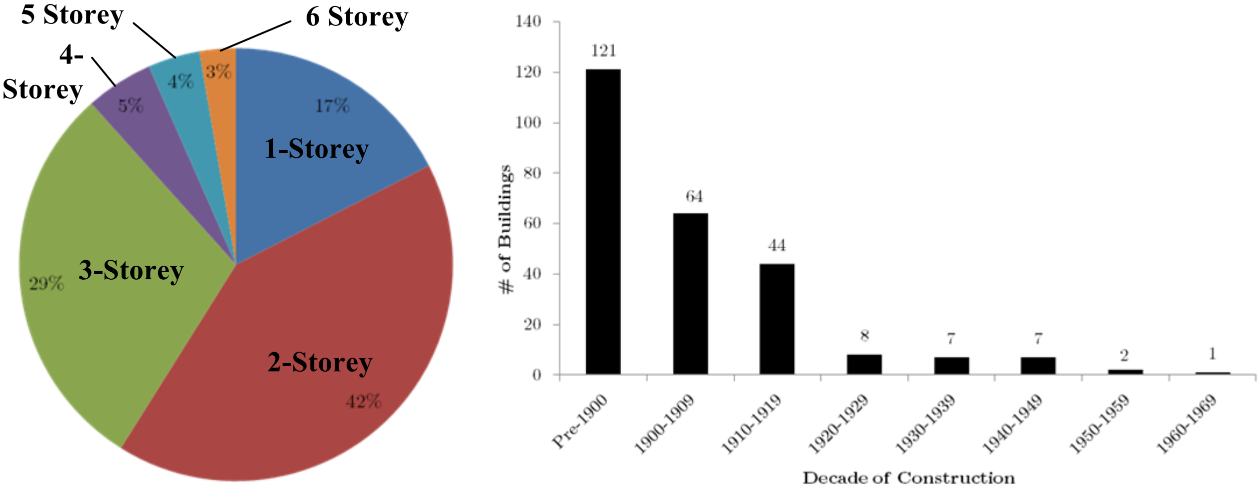

Figure 2 – Victoria URM Buildings, Number of Storeys (left) and Decade of Construction (right)

3. URM Seismic Risk Mitigation: Comparing Victoria to Locations Abroad

The foremost example of URM seismic risk mitigation efforts in North America is that of California. In response to the Long Beach earthquake of 1933, the California Legislature passed the Riley Act (California Legislature 1933, FEMA 1998, Turner 2004). This Act required all cities in California to regulate building construction and also required that buildings and individual components of buildings be designed for lateral forces. The required resistances could not be practicably achieved with URM, effectively ending the construction of new URM buildings in California. The 1933 Field Act imposed stringent design regulations for new public school buildings (including K-12, community colleges, and vocational schools). The 1939 Garrison Act and 1967/1968/1974 Greene Acts required existing public school buildings to evaluated and retrofitted to meet the requirements of the Field Act (CSSC 2009, Alesch, Arendt and Petak 2011, Paxton, Turner, et al. 2015a). In 1986 California enacted its "URM Law" which required each of the 365 local governments in California's highest seismic zone to: complete and inventory of URM buildings with their jurisdiction, establish loss reduction programmes, and report on progress to the California Seismic Safety Commission (CSSC) by 1990. Note that the law recommends, but does not require, that the loss reduction programmes include mandatory strengthening ordinances. Approximately 26,000 URM buildings have been inventoried as a result of the law and, as of 2006, approximately 70% of these buildings had been mitigated (55% retrofitted + 15% demolished) (CSSC 2006). Most jurisdictions included mandatory strengthening ordinances and 87% of buildings in such jurisdictions have been mitigated, compared to just 13%-31% for other programme types overall. In certain jurisdictions, such as Long Beach and Los Angeles, essentially 100% of identified URM buildings have been mitigated. Paxton et al. (2015a) provides details on the programmes employed by selected individual cities as well as the design techniques commonly employed. Note that the URM law applies equally to bearing wall and non-bearing wall buildings. In addition to the comprehensive seismic retrofitting associated with the above programmes, several communities such as Long Beach, Los Angeles, and San Francisco had previously implemented parapet strengthening ordinances dating as far back as 1949 (Paxton, Turner, et al. 2015a).

In Seattle, Washington, URM seismic risk mitigation policy is at the forefront as the city is currently developing a risk mitigation ordinance. Draft documents indicate that, if passed, URM buildings would be required to be either strengthened or demolished within 7 to 13 years (depending upon the risk classification of the facility) of their owners being served noticed that said building falls within the scope of the ordinance (City of Seattle 2013). A variety of design techniques/standards are proposed as being acceptable, including ABK-inspired "special procedure" type standards such as those found in ASCE 31-03 (ASCE 2003) and Chapter A1 of the International Existing Building Code (ICC 2012). ASCE 41-13 was not yet published at the time the draft ordinance was created but also includes a version of the special procedure. Similar to the ordinance of San Francisco, certain buildings may also qualify for a relaxation to partial strengthening (City of Seattle 2012, Paxton, Turner, et al. 2015a).

The City of Portland, Oregon has some limited requirements in Chapter 24 of its city code: when more than 50% of the roofing of a URM building is replaced within five years, parapet bracing (complete with roof tension and shear anchors) are to be provided. Furthermore, the city has specified a trigger value for building repair/renovation costs, beyond which comprehensive seismic evaluations/upgrades are required for URM buildings. The trigger values are $430/m^2 ($40/sq.ft.) and $323/m^2 ($30/sq.ft.) for single-storey buildings and all other buildings, respectively (City of Portland 2014).

