# Making an Australian brick house more earthquake-resistant for $100 or less: Ideas, Practice and Loss Analysis

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## ABSTRACT:

The average loss per building in Australia due to earthquakes will be greater than $300 over a political lifetime of 3 years (via a stochastic risk assessment). So, a good question is: what is the best investment of $100 and a bit of hard work to strengthen and retrofit an Aussie double brick or brick veneer house. Much of the loss occurs in a few large events, but significant damage also occurs from more frequent smaller events. 57% of deaths from earthquakes globally have occurred in masonry buildings since 1900. Thus, with a view towards life safety and the maximum return on investment, different options are tested and discussed for retrofitting the average Australian double brick house for earthquake resistance.

Bolting and bracketing furniture, electrical equipment and valuables to walls, the removal or tying-in of certain non-structural elements, as well as adjustments such as seismic wallpaper and reinforcement, are tested from empirical and analytical experience from around the world. Of course, earthquakes are not the only main concern for Australians, so a view as to the best use of the $100 is looked at with thoughts as to insurance and also other disaster types. It can be seen that the benefits of the $100 investment can be seen to be over $700 in Adelaide over a period of 20 years and additional life safety to occupants. Different options of structural and non-structural elements such as chimneys are also tested when in excess of $100 in order to see the possibility for reduction of losses over a longer period exceeding a $1 investment to $7 return ratio.

**Keywords:** Earthquake resistant design, earthquake safety, Australian earthquake risk, insurance.

# 1. Introduction

Brick buildings (cavity wall double brick, URM) or wood frame with brick (brick veneer) make up the greater proportion of Australian housing (Figure 1). From the 6.962 million buildings, 73% of the buildings are brick or brick veneer. The economic value of the structural components was $2.737 trillion AUD and the contents were $1.105 trillion AUD via NEXIS (2011). The modification and retrofitting of such brick buildings may be able to be undertaken in the future in order to save much of the population from impending deaths and economic losses from earthquakes. The risk of losses occurring in an earthquake, although small, are certainly significant for a household over a number of years in nearly every major city around Australia.

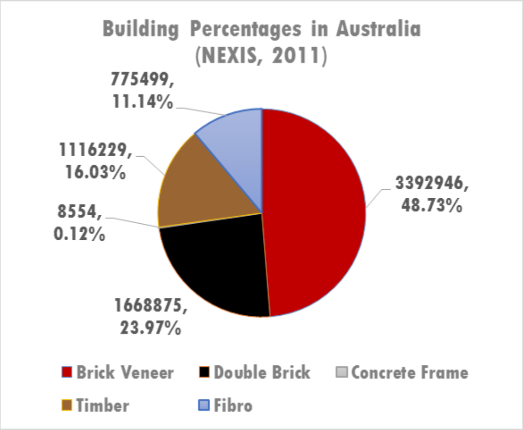


*Figure 1: Building percentages in Australia via NEXIS (2011) of masonry building typologies. It can be seen that over 72% are masonry or brick veneer.*

In the last 113 years globally, there have been 2035 fatal events in the 7200+ damaging earthquakes. Without getting into the depth that the Daniell et al. (2011) paper examines, it can be seen that approximately 59% of deaths have been in masonry buildings, and around 29% from secondary effects (Figure 2).

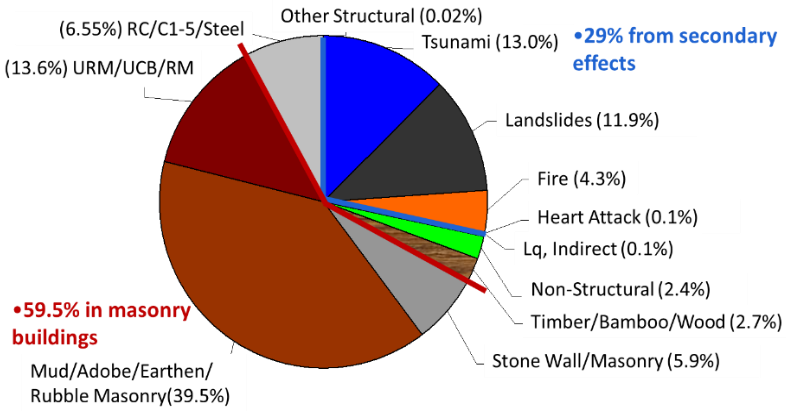


*Figure 2: The death toll disaggregation in the CATDAT Damaging Earthquakes Database, as of v6.22. It can be seen that 59.5% of deaths have occurred in masonry buildings.*

Although non-structural elements have been deemed to have caused 2.4% of fatalities since 1900, this total is difficult to quantify and could be much higher. The reassessment of the

Haiti death toll to around 73,000 deaths (with a range from 46,000-130,000) via the survey work of numerous authors means that the current version v6.22 of the CATDAT Damaging Earthquakes Database [Doocy et al. (2013) - (49,033-81,862 via building damage; 63,061-86,555 via population), Garfield (2013) – 60,000-80,000, Schwartz et al. (2011) – 46,190-84,961, Melissen (2010) – 52,000-92,000, Kolbe et al. (2010) – 93,273-130,316] has a median 2.311 million fatalities; of these 1.362 million can be attributed to masonry buildings.

There is no question that for life safety, correct design and stricter loading criteria for brick buildings is paramount in future versions of the Australian Standard on Earthquake Actions AS1170.4 code and changes to the material standards for masonry. Given the uncertainties in hazard assessment in Australia depending on the parameters used, the simple use of the loading coefficients for the current 475 year return period zoning for residential design should be reviewed (Schaefer and Daniell, 2014).

The structural stability of brick buildings (either brick veneer or double brick) is a topic that merits significant study in Australia, and has been the focus of many analyses (Doherty et al., 2002, Griffith et al., 2010). However, with the exception of a few studies, there has been little work examining the financial effects of implementing changes to non-structural and contents elements to potentially reduce the chance of losses for the average Australian. Most Australians have some form of insurance towards earthquakes; however, in many cases the contents and insurance is inadequate due to earthquake exclusion clauses.

## 2. Non-structural losses historically

### 2.1 Costs of each component

The top 5 components to total construction cost are generally the following:

1. Exterior Walls
2. Elevators and Lifts
3. Partitions
4. Plumbing fixtures
5. Cooling generating system.

The non-structural cost is generally between 25%-45% of the total cost of a house, with contents being an additional 20%-45%. These components are often confusing to define, with crossovers of definitions commonplace in literature with our definition in Table 1.

*Table 1: Various components contributing to the structural, non-structural and contents components.*

| Categories | Examples |
|---|---|
| Structural | Roof, Beams, Columns, Diaphragms, Foundation, Braces, Walls (Masonry/Concrete/Timber etc.) |
| Non-structural | Architectural (Cladding systems, chimneys, false ceilings, parapets, partitions, elevators etc.)<br>Mechatronic Equipment (transformers, panel-boards, wires, boilers, air conditioning, piping, plumbing, motors, pumps)<br>Life-safety systems (Fire, safety, security, emergency power) |
| Contents | Furniture, production equipment, shelves, TVs, heavy items, free-standing items, non-connected elements. |

The structural components generally only make up 10-25% of the original construction cost (FEMA-74, Rawlinsons). However, for different types of buildings there are significant losses that can be expected in offices, hotels and hospitals as to the non-structural components. The Brick Veneer costing split using EQRM is 23.44% structural, 50% non-structural drift sensitive, and 26.56% non-structural acceleration sensitive.

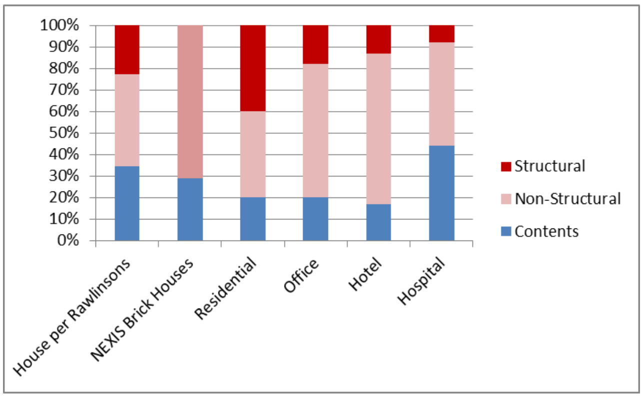


*Figure 3: The relative percentages of structural, non-structural and components houses (Rawlinson, 2010) estimated, NEXIS (GA, 2011), Residential RC Construction (Kanda, 1998), Office/Hotel/Hospital (Taghavi and Miranda, 2003)*

Using the NEXIS study of Geoscience Australia, the relative value of contents is 28.8% and for non-structural and structural elements combined is 71.2% for residential buildings. This is quite close to the assumption that contents comprise 50% of the value of the building for residential types, as per HAZUS repair costs. George Walker via the EQRM software suggests this value to be 60% of R4. For the purposes of this study, the value of the average brick veneer and/or double brick house are determined as shown in Table 2, with some major assumptions averaging a one and two family home.

