Modelling the vulnerability of old URM buildings and the benefit of retrofit

Edwards, M.[1,3], Wehner, M.[1,3], Ryu, H.[1,3], Griffith, M.[2,3], and Vaculik, J.[2,3]

1. Geoscience Australia
2. University of Adelaide
3. Bushfire and Natural Hazards Cooperative Research Centre

Abstract

The Shire of York is partnering with the WA Department of Fire and Emergency Services (DFES), the University of Adelaide and Geoscience Australia in a collaborative project that will examine the opportunities for reducing the vulnerability of the township of York to a major earthquake. The project forms part of the Bushfire and Natural Hazards Collaborative Research Centre (BNHCRC) project "Cost-effective Mitigation Strategy Development for Building Related Earthquake Risk". The township of York has a number of valuable historical buildings that contribute greatly to the town's economic prosperity and, at the same time, are vulnerable to earthquakes.

One of the benefits of retrofitting an old building is the reduction in physical building repair required following a damaging earthquake. To evaluate this benefit it is necessary to know the vulnerability of the unmitigated building and how this changes following retrofit.

This paper describes the approach taken to quantitatively estimate the vulnerability of unmitigated and retrofitted pre-WW1 unreinforced masonry (URM) buildings typical of the buildings found in York. Challenges in estimating vulnerability are discussed. Vulnerability curves are presented for one of six generic building types subjected to a range of retrofit scenarios and the economic benefit of each retrofit scenario is presented and discussed.

1. INTRODUCTION

Earthquake hazard was only fully recognised for Australian building design in the early 1990s following the Newcastle Earthquake of 1989. This has resulted in a significant legacy of buildings that are inherently more vulnerable to this hazard. Consequently many Australian buildings are quite vulnerable to low to moderate earthquake ground shaking. Knowledge of the most effective retrofit measures for older masonry buildings will enable and promote the strengthening of buildings resulting in more resilient communities. A key part of evaluating the effectiveness of retrofit is estimating the vulnerability of a building and how it changes as different levels of retrofit are implemented.

This project entailed a case study of the Western Australian town of York located in the Wheatbelt approximately 37km from Meckering, the location of the 1968 magnitude 6.5 earthquake – one of Australia's largest. In an Australian context, York is located in the so-called Southwest Seismic Zone, an area of elevated seismic hazard. Similar to many Australian country towns, York's building stock has a significant number of one and two storey unreinforced masonry (URM) buildings dating from before the First World War. Figure 1 is one view of the main street of York. To understand the number, type and distribution of buildings in York, an exposure survey was conducted (Corby et al, 2018) and from that, a selection of six generic building types was made (Vaculik et al, 2018). The selected building types represented the majority of old URM buildings in York and were the subject buildings for the study of the benefit of retrofit. This paper reports on the results of the retrofit of one type – a two storey retail building (Figure 2) with a tall parapet and medium slenderness chimneys. The results of the other five generic building types can be found in Edwards et al, in prep.

Figure 1. Example York streetscape.

Figure 2. Example of a two storey retail URM building in York.

2. MODELLING VULNERABILITY

The computation of average annual loss requires the development of a loss versus probability curve. For this project, this was established by transforming a vulnerability curve (damage index versus hazard magnitude curve) to the loss – probability curve. The transformation is accomplished by equating damage index to loss (multiplying damage index by replacement cost) and replacing each ground-motion value with its probability of annual exceedance at the building location. Damage index is defined as repair cost divided by replacement cost.

Vulnerability curves were produced for each generic building type in its current or 'unretrofitted' state and also for each retrofit scenario. A retrofit scenario is a set of upgrade works applied to a building type to increase its resilience to earthquake actions. The upgrade works can range from full retrofit of all components to retrofit of just one component, e.g. bracing chimneys. Several retrofit scenarios were selected for each generic building type to explore the variability in benefit-cost of undertaking a range of retrofit works.

