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VULNERABILITY OF HISTORICAL MASONRY STRUCTURES: EFFECT OF MITIGATION STRATEGIES ON REGIONAL LOSS ESTIMATION

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Abstract

The vulnerability of unreinforced masonry structures (URMs) was highlighted during the 2010-2011 Canterbury Earthquake Swarm which impacted the city of Christchurch, New Zealand. In particular, losses from this class of building had a significant influence the extent of damage especially within the central business district (CBD) of Christchurch. Since the earthquakes, research efforts have focused on learning from the impact of these events in order to facilitate seismic risk assessment practices in order to better understand and ultimately help mitigate the expected losses due to URM damage during future events. From these efforts have come empirical studies on the effect that various retrofitting strategies have had on reducing the vulnerability of URM structures and ultimately mitigating damage and loss. Various mitigation strategies have been considered which range in complexity and scope from simply bracing unreinforced masonry parapets to the addition of supplemental lateral bracing.

Keywords: risk; vulnerability; masonry; retrofit; mitigation

1. Introduction

Past earthquakes have demonstrated the danger posed by historical unreinforced masonry buildings (URMs). Since these historical unreinforced masonry buildings are built without the reinforcing steel which provides desired ductility under lateral loading, they are particularly vulnerable to earthquakes. This has been observed during earthquakes throughout the world where substantial inventories of historical URMs exist. This includes regions ranging from Italy where many URMs were damaged during the 2009 L'Aquila [1] and 2012 Emilia-Romagnia earthquakes [2] to California in the United States where widespread URM damage was caused by the 2014 South Napa earthquake [3]. In both instances damage was extensive and included not only damage to the buildings themselves but also their contents. In the case of the 2012 Emilia-Romagna and 2014 Napa earthquakes this included monetary losses sustained due to the damage of valuable inventories of cheese in Italy and wine in California.

While the damage sustained to URMs during these two events was extensive, it could have been much worse. Both Italy and California are seismically active and frequent earthquakes are common. Earthquakes are so common in California that the Field Act, mandating earthquake resistant construction and effectively constituting a ban on the construction of new URMs, became law after the 1933 Long Beach Earthquake. Additional legislation was passed in California in 1986 requiring the seismic retrofitting of existing URMs that had been built before the Field Act came into effect. As a result of these two pieces of legislation it is easy to imagine that URM construction is much less prevalent in California as compared to other regions in the world where this type of structure is very prevalent. This was evidenced in the 2010-2011 Canterbury Earthquake Swarm which impacted the southern island of New Zealand. During the course of the three strong events that impacted the region from September 2010 to June 2011, significant damage occurred in and around the Central Business District (CBD) of Christchurch, New Zealand where over 190 URM buildings had to be demolished [4]. This number represents 85% of the total number of buildings that required demolition as a result of these events further highlighting the disproportionate vulnerability exhibited by these buildings.

Understanding the danger that URMs can pose to society, past research efforts have sought to investigate the seismic vulnerability of URMs. With the same goal in mind, studies have approached this problem in different ways. While some studies have focused on the historical performance of URMs in past earthquakes, other studies have relied on experimental tests of unreinforced masonry specimens to better understand the behavior of this type of construction under cyclic and dynamic loading. With the proliferation of advanced analytical tools and greater computational power, analytical studies have sought to leverage the data that has become available through field investigations and laboratory experiments to develop and calibrate numerical models of URM buildings. The body of work that has been devoted to the study of URM buildings during earthquakes is immense and continues to grow.

However, as the wealth of knowledge regarding the seismic vulnerability URM buildings develops, we increasingly need a way in which to translate this knowledge into a form that is meaningful for decision-making. This can be accomplished through the practice of portfolio loss estimation. Portfolio loss estimation is a critical component of assessing vulnerability and resilience on regional or community-wide basis. The main components that are required to estimate regional losses associated with natural and manmade catastrophes are an inventory of risks that are exposed to the various hazards, parameters that define the hazard both in terms of event generation as well as local intensity, and finally an understanding of the vulnerability of the different types of property in the exposed inventory. Within the context of this framework it is possible to estimate expected losses from either a single scenario event or a catalog of many events. In this paper we will apply a portfolio loss estimation framework to investigate the impact that various approaches to retrofitting URMs can have on the regional loss estimate for Boston and the outlying towns of Massachusetts under several plausible earthquake scenarios.