*Table 2: Various costs of residential housing as a component basis for the average Australian house (Rawlinson, 2010)*

| **Category (Residential)** | **Percentage of Structural/Non-Structural Cost** | **% of total house** |
|---|---|---|
| Structure | Site Preparation (0.4%), Substructure (generally 1.2%), Frame/Structural Walls (11%), Average Upper Floors (0.4%) | 13% |
| External Fabric | Roof (11.9%), Chimney (1.5%), External Walls (9.5%), *Windows and Doors (9.3%), Exterior Façade Tiles* | 32.2% |
| Internal Finishing | Stairs (1%), Internal Walls/*Partitions* (2.5%), *Internal Doors (2.4%),* Floor Finishes (3.6%), Wall Finishes (11%), Ceiling Finishes (3%), Fittings and Fixtures (13%), *Suspended False Ceilings* | 36.5% |
| Services | *Sanitary Plumbing (5.6%),* Mechanical Services (0.1%), Fire Services (0.1%), *Electrical Services (3.8%),* Special Services (2.5%), *Drainage (0.5%),* Boilers, Vessels | 12.6% |
| External Works and Sundries | | 0.4% |

| | | |
|---|---|---|
| Preliminaries and Contingency | Preliminaries (4.0%) – plant, scaffolding insurance etc., Contingency (1.3%) | 5.3% |

*Adjusted from Rawlinson's Guide, 2010; Italicized components are drift-sensitive,* normal font is acceleration-sensitive. *If no percentage given, then the components are included in other parts or are not often in houses.*

In addition, the relative costs of contents need to be added to this. If we use the average housing cost of around $1800 per square metre for a 175 square metre home, the cost would be $313,000 to build. Additionally, the contents would be around $156,500 according to some of the rules of thumb, including HAZUS. Using the Sum Insured Ltd, the cost is slightly higher at $165,000. The components of a house obviously differ; however, by using insurance formulae, the average contents ratios can be seen in Figure 4. This uses the assumption that well-known brands, superior equipment and joinery standard furniture are used. These will be used for the comparative analysis of savings of the potential processes versus losses.

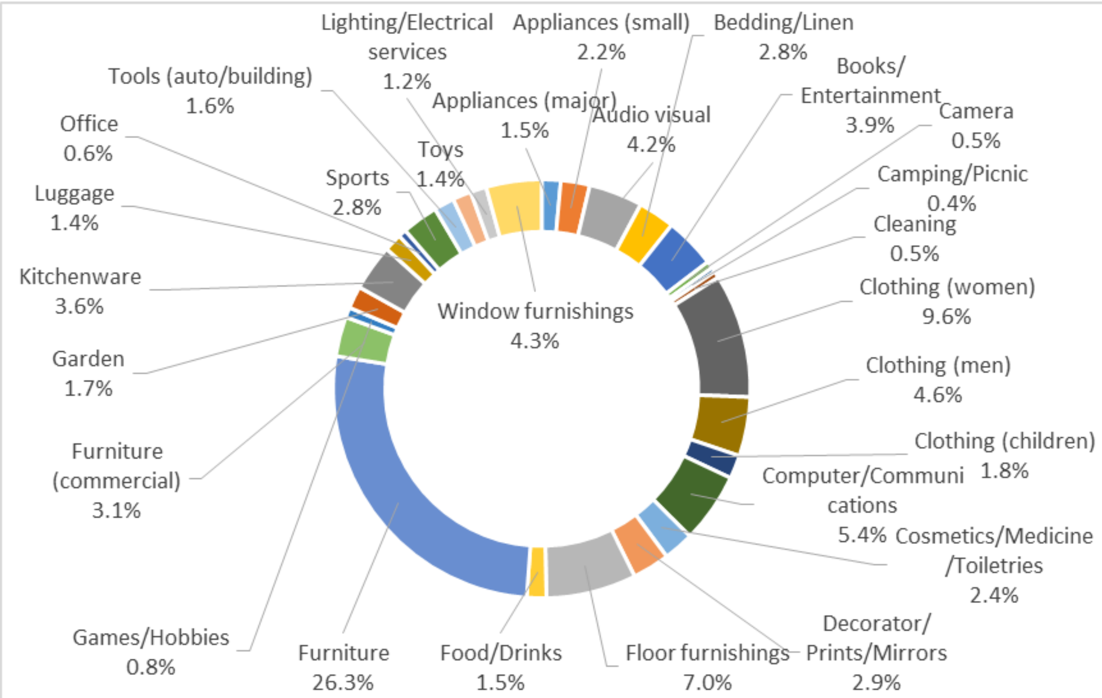


*Figure 4: Contents value as a percentage of all contents in Australian houses (average) in order to calculate the relative components for the benefit-cost ratio.*

## 2.2 Damage Potential of House Elements

The most extensive database of non-structural damage is that of Kao et al. (1999), who looked at 52 earthquakes globally, and 2909 entries characterising non-structural damage, with most in the USA. Using Kircher et al. (1997) with the basis for HAZUS, the structural components are generally defined to be drift-sensitive, whereas the non-structural elements are analysed as acceleration-sensitive (most damage due to floor acceleration, with the components mainly being floor-mounted and at risk of overturning); however, some nonstructural components are also drift-sensitive (most damage due to excessive inter-storey drift, including partitions, windows etc.).

Non-structural elements and contents generally either break, overturn, move or crack, depending on the type of element. In Newcastle (1989) it was the parapets and brick facades not adequately tied to the structure that caused major damage. In some other earthquakes, breakage of pipelines, ducts and fixtures have also caused major damage in buildings.

An extensive study of 686 reinforced concrete (RC) buildings in five different Japanese earthquakes (Kambara et al., 2006) forms an important basis to the potential for failure of non-structural elements. An intensity-based damage criteria study was undertaken to look at a relationship of intensity and the damage state of the non-structural elements. In this way, the relative accelerations and drifts needed to cause damage will be determined to view the mitigation effects.

In terms of failure, overturning (tall furniture) and sliding (short furniture) of furniture can be evaluated via the Kaneko (2003) functions regarding floor acceleration and velocity. Support legs failing, connection failure due to sliding, anchor bolt failure, unrestrained suspended equipment, inadequate stopping and snubbing devices, equipment roll and disconnection of electrical devices and cables are just some of the potential damage modes for non-structural elements. The vulnerability of each component, given the differences in component, will essentially be house-specific, given the large difference in types of equipment. For instance, a flat screen TV with a thin base support unattached to a cabinet may have more susceptibility than an old CRT TV with a large base not as conducive to overturning. In many cases, simply anchoring and fixing these elements to a table can greatly increase the potential ground acceleration that the element can survive.

A number of different studies in Australia have been undertaken looking at non-structural elements; for example, Lam and Gad (2008) have indicated the various failure modes such as overturning, sliding (movement of the base), attached distortion (via structural element distortion of the non-structural element, pendulum damage (where swinging and knocking occurs) and pounding (where the object smashes against something else repeatedly).

### 2.3 Damage to each component

Empirical and analytical vulnerability functions for contents and non-structural components have been determined in Japan (Kutsu et al., 1982; Saeki et al., 2000; Kambara et al., 2006), USA (Scholl, 1981; ATC, 1985; Johnson et al., 1999 (equipment); ATC-38, 2000; Hutchinson and Chaudhuri, 2006; Porter and Cobeen, 2009; Porter, 2010), and Mexico (Badillo et al., 2006 (suspended ceilings), Jaimes et al., 2013).

Saeki et al. (2000) looked at 965 questionnaires on damage ratios for contents. This provides a useful context. Karaca and Luco (2008) determined fragility functions based on these principles. Kanda and Hirakawa (2004) had a study of losses from the 1995 Kobe earthquake from 210 RC buildings and found that 40% of the losses were structural, 40% non-structural and 20% were contents based. Arnold et al. (1987) showed 79% of damage was non-structural in 355 highrise buildings during the 1971 San Fernando earthquake. From the 1994 Northridge earthquake, an estimated 83% of damage to non-residential buildings was via non-structural losses (ATC-58, 2008).