To produce a vulnerability curve for each generic building type, a Monte Carlo process was adopted that sampled the fragility of each major component of the building and computed the repair cost for the set of component damage states. The process was repeated many times for each hazard magnitude to capture the variability in component fragility. The components of the URM buildings that were considered vulnerable to earthquake were:

- Chimneys (squat, medium and slender),
- Parapets (short and tall),
- Gable walls,
- 1 storey URM 'boxes',
- 2 storey URM 'boxes'.

The term 'box' is used to describe that portion of a URM building other than vulnerable roof level URM components (chimneys, parapets and gable walls). The 'box' typically consists of external URM walls, internal URM walls, timber floor structure and timber roof structure.

The process for a single building type is outlined in Figure 3. It is used for each generic building type in its current or 'unretrofitted' state and also for each retrofit scenario. It produces a scatter of vulnerabilities at each intensity measure which can be averaged to produce a single vulnerability curve for the generic building type in question.

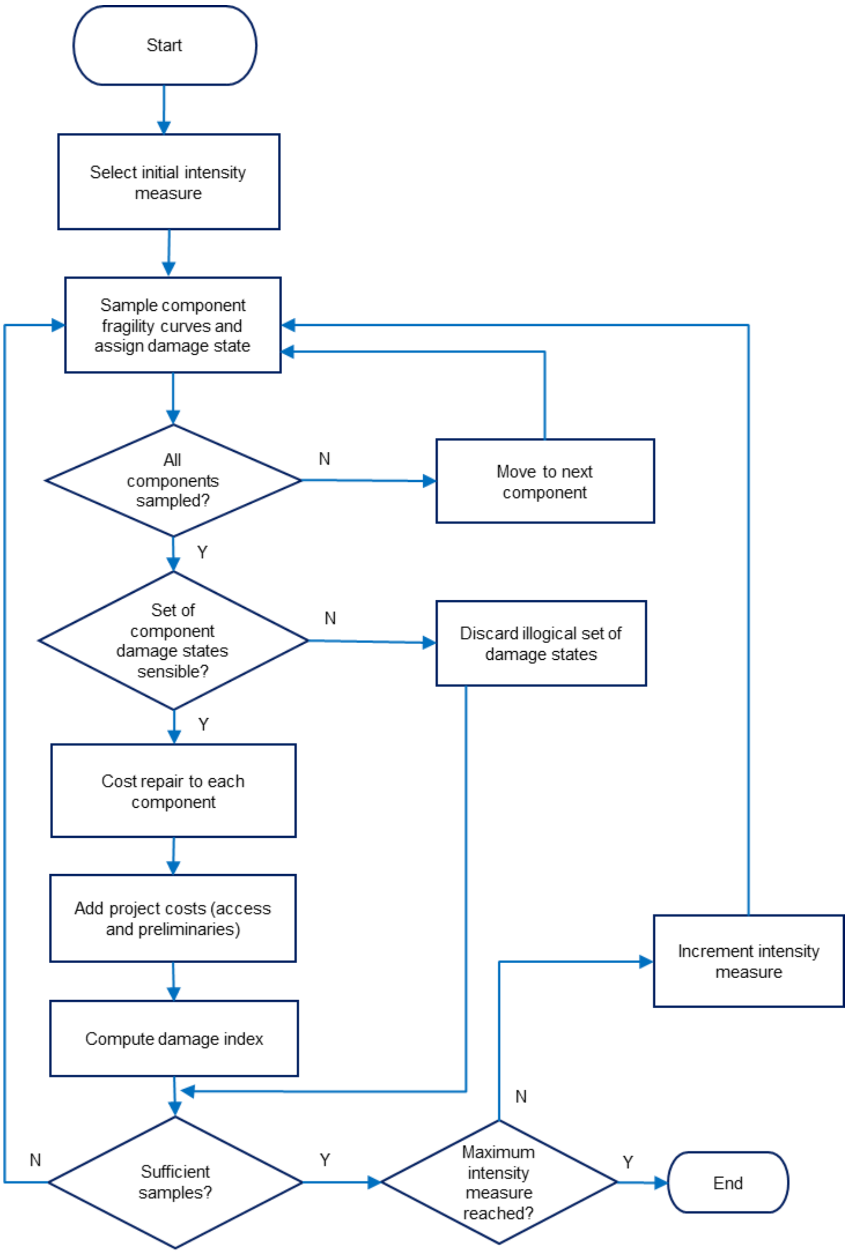


Figure 3. Procedure used to generate vulnerability curves from component fragility curves. A sensible set of component damage states is one where the set is logical. For example, if the building 'box' was in a complete damage state then it is not sensible for roof-level components to be in an undamaged to moderate damage state as the building below them has collapsed.

