Benefit-cost analysis for seismic rehabilitation of unreinforced masonry buildings in Victoria, Canada

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B. Paxton

Read Jones Christoffersen, Victoria, Canada.

K.J. Elwood & J.M. Ingham

University of Auckland, Auckland, New Zealand.

B. Lizundia

Rutherford + Chekene, San Francisco, U.S.A.

ABSTRACT: Like many cities in New Zealand, Victoria (British Columbia, Canada) suffers from the combined impact of high to moderate seismic hazard and a concentration of vulnerable unreinforced masonry (URM) buildings in the central business district. Unlike New Zealand, however, there are few legal provisions for mitigating seismic risk. To promote seismic upgrading of URM buildings, a study was undertaken to perform benefit-cost analyses specifically for seismic rehabilitation in Victoria, considering the seismic hazard, building assets, occupant/pedestrian exposure, a variety of strengthening measures, and local construction costs. The analyses are underpinned by building motion-damage relationships developed based on observed damage in past earthquakes in California and New Zealand. Upgrading measures considered range from parapet bracing to comprehensive seismic upgrades consistent with local practices. Parapet bracing and other partial retrofits are shown to have favourable benefit-cost ratios and thus be strong candidate measures for risk mitigation programs. Full upgrades are shown to have less favourable benefit-cost ratios. While applied to Victoria, the generality of the methodology and the use of Canterbury damage data make the findings of this study particularly relevant for New Zealand cities grappling with the introduction of new earthquake-prone building legislation.

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). For comparison, Paxton et al. (2013) showed that the design spectra for 475 and 2475-year return periods for Victoria and Christchurch are similar. Despite this hazard Victoria has yet to experience shaking beyond MMI VI intensity since the middle of the 19th century (Lamontagne et al., 2008), when URM building construction began in Victoria. "Active" programs to identify or mitigate URM (or other) seismic risks are currently lacking in comparison to regions facing similar seismic hazards (Paxton et al., 2013). Typically seismic strengthening is only required when buildings undergo a change of use or substantial alteration. Furthermore, there are no ordinances in place addressing falling hazards posed by parapets or other similar components, as have been implemented as a minimum in many cities facing similar risks such as Los Angeles and San Francisco. This lack of action was the impetus for the study summarized herein on benefit-cost analysis of URM seismic rehabilitation. The remainder of the discussion is on the methodology and results of the benefit-cost analyses. 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 analyses, a detailed description of the derivation of the building structural vulnerabilities, using data from both California and New Zealand, is provided. Further details of the study can be found in Paxton (2014).

2 QUANTIFYING BUILDING VULNERABILITY THROUGH OBSERVED DAMAGE

There are three well-accepted methods to quantify building vulnerability functions, commonly referred to as “empirical,” “analytical,” and “expert opinion” methods (Porter et al., 2012). An empirical approach was used in this study, whereby observed building structural damage is expressed as a function of the estimated ground motion intensity at the site. The observed damage is used to generate fragility functions, which are used to estimate losses for URM buildings in Victoria. URM damage data from the 1989 Loma Prieta, 1994 Northridge, and 2010/2011 Canterbury earthquakes were employed. Damage data were generally in the form of ATC-13 (ATC, 1985) damage states, as discussed in Paxton (2014) and were collected by others (Rutherford and Chekene, 1990; Rutherford and Chekene, 1997; Lizundia, 1993; and Moon et al., 2012).