In contrast to the aforementioned examples, seismic risk mitigation efforts in Victoria (URM or otherwise) are considered to be lacking. A tax abatement program for heritage buildings undergoing comprehensive seismic retrofitting as part of code-triggered strengthening has resulted in 34 seismic upgrades (Paxton, Elwood and Barber, et al. 2013) and the Victoria Civic Heritage Trust has recently developed a grant program to assist in funding voluntary partial seismic strengthening measures, such as parapet bracing and wall anchorage (Umland 2015). However, even minimal active risk mitigation measures such as a parapet-bracing ordinance are not in place and the aforementioned 34 retrofits – most of which were to URM buildings – likely represent just 5-10% of the total URM building stock (extrapolating from the aforementioned survey that found 260 URM buildings in just a portion of the downtown core).

4. BCA Methodology

Benefit-cost analyses for seismic retrofitting of a prototypical URM building of commercial occupancy with a floor area of 744m^2 (8000sq.ft.) in downtown Victoria were completed in terms of annual expected costs, where reduced expected losses represent the benefits. The losses considered were:

- *building owner losses*: repair costs, lost rental income, and tenant relocation expenses; and
- *public losses*: occupant and pedestrian casualties (deaths and injuries)

The expected losses are calculated using annual earthquake probabilities and using mean or best estimate parameters as discussed herein. A flow chart is presented in Figure 3, illustrating the various components of the loss estimate process. The benefits are accrued over a specified time horizon, converted to a present value as discussed in Section 4.6, and compared with seismic retrofitting costs.

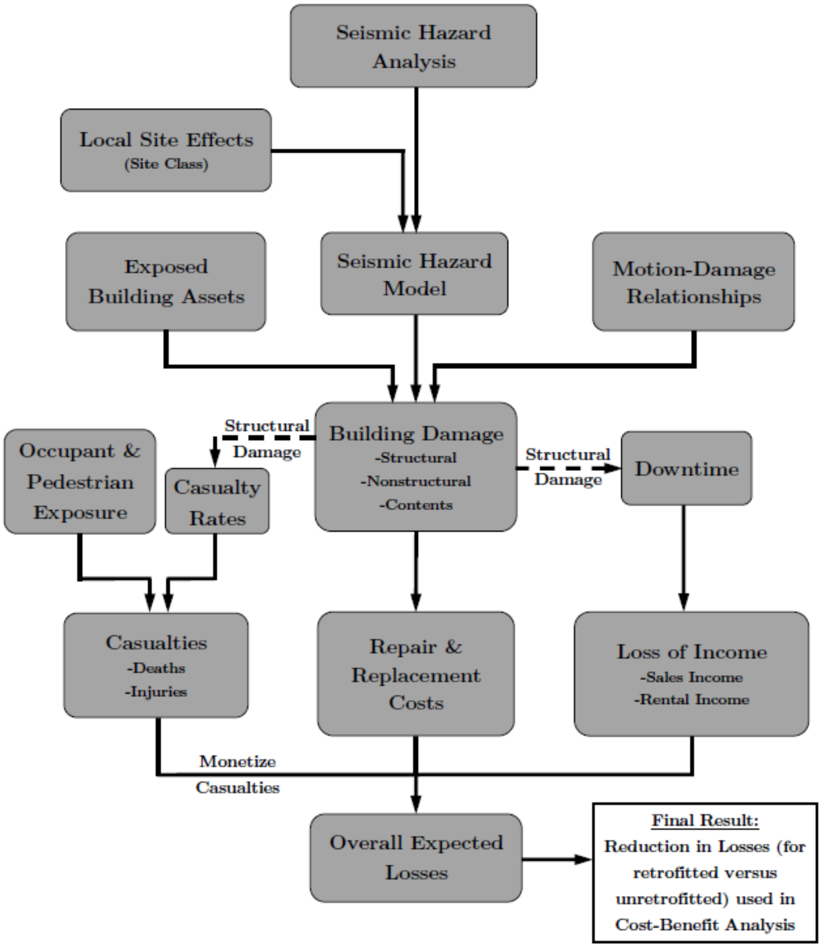

Figure 3 – Flow Chart of Loss Estimation Process

4.1. Seismic Hazard

The sole hazard parameter used in the analysis is the 5%-damped spectral acceleration at a period of one second, $S_a(1)$. The rationale for selecting this parameter is discussed in detail by Paxton (2014) and here it is simply acknowledged that this parameter was a compromise between technical accuracy and ease of use. The $S_a(1)$ hazard curve for site class C (Figure 6, left, Section 4.7) was calculated using computer program EZ-FRISK (Risk Engineering 2012) and best-estimate input parameters from the Geological Survey of Canada's Open File 4459 (GSC 2003) and including the probabilistic hazard contribution from a Cascadia subduction earthquake. The model indicated $S_a(1)$=0.6g at the 2%/50-year hazard level. At the time of the study, complete results for the 2015 National Building Code of Canada hazard values had not been published, but preliminary results were available for 2%/50-year spectral parameters (GSC 2014), which indicated $S_a(1)=0.67g$ for Victoria. Thus the calculated hazard curve was scaled up by approximately 10% to match this value for the analysis herein.

4.2. Building Assets

Building assets were represented by four separate components as defined in HAZUS (FEMA 2012):

1. Structural components
2. Drift-sensitive nonstructural components (NSCs) (eg. partitions)
3. Acceleration-sensitive NSCs (eg. storage tanks, electrical transformers)
4. Building contents (eg. bookcases, computer equipment)

The overall building replacement value for the base case was taken as $2797/m^2 ($260/sq.ft.), representing the replacement value for a URM building in British Columbia from Thibert (2008) converted to 2014 Canadian dollars. In passing is it noted that the notion of a "replacement value" for a URM building is somewhat flawed in that the construction of URM buildings is prohibited in locations of significant seismicity such as Victoria and, even if it were permitted, one could not truly recreate a century-old building and its associated heritage value. Rutherford and Chekene (1990) proposed that the replacement value of a concrete shearwall building be used for San Francisco, as this was the most likely replacement. Concrete shearwall buildings are also a favored type of construction in BC and so the corresponding value of 3227/m^2 was used as the 'high' value in the sensitivity analysis (see Section 5). HAZUS (FEMA 2012) specifies replacement values by occupancy and the replacement value for a retail trade (COM1) occupancy building therein is approximately $2420/m^2, which was used as the 'low' value in the sensitivity analysis (see Section 5). It was also necessary to specify the fraction of the overall replacement value represented by each component. The breakdown as specified by HAZUS (FEMA 2012) for a COM1 occupancy building was used, as shown in Figure 4.