Component fragility curves for five damage states were provided by the University of Adelaide (Vaculik, 2019) for both the unmitigated condition and with retrofit applied. An example is shown in Figure 4 for a 1m tall parapet. The fragility curves are cumulative log-normal curves defined by the mean and beta values shown in Figure 4. The fragility curves for planar components (parapets and gable walls), whose out-of-plane vulnerability is substantially higher than their in-plane vulnerability, were adjusted to account for the random direction of earthquake shaking relative to their plane (Vaculik, 2019).

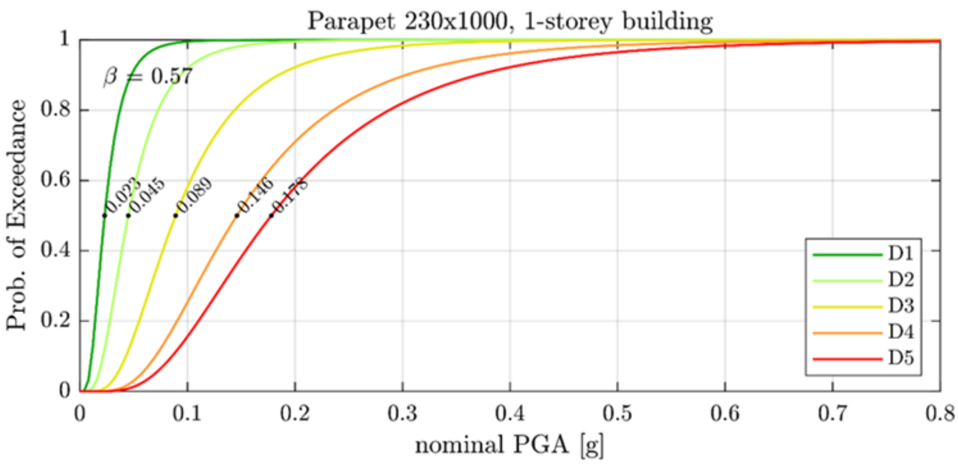
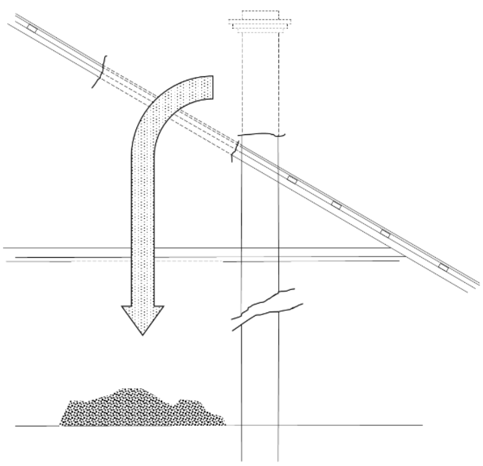


Figure 4. Computed fragility curves for an unreinforced parapet, 1m tall on a single storey building (Vaculik, 2019). PGA is the Peak Ground Acceleration at the ground surface at the building of interest. D1 to D5 are damage states of increasing severity defined in Vaculik (2019).

In computing vulnerability curves via the above process, it is necessary to know the costs to repair a building in a given damage state and also the replacement cost of the building in order to compute the damage index. Detailed descriptions of repair work for each component type and each damage state were prepared which were then costed by a professional quantity surveyor (Turner and Townsend, 2019). Table 1 illustrates the costing process with data for the repair of a single collapsed chimney. Note that the costs in Table 1 do not allow for scaffolding to roof level, preliminaries or profit as these depend on the total amount of repair work required for the entire building. Figure 5 describes the logic used to cost repair work for an entire building. Once the building repair cost is known, the damage index can be computed by dividing by the building replacement cost.