In order to develop vulnerability functions it was necessary to select a common ground motion intensity measure (IM) and method of estimating the IM at the site. ATC-13 employed modified Mercalli intensity (MMI) due to a paucity of more objective data at the time. Lizundia (1993), Rutherford and Chekene (1997), and King et al. (2002) investigated a host of IMs including MMI, instrumental intensity (I_{MM}), peak ground acceleration/velocity (PGA/PGV), and spectral response values. Lizundia (1993) and King et al. (2002) concluded that spectral acceleration correlated reasonably well with observed damage, although parameters such as I_A, MMI, and PGV correlated better on average. Cabanas et al. (1997) investigated the use of Arias intensity (I_A) and cumulative absolute velocity (CAV) and concluded that both were good indicators of structural damage, particularly because they directly capture duration effects. However, hazard values for CAV and I_A are not commonly available. Because the ultimate goal of the study herein was to complete loss estimates and benefit-cost analyses, the choice of IM was based on a compromise between accuracy and ease of use. Ultimately, 5% damped spectral acceleration at a period of 1 second ($S_a[1]$) was selected. A period of one second was selected for a variety of reasons: Turner et al. (2010) showed that the spatial variability for $S_a(1)$ was much less than that for $S_a(0.2)$; Penner (2013) showed that a period of one second was preferable in the assessment of out-of-plane URM walls; and Lizundia (1993) showed that damage to URM buildings in the Loma Prieta earthquake was much greater for buildings on soft soils, suggesting correlation of observed damage with long period spectral parameters. It was also necessary to select a method to estimate the IM at each building site based on nearby recorded values. A weighted interpolation method using ground motion prediction equations (similar to that described by Lizundia, 1993) was used in this study. Note that the use of a more advanced method employing conditional probability theory (Bradley and Hughes, 2013) was considered, but that a preliminary comparison indicated that there was little change in the resulting motion-damage relationships, as the binning process masked the differences in intensity measurements (Paxton, 2014).

With each building assigned an ATC-13 damage state and a ground motion intensity, damage probability matrices (DPMs) were constructed for the Canterbury data and the braced-parapet data from Loma Prieta following the methodology described by King et al. (2005). The remainder of the DPMs were obtained by converting published DPMs (Lizundia, 1993; Rutherford & Chekene, 1997) from various IMs to $S_a(1)$ as discussed in Paxton (2014). From these DPMs, the resulting mean damage factor (MDF) as defined in ATC-13 as well as the standard deviation of the MDF (SE_i) were calculated for each intensity bin and a beta cumulative probability distribution was fit to the observed $S_a(1)$ versus MDF data using a weighted least squares criterion. The weighting factor (WF_i) for each data point was defined as $WF_i=MDF_i/SE_i$. Example $S_a(1)$ versus MDF relationships as derived from the 2010/2011 Canterbury earthquakes database are shown in Figure 1. Relationships for unretrofitted buildings, buildings with braced parapets, and fully-retrofitted buildings are included. Similar relationships were derived for the 1989 Loma Prieta and 1994 Northridge earthquake data (see Paxton, 2014). The results for the various databases were compared to one another and to published sources (e.g. HAZUS). Results for unretrofitted and fully-retrofitted buildings are shown in Figure 2 (note: "NSCs" refers to nonstructural components and their significance is discussed shortly). Observe that the HAZUS curve compared to retrofitted buildings is for a "RM1L" category structure, which is a low-rise reinforced masonry building with wood or metal diaphragms. HAZUS does not provide fragilities for retrofitted URM buildings and the HAZUS technical manual (FEMA, 2012) recommends this structure category as a proxy.

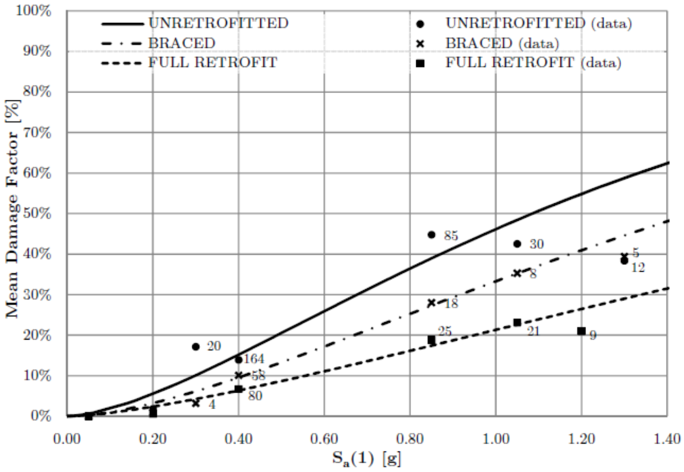


Figure 1. $S_a(1)$ versus MDF relationships for the Canterbury earthquakes (Number of buildings for each data point are also indicated)

