Seismic Performance Expectations for Australian Unreinforced Masonry Buildings

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Abstract

Professor Griffith will give an overview of recent and ongoing research into the seismic behaviour of unreinforced masonry (URM) construction in Australia. His talk will focus primarily on:

- the seismic vulnerability of URM walls to out-of-plane bending and the associated local failure mechanisms;
- the influence of flexible floor and roof diaphragms on the seismic response of URM buildings up the height and the impact on non-structural components; and
- a progress report on work studying the seismic resistance of Heritage URM (stone and brick) construction.

Keywords: seismic, design, yield, curvature, displacement, performance

INTRODUCTION

As part of its work to encourage the adaptive reuse of existing buildings in Adelaide, DPTI formed a small working group of relevant professionals to assess the safety risks posed by existing buildings in the event of an earthquake and engaged Risk Frontiers to assist in this work. The working group subsequently developed a 'simple' Seismic Risk Assessment process (Figure 1) that could be used by building owners to identify appropriate levels of seismic upgrading needed when an existing building is undergoing alterations or a change of use, and that councils and building certifiers could use when assessing applications for alterations to existing buildings and checking the overall safety of the building. This process has been incorporated into a *Minister's Specification SA Upgrading health and safety in existing buildings*, which was adopted in South Australia on 19 September 2017, with the aim of incorporating seismic strengthening into upgrading work where the seismic risk assessment indicates significant life safety risks from falling hazards.

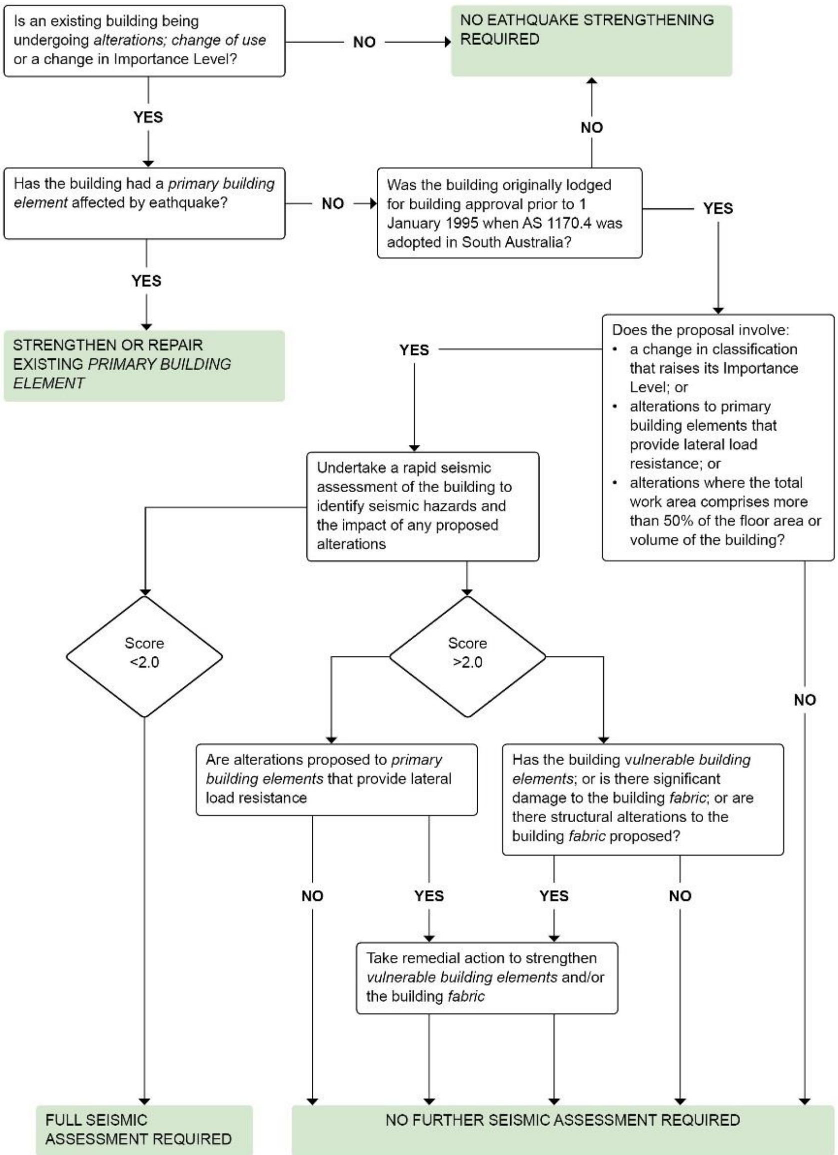


Figure 1. Seismic Risk Assessment of Existing Buildings – Logic Tree (*https://www.sa.gov.au/__.../Ministers-Specification-SA-Upgrading-health-and-safety-i...*)