Via HAZUS, the structural damage consists of 15.6% of the total cost of building, acceleration-sensitive non-structural damage is 17.7% of the total cost, whereas non-structural drift-sensitive damage (33.3%) and contents (33.3%) make up the largest share.

Dowrick (2003) defines equipment losses with a function of intensity, in order to investigate the difference between fragile and robust equipment as seen below in Figure 5.

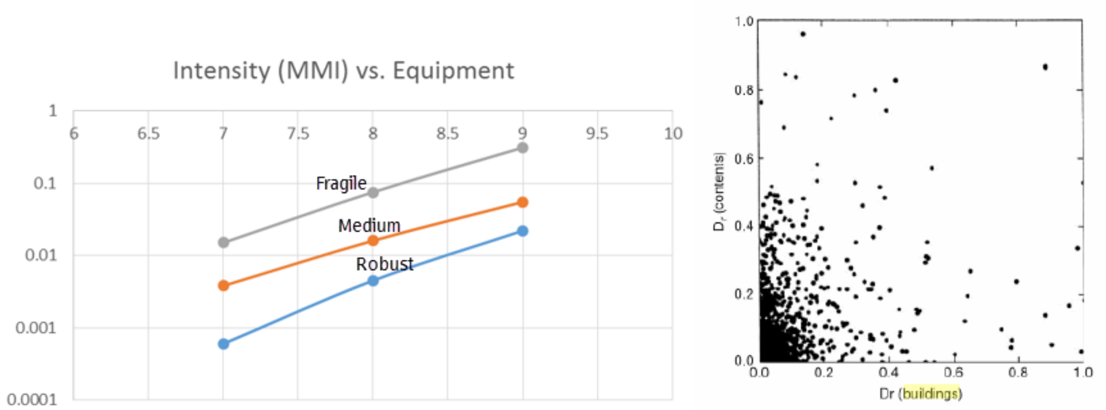


*Figure 5: Left: Fragile, Medium and Robust equipment vs. MMI from New Zealand; Right: Building vs. Contents damage ratio. (Dowrick, 2003)*

The non-structural losses historically have a higher percentage of damage from low intensity earthquakes in comparison to structural losses (Dowrick, 2003; Grünthal, 1998). In terms of earthquakes to be expected in most Australian cities, lower ground motions can be expected and thus minor changes to most buildings may also allow for major comparative changes in loss ratios to be expected from Australian earthquakes.

## 3. Methods for retrofitting existing buildings (non-structurally and structurally)

Various methods for retrofitting existing buildings are discussed and costed using materials from local hardware stores in order to work out the cost-benefit ratio of retrofitting versus not retrofitting elements. It should be noted that the lack of historical loss data from Australian earthquakes leaves much uncertainty in the calculations which are covered via Monte Carlo simulations.

### 3.1 Non-Structural Elements and Contents

Non-structural elements were discussed in Section 2. The solutions are now discussed in Table 3 for retrofitting these in order to improve the earthquake resisting ability of elements for Australia. For the analysis, it is assumed that the household has at least a hammer, screwdriver and other power tools.

*Table 3: Retrofit options for non-structural and contents in Australian housing, including the approximate cost from hardware stores and literature estimates*

| **Type of Retrofit** | **Elements Affected** | **Fix** | **Cost** |
|---|---|---|---|
| **Fastening brackets (x1)** | **Contents:-** TV, bookshelves, cabinets, furniture, cupboards. | Using basic steel L brackets and screws connecting the wall to the furniture. Interior Brackets, Screws into the back wall or side and top brackets can be used and should be tied into the building structure. For wood studs – long screws (75mm+), metal studs, long enough screws for penetrating flange material. | $1.53 per bracket (1 element = $6.11) with 2 on top, and 2 attached to floors |

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|---|---|---|---|
| **Restraint straps** | Fragile Items | Restraint straps can also be used for fastening as well as linking to the wall studs. These can be used for televisions as well as other fastening. | $1 for okky straps up to $45 for a metal restraint for water heaters. |
| **1) Non-slip mats, 2) Velcro fastener or 3) little rubber cup pad.** | Stoves, Ovens, Garbage bins, Dishwashers, Refrigerators. | For small appliances such as microwaves and those susceptible to sliding the best are little rubber cup pads, or velcro fasteners.<br>Washing Machine, Ironing Equipment, Barbeques with non-slip mats. | 1) Non-slip mat = $47 per m2 (averaged from 600x 900mm and a 1500x900mm)<br>2) Velcro fastener (1.8m by 20mm = $20.70).<br>3) 16 rubber feet = $2, or bigger 8 feet = $2 |
| **Blu Tack or Quake Wax** | Small Elements | Museum Wax or Dental Utility Wax (Morton, 2006) usually measured by tilt tests. Works very well for glass vases. | Dental Wax, $25/kg<br>Blu-tack, $30/kg in 75g packs |
| **Glue/Adhesive** | Non-fragile elements, or fixed elements | For fastening various components around the house. | $12 per 400ml |
| **Creating covers and lips** | Electrical appliances, | Many appliances can be fastened using brackets or metal. Edge restraints / wood moulding can be used, or wire guard rails. | Out of metal, a 50cm edge restraint costs around $6 with screws. |
| **Latches, catches** | Cupboards | Magnetic catches<br>Latches (simple)<br>Quality double latch | $14.10<br>$2.50 for latches (2 set),<br>$9.40 |
| **Cord or nylon wire** | Bookshelves, Food contents | In order to catch important items such as books or other items, this can reduce the chances of problems. | $1.14/m – nylon wire<br>$25c/m – cord |
| **Bolting** | Free standing elements | Now covered by AS1170.4 | $3-4 per corner including bracket. |
| **Hooks** | Pictures and mirrors | 1) Closing hooks across a picture<br>2) Adding extra screws and nails<br>3) 30kg hanging set | 1) Free<br>2) 14c<br>3) $8.99 |
| **Chaining, bolting and adjusting** | Air conditioning units, Gas bottles. | Chaining, bolting, adjusting. Timber blocks and then screw adjustments. Bolting into the concrete slab or weld bracing can help. | Bolts = $3-4 per bracket per system = $16 for a unit. |
| **Moving** | Heavy Items | Move incompatible chemicals and breakable items to the bottom shelves. Move heavy items into safer lower positions (not free falling positions) | Free ($0/m2) |
| **Safety Cables** | Lighting, other wall or ceiling joined elements | Pendulum effects of items. Safety cables can prevent the lighting from being destroyed. | $4.78 per safety cable |
| **Tie anchorage** | Parapets, Awnings, Tiled Roofing | Chimney anchorage at each floor level. | Approximately $40/m2 of house. |
| **Reinforcement, bracing and replacement** | Chimney, Parapets, Canopies, Veneers, Walls | Various solutions. See Ingham and Griffith (2011), Moore (2014). | Different costs for the various values, some shown in Section 4.2. |
| **Flexible Connections** | Pipes | Piping and conduit where they cross seismic joints or connect to rigidly mounted equipment | Depends on the conduit |
| **Wire catch** | Tiles | A wire catch vertically around a house in order to catch falling tiles and items | 10m by 8cm for $2.50. |

In many cases, the tie anchorage, flexible connections and bracing/replacement need engineering experience and detailing which mean that canopies, chimneys, parapets, partitions, veneers, exterior walls and some mechanical equipment will not be able to be undertaken in the $100 adjustment, except by experienced individuals.

Adjacent structural components often cause non-structural component failures, with deformations of non-structural components occurring. In the opposite way, non-structural components can cause losses in structural members, such as short column problems via masonry infill or veneer. Separation joints often cause problems in piping, HVAC and partitions. The pounding that often can occur causes damage to parapets, veneer and facades etc.

## 3.2 Structural Elements

Structural elements have been looked at by various authors, including Moore (2014), El Gawady et al. (2004), Bhattacharya et al. (2013), Moon et al. (2012), and Moon et al. (2006). Below in Table 4 is a combined list of the various retrofits available for structural elements. The costs are approximated from literature values.