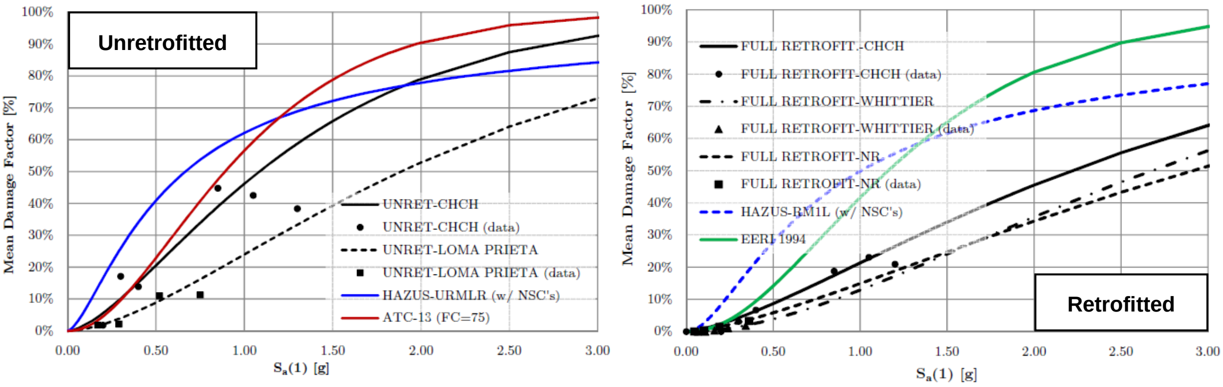


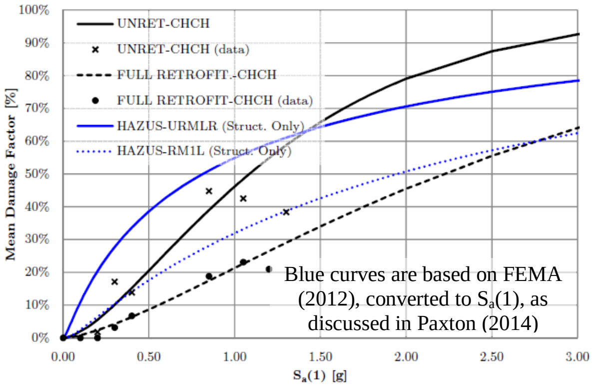
Figure 2. Comparison of observed data across databases and to published sources

The results of the curve-fitting were generally quite intuitive in that increased retrofitting scope corresponded to decreased damage as well as decreased variation among the databases (see Fig. 2). All of the relationships from published sources reviewed (ATC, 1985, EERI 1994, and FEMA, 2012) appeared to overestimate damage relative to the observed data. Rutherford and Chekene (1997) came to a similar conclusion about the EERI (1994) relationship based on an analysis of the 1994 Northridge database. It should be noted that the curves (cumulative probability distributions) have been shown to intensities well beyond the range of the observed data and that King (2005) cautions against such extrapolations. The curves herein are shown to $S_a(1)$=3g primarily for comparison with the published data. Fortunately, the results beyond $S_a(1)$=1g have little impact on the benefit-cost analysis for Victoria's seismic hazard. Another observation is that the New Zealand data (from the 2010/2011 Canterbury earthquakes and denoted as "CHCH" in the figures) indicates substantially more damage than do the remaining databases, all of which are from earthquakes in California. While purely speculative, this observation may be at least partly explained by the following:

- cavity wall construction was reportedly quite common in the Canterbury region (Ingham and Griffith, 2011), whereas cavity wall construction is reportedly quite rare in California (Lizundia, 1993, Rutherford and Chekene, 1997);
- two wythe walls are reportedly common in the Canterbury region (Derakhshan, 2011) whereas walls are typically a minimum of three wythes in California (Rutherford and Chekene, 1997);

- the cumulative effects of the ground motions in the 2010/2011 Canterbury earthquakes likely acted to increase damage (Moon et al., 2014); while the cumulative effects of damage may impact the validity for certain applications, severe aftershocks and triggered events are a possibility (especially for Victoria which lies in a subduction zone) and thus to ignore these possible impacts would also be questionable;
- many cities in California have experienced damaging earthquakes in the past and thus some of the more vulnerable buildings may have been demolished before the events in question; and
- There is a lack of data for the California buildings in the high-intensity range.