A seismic risk study for the city of Adelaide (Schindler et al, 2013) considered three earthquake scenarios, Mw 5.0, 5.5 and 6.0. Their study used the existing vulnerability curves in HAZUS and the curves provided by Griffith (Figure 2) which were based on consensus opinion of experts from a GEM workshop held at the 2012 WCEE in Lisbon. The 67%NBS and 100%NBS curves show indicative reductions in damage that are anticipated if unreinforced masonry (URM) buildings are retrofitted to 2/3rd and 100% of the strength demands given by AS1170.4 (2007). When scaled and normalised to the damage costs reported for the Christchurch 2010-11 earthquake sequence, the estimated cost of a Mw 6.0 earthquake in Adelaide would be almost an order of magnitude more than that experienced in Christchurch in terms of damage to buildings and contents, business interruption costs and fatalities owing to the larger population and significantly higher number of URM buildings in Adelaide.

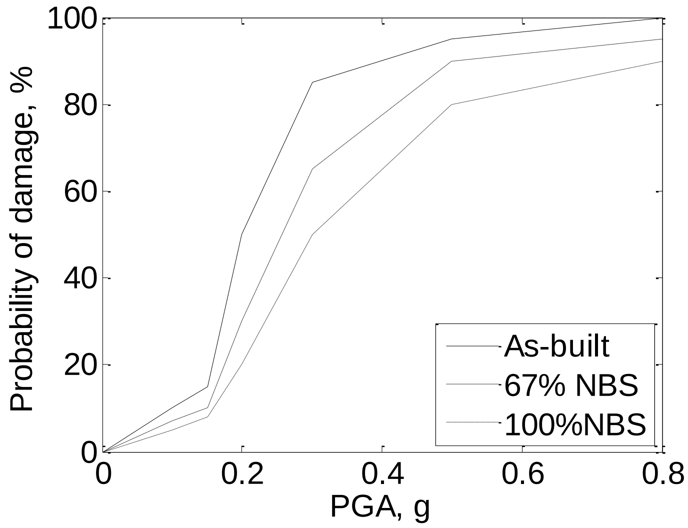


Figure 2. Vulnerability curves for URM buildings.

So, what are we doing to try and reduce this risk to the public? The following sections of this paper report on the work that is progressing on a number of fronts through a number of individual projects around the country as well as a coordinated effort by the earthquake research cluster working under the umbrella of the ARC's Bushfire and Natural Hazards Cooperative Research Centre (BNH CRC).

BNH CRC EARTHQUAKE RESEARCH

The earthquake research cluster working under the umbrella of the BNH CRC involves staff from Geoscience Australia, Swinburne University of Technology and the Universities of Melbourne and Adelaide and has focussed on what are perceived to be the most seismically vulnerable forms of construction – URM and low ductility reinforced concrete (LDRC) buildings. The cluster is working towards an improved assessment methodology that can give reliable estimates of cost and benefit for a range of earthquake magnitude and seismic strengthening scenarios. The ultimate aim is to develop a "Cost-effective mitigation strategy for building related earthquake risk" which can inform decision makers on the mitigation of the risk posed by the most vulnerable forms of Australian buildings.

Specific sub-aims of the project include:

- Classification of Australian building stock;
- Vulnerability assessment of current and retrofitted buildings;
- Development of seismic damage mitigation strategies for buildings;

- Costing of earthquake damage mitigation and repair strategies;
- Cost-benefit analysis methodology at building and regional levels; and
- Case study of several CBDs (York Shire Council in WA and Melbourne).

Work on the first two aims are nearing completion. As indicated by Figure 2(a), working versions of vulnerability curves exist for URM and LDRC buildings. The project is now using building damage data from the Christchurch 2010-2011 earthquake sequence as spot checks to validate the accuracy of the curves for URM construction in particular.