*Table 4: Retrofit options for structural elements in Australian housing, including the approximate cost from literature estimates*

| Type of Retrofit | Elements Affected | Fix | Cost |
|---|---|---|---|
| **Shotcrete Application** | Masonry Walls and structural elements | The concrete is generally pumped onto the structure using high pressure. Then steel reinforcement is added. Stiffness at peak loading was increased by factor of 3-4 (El Gawady et al., 2006). | This is costly. $1200/m3. For 60mm thickness, this covers approximately 16m2. |
| **Stitching and Grout Injection** | Masonry Walls and structural elements | Restoration of initial stiffness. Mortar replacement proved to be not so useful. | High cost of epoxy but grout and stitching is reasonably cheap. |
| **Repointing** | Masonry mortar/connections | Stronger mortar is mixed for strengthening | Cheap – cost of grout but is also time consuming and is just for locations where mortar is weak or weakening. |
| **Steel Mesh** | Columns/Beams | Steel Mesh on corners of adobe buildings and free ends with mortar over (Bartolome et al., 2008), increased weight. | 30m2 house = $400, $24/m2 structural, $13/m2 improved. |
| **Bamboo Reinforcement** | External walls, structure | Extends life of structure, but same cracking still occurs. ($7/m2) | 56% of steel reinforcement. |
| **PP Strip Reinforcement** | External walls, structure | Polypropylene packaging strips, intertwined into a mesh attached to the wall (Macabuag, 2007). | Polypropylene strip reinforcement = 5% of the cost of the house. |
| **CFRP, FRP** | External and internal walls, load-supporting structure. | Extension of strength and displacement depending on externally or internally confined systems. In-plane and out-of-plane strength is improved. | GFRP = $40-70/m2<br>CFRP = $120-200/m2 |
| **Seismic Wallpaper or Reinforced Plaster** | External and Internal walls and structure. | Seismic wallpaper is an inexpensive method, but is generally for life safety. 200% increases in load and ductility.<br>Reinforced plaster – similar increase in ductility, and also improves stability | Unknown Cost for SismaCalce seismic wallpaper or EQ-Top. |

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|---|---|---|---|
| **Post-tensioning using Rubber Tyres** | Structure | Works with wood and bolting in order to allow for post-tensioning (Turer et al., 2007). In-plane strength improved markedly (5-6 times). | $0.60/m2 including connectors according to Smith and Redman (2009) |
| **Confinement** | Columns and structural load bearing components | Costly when looking at existing buildings, given the need for reconstruction. | Unfeasible |
| **Anchoring URM walls to floors and foundation** | URM walls | "Bolts-only" type approach solving not only parapets, but also anchoring. ($250-5000 depending on difficulty) | Additional concrete, labour and steel reinforcement or bolting. |
| **Geogrid polymer mesh 100, 75, 50** | Structure and walls | 100% best or soft mesh 80% coverage ($2/m2, $19/m2) as per Smith and Redman (2009). ($0.5/m2, $4/m2 = soft mesh). Rural masons (Macabuag,2007) much lower. | $4.50/m2 for application and materials for soft mesh.<br>$21/m2 for industrial geogrid. |
| **Plastic braided mesh** | Structure and walls | Tetley and Madabushi using steel mesh. Plastic carrier bags, braided together and fixed to the wall in a kind of mesh (not for retrofit!) This is time-consuming. | Cheap solution and cheap cost but time-consuming. |
| **Ties or tie rods** | Support for URM walls and joists | Ties at diaphragm joining joists or Tie rods for confining URM walls | $95-105/m2 |
| **Friction Dampers** | Foundation to structure | Various forms of base isolation but is costly for an existing building | 30-50% that of viscous dampers. 250-300 kip friction damper = $3000 (Shao and Miyamoto, 1999) |
| **Fluid Viscous Dampers** | Foundation to structure | Dissipates energy by pushing fluid through producing damping pressure and a significant increase in damping | Viscous dampers = $6000 for the 250-300 kip version. |
| **Base Isolation** | Foundation to structure | Elastomeric pads or sliding bearings or rocking pillar, providing a gap between the structure and the ground. The columns are cut and then included. | Difficult to cost, given the differences in work needed to isolate the structure. |
| **Steel Jacketing** | Confinement of columns | Jacketing of URM columns confining the elements. | $120-150/m2 of column. |
| **Steel Coring** | External walls | Addition of steel cores in the centre of URM walls via drilling and replacement (can have the problem of creating differing stiffness over a structure). | Expensive |
| **Shear resisting features** | Bearing walls and external walls. | Bearing wall adjustment by sheathing and anchoring. Addition of other shear resisting walls. Or addition of a new steel moment frame. | Shear wall in Iran = $94/m2. In Australia it is in the order of $250/m2 |

## 4. Loss Analysis for the house types in Australia

For most Australian cities, through the work of Schaefer and Daniell (2014) shown in Table 5, Figure 6 and explained in an adjoining paper in this conference; the number of events that will occur with a ground motion which causes the expected failure of a certain element will determine the Annual Average Loss (AAL, defined below) as well as the cost-benefit ratio for the aforementioned solutions for the contents, non-structural and structural components.

$$AAL = Annual\ Average\ Loss = \frac{\sum_{i=1}^{n} Economic\ loss\ in\ year\ i}{n}$$

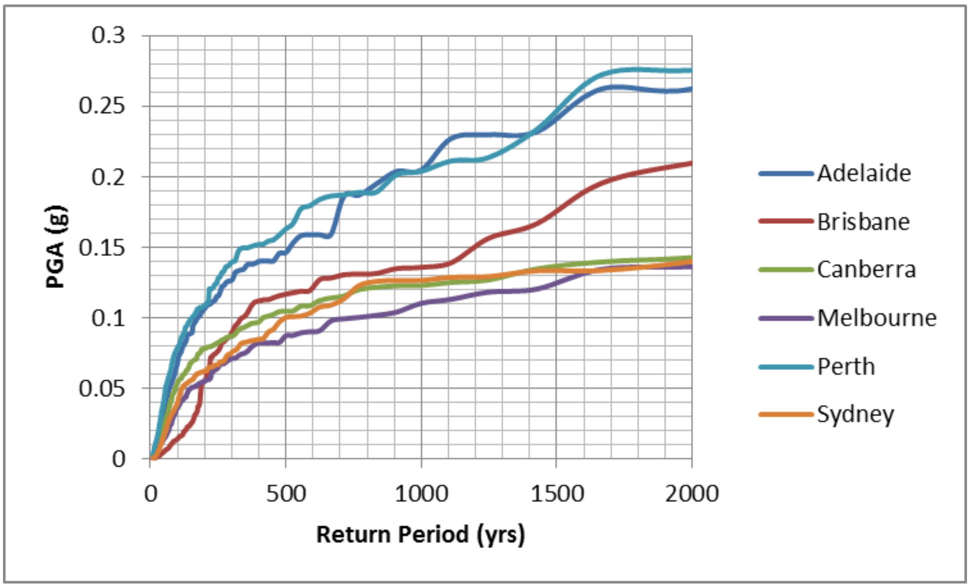


*Figure 6: The input PGA(g) for particular return periods for a 10,000 year stochastic analysis from the work of Schaefer and Daniell (2014)*

*Table 5: No. of events exceeding a certain PGA (g) in a 10,000 year stochastic scenario (via Schaefer and Daniell, 2014)*

| PGA exceedance (g) | Adelaide | Brisbane | Canberra | Melbourne | Perth | Sydney |
|---|---|---|---|---|---|---|
| **0.01** | 527 | 134 | 384 | 272 | 569 | 263 |
| **0.02** | 292 | 79 | 219 | 150 | 332 | 178 |
| **0.04** | 176 | 54 | 135 | 90 | 207 | 99 |
| **0.08** | 82 | 38 | 44 | 26 | 97 | 30 |
| **0.12** | 38 | 16 | 13 | 7 | 46 | 13 |
| **0.16** | 14 | 7 | 3 | 2 | 20 | 2 |
| **0.2** | 11 | 5 | 0 | 0 | 11 | 0 |
| **0.3** | 3 | 1 | 0 | 0 | 2 | 0 |

Placing the brick building in one of these cities in Table 5, the functions either from existing software or those in Appendix A can be used in order to calculate the structural and non-structural losses. However, as mentioned previously, there have not been a lot of different functions that have been created for contents historically (Table 6), and thus engineering judgement and the work of ATC-58, Porter et al. (2012) will need to be applied in a lot of cases. In reality, more data is needed for more accurate fragility functions for Australian conditions.