The aforementioned discrepancies between observed and published relationships led to questioning whether the observed damage data better represented damage to the overall building, including nonstructural components (NSCs), as implied by the use of ATC-13 damage states (ATC, 1985), or to just the *structure*. A comparison between the observed data and structural-only damage as specified in HAZUS (FEMA 2012) is provided in Figure 3 (whereas the HAZUS models in Fig. 2 include non-structural components). The observed damage data is more consistent with the structural-only damage relationships, which is perhaps intuitive given that buildings are surveyed only from the exterior in some, if not most, cases. Based on this result, it was decided that the observed data should be used to represent the motion-damage relationships for just *structural* damage.



Blue curves are based on FEMA (2012), converted to $S_a(1)$, as discussed in Paxton (2014)

Figure 3. Comparison of observed data to structural-only damage (from Paxton, 2014)

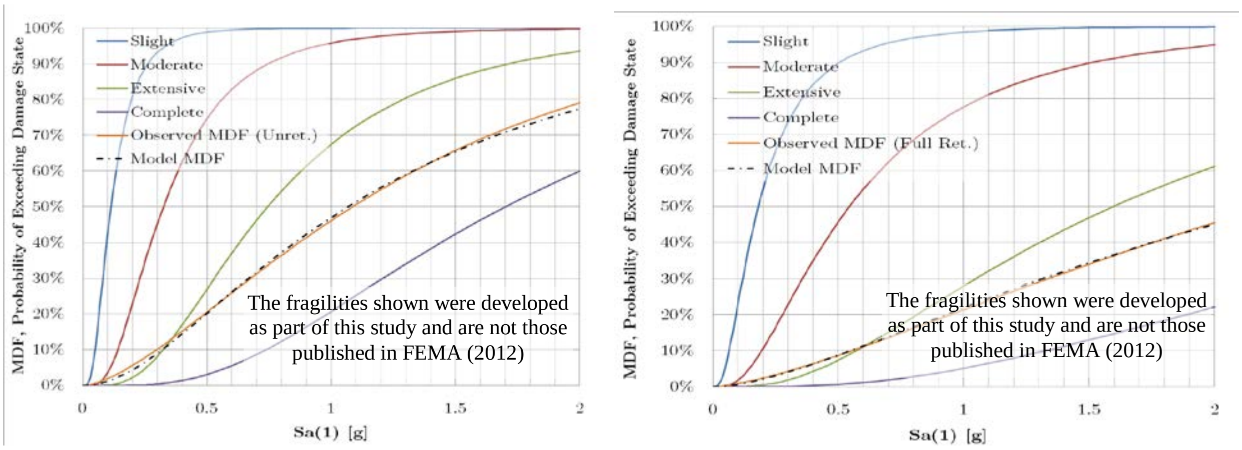
The results thus far have focused solely on the mean damage factor (also commonly referred to as a “damage ratio”). While developing the MDF vs. $S_a(1)$ relationships based on the observed data was fairly simple, developing damage state fragilities presented a challenge: it was desired that the fragilities be developed in terms of HAZUS damage states because it is now the most common loss estimation methodology in North America, but the observed data were in terms of ATC-13 damage states. Thus a conversion process was required. Fragilities in terms of HAZUS damage states were thus developed heuristically based on two criteria:

1. The derived fragilities should match the observed data in terms of their MDF vs. $S_a(1)$ relationships (i.e. the observed and predicted mean damage should match over the range of practical interest)
2. The damage state distributions should reflect the observed data (eg. If 40% of buildings were observed to be undamaged at a given intensity, then the derived damage state fragilities should indicate this)