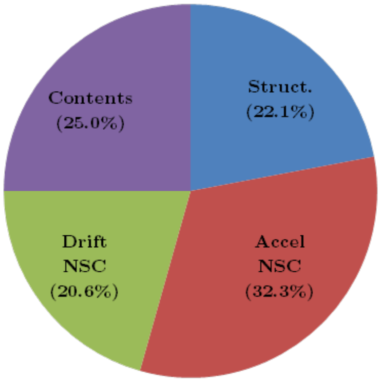

Figure 4 – Component Breakdown of Building Replacement Value

4.3. Motion-Damage Relationships

The motion-damage relationships employed are damage state fragilities (in the form of lognormal cumulative probability distributions) for structural components, drift-sensitive NSCs, acceleration-sensitive NSCs, and building contents; each individual curve (eg. Figure 5 which shows the fragilities for structural components) provides the probability of exceeding a given damage state as a function of the shaking intensity at the site, as represented by $S_a(1)$. The damage state definitions and associated loss values are those from HAZUS (FEMA 2012). Instead of using default data from HAZUS, the structural fragilities are based on damage data from the 1989 Loma Prieta, 1994 Northridge, and 2010/2011 Canterbury earthquakes, which were collected and analyzed to various degrees by others (Rutherford and Chekene 1991, Lizundia, Dong and Holmes 1993, Rutherford and Chekene 1997, Ingham and Griffith 2011a, Ingham and Griffith 2011b, Moon, et al. 2012). The fragilities were derived heuristically for four strengthening statuses as discussed in Paxton (2014):

1. *unretrofitted*;
2. *braced-parapet* (including roof-level tension anchors throughout);
3. *partially-retrofitted* (representing tension anchorage at all floors, as a minimum); and
4. *fully-retrofitted* (eg. Type. A+B strengthening as defined by Ingham, 2011b).

Paxton, Elwood, et al. (2015b) provides the fragility functions as derived separately for Canterbury and California and provides further discussion on their derivation. The vulnerability of Victoria's buildings is expected to fall somewhere between those of California (i.e. Loma Prieta and Northridge) and Canterbury and thus the fragilities were defined using weighted averages as follows:

- *base case (shown in* Figure 5*)*: 67% Canterbury, 33% California;
- *upper Bound*: 100% Canterbury, 0% California; and
- *lower Bound*: 50% Canterbury, 50% California.

This paper focuses primarily on the base case and provides selected results of the sensitivity analysis in Section 5.