*Table 6: Software functions in various structural, non-structural and contents*

| Software | Structural functions | Non-structural functions | Contents functions |
|---|---|---|---|
| CREST | Structural function | Structural calculated | n/a |
| DBELA | Structural drift ratios | Nonstructural drift ratios included with structural analysis | n/a |
| ELER | 5 damage classes, structural derived | Structural calculated | n/a |
| EQRM, HAZUS | Brick veneer and URM, roof types tile and metal. | HAZUS drift (0.5) and acceleration (0.6) sensitive | As a % of the non-structural analysis. |

| | | | |
|---|---|---|---|
| Ergo (mHARP) | Masonry functions | Non-structural damage functions | Building content damage factors |
| SeisVARA | Calculated structural functions for Indian building types | Calculated non-structural ratios | Calculated contents ratios |
| SELENA | Only Structural | Structural calculated | n/a |

### 4.1 Structural Elements Analysis

Structural fragility functions for URM and other brick typologies have been looked at for the structural components in terms of having some comparability to Australia as per the table included in Appendix A, only including a few of the masonry vulnerability and fragility functions globally.

For the fragility functions, much effort has been made to collect particular functions used around the world; however, this is no substitute for analytical and empirical testing of the non-structural, contents and structural components in order to calculate the damage ratios and final losses. Much of the analysis has occurred in earthquake-prone countries which could mean an overestimate of the resisting features that could be expected in Australia. The lack of studies into the change in losses, as well as the lack of earthquake history and data, makes this very difficult (or impossible currently) to validate. Much more work is needed for this part of the analysis in order to calculate something like the Seattle URM Retrofit Policy (Gibson et al., 2014) or to have statistics like those of the Christchurch event collected by Moon et al. (2012) showing the high percentage of URM buildings lost, but the great reduction in those that were retrofitted to 33%, 67% and 100% of the %NBS.

From the EQRM Manual v3 for Australian Earthquake Risk from Geoscience Australia (Fulford et al., 2002), the following expert opinion coefficients have been derived and then implemented in the SeisVARA framework (Haldar et al., 2013). Two alternative functions were used for URM vs. double brick (Figure 7) and brick veneer (Figure 8). The recent Christchurch event mimics what has been seen in the study, where huge demolition rates will be present approaching PGA=0.4g.

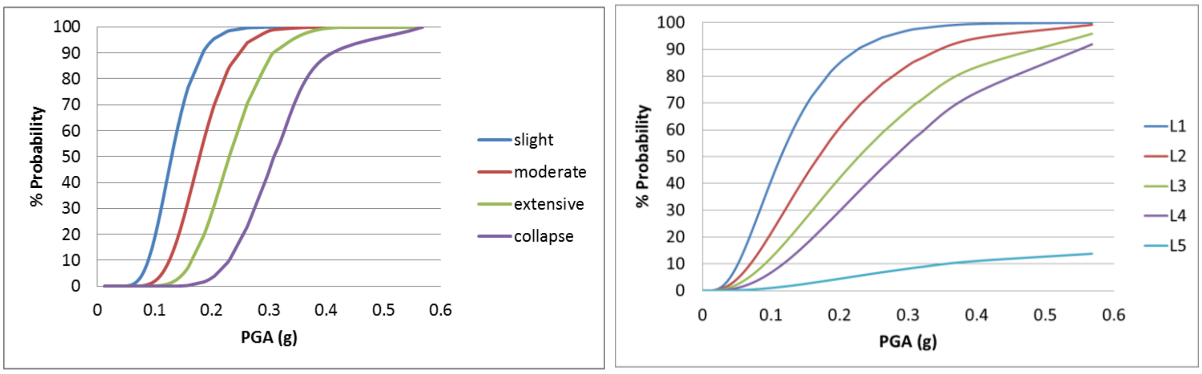


*Figure 7: Double brick (cavity wall) loss functions using the two classifications of Left: EQRM (AAL = 0.11% for Adelaide), Right: Kappos et al. (2006) – (AAL = 0.08% for Adelaide); it can be seen that this matches well with the URM losses seen in Christchurch.*

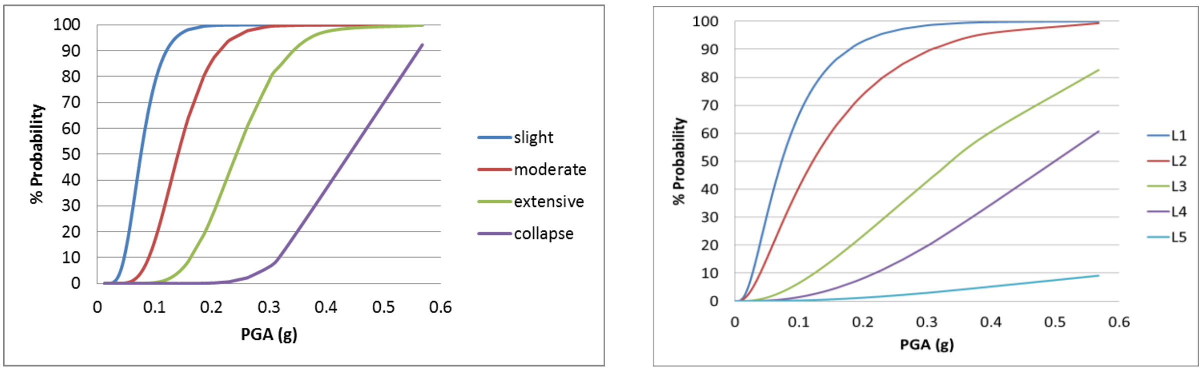


*Figure 8: Brick Veneer (wood frame) using the two classifications of Left: EQRM (AAL = 0.05% for Perth), Right: Kappos et al. (2006) – (AAL = 0.04% for Perth)*

Unfortunately, the costs of the relative options in Section 3.2 for the retrofit of structural elements greatly exceed \$1000, let alone \$100, with the exception of plastic braided mesh, some seismic wallpaper options, repointing and rubber tyre post-tensioning. In these cases, the AAL of \$100 at the most for the structural elements does not mean that it is cost-effective over the short term. However, just using the AAL for such decisions is misleading, as the failure of a building can result in additional non-structural, contents and life safety issues. This will be discussed in a future paper on Australian risk assessment (Daniell and Schaefer, 2015 (in review)).

## 4.2 Non-Structural Elements Analysis

Krawinkler et al. (2012) has produced a combination of empirical and analytical damage fragility functions for URM chimneys and parapets. These include 2 states of loss, cracking/sliding, and toppling. The fragility functions use PGA, Sa ($T_{fund}$ and $T_{(1s)}$) and peak total roof velocity (PTRV). They seem to be reasonably consistent with the findings of Griffith et al. (2010), Moon et al. (2013) with the parallels drawn by Ingham et al. (2011) as seen in Figure 9 showing the potential for losses like those seen in Christchurch. The work of ATC-58 has been also reviewed for those components not covered as part of the initial analysis.

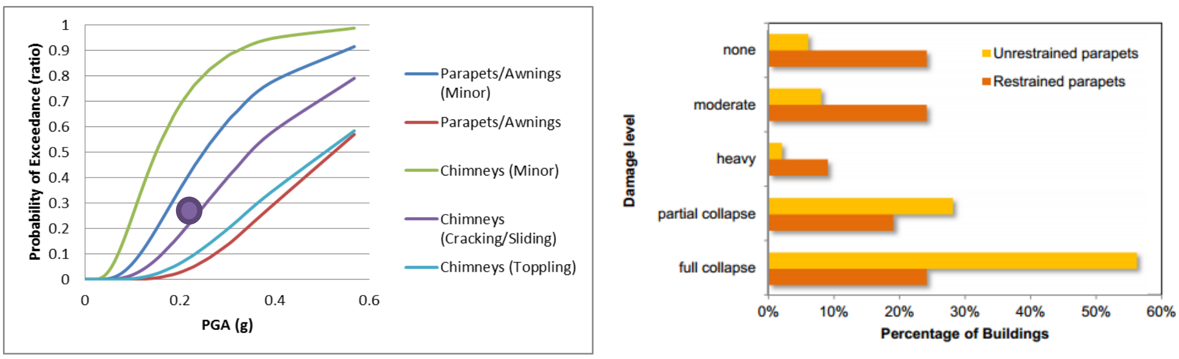


*Figure 9: Chimney (cracking/sliding and toppling) and Parapet failure (loss) via Krawinkler et al. (2012) and other estimates, and marking the 2010 Darfield earthquake chimney damage; Unrestrained vs. restrained parapets (Ingham and Griffith, 2011)*