Developing structural damage state fragilities in terms of HAZUS damage states was advantageous because default HAZUS fragilities could be used for nonstructural components and contents (which could not be developed with the data herein) and combined to estimate overall losses. ATC-13 and HAZUS damage state equivalencies were assumed as shown in Table 1 for the purposes of achieving criterion #2. The associated loss value for each damage state is also shown. The process was applied in developing damage state fragilities for both the Canterbury data and the California (Loma Prieta + Northridge) data for unretrofitted buildings, buildings with braced parapets, and “fully-retrofitted” buildings (“Fully retrofitted” refers to Type A+B strengthening as per Ingham & Griffith, 2011). Damage state fragilities were defined for “partially retrofitted” buildings by taking a weighted average of the "braced-parapet" and "fully retrofitted" results due to a lack of sufficient observed data; a weight of 67% was placed on the braced-parapet results. The results for unretrofitted and fully retrofitted buildings for Canterbury and California are shown in Figures 4 and 5. Fragility functions were in the form of lognormal cumulative distributions and the parameters for each curve are given in Table 2. Meeting criterion #2 with a high degree of consistency was not possible due to both the subjective nature of mapping damage states as well as scatter in the observed data. Criterion #1, however, was achieved quite successfully: the resulting MDF vs. $S_a(1)$ relationships ("MODEL MDF" in Figs.4 and 5) are highly consistent with the relationships derived from the observed data ("Observed MDF" in Figs. 4 and 5). It is also noted in passing that the "Observed MDF" curves in Figure 4 are the same as the "UNRET-CHCH" and "FULL RETROFIT-CHCH" curves from Figure 3 (i.e. the black curves from Fig. 3 have been copied to Fig. 4 for comparison).

Table 1. Assumed ATC-13 and HAZUS damage state equivalencies

ATC-13		HAZUS	
Damage State	**Loss Value***	**Damage State**	**Loss Value**
None	0%	None	0%
Slight	0.5%	Slight	2%
Light	5.5%	Moderate	10%
Moderate	20%		
Heavy	45%	Extensive	50%
Major	80%	Complete	100%
Destroyed	100%		



The fragilities shown were developed as part of this study and are not those published in FEMA (2012)

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Figure 4. Fragilities for structural damage to unretrofitted (left) and fully-retrofitted buildings (right) based on the Canterbury data

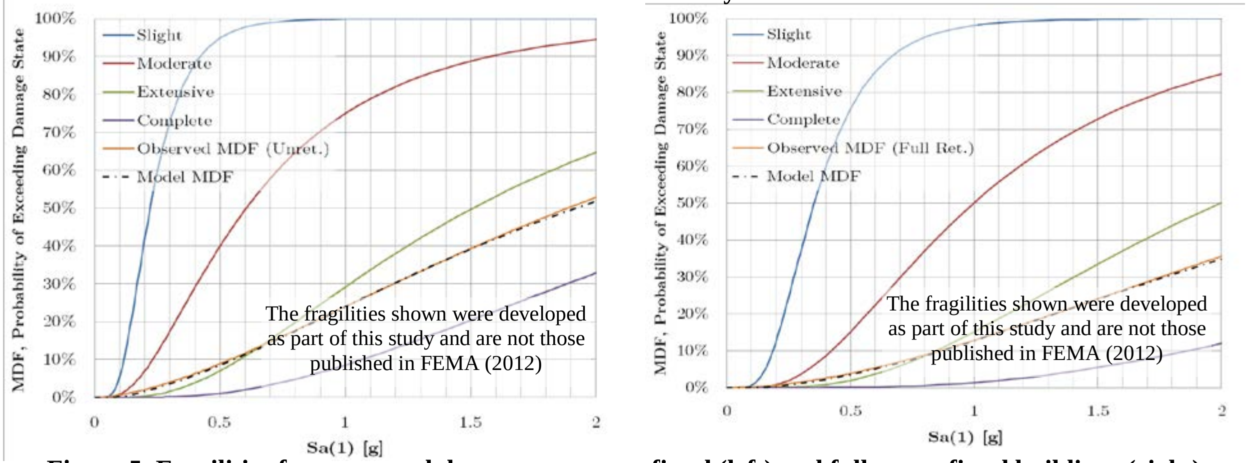

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Figure 5. Fragilities for structural damage to unretrofitted (left) and fully-retrofitted buildings (right) based on the California data