Seismic retrofit research has been a largely international activity for several decades but is now a major focus of the CRC's earthquake cluster. A number of reports on the current state of retrofit research are already publically available on the CRC's website (https://www.bnhcrc.com.au/publications/) including that on retrofit of URM cavity walls (Derakhshan et al, 2017a). Others will follow in the next 12 months.

Costing of the various seismic retrofit and damage mitigation strategies will be undertaken by economists/quantity surveyors at GA in Canberra over the next few years. In the meantime, the cluster has its first case study starting in early 2018 – York Shire Council. York township, population 2387 (2011 census), is roughly 100 km inland from Perth and most of its buildings have 'heritage' classification (refer Figure 4). Because of the town's heritage, its primary economic activity revolves around tourism and any loss of heritage amenity could have potentially catastrophic economic consequences for the town. Thus, there is widespread support from the residents and building owners to learn how they can best mitigate against the earthquake hazard that they live with.

Figure 4. York, WA (source, http://www.aussietowns.com.au/town/york-wa)

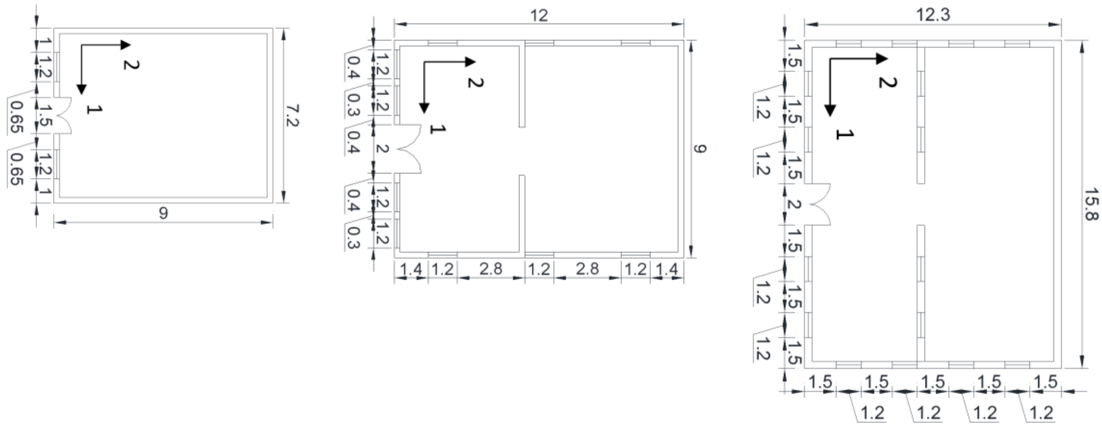
TYPICAL URM FAILURE MECHANISMS

One of the most common failure mechanisms observed in various earthquakes has been localised 'non-structural' failure of URM components including the out-of-plane collapse of URM partitions, facades, gable ends, and chimneys (Bruneau 1994; Ingham and Griffith 2011; Moon et al. 2014). This poor performance, especially that reported for the recent New Zealand earthquakes (Moon et al. 2014), has motivated the current research project to be primarily focused on seismic evaluation and retrofit of these components. Recent research activities have included a study of seismic loading on non-structural components, improvement of wall strength predictive methods as applied to in-situ walls, the chimney flexural/overturning failure mechanism and and research on durability of FRP strengthening methods. The results of in-situ testing on chimneys and walls including an in-situ study of material properties were published in Derakhshan et al. (2017b; 2017c). An improvement to two-way wall strength predictive method was made to account for in-situ wall details (Derakhshan et al. 2017d).