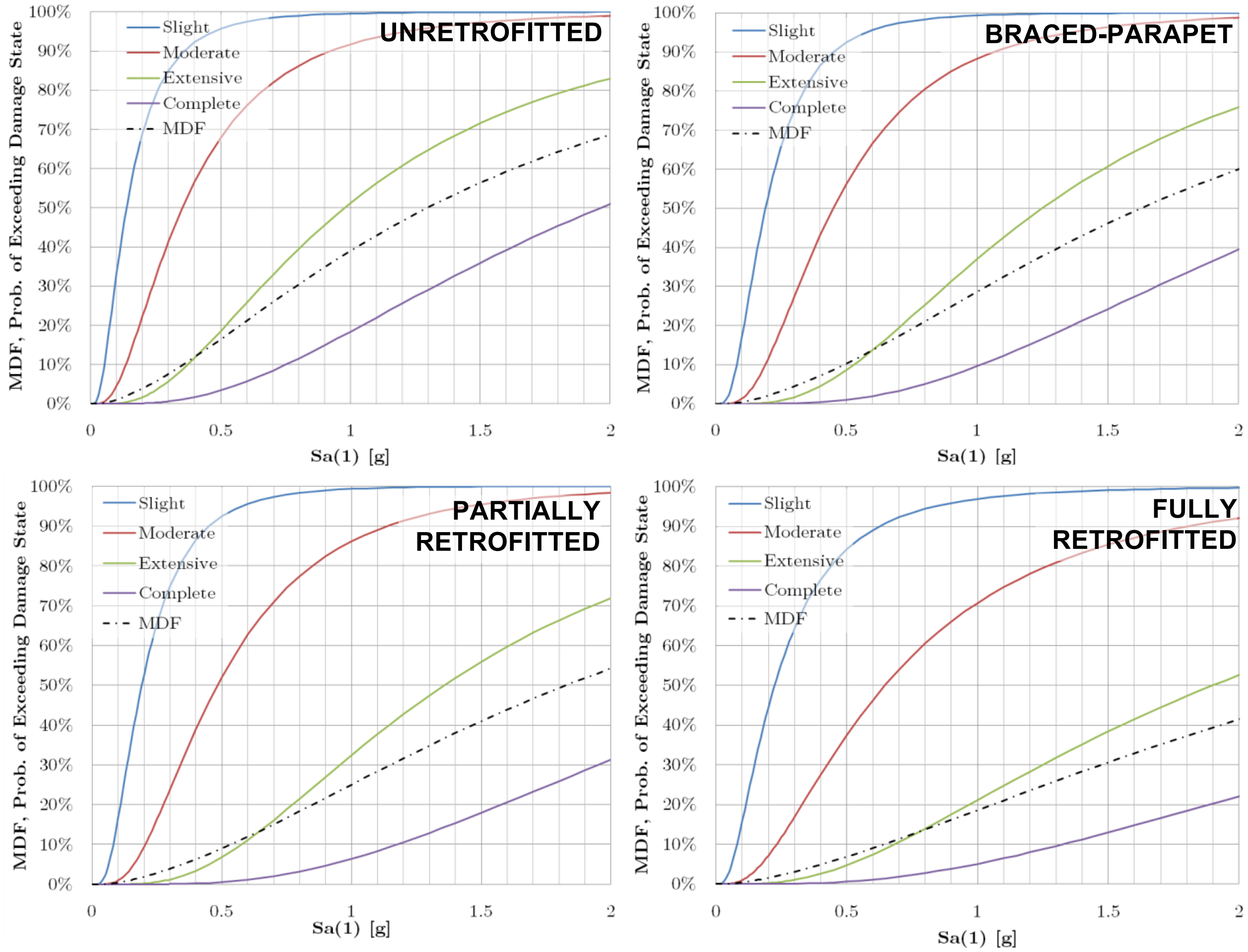

Figure 5 – Structural Fragilities Assigned to URM Building in Victoria

Fragilities for drift-sensitive NSCs, acceleration-sensitive NSCs, and building contents are based on default data from HAZUS (FEMA 2012), except that the loss values were adjusted to reflect increased losses due to structural collapse, following the methodology of Farokhnia (2013). Note that HAZUS provides the relevant relationships in terms of spectral displacement/acceleration at a variety of periods and all relationships were converted to be in terms of $S_a(1)$, using standard pseudospectral relationships

(Chopra 2012) and a spectral shape based on Victoria's 2475-year uniform hazard spectrum (NRC 2010). The fragilities for a "URML" category structure was used for unretrofitted buildings. HAZUS does not contain relationships for retrofitted URM buildings and instead recommends the use of its relationships for RM1L (moderate code) essential facilities. No guidance is provided for strengthening statuses #2 or #3 and thus appropriate relationships were selected based on judgment. Paxton (2014) discusses the relationships that were used and provides function parameters in terms of $S_a(1)$. With the motion-damage relationships defined for each of the four component types, the overall MDF vs. $S_a(1)$ curve for each strengthening status is then defined as the average of the four component types, weighted in proportion to their contribution to the overall building value as shown in Figure 4. The resulting curve for an "unretrofitted" building is shown in Figure 6 (right). Similar curves were derived for the remaining three strengthening status, as provided in Paxton (2014).

4.4. Casualties

The key parameters required to estimate casualties are the exposure (i.e. number of pedestrians and occupants) and the casualty rates. The occupant and pedestrian densities used in this study were 0.00033 persons/m^2 (0.0036 persons/sq.ft.) of floor area and 30 persons/304 m (30 persons/ 1000ft) of sidewalk, which represent time-averaged values from Rutherford and Chekene (1990). Note that several different densities are provided by Rutherford and Chekene (1990) for San Francisco and the aforementioned values were judgmentally selected as being representative of Victoria.

The occupant and pedestrian fatality rates used in this study are shown in Table 1. The occupant fatality rates are those specified by HAZUS (FEMA 2012) for URM buildings. The pedestrian fatality rates from HAZUS were considered too low (a maximum of 0.6% percent for buildings in the "complete" damage state) considering experience in Christchurch (Canterbury Earthquakes Royal Commission 2012) and thus the pedestrian fatality rates shown were adapted from Rutherford and Chekene (1990) by converting to the HAZUS structural damage states as discussed in Paxton (2014). "Hospitalized injuries" were also accounted for and were taken as four times the number of deaths, similar to assumptions by Rutherford and Chekene (1990). Casualties were monetized using the "value of a statistical life" (VSL) as specified by United States Department of Transportation (2013) guidance, which specifies a best estimate value of $9.1 million as well as upper and lower bound values of $12.9 million and $5.2 million, respectively, which are considered in the sensitivity analyses. Note that the VSL and its method of determination has been a controversial topic for decades, with highly variable recommendations on the appropriate value (FEMA 1992, FEMA 1994, Miller 2000, Viscusi and Aldy 2002).

Table 1 – Fatality rates (deaths/person exposed)

Structural Damage State	Occupants	Pedestrians
None	0%	0%
Slight	0%	0.02%
Moderate	0.001%	0.30%
Extensive	0.002%	12%
Complete* (no collapse)	0.02%	15%
Complete* (collapse)	10%	15%

*HAZUS (FEMA 2012) specifies that 15% of buildings in the "complete" damage state collapse

4.5. Downtime

From a building owner's perspective the relevant downtime is the time required to assess and repair the building to a state that it could be re-occupied and resume generating rental income (i.e. "loss of function" time as defined in HAZUS). This is a complex issue dependent upon many factors (Comerio 2006), but the methodology and default data for calculating loss of function time from HAZUS (FEMA 2012) were used, except that a modification to account for increased downtime due to concentrated severe damage in a community many URM buildings (as was observed in the 2010/2011 Canterbury earthquakes) was employed, as discussed in Paxton (2014). This modification was found to have a minor impact on the resulting benefit-cost analyses as the additional downtime occurs for low-probability ground motions. Downtime losses were monetized by assuming a rental rate of \$0.0065/m^2/day (\$0.07/sq.ft/day), which is typical for URM buildings in desirable downtown Victoria locations. Tenant relocation expenses were calculated following the HAZUS (FEMA 2012) methodology, but were found to represent less than 1% of the overall losses.