Table 2. Fragility function parameters

		Canterbury			California*		
	Damage State	Median $S_a(1)$ (g)	Mean $S_a(1)$ (g)	Std. Dev. $\ln(S_a(1))$ (g)	Median $S_a(1)$ (g)	Mean $S_a(1)$ (g)	Std. Dev. $\ln(S_a(1))$ (g)
Un-retrofitted	Slight	0.11	0.14	0.65	0.22	0.25	0.50
	Moderate	0.32	0.40	0.65	0.60	0.80	0.75
	Extensive	0.74	0.92	0.65	1.5	2.0	0.75
	Complete	1.7	2.1	0.65	2.8	3.7	0.75
Parapets Braced	Slight	0.14	0.18	0.67	0.31	0.35	0.50
	Moderate	0.40	0.50	0.67	0.88	1.1	0.67
	Extensive	1.0	1.25	0.67	1.6	2.0	0.67
	Complete	2.3	2.9	0.67	3.0	3.7	0.67
Partially Retrofitted	Slight	0.16	0.20	0.67	0.35	0.40	0.50
	Moderate	0.48	0.60	0.67	0.96	1.2	0.67
	Extensive	1.1	1.35	0.67	1.7	2.1	0.67
	Complete	2.8	3.5	0.67	3.2	4.0	0.67
Fully Retrofitted	Slight	0.18	0.25	0.80	0.35	0.40	0.50
	Moderate	0.54	0.75	0.80	1.0	1.25	0.67
	Extensive	1.6	2.2	0.80	2.0	2.5	0.67
	Complete	3.7	5.1	0.80	4.4	5.5	0.67

*Refers for a combination of data from the 1989 Loma Prieta earthquake (for unretrofitted and braced-parapet buildings) and the 1994 Northridge earthquake (for fully-retrofitted buildings).

3 BENEFIT-COST METHODOLOGY

Benefit-cost analyses for seismic retrofitting of a prototypical URM building of commercial occupancy 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
- Public losses: occupant and pedestrian casualties (deaths and injuries)

The expected annual losses (EAL) for a prototypical URM building in Victoria were calculated as shown in Equation 1 and Figure 6. The $S_a(1)$ hazard curve (fig. 6, left) for site class C 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. Thus the calculated hazard curve was scaled up by approximately 10% to match this value for the analysis herein. The example shown is for losses due to building damage (for an “unretrofitted” building based on a weighted average of the Canterbury and California data as subsequently discussed), but the process is similar for other losses. 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.

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

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

The process was performed for the four aforementioned strengthening statuses (unretrofitted, parapets-braced, partially-retrofitted, and fully-retrofitted) and for four different soils site classes (B, C, D, and E as defined in the National Building Code of Canada [NRC, 2010]). The following subsections briefly describe several of the key parameters including: building vulnerability, seismic hazard, building value, downtime, casualty rates, and economic parameters. More detailed discussion is provided in Paxton (2014).