In many cases, these are combined with structural functions when calculating non-structural losses. For this calculation, only the chimney and parapets will be calculated using the cost-benefit analysis, with the other non-structural analysis components to be combined with the structural analysis in EQRM. The costs of a chimney retrofit ($2000-$12,000) often much outweigh the probability of total damage ($15,000 (replacement) -100,000 (additional house damage caused)) (as per US calculations of chimney adjusting). Cheaper versions of simply bracing the chimney back into the structure cost around $200-700, depending on labour costs, with material costs of around $50-60. Using a non-continuous damage ratio system and noticing that the destruction (toppling) of a chimney will have a higher ratio of damage than 1 (given that additional damage will occur to the house), the other types of damage can be set at a damage ratio of 0.45 for cracking/sliding, minor damage of 0.1, and very minor damage (very minor cracks) of 0.005. The following loss analysis is then made as seen in Figure 10 and Figure 11. The AAL at Adelaide in this case is close to 0.2% for chimneys and in the order of 0.1% for parapets.

| | |
|---|---|
| Destruction (+ toppling effects) | 1 in 2000 |
| Major damage (sliding, foundation) | 1 in 666 |
| Minor damage (cracking) | 1 in 160 |
| Very minor damage (hairline cracks) | 1 in 40 |

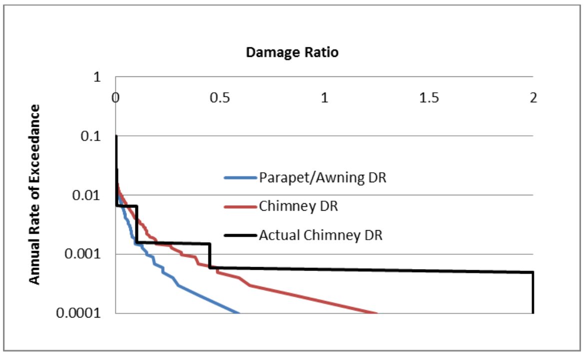


*Figure 10: The chimney and parapet/awning damage ratios for Adelaide; and the chance of damage happening to a chimney in Adelaide probabilistically over a 10,000 year Monte Carlo Simulation.*

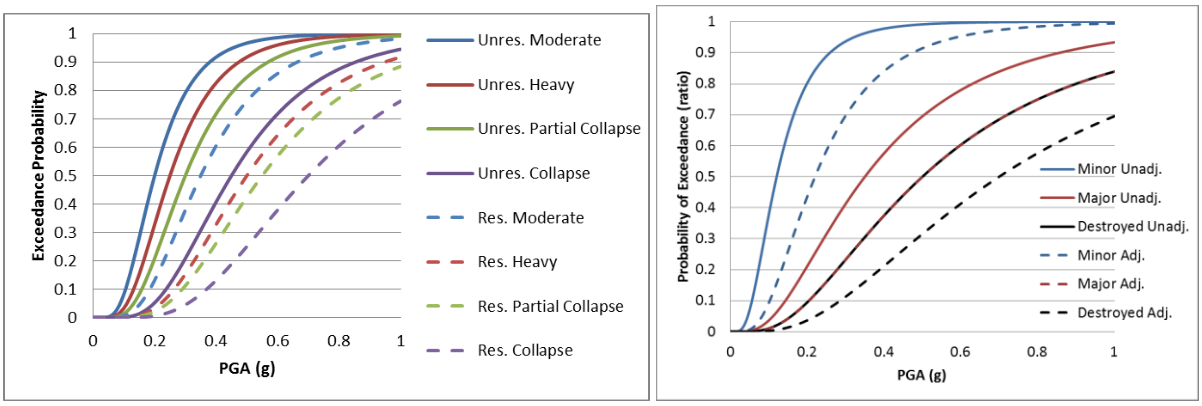


*Figure 11: Adjusted fragility functions from the data of Ingham and Griffith (2011) for Left: Parapets in the CBD of Christchurch, and Right: Retrofit of chimneys*

The retrofit options for the AAL of chimneys and parapets, including the cost of work, are shown here for a 'lifetime' ownership of 20 years and the total unit value is shown in Section 2.1. The cost of retrofit for parapets was calculated at $525 + labour, using a bracing retrofit. For chimneys, the cost was calculated to be $350 + labour. It is interesting to note that the cost of retrofit greatly outweighs the expected loss if the owner is there for 20 years. The retrofitted AAL with respect to the non-retrofitted AAL is in the order of 5 times less, but with work included is in the order of 8 times more for parapets and around 2-4 times more for chimneys. This is shown in Figure 12 This does not, however, take into account life safety.

In Adelaide, 15 times in 10,000 years, there will be a dangerous situation occurring with major to full loss. For the toppling chimney case, one could assume around 1.1% chance of death due to bricks falling through the house. For the major damage, there is around 0.15% chance. In total, the chance of death in 10,000 years is around 7% (5 toppling, 10 major). Calculating the average value of life at $3.7 million, and 4.5 people in a brick house as of 2014 in CATDAT for Adelaide, the total AAL for life costing is around $1665, and the chance of death (7%), is then $117/year. This far outweighs the costs of retrofitting a chimney, and thus, in terms of the cost-benefit ratio, it is very much worth it to retrofit.

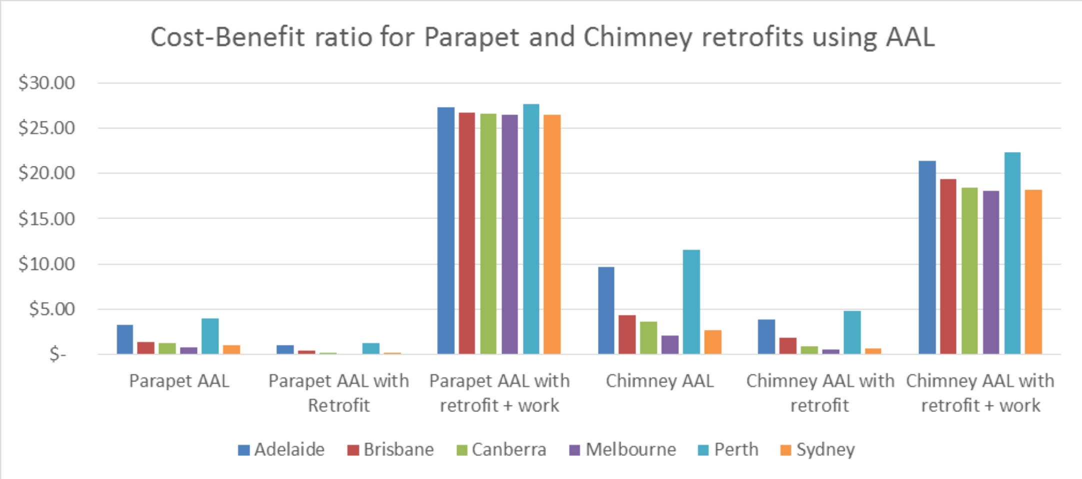


*Figure 12: Parapet and chimney AALs in contrast to retrofit AALs vs. retrofit+work AALs for the major Australian capital cities.*

### 4.3 Contents Analysis

ATC-58 and Porter et al. (2001, 2012) as well as Farokhia and Porter (2012) detail years of work for contents fragility functions looking at a single damage state with the repair cost equalling the replacement cost. We use the storey replacement cost method of Porter et al. (2012) and ATC-58. The contents values from Section 2.1 are utilised. Judgement is used in order to calculate the maximum value of contents at risk if structural failure effects on top of contents are not included. In total, of the $164,000 contents at risk, $114,000 is at risk or approximately 70% of the total contents as seen in Figure 13.