4.6. Economic Parameters

The key economic parameters for the benefit-cost analyses are the time horizon (the future duration over which the annual expected benefits are calculated) and the discount rates (which reduce the present value of future losses/benefits). FEMA 227 (FEMA 1992) recommends discount rates of 3-6% for use in benefit-cost analyses for seismic rehabilitation. FEMA 255 (FEMA 1994), which focuses on benefit-cost analysis for seismic rehabilitation of federally-owned buildings in the U.S.A., recommends a discount rate of 4%. Additionally, the United States Office of Management and Budget (OMB 2003) notes that lower discount rates, of 1-3%, are appropriate for intergenerational benefits. Discount rates were applied in this study as follows:

- *Base case:* 5% for owner losses and 3% for public losses (Section 5.1)
- *High:* 7% for owner losses and 5% for public losses (see Paxton 2014)
- *Low:* 3% for owner losses and 1% for public losses (see Paxton 2014)

4.7. Calculating "Expected" Losses

The expected annual losses (EAL) due to building damage for a prototypical URM building in Victoria were calculated as shown in Equation 1. The calculation for one term of the summation is illustrated in Figure 6. Note that the "loss value" (LV) here is repair/replacement costs as a fraction of the building replacement value, which is subsequently converted to a dollar value. Although the example shown is for losses due to building damage, the process is similar for other losses.

$$EAL = \sum_{Sa(1)} [(LV \mid Sa(1) = i) * P(Sa(1) = i)] \qquad (1)$$

where LV = Loss Value (equal to the damage ratio)

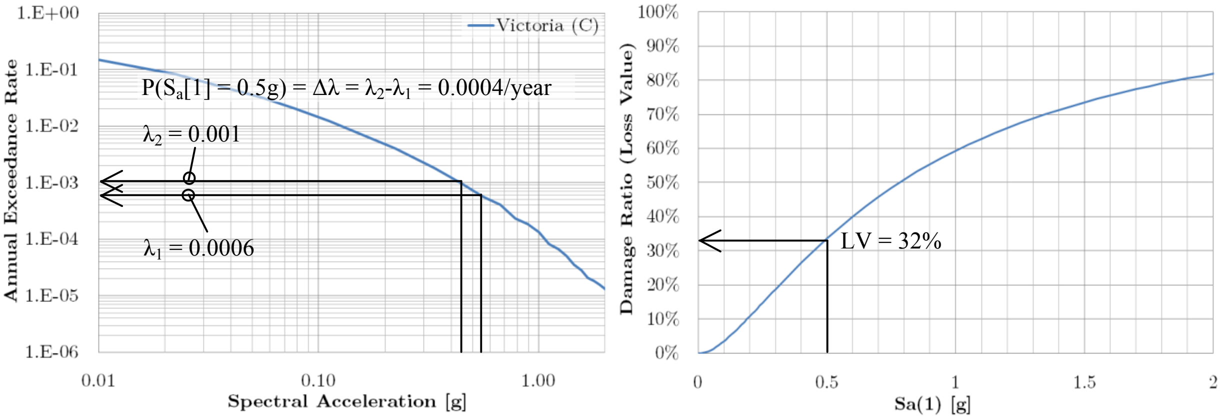

Figure 6 – Example Calculation of LV for $S_a(1)$=0.5g ("Unretrofitted" building, Site Class C, Victoria)

It can be seen from Figure 6 that the expected annual loss corresponding to $S_a(1)$=0.5g is equal to 0.0004*32%=0.0128 %/year, where the % refers to repair costs as a fraction of the building replacement value. The corresponding dollar value for the prototypical building with a floor area of 743m^2 and a replacement value of \$2797/m^2 is:

$$0.000128 / year * \$2797 / m^2 * 743m^2 = \$266 / year \qquad (2)$$

Repeating these calculations for each term of Equation 1 results in a total expected annual loss \$3,283/year. For a time horizon of 50-years and a discount rate of 5%, the resulting present value of the annual expected losses is equal to \$59,935. Obviously the accuracy of this prediction is not commensurate with the precision to which it has been presented, but the figures have not been rounded to allow one to more easily follow the example. The process was performed for the four aforementioned strengthening statuses and for four different soils site classes (B, C, D, and E as defined in the National Building Code of Canada [NRC, 2010]). The reduction in the present value of the expected losses between the "unretrofitted" case and a given strengthening status represents the benefits of said strengthening measure that are compared to the cost of strengthening. Note that losses due to building damage are only one of the five losses considered herein. Paxton (2014) provides detailed calculations and results for the remaining losses.

4.8. Retrofit Costs

The only costs considered in the analyses were the construction cost of the seismic upgrade work as well as the related soft costs (design fees, permit fees, and taxes). Architectural costs associated with a substantial remodelling were not considered. A variety of additional soft and hard costs could be incurred depending upon building authority and owner decisions. Lizundia et al. (1993) provides a list of possible costs. Benefits associated with a resulting increase in market value or rental rates was also not accounted for, which is considered appropriate in Victoria, where seismic risk in buildings generally does not impact the rental rates or property market. However substantial value could be realized in other areas, such as New Zealand, where property values have reportedly been impacted by the nation's earthquake prone building policy (Chapman 2012, Tarrant 2012). Sources for construction costs included detailed estimates for sample buildings and actual costs from 19 local seismic upgrade projects. Published unit rates (FEMA 1988, FEMA 1994b, Rutherford & Chekene 1990, Rutherford and Chekene 1997) were also considered for partial retrofitting, although preference was given to other sources as the published data was rather dated. The costs (in terms of gross floor area) used in the study are shown in Table 2.