2. Prevalence of Unreinforced Masonry Construction

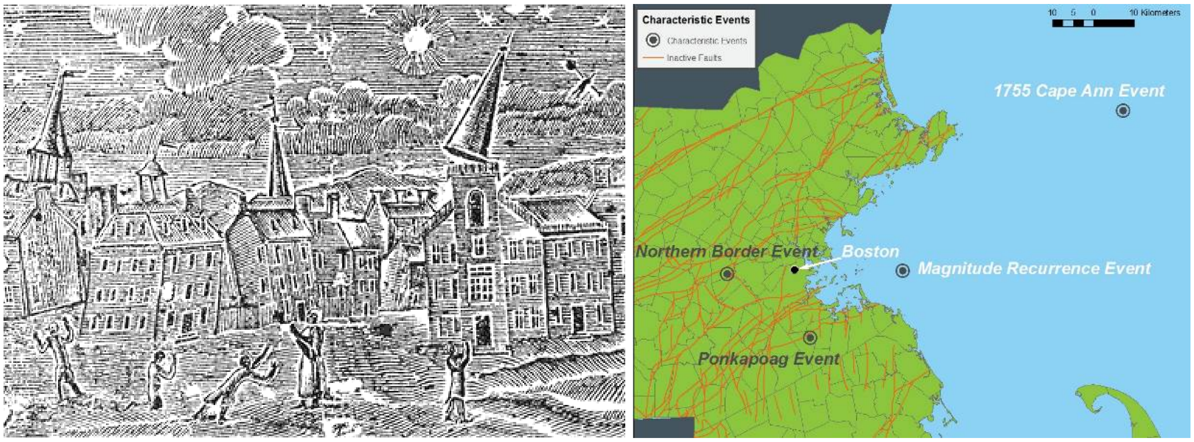
While the URM building stock is slowly dwindling or in the process of going through mandatory retrofits in areas of high seismicity such as California that is not necessarily the case elsewhere. Just as manu URM buildings in Christchurch were still in use during the 2010/2011 earthquakes, URMs in many cities around the world are still being used. This is especially the case in regions of low to moderate seismicity where relatively weak and infrequent events do not provide a persistent reminder of the danger that these buildings can pose to society. Additionally, it is very likely that many historical URM structures that were built before the advent of modern design and construction practices, have not yet experienced an earthquake meaning their seismic vulnerability is highly uncertain.

This is especially the case in the Central and Eastern regions of the United States (CEUS). The United States was settled in the 1620s by British colonists. They went on to establish the 13 original colonies that eventually gained their independence from the Greta Britain in 1776. Although free from British dominion, the inhabitants of this newly formed country still retained much of their construction heritage from their British roots. Owing to their similar British heritage, New Zealand and the United States share very similar building stocks with much of the development in the 18th and 19th centuries coming in the form of unreinforced masonry construction. A prime example of the prevalence of the American URM building stock is Boston, Massachusetts where many of the URMs are still in use today. According to the Northeast States Emergency Consortium (NESEC) there are over 1.6 million URM buildings in the Northeastern United States and close to 19 thousand in the city of Boston alone [5].

Fig. 1 – Photographs of URM buildings in Boston’s Back Bay neighborhood.

3. Seismicity of the Boston Area

While Massachusetts may not be as seismically active as other parts of the world, it is definitely not free from the occasional tremblor. One of the most well-known earthquakes to impact the Boston area was the 1755 Cape Ann Earthquake. Due to the sparse inhabitance of the colonies at that time and the unavailability of seismic recording stations in 1755, it is difficult to know for sure what the exact magnitude and location of the event was. However, after examining historical accounts of the event and leveraging modern ground motion attenuation relationships researchers believe that this earthquake occurred approximately 40 km ENE from Cape Ann, MA with a moment magnitude between 5.8-6.3 M_w as shown in Fig.2(b) [6].