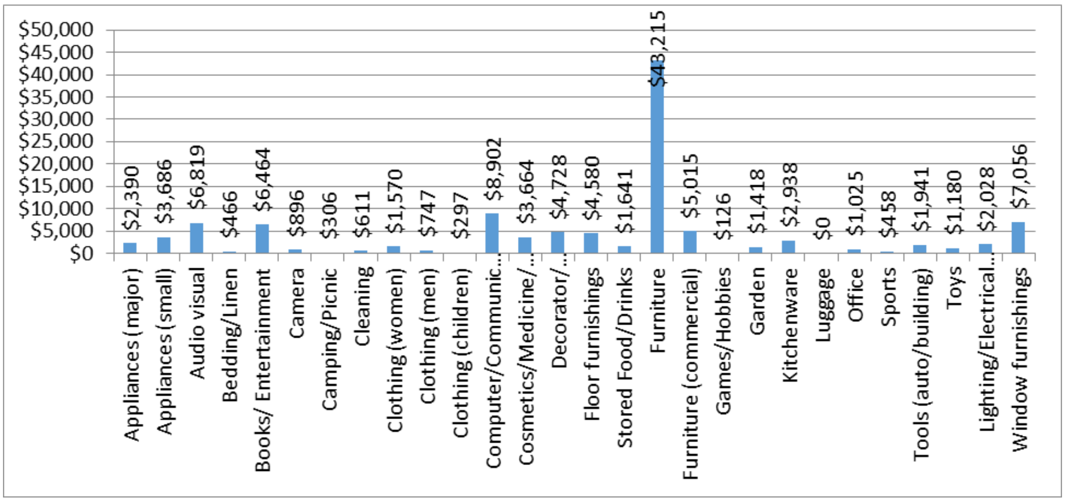


*Figure 13: The contents which are exposed to earthquake losses as a percentage of those shown previously as a percentage of the whole house.*

Using the fragility functions set out in ATC-58 adjusted for Australia and the costs for each option of retrofitting in Section 3, the cost of retrofit using all contents functions totals to $735. Given a 20-year lifetime of contents in a house (the average of home owners in Australia), the following options are the AAL without retrofit and the AAL with retrofit and the cost of work. It can be seen in Figure 14 that the cost of the total work offsets the benefit for Melbourne and Sydney. In these cases, it is better to only do a percentage of the work when living in these cities and only do work for contents. In Adelaide and Perth, the benefits far outweigh the outlaid costs without the inherent life safety improvement.

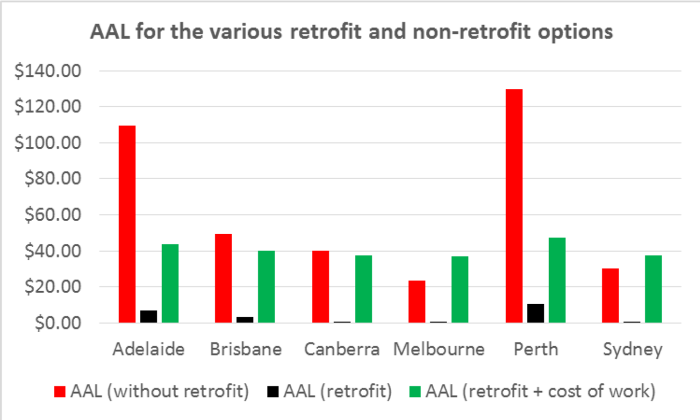


*Figure 14: The AAL (without retrofit) for the contents losses in each major city in Australia; The AAL after retrofitting in each of the major cities and the AAL with the cost of the work added in for each major city in mainland Australia..*

## 5. In what order should the work be done to optimise the loss to cost ratio in major Australian Cities?

It has become abundantly clear during this analysis that many of the retrofitting options cannot be done for $100. The optimisation, however, is one that uses the free and cheap options first to fix the contents, and some of the non-structural elements that require non-engineered solutions as seen below in Table 7.

*Table 7: The final optimised solution for Adelaide for the $100 in order to reduce losses over 20-year lifetime (this is a saving of $600 in average annual terms without risk)*

| **Measure** | **Approximate benefit to AAL reduction ($393 to begin with for Adelaide)** | **Cost so far** |
|---|---|---|
| Move pictures, fragile items and those items that would fall in an earthquake easily.* | $6.89 | $0 |
| Relocate heavy fragile items to lower locations (artwork etc.).* | | $0 |
| Relocate furniture | | $0 |
| Install latches for drawers with fragile items | $0.98 | $5.50 |
| Install cords/wire across shelves | $6.91 | $12.30 |
| Secure artwork/mirrors | | $32.30 |
| Secure electrical equipment | $9.11 | $70.76 |
| Secure expensive furniture via bracketing | $7.79 | $79.94 |
| Fasten bookcases (single bracket)* | | $82.99 |
| Safety cables for expensive lighting | $1.46 | $92.55 |
| Chicken wire roof gutter catch | $1.23 | $100.00 |
| **Total (over 20 years = ca. $700)** | **$34.37 (ca. 9%)** | $100 |

***also life safety benefits.**

The next steps are the $635 contents changes such as safety film on windows, other furniture catches etc. that can be undertaken in order to improve the contents losses. The non-structural analysis showed that the chimney and parapet cost-benefit ratios were not viable unless taking into account life costing. There are a number of additional analyses that could be financially viable for structural and non-structural measures, as detailed in Section 3.1 and 3.2; however, the costs are greater than $100, and thus are not included in this optimised analysis, such as water heater restraints, anchoring a home to the foundations, improving walls, and relative retrofitting and strengthening for external walls, roof and floors.

Depending on insurance takeout, contents are sometimes covered but often not covered with respect to earthquakes. The solution attempts to protect things that are likely to not be claimed under a small earthquake contents claim. Exclusion clauses with respect to non-structural and contents losses as well as deductibles often need to be checked and the benefit vs. loss analysed for the period of insurance takeout. With respect to the implemented changes for other disaster types, there is an amount of overlap with windstorm losses. The implemented changes however, may need to be adjusted in the case of a flood, with susceptible low items moved. In terms of stability of the house, most measures provide a multiple solution to other disaster types.

## 6. Conclusion: Spending more and making the public aware

It is important to note that the key aspects of this paper are only in part the AAL results for the various mitigation options that have been shown for non-structural, contents and structural losses but hopefully also in part, the realisation that Australians can do minor things around the house in order to reduce the chance of fatalities and economic losses.

A tale of two cities, Christchurch and Washington DC, provides recent examples of a hazard and risk to earthquakes much higher than to any earthquake previously. This also provides valuable learning experiences for Australia. It was not necessarily a lack of preparedness or research in these cities, but the short earthquake catalogue history in these locations that provided little clues as to the impending doom, the lack of planning for “tail-end risk” in an unknown distribution and the fact that such developed nations failed to take a higher factor of safety into account because they simply accepted the “475-year earthquake hazard map” for residential construction and did not dare to push the boundaries higher. This is key when examining the potential impacts of losses, as life costing can make a huge difference to benefit-cost ratio analysis.

It is hoped that this analysis will fuel discussions for combined solutions for future earthquake design in Australia to look at combining existing short-term probabilistic seismic hazard assessments with scenario analysis and even “black swan scenarios”, as well as promoting small household family projects and awareness to reduce earthquake risk.

In reality, though, major engineering retrofits to combat non-structural and structural component losses in masonry buildings (as well as other buildings) should be undertaken which offset many times the initial costs and there should be better building practices for new buildings by including earthquake resistant features, rather than having to retrofit.

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# Appendix A

*Table 8: Masonry vulnerability and fragility functions globally from the review done as part of Daniell (2014)*

| Author | Typology | Country | Hazard Parameter | Type | Storeys | Damage States |
|---|---|---|---|---|---|---|
| Ahmad et al. (2010) | Masonry (high and low voids) | Europe | PGA | Analytical-Nonlinear Static | 2 | 5 (+ out of plane) |
| Borzi et al. (2008) | Masonry (high and low voids) | Italy | PGA | Analytical-Nonlinear Static | 2 | 3 (+ out of plane) |
| Blong (1993) | URM, Brick Veneer. | Australia | MMI | Empirical | 1-2 | Cont. |
| Colombi et al. (2008) | Masonry | Italy | Sd | Empirical | 1-2 | 3 |
| Cochrane and Schaad (1992) | Brick Veneer and URM | Worldwide | MMI | Empirical | 1-2 | Cont. |
| Cousins et al. (2009) | URM | New Zealand | MMI | Empirical | 1-2 | Cont. |
| D'Ayala et al. (1997) | Masonry | Lisbon | MMI and PGA | Analytical-Nonlinear Static | 2-6 | 5 |
| EQRM (Fulford et al., 2002) | Brick Veneer (tile and metal roofs), URM (Mean, tile, metal) | Australia | PGA and MMI | Hybrid and Expert-Opinion | 1-2 | 4 |
| Erberik (2008) | Masonry (Engineered, Non-engineered Urban/Rural) | Turkey | PGA | Analytical-Nonlinear Static | 1-2 | 2 (mod. & collapse) |
| Goretti and Di Pasquale (2004) | Masonry | Italy | MMI | Empirical | 1-2 | 4 |
| HAZUS (1997) | URML | USA | Sd/Sa | Analytical- Nonlinear Static | 1-2 | 4 |
| Kappos et al. (2006) | URM | Greece | Sd (Ty) | Hybrid | 2 | 4 |
| Kostov et al. (2004) | Masonry | Bulgaria | PGA | Expert-Opinion | 1-5 | 4 (EMS-98) |
| Lagomarsino and Giovinazzi (2006) | Masonry (M4, M5, M6) | Italy | EMS-98 and PGA | Empirical | Unk. | 5 |
| Lang (2002) | URM and Confined Masonry | Switzerland | Sd (Ty) | Analytical – Nonlinear Static | 2-7 | 5 |
| LESSLOSS (2005) | Masonry (Low-rise) | Lisbon, Turkey | Sd (Ty) | Analytical – Nonlinear Static | 1-2 | 4 |
| Moon et al. (2014) | URM | Christchurch | Damage | Empirical | 1-3 | Various |
| Nuti et al. (1998) | Masonry (Low-Rise) | Italy | MCS | Empirical | 1-3 | 2 (mod. & coll.) |
| RISK-UE (2003) | Masonry (Low-Rise) | Europe | Sd | Analytical – Nonlinear Static | 1-2 | 4 |
| Rota et al. (2008) | Masonry (8 types – with and without tie rods, regular/irregular) | Italy | PGA | Empirical | 1-2 | 5 |
| Spence et al. (1992) | Masonry | Global | PSI | Empirical | 1-3 | Cont. |
| University of Patras (2011) | Masonry (4 types with flexible/regular) | Europe | PGA | Analytical – Nonlinear Static | 2 | 5 (EMS-98) |

There is a list of 94 additional masonry functions relating to high development countries in Daniell (2014).