Table 2 – Retrofit Costs (\$/m^2 floor area)

Upgrade Type	Base	High	Low	Principal Source
Parapet Bracing*	33	65	22	Detailed estimates for sample buildings
Partial Retrofitting**	108	150	65	Detailed estimates for sample buildings
Full Retrofitting***	355	538	183	Cost data for actual Victoria projects

*represents tension anchorage at all roof-wall interfaces and structural steel braces for parapets exceeding height/thickness ratios of 1.5:1 (median value across 12 sample buildings)

**represents the installation of tension ties at all floors (shear connection and out-of-plane strengthening for walls not included)

***Full retrofits were generally designed in accordance with Appendix A of the *Guidelines for Seismic Evaluation of Existing Buildings* (NRC, 1993)

5. BCA Results

5.1. Base Case

The overall benefit-cost results include both owner benefits (reduced damage and downtime) as well as public benefits (reduced casualties). Costs (C), benefits (B), and Benefit/Cost Ratios (BCR) were calculated for a hypothetical two-storey building in downtown Victoria, with a gross floor area of approximately 743m^2 (8000sq.ft.) and 9.1m (30ft) of streetfront sidewalk exposure (Table 3). Results are provided for site classes B, C, D, and E. All costs and benefits are in terms of third quarter 2014 Canadian dollars and benefits have been rounded to the nearest hundred dollars. Based on these results, parapet-bracing appears to be a viable investment for most buildings, while "partial retrofits" may be a viable investment for buildings on soft soils. It is acknowledged that the costs likely also vary with the site soils, particularly for "full" retrofits. Because full retrofits did not exhibit favourable (>1.0) BCRs, such a refinement was not pursued. It should be noted that the losses were impacted heavily by site class because the soils amplification factor (F_v) varies highly with the selected IM, $S_a(1)$. If $S_a(0.2)$ had been selected, the difference would be less dramatic. Observed damage, however, has been shown to correlate highly with soil type (Rutherford and Chekene 1991).

Table 3 – Overall BCA Results (Favourable BCRs shown in bold)

Site Class	Braced Parapets			Partially-Retrofitted			Fully-Retrofitted		
	B	C	BCR	B	C	BCR	B	C	BCR
B	19,000	24,000	0.79	26,200	80,000	0.33	34,000	264,000	0.13
C	32,900	24,000	**1.37**	47,400	80,000	0.59	62,100	264,000	0.24
D	48,700	24,000	**2.03**	69,900	80,000	0.87	92,600	264,000	0.35
E	96,600	24,000	**4.03**	135,400	80,000	**1.69**	180,700	264,000	0.68

In many cases owners are expected to bear the costs of seismic retrofits alone. Thus analyses were also completed considering only the owner benefits (Table 4), ignoring benefits from casualties. It can be seen that, in general, even limited upgrades such as parapet bracing are often not economically justifiable from an owner's perspective, which provides strong evidence for cost-sharing between building owners and the public.

Table 4 – Owner-Only BCA Results (Favourable BCRs shown in bold)

Site Class	Braced Parapets			Partially-Retrofitted			Fully-Retrofitted		
	B [$]	C [$]	BCR	B [$]	C [$]	BCR	B [$]	C [$]	BCR
B	7,700	24,000	0.32	12,700	80,000	0.16	19,300	264,000	0.07
C	13,500	24,000	0.56	23,900	80,000	0.30	36,400	264,000	0.14
D	18,900	24,000	0.79	34,200	80,000	0.43	53,800	264,000	0.20
E	31,600	24,000	**1.32**	55,500	80,000	0.69	91,700	264,000	0.34

5.2. Sensitivity Analysis

Sensitivity analyses were completed for many of the aforementioned parameters. The three most significant results are presented herein and Paxton (2014) provides complete results.

5.2.1. Cost of Upgrades

The costs of upgrades are highly variable for actual projects and the BCRs are directly proportional to the costs. The results for the aforementioned alternative costs are presented in Table 5. Noticeable changes in conclusions appear in the braced-parapet category, where the BCR is only favourable for buildings on soft soils for the higher cost of $\$65/m^2$, which is a plausible cost. Even at the extremely low cost of $\$183/m^2$ the results for full retrofits are not favourable except for very soft soils (Site Class E).

Table 5 – Sensitivity Results for Cost of Upgrades (Favourable BCRs shown in bold)

Site Class	BCR (Braced Parapets)			BCR (Partially-Retrofitted)			BCR (Fully-Retrofitted)		
	High	Base	Low	High	Base	Low	High	Base	Low
B	0.40	0.79	**1.19**	0.23	0.33	0.55	0.09	0.07	0.25
C	0.69	**1.37**	**2.06**	0.42	0.59	0.99	0.16	0.14	0.46
D	**1.01**	**2.03**	**3.04**	0.62	0.87	**1.46**	0.23	0.20	0.68
E	**2.01**	**4.03**	**6.04**	**1.21**	**1.69**	**2.82**	0.45	0.34	**1.33**

*note that "high" and "low" refer to the parameter in question (costs in this case), not the BCR

5.2.2. Value of a Statistical Life

As aforementioned, the VSL has been a controversial topic in the literature for decades. BCA results for the alternative VSL values are presented in Table 6. It can be seen that the conclusions of the BCA are relatively unchanged.

Table 6 – Sensitivity Results for VSL (Favourable BCRs shown in bold)

Site Class	BCR (Braced Parapets)			BCR (Partially-Retrofitted)			BCR (Fully-Retrofitted)		
	High	Base	Low	High	Base	Low	High	Base	Low
B	0.99	0.79	0.59	0.40	0.33	0.26	0.15	0.07	0.10
C	**1.71**	**1.37**	**1.03**	0.71	0.59	0.47	0.28	0.14	0.19
D	**2.55**	**2.03**	**1.50**	**1.06**	0.87	0.68	0.41	0.20	0.29
E	**5.16**	**4.03**	**2.87**	**2.11**	**1.69**	**1.26**	0.83	0.34	0.54

*note that ”high” and “low” refer to the parameter in question (VSL in this case), not the BCR

5.2.3. Length of Streetfront Exposure

The length of streetfront exposure is a parameter that will vary highly from building to building. The base case used a length of approximately 9.1 m (30 ft). A “high” value of 27.4 m (90 ft) and a “low” value of 0 m were investigated in the sensitivity analysis (Table 7). From these results, one might conclude that buildings with greater streetfront exposure are prime candidates for increased strengthening as part of a strengthening ordinance.