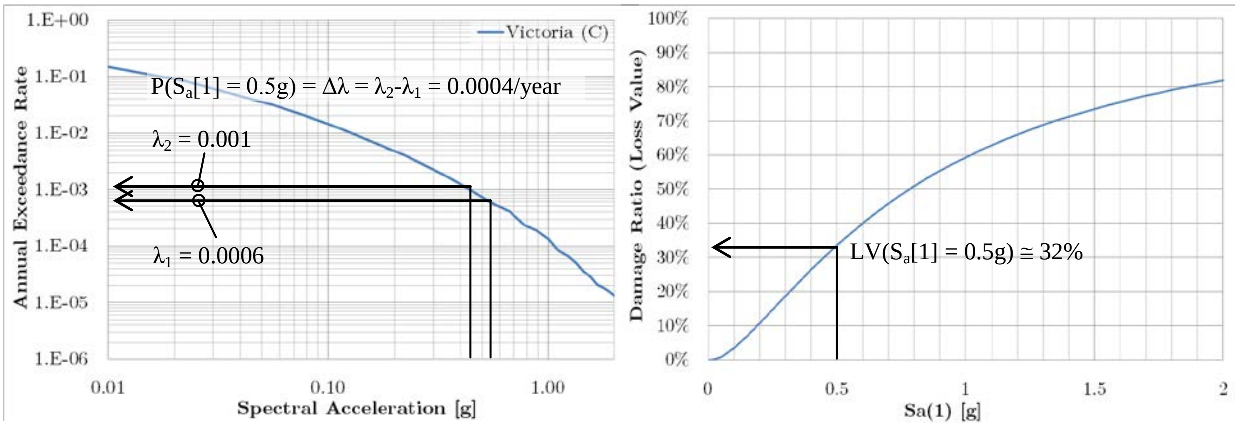

Figure 6. Example calculation of LV for Sa(1)=0.5g for an "unretrofitted" building

3.1 Building Vulnerability

Building vulnerability was represented through separate motion-damage relationships for structural components, acceleration-sensitive nonstructural components (NSCs), drift-sensitive NSCs, and building contents, similar to the procedure contained in HAZUS (FEMA, 2012). Structural damage was represented using damage state fragilities based on the observed damage data, as discussed in Section 2.0. The vulnerability of Victoria's buildings is expected to fall somewhere between those of California (i.e. Loma Prieta and Northridge) and Canterbury and so the fragilities were defined using weighted averages as follows (Paxton, 2014):

- Base case: 67% Canterbury, 33% California
- Upper Bound: 100% Canterbury, 0% California
- Lower Bound: 50% Canterbury, 50% California

This paper focuses on the base case, while a sensitivity analysis is provided in Paxton (2014). Note that the fragilities used in this analysis were developed by first taking the weighted average of the observed MDF vs. $S_a(1)$ relationships and then generating the individual structural damage state fragilities to match the resulting MDF vs. $S_a(1)$ curve. Motion-damage relationships for nonstructural components and contents were based on default HAZUS data (FEMA, 2012) with modifications to account for additional losses due to structural collapse following the methodology proposed by Farokhnia (2013). Contents fragilities were equal to the acceleration-sensitive NSCs, except that the resulting losses are reduced as it is assumed that some contents will be recovered (FEMA, 2012). Note that HAZUS specifies fragilities in terms of various intensity measures and thus conversions based on pseudospectral relationships (Chopra, 2012) and spectral shape (for site class C in Victoria) were required to obtain fragilities in terms of $S_a(1)$. The damage state fragilities for drift-sensitive NSCs and acceleration-sensitive NSCs are provided in Paxton (2014).

With the damage state fragilities for each component defined, the overall relationship for building damage losses (similar to that shown in Figure 6) can be calculated as the weighted average of the four components, based on their relative contributions to the overall building replacement value. The value of the structural components, acceleration-sensitive NSCs, drift-sensitive NSCs, and contents were assumed to be 22.1%, 32.3%, 20.6%, and 25.0% of the building value, respectively, as specified by HAZUS for a commercial ("COM1") occupancy building. The building replacement value was taken as \$260/sq.ft. (≈\$24/m^2) as recommended by Thibert (2008) for URM buildings in British Columbia. In passing it is noted that the notion of a “replacement value” for a URM building is somewhat flawed in that URM building construction is prohibited in many 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. Finally, an "economic critical loss ratio" (ECLR) was employed. The ECLR is the (overall) damage ratio at which a building is assumed to be uneconomical to repair and is instead replaced. Rutherford and Chekene (1990) suggested using an ECLR of 40% for unretrofitted URM buildings and 50% for retrofitted URM buildings. EERI (1989) suggested an ECLR of up to 65%. It is acknowledged that demolition decisions are governed by many factors in addition to building damage, and there is potential for widespread demolitions to more lightly damaged buildings as was observed in the 2010/2011 Canterbury earthquakes (Marquis et al., 2015). An ECLR of 50% was used for all cases herein.