(a) (b)

Fig. 2 – 1755 Cape Ann Earthquake: (a) Woodcut illustration showing an account of the damage due to the 1755 Cape Ann Earthquake [7]; (b) Approximate location of the event epicenter relative to Boston, MA

In addition to considering this historical event as a referential benchmark it is also necessary to consider possibilities of potential future earthquakes that could eventually impact the Boston area. To accomplish this, two different approaches to the probabilistic hazard were considered. Based on historical data and the current understanding regarding the local seismicity of the Boston Area, the first perspective is predicated on the return period of a M_w 5.9 earthquake within 100 km of Boston being approximately 2500 years. As such this return period would be roughly analogous to a Maximum Considered Earthquake (MCE) event for the city of Boston. This perspective is straightforward to conceptualize however it is rather vague and unconstrained resulting in a theoretically infinite number of scenarios that would satisfy the magnitude recurrence perspective. Therefore, the portfolio loss modeling framework that was discussed earlier in this paper was used to select a characteristic event from a multitude of events that satisfy these magnitude recurrence criteria. From a large set of 30,000 plausible earthquake scenarios one scenario was selected such that it satisfied two additional constraints:

1.) The ground shaking intensity (defined as the short period (T=0.3s) spectral acceleration) should be sufficiently close (+/- 25%) to the short period MCE design spectral acceleration for Boston which is 0.29g [8].

2.) The estimated economic loss should be sufficiently close (+/- 25%) to the average (statistical mean) of the economic losses resulting from all plausible scenarios satisfying the event set criteria.

Taking these two additional criteria into account it was possible to select a single scenario that characterized the magnitude recurrence perspective and was sufficiently consistent with the code-prescribed short period spectral acceleration design intensity. Given the large amount on uncertainty that is associated with earthquake event scenarios that could potentially impact the Northeastern United States the aforementioned criteria were adopted to constrain the selection of the scenarios that were used for the analyses presented in this study to ensure that sufficient ground motion intensity was modeled in the Boston area to induce damage in a significant portion of the modeled URM inventory. This approach was deemed appropriate for this study because the goal of this paper is highlight the impact of varying URM vulnerability on event losses rather than quantification of the absolute risk in which case scenario selection through PSHA or hazard disaggregation would be more appropriate approaches.

While the Northeastern United States (NEUS) is not near any active seismic boundary there are inactive faults that underlay the geography. In particular, there are two bands of inactive faults that are adjacent to Boston, the Northern Border Fault to the north of the city and the Ponkapoag Fault which is just to the south. Given that these are inactive faults that have been dormant for many years it would not be practical or reasonable to assume that stress has accumulated on these inactive faults such that an earthquake could be produced as would as is the case along an active tectonic boundary. However, it is reasonable to assume that these inactive faults do present a plane of weakness in the regional geology that could be exploited and subject to rupture in the event that sufficient intra-plate stress has accumulated and released.

Using these inactive fault locations as a basis for constraining the location of plausible earthquakes, a second perspective was developed that considers events along either of these fault clusters as plausible worst-case-scenarios. Similar to the magnitude-recurrence perspective that was discussed in the preceding paragraphs more than 700 Mw 5.9 scenarios were uniformly distributed along these bands of faults. From these events one characteristic scenario was selected from each inactive fault cluster. Again, the MCE design spectral acceleration intensity and average loss criteria (points 1 and 2 above) were adopted to select the characteristic events. The locations of the selected characteristic events for both the magnitude recurrence and adjacent inactive fault perspectives as well as the presumed location of the 1755 Cape Ann earthquake can be seen in Fig.2(b). The statistics of the distributed scenarios that were used for the selection of the characteristic scenario events as well as the event economic losses and ground shaking intensity for downtown Boston can be seen in Table 1.

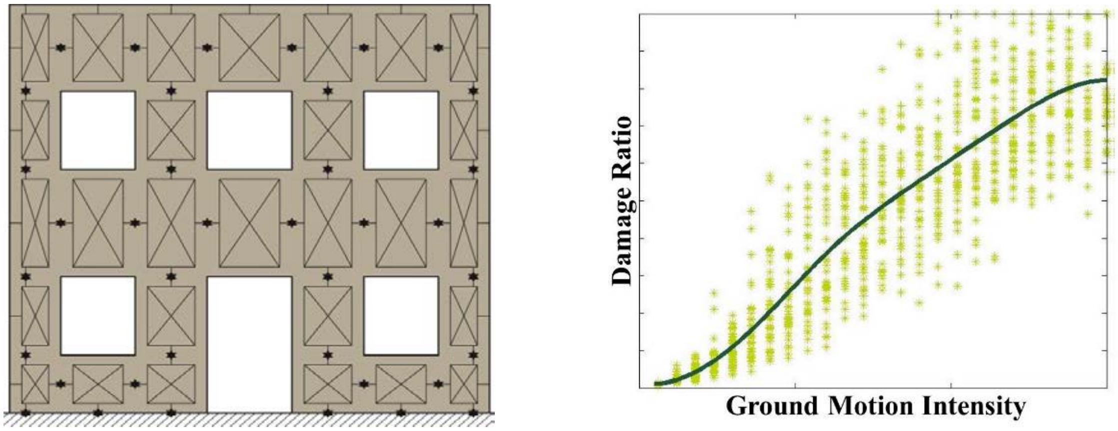
Table 1 – Statistics of distributed simulated events for each hazard perspective and results from characteristic scenario events.