Table 7 – Sensitivity Results for Streetfront Exposure (Favourable BCRs shown in bold)

Site Class	BCR (Braced Parapets)			BCR (Partially-Retrofitted)			BCR (Fully-Retrofitted)		
	High	Base	Low	High	Base	Low	High	Base	Low
B	**1.24**	0.79	0.57	0.48	0.33	0.25	0.18	0.07	0.10
C	**2.44**	**1.37**	**1.08**	0.97	0.59	0.50	0.37	0.14	0.21
D	**3.72**	**2.03**	**1.55**	**1.47**	0.87	0.72	0.56	0.20	0.30
E	**7.44**	**4.03**	**3.08**	**2.91**	**1.69**	**1.38**	**1.12**	0.34	0.58

*note that ”high” and “low” refer to the parameter in question, not the BCR

6. Conclusions

It was noted herein that seismic risk mitigation efforts for unreinforced masonry buildings are lacking in Victoria as compared to other regions facing similar risks. While incentive programs for heritage buildings have been reasonably successful, the vast majority of URM buildings in Victoria have yet to receive any strengthening. Many other communities facing similar risks implemented parapet bracing ordinances throughout the mid to late 20th century while Victoria has not yet to date.

When both owner and public benefits are considered, parapet bracing appears to be economically justified (BCR > 1.0) for many buildings. Favourable results (BCR > 1.0) were also obtained for partial retrofits of buildings on soft soils. When only owner benefits were considered, even parapet bracing was generally not economically justifiable, except perhaps for buildings on soft soils. This provides strong evidence for cost-sharing among building owners and the public.

All of the aforementioned results have been based on expected costs but risk-averseness and political factors can significantly influence decision-making and future research should address these effects. Some benefits such as historic preservation and overall community resiliency are somewhat intangible and were not accounted for herein. Many decisions about the built environment are not based solely on expected cost and so to do so for seismic retrofitting may actually put seismic safety at a disadvantage relative to other initiatives. One possible remedy for this issue is to combine expected cost with other goals in a multi-objective optimization-based approach (eg. minimize expect costs while limiting the number of deaths or demolitions for a given level of shaking). Haimes (2004) discusses such a methodology. Additionally, it must be recalled that the average member of the public may not be aware of the increased seismic risk of URM buildings relative to others and even those aware of the risk may not be able to avoid such buildings. Finally, the values assigned to many of the aforementioned parameters were highly uncertain and required significant assumptions. The results should be considered as a general indication only and there is much potential for refinement, particularly in the areas of nonstructural damage, downtime, and demolition vs. repair decision-making.

7. Acknowledgements

The damage data that underpinned this study was collected as part of past research efforts. Data collection from the 2010/2011 Canterbury earthquakes was funded by the New Zealand Natural Hazards Research Platform. Funding for collection of data for the Loma Prieta earthquake was from the California Seismic Safety Commission and the USGS; funding for the Northridge Earthquake was from the US National Institute of Standards and Technology. The work presented herein was funded jointly by The Victoria Civic Heritage Trust and the Natural Sciences and Engineering Research Council of Canada through an Industrial Postgraduate Scholarship.

8. References

Alesch, D.J., L.A. Arendt, and W.J. Petak. *Natural Hazard Mitigation Policy.* New York, NY, USA: Springer Publishing, 2011.

ASCE. *ASCE 31-03 - Seismic Evaluation of Existing Buildings.* Reston, VA, USA: American Society of Civil Engineers, 2003.

California Legislature. "Session Laws of The California Legislature, Chapter 601, Statutes of 1933, 50th Session." 1933.

Canterbury Earthquakes Royal Commission. *Volume 4.* Government of New Zealand, 2012.

Chapman, K. *Quake valuations to hit Wellington homeowners.* January 11, 2012. http://www.stuff.co.nz/business/money/7890547/Quake-valuations-to-hit-Wellington-homeowners.

Chopra, A.K. *Dynamics of Structures, 4th edition.* Upper Saddle River, NJ, USA: Prentice Hall, 2012.

City of Portland. "Portland City Code Section 24.85 - Seismic Design Requirements for Existing Buildings." Portland, OR, USA, 2014.

City of Seattle. "Final Report from URM Technical Committee & Proposed Retrofit Standard." Seattle, WA, USA, 2012.

City of Seattle. "Recommendations for an Unreinforced Masonry Policy." Seattle, WA, USA, 2013.

City of Victoria. *1989 Survey.* Unpublished Internal Report, 1989: City of Victoria, 1989.

Comerio, M.C. "Estimating Downtime in Loss Modeling." *Earthquake Spectra* (Earthquake Spectra), 2006: 349-365.

CSSC. *Status of The Unreinforced Masonry Building Law.* Sacramento, CA, USA: California Seismic Safety Commission, 2006.

CSSC. *The Field Act and its Relative Effectiveness in Reducing Earthquake Damage in CA Public Schools.* Sacramento, CA, USA: California Seismic Safety Commission, 2009.

Farokhnia, K. *Nonstructural Vulnerability Functions for Buildign Categories.* PhD Thesis, Boulder, CO, USA: University of Colorado, 2013.

FEMA. *FEMA 156: Typical Costs for Seismic Rehabilitation of Existing Building, 1st edition.* Washington, DC, USA: Federal Emergency Management Agency, 1988.

FEMA. *FEMA 156: Typical Costs for Seismic Rehabilitation of Existing Buildings, 2nd Edition.* Washington, DC, USA: Federal Emergency Management Agency, 1994b.