Table 1. Example costing of repair work for the repair of a collapsed chimney.

Description	**Repair work**	**Quantity**	**Rate**	**Cost ($)**
	Remove chimney, roof and ceiling debris from floor and roof	7m^2	38.05	266
	Prop roof structure from floor	8m^2	50	400
	Repair roof sheeting and battens	8m^2	84.67	677
	Repair lath and plaster ceiling	8m^2	345.75	2766
	Clean-up at floor level	Item	200	200
	Scaffold from roof level for access	21.7m^2	43	933
	Reconstruct brickwork	7m^2	274.83	1923
	Extra for capping	1	274.82	274
	Remove scaffold	Included	0	0
	Waste disposal (item)	1	50.13	50
Chimney fallen through roof and ceiling to first floor.	**TOTAL**			**7489**

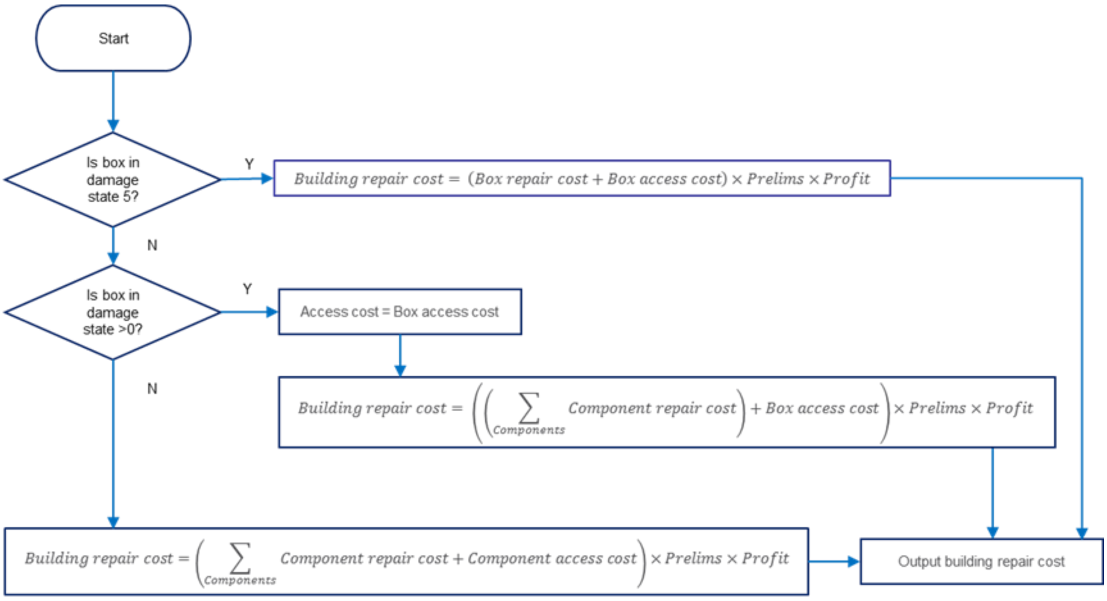


Figure 5. Logic used to estimate building repair cost.

The above process produced vulnerability curves such as the example shown in Figure 6. Most of the curve is strongly influenced by the fragility of the building box as this represents the bulk of the building's cost and, hence, if damaged, the majority of the repair cost. The repair of damaged roof-level components, chimneys and parapets in this example influence the shape of the curve at low hazard magnitudes as they are substantially more fragile than the building 'box'.