		100km Radius	**Northern Border Fault**	**Ponkapoag Fault**
Distributed Scenarios	**Mean Loss (USD $1M)**	12,890	65,932	45,317
	COV	1.16	0.31	0.19
Selected Scenarios	**Loss (USD $1M)**	15,968	60,312	45,409
	***Sa*(0.3) (g) in Boston**	0.23	0.31	0.29

4. Developing Vulnerability Relationships for URM Buildings

In performing portfolio loss estimation for a particular region it is important to have an accurate understanding of the unique building stock that exists in the area of interest. To gain a better understand of the building stock in the Boston area the AIR Industry Exposure Database (IED) is leveraged. The IED is a proprietary database of known insurable exposure and includes information such as construction type, occupancy, number of stories, and replacement value for all such exposures. Upon analysis of the IED for Massachusetts it was determined that the vast majority of URM buildings were low-rise construction of residential occupancy. As such, a low-rise residential URM building was selected to be the focus of the vulnerability assessment for this study. It should also be noted that URM buildings constitute approximately 8% of the replacement value of all insurable property in the study area.

As mentioned previously, the vulnerability of URM buildings has been studied using multiple approaches whether it is through empirical observations that take into account the observed performance of URM buildings in past earthquakes or experimental and analytical studies that seek to characterize the behavior of URMs in the context of laboratories and computer simulations. In this paper a hybrid approach is adopted for the vulnerability assessment of URM buildings. A validated macro-element modeling framework for the dynamic analysis of URM buildings [9] was used to generate a model of a prototypical URM building in the OpenSEES structural analysis platform [10]. A model was developed to emulate a prototypical two-story residential building that would be typically found in the Boston area and surrounding towns. A schematic of this model can be seen in Fig.3(a).



(a) (b)

Fig. 3 – Analytically derived vulnerability of URM buildings: (a) Schematic of prototypical two-story residential URM building used for vulnerability assessment; (b) Typical URM building damage function.

The ultimate goal of the vulnerability assessment is to develop a curve called a damage function. A damage function is a relationship that associates a given level of ground shaking intensity with an estimated level of damage that is quantified as a damage ratio where the damage ratio is defined as the cost required to repair a building divided by the building's replacement value. To develop this curve it is necessary to analyze the structure across a broad range of shaking intensities. For a low-rise building the ground shaking intensity was selected to be the spectral acceleration at a period of 0.3 seconds ($S_a(0.3)$). This intensity measure was selected to maintain compatibility with the loss modeling framework that is currently employed by AIR which is based on the assumption that the majority of low-rise buildings (1-3 stories) will have a fundamental period of vibration close to 0.3 seconds. Incremental dynamic analysis [11] was conducted using a suite of 40 ground motions representative of the Boston area that was obtained from SAC Steel Project database [12]. The prototype structure was analyzed using the suite of 40 SAC ground motions scaled to 25 different intensity bins with each successive intensity bin corresponding to an incrementally larger $S_a(0.3)$ spectral acceleration intensity. These analyses resulted in the light green data points shown in Fig.3(b) which represent the estimated damage ratio corresponding to the each of the 1,000 dynamic analyses that were performed. The solid dark green line is a sigmoidal best fit through the data and is the damage function that was derived to represent the vulnerability of low-rise URM buildings in this study.

Utilizing a different approach to vulnerability estimation, researchers in New Zealand collected empirical damage data resulting from the February 22, 2011 Christchurch earthquake [13]. The focus of their research was to investigate the performance of URM buildings that been strengthened prior to the earthquake and compare their behavior to the URM buildings in the CBD that were unstrengthened at the time of the event. This research resulted in an interesting and valuable dataset that provided a comparison between the performances of strengthened and unstrengthen URM buildings. The retrofits that were performed on the buildings were classified into three different categories [14]:

1.) Braced Parapet or Chimney – A concrete ring beam has been added and sufficient bracing has been provided which ties either the parapet or chimney back to the roof, restraining it from collapse.