SEISMIC LOADS ON NONSTRUCTURAL URM COMPONENTS

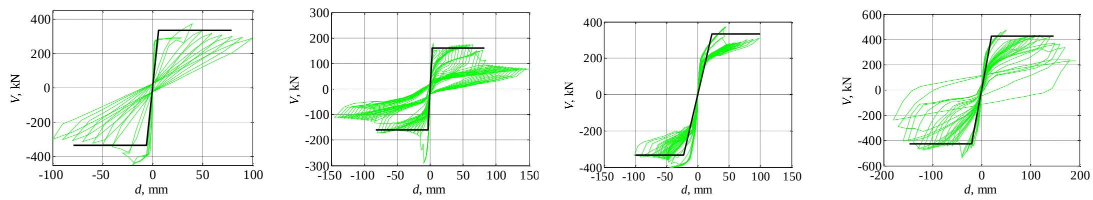
Seismic loads that are applied to non-structural URM components are typically estimated using simple codified methods. The Eurocode 8 (CEN 2004), the New Zealand code NZS 1170.5 (NZS 2004), and the Australian code AS 1170.4 (AS 2007) all propose, with some exclusions, a linear increase in 'peak floor acceleration' (PFA) with building height. This acceleration is the basis for calculation of non-structural seismic loads, although a further "part response modification factor" may be applied to PFA. An investigation was made into the relevance of PFA formulae to URM buildings.

Four buildings (Figure 5) were modelled in TREMURI (Lagomarsino et al. 2013) using material properties that represented older URM construction. The first mode period ranged from 0.06 sec (single-storey building 1) to 0.40 sec (three-storey building 4), with the hysteresis behaviour suggesting a mix of shear and flexural response. The diaphragm in-plane stiffness was also then taken as a variable and its effect on the acceleration amplification factor was investigated. The used software is capable of modelling in-plane loaded URM wall damage under earthquake loading. An approach proposed in Nakamura et al. (2017) was used to study in-plane vibrations of the flexible floors.



a) B1 (single-storey) b) B2 (single-storey) c) B3 and B4 (2- and 3-storey)

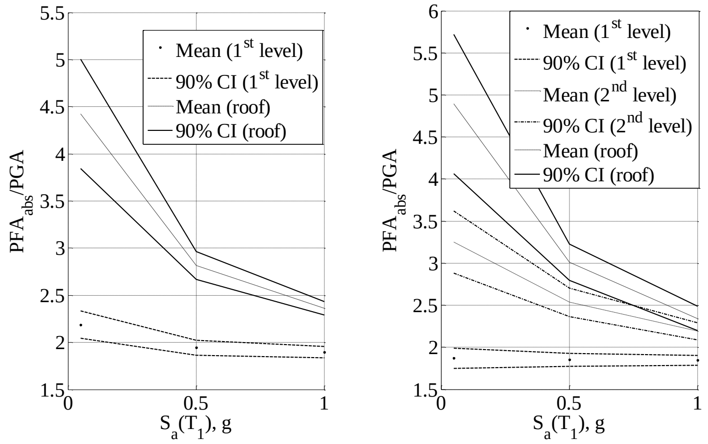
Figure 5: Case study building plans



a) Building 1 b) Building 2 c) Building 3 d) Building 4

Figure 6: Building behavioural data from pushover analysis

Time-history analyses were conducted incrementally and using 30 different records, that were scaled relative to spectral acceleration at the building period, $S_a(T_1)$. The amplification factor was found to decrease with an increase in excitations (Figure 7).



a) Building 3 b) Building 4

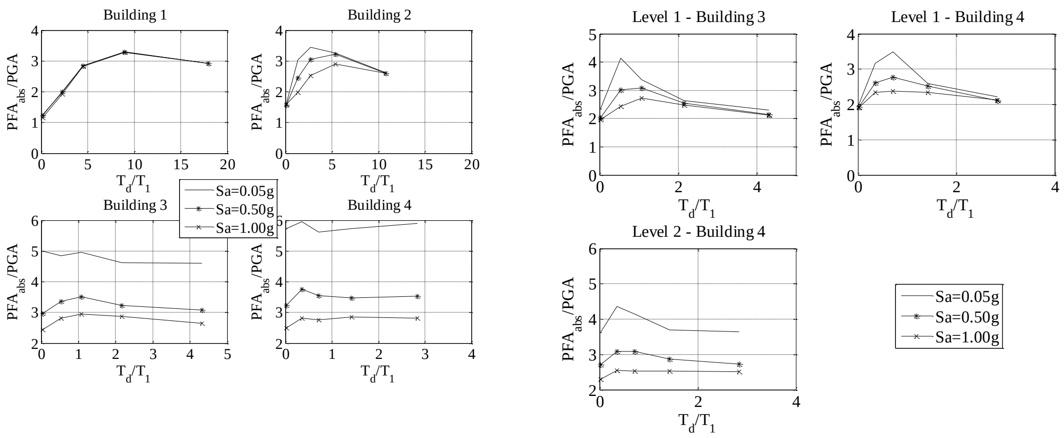
Figure 7: Peak floor accelerations normalised to PGA for two buildings