*Table 9 - The damage factors for various damage classes as per Left: PartnerRe (2010); Right: EMS-98*

| Damage state | Basic description | Damage factor range | Central Damage Factor (%) |
|---|---|---|---|
| $D_0$ | No damage | 0 | 0 |
| $D_1$ | Negligible to slight damage | 0–5 | 2.5 |
| $D_2$ | Moderate damage | 5–20 | 12.5 |
| $D_3$ | Substantial to heavy damage | 20–50 | 35.0 |
| $D_4$ | Very heavy damage | 50–95 | 72.5 |
| $D_5$ | Destruction | 95–100 | 97.5 |

| Classification of damage; after Grünthal (1998) | MDR % | Mean value % |
|---|---|---|
| Grade 0: No damage | 0 | 0 |
| Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage) | 0-1 | 0.5 |
| Grade 2: Moderate damage (slight structural damage, moderate non-structural damage) | 1-20 | 10 |
| Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage) | 20-60 | 40 |
| Grade 4: Very heavy damage (heavy structural damage, | 60-100 | 80 (100) |
| Grade 5: Destruction (very heavy structural damage) | 100 | 100 |

*Table 10 – Factors used for the contents loss analysis (Porter et al., 2012).*

| **Content category** | **IMT** | **θ** | **β** |
|---|---|---|---|
| C1 dishes and glasses | | | |
| Poor (from E2022.013 Unsecured fragile objects on shelves, low friction surface) | PFA | 0.25 | 0.5 |
| Moderate (from E2022.012 Fragile contents on shelves in storage cabinets with latches) | PFA | 0.60 | 0.6 |
| Superior (from E2022.011 Fragile contents secured by museum putty, Velcro or other weak but sticky stuff) | PFA | 1.0 | 0.5 |
| C2 home-entertainment equipment | | | |
| Poor (from E2022.023 desktop electronics including computers, monitors, stereos, etc., smooth surface) | PFA | 0.40 | 0.5 |
| Superior (from E2022.022 Desktop electronics including computers, monitors, stereos, etc. on a slip resistant surface) | PFA | 1.0 | 0.5 |
| C3 fragile artwork | | | |
| Poor (from E2022.013 Unsecured fragile objects on shelves, low friction surface) | PFA | 0.25 | 0.5 |
| Superior (from E2022.011 Fragile contents secured by museum putty, Velcro or other weak but sticky stuff) | PFA | 1.0 | 0.5 |
| C4 commercial shelving | | | |
| Poor (from E2022.106a Bookcase, 6 shelves, unanchored laterally) | PFA[1] | 0.25 | 0.5 |
| Superior (from E2022.106b Bookcase, 6 shelves, anchored laterally) | PFA[1] | Not available | |
| C5 stock and supplies on shelves | | | |
| Poor (from F1012.001, Storage racks designed and installed before 2007, big box retail, 12' to 15' tall, damage state 1, significant merchandise shedding from rack shelves.) | PFA | 0.42 | 0.4 |
| Moderate (from E2022.012 Fragile contents on shelves in storage cabinets with latches) | PFA | 0.60 | 0.6 |
| C6 computer equipment | | | |
| Poor (from E2022.023 desktop electronics including computers, monitors, stereos, etc., smooth surface) | PFA | 0.40 | 0.5 |
| Superior (from E2022.022 Desktop electronics including computers, monitors, stereos, etc. on a slip resistant surface) | PFA | 1.0 | 0.5 |
| C7 industrial racks | | | |
| Moderate (from F1012.001, Storage racks designed and installed before 2007, big box retail, 12' to 15' tall, damage state 2, significant structural damage to rack structure.) | PFA | 0.42 | 0.4 |
| C8 movable equipment | | | |
| Poor (from D5092.031a Diesel generator - Capacity: 100 to <350 kVA - Unanchored equipment that is not vibration isolated - Equipment fragility only | PFA | 0.9 | 0.4 |
| Superior (from D5092.033b Diesel generator - Capacity: 100 to <350 kVA - Equipment that is either hard anchored or is vibration isolated with seismic snubbers/restraints - Equipment fragility only) | PFA | 2.0 | 0.2 |

[1] ATC-58 offers in terms of peak floor velocity. PFV in m/sec is approximately equal to PFA in units of g

*Table 11 – Parameters used for structural analysis in EQRM.*

| | $C_s$ | $h$ | $T_e$ | $\alpha_1$ | $\alpha_2$ | $\gamma$ | $\lambda$ | $\mu$ |
|---|---|---|---|---|---|---|---|---|
| W1MEAN | 0.077 | 13 | 0.275 | 0.9 | 0.7 | 1.75 | 2 | 7 |
| W1BVTILE | 0.063 | 13 | 0.32 | 0.9 | 0.7 | 1.75 | 2 | 7 |
| W1BVMETAL | 0.082 | 13 | 0.28 | 0.9 | 0.7 | 1.75 | 2 | 7 |
| URMLMEAN | 0.15 | 15 | 0.15 | 0.75 | 0.75 | 1.5 | 2 | 2 |
| URMLTILE | 0.15 | 15 | 0.15 | 0.75 | 0.75 | 1.5 | 2 | 2 |
| URMLMETAL | 0.2 | 15 | 0.13 | 0.75 | 0.75 | 1.5 | 2 | 2 |
| URMMMEAN | 0.1 | 35 | 0.28 | 0.75 | 0.75 | 1.5 | 2 | 2 |
| URMMTILE | 0.1 | 35 | 0.28 | 0.75 | 0.75 | 1.5 | 2 | 2 |
| URMMMETAL | 0.15 | 35 | 0.23 | 0.75 | 0.75 | 1.5 | 2 | 2 |

| Damage state | S | M | E | C |
|---|---|---|---|---|
| Non-Structural damage drift sensitive (drift ratios) | | | | |
| nonres | 0.004 | 0.008 | 0.02 | 0.03 |
| res | 0.001 | 0.008 | 0.015 | 0.025 |
| Accel. sensitive (g) | | | | |
| Accel | 0.2 | 0.4 | 0.8 | 1.6 |
| Structural Damage drift ratios | | | | |
| W1MEAN | 0.001 | 0.004 | 0.008 | 0.015 |
| W1BVTILE | 0.0005 | 0.001 | 0.002 | 0.005 |
| W1BVMETAL | 0.0005 | 0.001 | 0.002 | 0.005 |
| URMLMEAN | 0.0005 | 0.0008 | 0.0012 | 0.002 |
| URMLTILE | 0.0005 | 0.0008 | 0.0012 | 0.002 |
| URMLMETAL | 0.0005 | 0.0008 | 0.0012 | 0.002 |

| Type | $\kappa_S$ | $\kappa_M$ | $\kappa_L$ | $B_E$ |
|---|---|---|---|---|
| W1MEAN | 0.001 | 0.001 | 0.001 | 0.08 |
| W1BVTILE | 0.001 | 0.001 | 0.001 | 0.08 |
| W1BVMETAL | 0.001 | 0.001 | 0.001 | 0.08 |
| URMLMEAN | 0.001 | 0.001 | 0.001 | 0.05 |
| URMLTILE | 0.001 | 0.001 | 0.001 | 0.05 |
| URMLMETAL | 0.001 | 0.001 | 0.001 | 0.05 |