2.) Type A Retrofit – The diaphragms which are typically flexible timber are stiffened and strengthened and positive connections are added to tie the URM walls to the diaphragms to prevent out-of-plane failure.

3.) Type A+B Retrofit – Includes the improvements of Type A as well as the addition of strongbacks to prevent out-of-plane failure and increase the in-plane resistance of the URM walls.

The results of these field investigations were used to develop vulnerability functions corresponding to not only unstrengthened URMs but also URM buildings that had undergone some sort of strengthening [13]. The vulnerability functions for URM buildings in various stages of strengthening that were derived from the damage data obtained through the field investigations conducted in New Zealand are shown in Fig.4. It should be noted that while the analytically derived vulnerability functions developed for the study presented in this paper were derived using an intensity measure of $S_a(0.3)$, the researchers who derived the vulnerability curves presented in Fig.4 used $S_a(1.0)$ as their preferred intensity measure [13]. Although the intensity measure of the vulnerability curves derived using damage data from New Zealand is different than the intensity measure used in this study, these vulnerability functions were used to quantify the relative vulnerability between URM buildings under various stages of strengthening. The relativities derived from the vulnerability functions shown in Fig.4 were applied to the damage function derived for a prototypical URM building in Boston shown in Fig.3 (b) to obtain a set of damage functions representing strengthened and unstrengthen URM buildings. These sets of damage functions were used for a portfolio loss analysis of the URM building inventory in the Boston area.

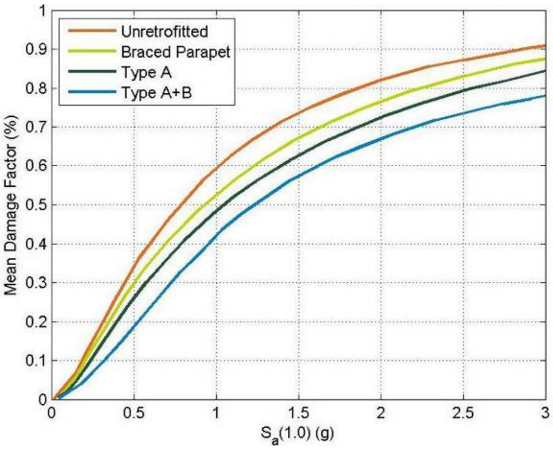


Fig. 4 – Vulnerability functions derived for URM buildings under various stages of strengthening [13].

5. Loss Estimation for Selected Events

Portfolio loss estimation was performed for the URM building stock in the Boston area under a total of four different earthquake scenarios that include the historical 1755 Cape Ann earthquake as well as the magnitude recurrence and adjacent fault scenarios discussed in Section 3. These analyses were performed using AIR's high resolution IED, which is developed at a resolution of 90m to ensure geospatial accuracy. Each of the four earthquake scenarios was analyzed four different times to consider the effect that different earthquake strengthening strategies has on the resulting portfolio loss estimation. For each of the four earthquake scenarios one analysis was performed assuming the entire URM building stock was unstrengthened, another analysis was performed with the assumption that the entire URM building stock had undergone some sort of parapet or chimney bracing, another analysis was performed assuming the URM building stock has been strengthened according to Type A retrofits, and the final analysis was performed assuming the URM building stock had been strengthened according to Type A+B retrofits.

The damage footprint for the unstrengthened URM building stock due to the historical 1755 Cape Ann earthquake can be seen in Fig.5(a). Due to its location a great distance off the coast it can be seen that the impact of this scenario to the URM building stock is not very significant. It is estimated that losses to the unstrengthened URM building stock due to this event would be approximately $56 million USD. However, if the building stock were strengthen according to parapet/chimney bracing, Type A, or Type A+B retrofits the losses would be $49, $39, and $29 million USD respectively.

The damage footprint for the unstrengthened URM building stock analyzed under the magnitude recurrence earthquake scenario can be seen in Fig.5(b). Given its proximity to Boston, the magnitude recurrence earthquake scenario resulted in significantly larger losses to the URM building stock as compared to the 1755 Cape Ann scenario. It was estimated that losses to the unstrengthened URM building stock was $5.7 billion USD as compared to the strengthened building stocks which resulted in $5.1, $4.3 and $3.1 billion USD for braced parapet/chimney, Type A, and Type A+B retrofits respectively.