The smallest level of shaking (spectral acceleration at the building period equal to 0.05g) can be considered to be associated with mostly elastic response and resulted in amplification factors that were up to 5.75 (upper 90% confidence interval, CI, from 30 records) for the top of the 3-storey Building 4 (Table 3; Figure 7b). Allowing for some reduction due to inelastic response corresponding to a design earthquake at Sydney, the average and upper 90% CI of amplification factor were found to be, respectively, 4.35 and 5.00. It is highlighted that these values far exceed the maximum amplification of 3.00 that can be obtained from Australian, New Zealand or ASCE seismic loading codes/guidelines (AS 2007; NZS 2004; and ASCE 2014). Similar underestimations were encountered for the two-storey Building 3, but the single-storey accelerations were overestimated by Australia/New Zealand codes (but not by ASCE 2014).

Table 3: Roof acceleration amplification factor as per seismic codes

	Building 1	Building 2	Building 3	Building 4
	h=4.25m	h=4.25m	h=7.75m	h=11.25m
ASCE (ASCE 2014)	3.00	3.00	3.00	3.00
AS 1170.4 (AS 2007)	1.72	1.72	2.32	2.91
NZS 1170.5 (NZS 2004)	1.71	1.71	2.29	2.88
Current study (Mean); Sydney	1.16	1.46	3.96	4.35
Current study (upper 90%); Sydney	1.24	1.59	4.41	5.00
Current study (Mean); elastic	1.20	1.45	4.40	4.90
Current study (upper 90%); elastic	1.25	1.60	5.00	5.75

Subsequent to the analyses with rigid diaphragms, five levels of diaphragm in-plane stiffness were assumed to study the effects of diaphragm vibrations on acceleration amplification. It was found (Figure 8) that, as diaphragm stiffness reduces, there is a sharp increase in the amplification factor followed by a moderate decrease in the overly flexible diaphragm range. Therefore, it can be expected that the previously calculated amplification factors that was relevant for rigid diaphragm case are an underestimation of what occurs in URM buildings with timber floors/roof.



a) Roof b) Floors

Figure 8: Peak floor accelerations vs. excitation intensity and diaphragm flexibility

HERITAGE URM BUILDINGS

A collaborative effort between the Universities of Adelaide, Newcastle and Auckland is currently underway aimed at addressing the seismic vulnerability of heritage URM buildings in Australia. The scope of this effort includes the vast majority of standing buildings built throughout the 1800s (before the introduction of steel or concrete) up to approximately the 1940's, and can comprise either stone, clay brick or often a combination of the two masonry materials. These early buildings were built well before the introduction of seismic or masonry design codes, and thus constitute arguably the most earthquake-prone subset of Australia's building stock.

In the context of this project, the term 'heritage' encompasses buildings that are deemed to have a significant level of cultural or historical value, many of which are listed on State or local heritage registers. However in a broader sense it also includes any vintage URM buildings that have not been officially recognised as heritage-listed but which can often be otherwise indistinguishable and can thus pose the same level of risk in terms of life safety.

The objectives of this project are therefore to:

- Gain a deeper understanding of the inherent seismic vulnerability of heritage masonry buildings;
- develop practical tools that can be used by engineers to undertake seismic assessment; and
- document indicative costing and effectiveness of various strengthening/retrofit techniques.

CHARACTERISATION OF BUILDING TYPOLOGIES

The work to date has been aimed largely at characterising Australia's inventory of heritage URM buildings in terms of their constituent materials and typical building geometries. As shown by the map in Figure 9, this work has included collection of data through street-level surveys of over 300 heritage-listed buildings in the Adelaide CBD. Importantly, the aim of this exercise has not been to attempt to collect population statistics that may be applied to Australia as a whole, but rather to understand the predominant building typologies in terms of common masonry material (brick or stone) as well as the likely presence of high-risk elements such as parapets, gable-end walls, chimneys, and other freestanding falling hazards. A similar data-collection exercise has also been undertaken for the city of Newcastle but on the basis of information provided in the publically available heritage registers (Howlader et al, 2016).