FEMA. *FEMA 227: A Benefit-Cost Model for The Seismic Rehabilitation of Buildings.* Washington, DC, USA: Federal Emergency Management Agency, 1992.

FEMA. *FEMA 255: Seismic Rehabilitation of Federal Buildings - A Benefit-Cost Model.* Washington, DC, USA: Federal Emergency Management Agency, 1994.

FEMA. *FEMA 275 - Planning for Seismic Rehabilitation: Societal Issues.* Washington, DC, USA: Federal Emergency Management Agency, 1998.

FEMA. *HAZUS-MH 2.1: Earthquake Model Technical Manual.* Washington, DC, USA: Federal Emergency Management Agency, 2012.

FEMA. *Techniques for The Seismic Rehabilitation of Existing Buildings.* Washington, DC, USA: Federal Emergency Management Agency, 2006.

GSC. *Open File 4459.* Ottawa, ON, Canada: Geological Survey of Canada, 2003.

GSC. *Open File 7576 Fifth Generation Seismic Hazard Model Input Files as Proposed to Produce Values for the 2015 National Building Code of Canada.* Geological Survey of Canada, 2014.

Haimes, Y. *Risk Modeling, Assessment, and Management.* Hoboken, NJ, USA: Wiley and Sons, 2004.

ICC. *2012 International Existing Building Code.* Country Club Hills, IL, USA: International Code Conference, 2012.

Ingham, J., and M. Griffith. "The Performance of Earthquake Strengthened URM Buildings in The Christchurch CBD in The 22 February 2011 Earthquake." Report to the Royal Commission of Inquiry on The Canterbury Earthquakes, 2011b.

Ingham, J., and M. Griffith. "The Performance of Unreinforced Masonry Buildings in The 2010/2011 Canterbury Earthquake Swarm." Report to The Royal Commission of Inquiry on The Canterbury Earthquakes, 2011a.

Lamontagne, M., S. Halchuk, J.F. Cassidy, and G.C. Rogers. "Significant Canadian Earthquakes of The Period 1600-2006." *Seismological Research Letters*, 2008: 211-223.

Lizundia, B., W. Dong, and W. Holmes. "Analysis of Unreinforced Masonry Building Damage Patterns in The Loma Prieta Earthquake and Improvement of Loss Estimation Methodologies." Technical Report to the United States Geological Survey, 1993.

Miller, T. "Variations Between Countries in Values of Statistical Life." *Journal of Transport Economics and Policy*, 2000: 169-188.

Moon, L., M. Griffith, J. Ingham, and D. Biggs. "Review of The Transect of Christchurch Following The 22 February 2011 Earthquake." *15th World Conference on Earthquake Engineering.* Lisbon, Portugal, 2012.

NRC. *National Building Code of Canada.* Ottawa, ON, Canada: National Research Council of Canada, 2010.

OMB. *Circular A-4: Regulatory Analysis. .* Washington, DC, USA: United States Office of Management and Budget, 2003.

Paxton, B. *Quantifying Unreinforced Masonry Seismic Risk and Mitigation Options in Victoria, BC.* M.A.Sc. Thesis, Vancouver, BC, Canada: University of British Columbia, 2014.

Paxton, B., F. Turner, K. Elwood, and J. Ingham. "URM Bearing Wall Building Seismic Risk Mitigation on The West Coast of The United States: A Review of Policies and Practices." *Bulletin of The New Zealand Society for Earthquake Engineering*, 2015a: vol. no. 48, issue no. 1.

Paxton, B., K. Elwood, J. Ingham, and B. Lizundia. "Benefit-Cost Analysis of Unreinforced Masonry Buildings in Victoria, Canada." *2015 NZSEE Conference.* Rotorua, New Zealand: New Zealand Society for Earthquake Engineering, 2015b.

Paxton, B., K. Elwood, S. Barber, and C Umland. "Addressing URM Seismic Risk in Victoria, Canada." *12th Canadian Masonry Symposium.* Vancouver, BC Canada, 2013.

Risk Engineering. "EZ-FRISK v7.62." Risk Engineering Inc., 2012.

Rutherford & Chekene. *Seismic Retrofitting Alternatives for San Francisco's Unreinforced Masonry Buildings.* San Francisco, CA, USA: City of San Francisco, 1990.

Rutherford and Chekene. "Damage to Unreinforced Masonry Buildings in The October 17, 1989 Loma Prieta Earthquake." San Francisco, CA, USA, 1991.

Rutherford and Chekene. *Development of Procedures to Enhance The Performance of Rehabilitated URM Buildings.* Gaithersburg, MD, USA: National Institute of Standards and Technology, 1997.

Tarrant, A. *Multi-billion dollar costs of earthquake strengthening and higher insurance premiums beyond Christchurch only now dawning on landlords, tenants and insurers.* February 10, 2012. http://www.interest.co.nz/property/57817/multi-billion-dollar-costs-earthquake-strengthening-and-higher-insurance-premiums-bey.

Thibert, K. *A Methodology for Assessing The Seismic Risk of Buildings.* M.A.Sc. Thesis, Vancouver, BC, Canada: University of British Columbia, 2008.

Turner, F. "Seventy Years of The Riley Act and its Effect on California's Building Stock." *13th World Conference on Earthquake Engineering.* Vancouver, BC, Canada, 2004.

Umland, C. "Personal Communication with Brandon Paxton." March 2, 2015.

USDoT. *Guidance on The Economic Value of a Statistical Life.* Washington, DC, USA: United States Department of Transportation, 2013.

Viscusi, K, and J Aldy. *The Value of a Statistical Life: A Critical Review of Market Estimates Throughout The World.* Cambridge, MA, USA: Harvard Law School, 2002.