The damage footprints for the unstrengthened URM building stocks under the two adjacent fault earthquake scenarios can be seen in Fig.5(c) and Fig.5(d) for the Northern Border Fault and Ponkapoag Fault respectively. These two scenarios were considered to be realistic worst-case-scenarios and as such resulted in the most significant losses of all of the scenarios analyzed. The Northern Border Fault scenario was estimated to result in $17 billion USD for the unstrengthened URM building stock while the Ponkapoag Fault scenario was estimated to result in $13.8 billion USD for the same unstrengthened URM building stock. The inclusion of strengthening by parapet/chimney bracing, Type A, and Type A+B retrofits reduced losses to $15.1, $13.5, and $10.5 billion USD for the Northern Border Fault scenario and $12.3, $10.9, and $8.4 billion USD for the Ponkapoag Fault scenario. A summary of the losses resulting from URM damage as well as the URM contribution to total loss can be seen in Table 2.

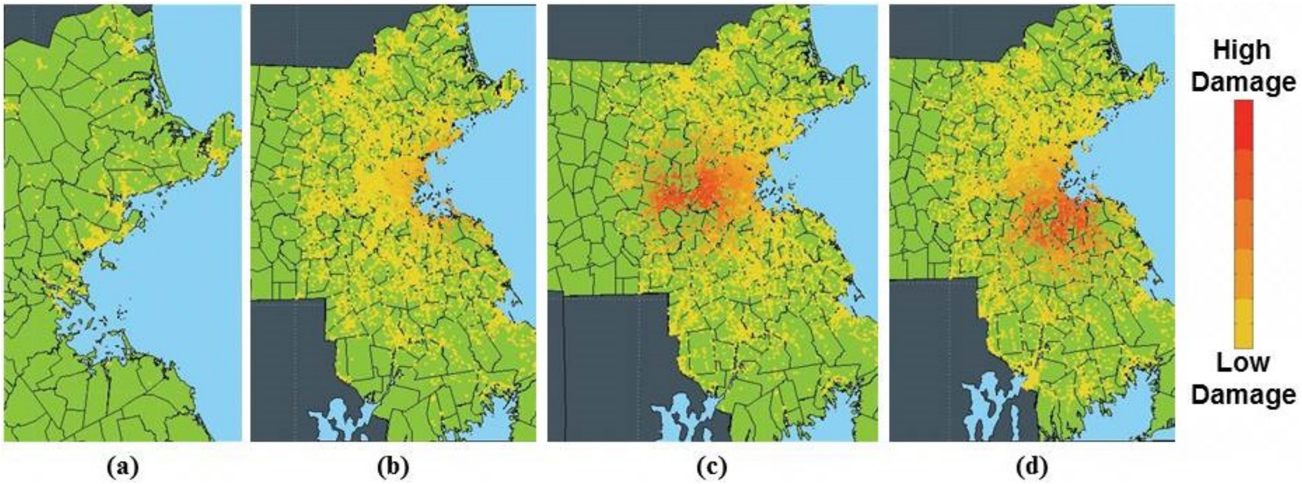


Fig. 5 – Loss footprint for unstrengthened URM building stock analyzed under 4 different earthquake scenarios: (a) 1755 Cape Ann; (b) Magnitude Recurrence; (c) Northern Border Fault; (d) Ponkapoag Fault.

Table 2 – Losses of URM structures for each characteristic scenario event.

Retrofit Condition	**1755 Cape Ann**		**100km Radius**		**Northern Border Fault**		**Ponkapoag Fault**	
	Loss (USD $1B)	**% of Tot.**	**Loss (USD $1B)**	**% of Tot.**	**Loss (USD $1B)**	**% of Tot.**	**Loss (USD $1B)**	**% of Tot.**
None	0.056	30	5.7	31	17.0	27	13.8	28
Braced Parapet/ Chimney	0.049	27	5.1	28	15.1	25	12.3	26
Type A	0.039	24	4.3	25	13.5	22	10.9	24
Type A+B	0.029	18	3.1	20	10.5	18	8.4	19