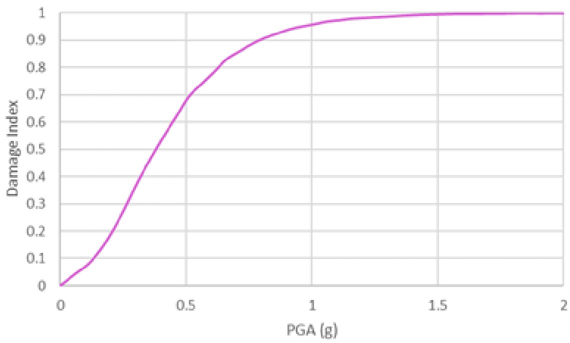


Figure 6. Vulnerability curve for two storey URM retail building similar to the example in Figure 2 without retrofit.

3. RETROFIT SCENARIOS

For each generic building type a range of retrofit scenarios were proposed involving retrofit of each component type individually, retrofit of each combination of component types and 'full' retrofit where all components were retrofitted. Cost estimates to install the retrofit work were obtained from a professional quantity surveyor (Turner and Townsend, 2019). Table 2 describes the retrofit scenarios for an example building including the estimated cost to install the retrofit.

Table 2. Retrofit scenarios for 2 storey URM retail building similar to example in Figure 2.

Retrofit scenario	**Retrofit to component**			**Retrofit cost**
	Chimneys	**Parapet**	**2 storey 'box'**	
18	Y	N	N	$16,326
19	N	Y	N	$24,006
20	N	N	Y	$89,878
21	Y	Y	N	$30,718
22	N	Y	Y	$104,488
23	Y	N	Y	$96,591
24	Y	Y	Y	$111,201

Vulnerability curves were computed using the process described in the previous section but utilising more resilient fragility curves for the retrofitted components. Figure 7 shows the vulnerability curve for full retrofit of a 2 storey retail URM building (retrofit scenario 24 in Table 2) similar to that shown in Figure 2 and for which the unmitigated vulnerability curve is shown in Figure 6.

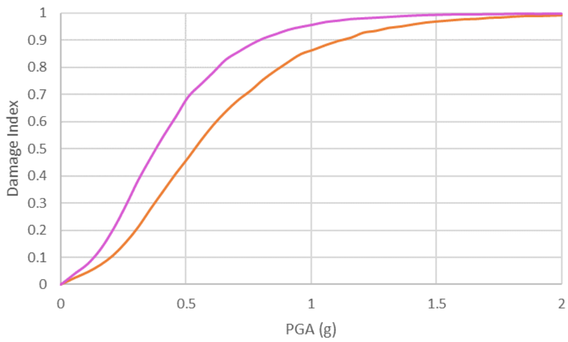


Figure 7. Vulnerability curve for retrofit scenario 24 (full retrofit) to the example building (orange curve). Compare to the vulnerability curve in Figure 6 for the same but unmitigated building (shown here in purple).

4. BENEFIT-COST CALCULATION

The benefit of mitigation measures realised through the reduction of repair cost following earthquake induced damage was calculated by transforming the vulnerability curves presented in Figure 6 and Figure 7 to loss-probability curves. This was done by applying the building replacement cost to the damage index to calculate loss and using the NSHA18 bedrock hazard (AS1170.4 site class B_e) curve shown in Figure 8 (adjusted to surface PGA for AS1170.4 site class D_e) to transform surface PGA to annual exceedance probability. An example loss-probability curve is shown in Figure 9.

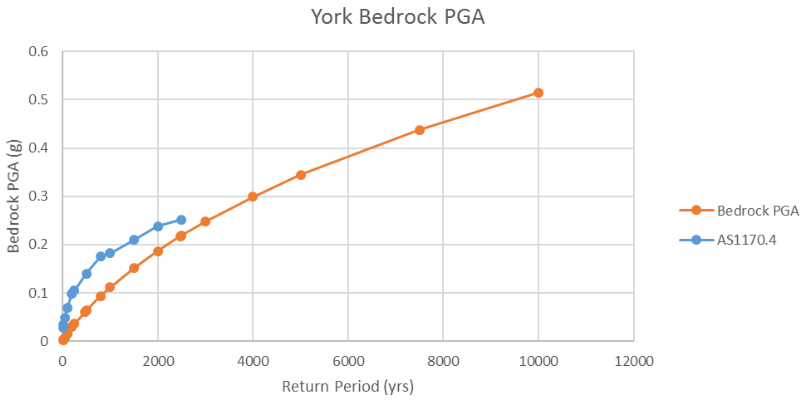


Figure 8. Bedrock (Site Class B_e) hazard curve for York extracted from NSHA18 (Allen et al, 2018) compared to the hazard specified in AS1170.4 (Standards Australia, 2007). The latest hazard assessment is significantly lower than the design hazard in the current building regulations.