3.2 **Downtime**

From a building owner's perspective the relevant downtime is the time 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 \$0.07/sq.ft/day (\$0.0065/m^2), which is typical for URM buildings in desirable downtown Victoria locations.

3.3 **Casualties**

The key parameters required to estimate casualties are the exposure (i.e. number of pedestrians/occupants) and the casualty rates. The occupant and pedestrian densities used in this study were 0.0036 persons/sq.ft. (0.00033 persons/m^2) of floor area and 30 persons/1000 ft 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 3. 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). 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). Johnson et al. (2014) reports 161 medically-treated injuries due to “masonry” in the February 2011 Christchurch earthquake, which is approximately four times the 39 deaths attributed to unreinforced masonry (Canterbury Earthquakes Royal Commission, 2012). 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, 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, 1994, Miller 2000, Viscusi, 2002).

3.4 **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. In this study, a discount rate of 5% was applied to owner benefits (i.e. damage and downtime) and a rate of 3% was applied to public benefits (i.e. reduced casualties). A time horizon of 50 years was used for the analyses. Paxton (2014) provides a sensitivity analysis for alternative parameter values.

Table 3. Fatality rates

Structural damage state	Occupant fatality rate (deaths/person)	Pedestrian fatality rate (deaths/person)
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 specifies that 15% of buildings in the "complete" damage state collapse

3.5 **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 authorities 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 may be seen in New Zealand where property values have reportedly been impacted by the 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 and 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 4. Higher and lower values were also considered as part of a sensitivity analysis (Paxton, 2014).

Table 4. Unit costs for seismic upgrading

Upgrade Type	Cost $/sq.ft. ($/m^2)	Source (See Paxton, 2014)
Parapet Bracing*	3 (0.27)	Detailed estimates for sample buildings
Partial Retrofitting**	10 (0.93)	Detailed estimates for sample buildings
Full Retrofitting***	33 (3.1)	Cost data for actual 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)

4 BENEFIT-COST RESULTS

4.1 Overall Benefit-Cost Results

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 8000sq.ft. (≅744m^2) and 30ft (≅9.1m) of streetfront sidewalk exposure (Table 5). 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 $S_a(1)$. If Sa(0.2) had been selected, the difference would be less dramatic. Observed damage, however, has been shown to correlate highly with soil type as previously discussed.

Table 5. Overall benefit-cost results (favourable BCRs shown in bold)

	Braced Parapets			**Partially-Retrofitted**			**Fully-Retrofitted**		
Site Class	**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

4.2 Owner-Only Benefit-Cost Results

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 6), 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 6. Owner-only benefit-cost results (favourable BCRs shown in bold)

	Braced Parapets			**Partially-Retrofitted**			**Fully-Retrofitted**		
Site Class	**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 CONCLUSIONS

The collected damage data from Canterbury and California was consistent with expectations in that increased retrofitting resulted in decreased damage and decreased scatter. New Zealand buildings appeared to be more vulnerable than their North American counterparts. Isolating and quantifying the causes of the apparent differences in vulnerability is an area for future research. It was also noted that an important distinction between structural damage and overall building damage perhaps has not been well addressed in the damage data collected to date. Future damage surveys should more clearly distinguish between types of damage (or be appropriately limited to specific components) and should examine potential differences in nonstructural damage patterns in URM buildings as compared to more modern buildings. It would also be useful to develop damage data collection methods in terms of HAZUS damage states instead of ATC-13 damage states, as HAZUS is now the most commonly used loss-estimation tool in North America. Nonetheless, the above reported study provides new fragility curves based on some of the most recently collected data worldwide for clay brick bearing wall buildings with flexible timber diaphragms.

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. 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. One possible remedy for this issue is to combine expected cost with other goals in an 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 (eg. URM buildings provide low-cost housing in many communities). Finally, the values assigned to many of the aforementioned parameters were highly uncertain and required significant assumptions. While a sensitivity study by Paxton (2014) support the above conclusions, 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.

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