The losses obtained for the four scenarios analyzed using the URM building stock exhibiting different degrees of strengthening were compared in terms of the contribution of URM loss to the total estimated event loss. This comparison is reflected through the bar graph shown in Fig.6. It can be seen from this bar graph that the impact of seismic strengthening on loss contribution of URMs to the total event losses is significant. For all of the scenarios the contribution of URM losses to the total was reduced from 27%-31% to 18%-20%, which is a reduction in URM loss contribution of approximately one third. These findings not only demonstrate the impact that strengthening URM buildings can have on the reduction of earthquake losses but also highlight the importance of considering seismic strengthening when performing portfolio loss analysis. It should be noted however that while the strengthening of URM buildings leads to a significant reduction in their contribution to the overall event loss, this loss contribution of 18% to 20% is still significantly greater than their 8%

contribution to the overall value of insurable property in the study area. This is an indication that even after employing the most comprehensive strategy for the strengthening of URM buildings, these structures still exhibit a disproportionately high degree of vulnerability to earthquake damage and could potentially contribute to significant losses in the event of an earthquake.

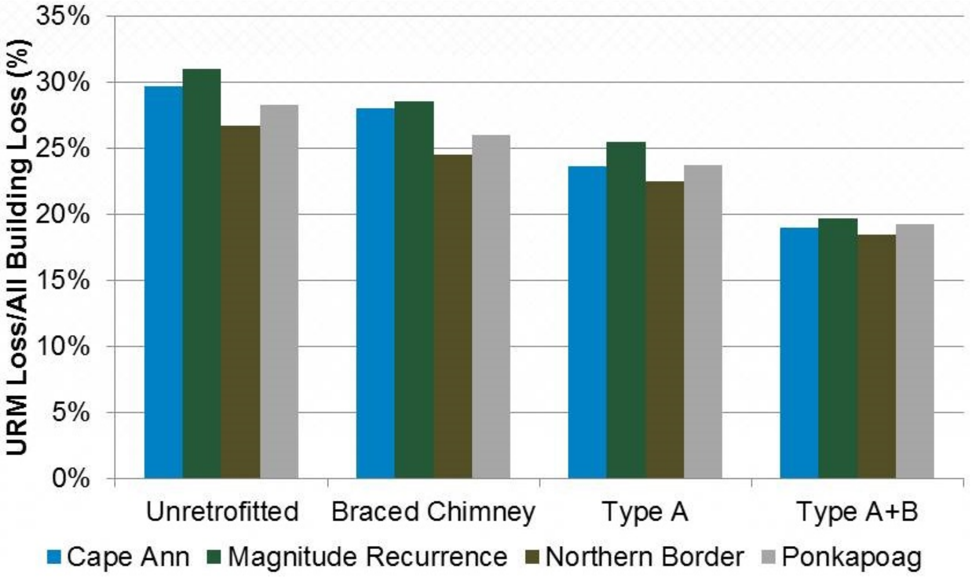


Fig. 6 – Contribution of URM losses to the overall event loss for four different earthquake scenarios assuming different levels of URM strengthening.

6. Conclusions

A scenario study was performed in which a high-resolution database of exposed risks was subjected to several plausible earthquake scenarios that could impact the Boston area. These scenarios were selected to be consistent with both the design spectral acceleration intensity for the city of Boston as well as the expected losses that could arise from various sources of seismicity adjacent to Boston. Particular attention was focused on the modeling of URM vulnerability. The results from post-event damage surveys were used to determine the relative effectiveness of incorporating retrofits into the URM building stock in New Zealand. The relative impact of different degrees of mitigation was incorporated in to a portfolio loss modeling framework and regional loss estimates were obtained for four different scenario events. The following conclusions can be drawn as a result of this study:

1. Unreinforced masonry buildings constitute a large portion of the building population in Massachusetts accounting for 8% of the exposed replacement value in the study area.
2. URMs have demonstrated significant vulnerability in past earthquakes; however, field surveys have demonstrated that seismic mitigation strategies for URM buildings can make a positive effect with regard to limiting damage and reducing losses during an earthquake. However, the disproportionate amount of loss exhibited by URM buildings demonstrates that these buildings still pose a significant economic and life-safety threat to society.
3. Incorporating the effect of mitigation strategies was shown to significantly reduce the expected losses arising from URM damage during an earthquake. In some instances the losses due to URM damage was shown to be reduced by as much as 33% when fully strengthened.

4. Based on the observed reduction in event losses resulting from the consideration of URM retrofit measures it can be concluded that the result of a regional loss estimation analysis can be influenced by accurately identifying and modeling retrofitted URM buildings with the appropriate vulnerability functions corresponding to the observed retrofit.

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