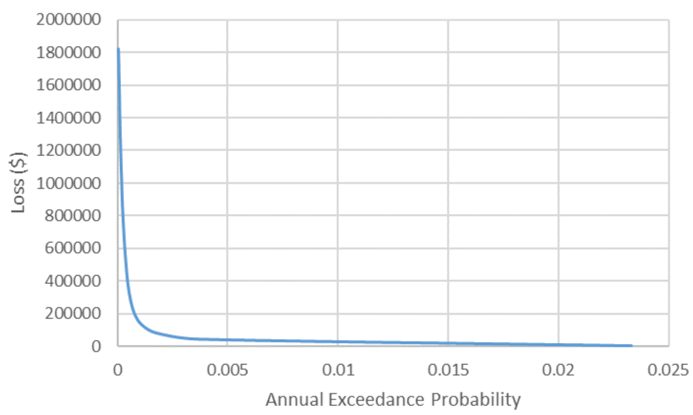


Figure 9. Loss-probability curve for a two storey retail URM building with retrofit scenario 24 applied.

The average annualised loss for each unmitigated building type and each retrofit scenario was computed by numerically integrating the area under the relevant loss-probability curve. The benefit is computed by the difference in annual loss between the unmitigated building and the retrofitted building as the sum over the remaining lifespan of the building with benefit from future years brought to present value assuming a discount rate of 4%. The present value of the benefit is compared to the cost of installing retrofit shown in Table 2. Table 3 presents the benefit-cost ratio for each retrofit scenario.

Table 3. Benefit-cost ratios for retrofit scenarios to two storey retail URM building. Note that these ratios take into account **only** those benefits arising from reduced repair costs following earthquake induced damage.

Retrofit Scenario	Description	Benefit – cost ratio
18	Chimneys only	0.093
19	Parapet only	0.230
20	2 storey ‘box’ only	0.071
21	Chimneys and parapet	0.223
22	Parapet and 2 storey ‘box’	0.116
23	Chimneys and 2 storey ‘box’	0.082
24	Chimneys, parapet and 2 storey ‘box’	0.122

It can be seen that the benefit arising from savings in the reduced repair cost of earthquake damage alone does not yield sufficient benefit to off-set the cost of installing retrofit (benefit-cost ratios well below 1.0). Despite this, the most benefit arises from retrofitting the parapet and chimneys, fragile components which are comparatively cheap to retrofit. For a more complete picture of benefit of retrofit other benefits such as reduced casualties, reduced homelessness, reduced contents losses, reduced loss of heritage buildings and reduced business interruption costs must be accounted for. For example, during the Christchurch earthquake sequence, 39 deaths were attributed to the failure of URM buildings with the majority killed in the street outside URM buildings (Moon et al, 2014). The economic value of a life is assessed as $4.2million (PM&C, 2014) which far exceeds the cost of retrofit.

5. CHALLENGES

There are many challenges in computing a quantitative estimate of vulnerability and the reduction in vulnerability afforded by retrofit. This section discusses the challenges encountered by the project team during the course of this work.

The building vulnerability curve is strongly influenced by the fragility of the building ‘box’, that is the bulk of the building excluding roof-level components such as chimneys, parapets and gable walls. This suggests that it would be worthwhile to subdivide this element into a finer collection of components. However modelling the fragility of individual wall elements in isolation from one another has not been undertaken presently. The behaviour of a particular element will be influenced by the damage state of other elements.

The validation of the unmitigated vulnerability functions is also a challenge. There is a lack of Australian empirical data of earthquake damage with which to calibrate fragility and vulnerability curves. Furthermore, data that is available is often inconsistent with different measures of damage and causative hazard used. For this project, an empirical vulnerability curve was developed from:

- aggregated loss data from the Newcastle 1989 earthquake (Ryu et al, 2013 and Maqsood et al, 2016),
- costing of surveyed earthquake damage following the 2010 Kalgoorlie earthquake (Edwards et al, 2010), and
- a heuristic data point (DI = 0.9 at Modified Mercalli Intensity IX) from the Meckering earthquake (Everingham et al, 1982).

Figure 10 shows the comparison with the vulnerability curves derived from the numerically modelled fragility curves for one and two storey old URM building ‘boxes’ with the substantially more resilient vulnerability indicated by the empirical curve. To overcome this discrepancy, the numerically modelled fragility curves for the building ‘boxes’ were adjusted so that the resulting vulnerability curves more closely matched the empirical curve. The ratios of medians between fragility curves for different damage states was maintained. Further, the fragility curves for two storey old URM buildings were adjusted so that the resulting vulnerability curve for two storey old URM buildings was 25% higher in damage index than single storey old URM buildings between hazard values of 0 and 0.5g. This reflects a trend observed in the Kalgoorlie damage survey data that showed two storey buildings to be more vulnerable than single storey buildings at MMI V and VI.

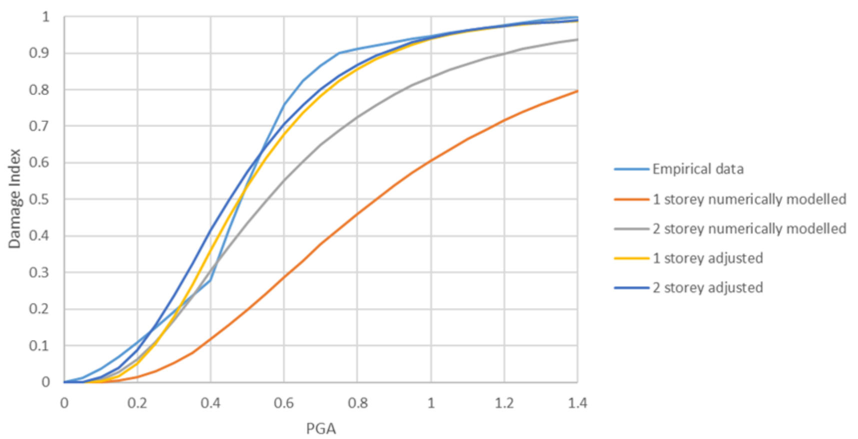


Figure 10. Vulnerability curves from empirical data, numerically modelled fragility curves and adjusted fragility curves.

The process adopted to compute benefit-cost of retrofit relies on several cost estimates: building replacement costs, installation of retrofit measures and repair of building components in a variety of damage states. The preparation of cost estimates is further complicated by the heritage status of some old URM buildings. Of these, the estimate of repair to building services is perhaps the most uncertain. Building services in modern buildings of this size can comprise 12 - 34% of the total building cost depending on use (Rawlinsons, 2019). However, the complexity of building services in old URM buildings can range from almost original condition with minimal services to a full upgrade to modern standards. For this study, the extent of building servicing was based on observations made while undertaking the exposure survey. Further, the identification of damage to building services and required repair when the building is in various damage states is difficult with little informative data.

6. CONCLUSION

This investigation into the benefit – cost of retrofitting old URM buildings to reduce earthquake damage has indicated that benefits beyond the savings in repair of earthquake damage need to be considered to justify the cost of retrofit. This is partly due to the hazard severity; if the study was undertaken in an area of higher seismic hazard the benefits would be larger. Nevertheless, past earthquakes in Australia and New Zealand have been seen to cause significant damage to old URM buildings and loss of life. Future work will consider additional benefits arising from reduced fatalities and injuries, reduced homelessness and reduced business interruption achieved by retrofit.

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