From the Adelaide survey it was found that of the heritage-listed buildings inspected:

- Approximately 40% of buildings are clay brick-only, 30% are stone-only, and 30% have a combination of stone and clay brick.
- Of the buildings with a combination of stone and brick, clay brick appears mainly in secondary walls (side or rear) whereas stone was the material used mainly in the building’s facades.
- Moreover, this trend extends also to the quality of stone, in that the higher quality, finely-dressed stone was generally reserved for facades, whereas more coarse ‘rubble’ stone was used in the less visible walls.
- As shown by the typical examples in Figure 10, the three most commonly encountered types of building stone used for structural masonry walls were sandstone, limestone, and the so-called Adelaide bluestone (the latter being used as an umbrella term for a dark-coloured particularly hard stone related to shale, schist and gneiss) (Young, 1993).
- The regularity of the stonework was also found to be largely correlated to the type of stone – being softer stones, sandstone and limestone are typically found to be regular, smooth finely-cut blocks (referred to as ‘ashlar’), whereas due to its hardness bluestone generally appears as a more oblique shape of block laid in thicker mortar joints (referred to as ‘rubble stonework’). Refer to Figure 10 for typical examples.

Importantly, gaining an understanding of the composition and integrity of street-facing walls is particularly significant, because out-of-plane failure of such walls can pose a major hazard to the life safety of passers-by as was evidenced by the 2010-11 earthquake sequence in Christchurch, NZ.

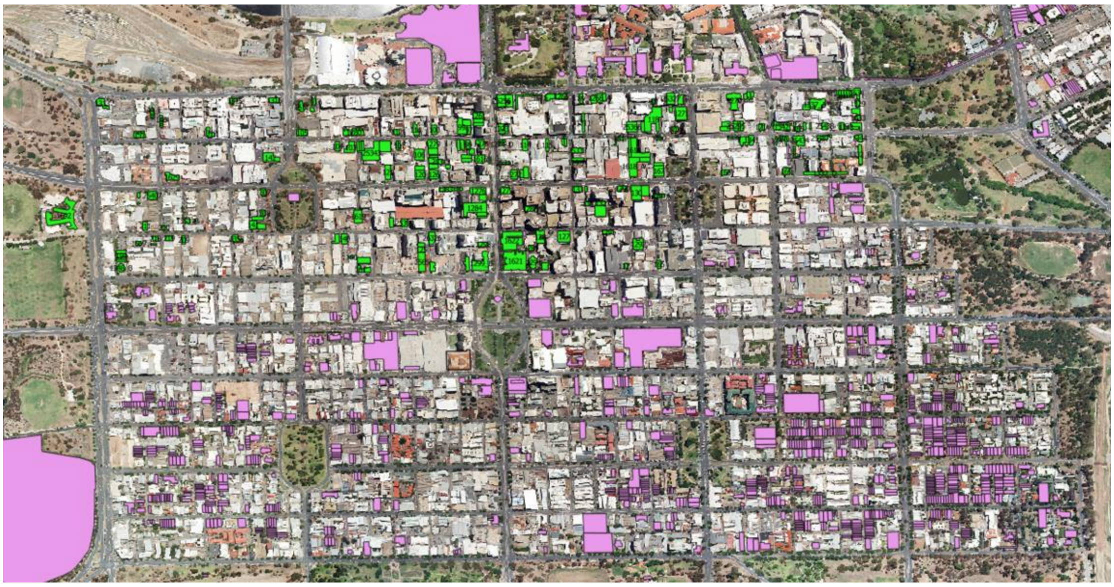


Figure 9: Survey of heritage-listed buildings across Adelaide CBD. Surveyed buildings shown in green.

(a) sandstone ashlar (b) limestone ashlar (c) bluestone rubble with brick quoins
Figure 10: Typical examples of stonework found in Adelaide.

FUTURE WORK

Having established that a large proportion of heritage buildings are built of stone, the upcoming phases of experimental and theoretical work to be undertaken at the Universities of Adelaide, Auckland and Newcastle are aimed with a specific focus on stone masonry.

To this end, the following work is being planned over the next 12 months:

- Cyclic in-plane shear tests on stone masonry panels. These tests will investigate the behaviour of walls built entirely with stone blocks as well as wall cross sections having a stone outer leaf and clay brick inner leaf. The latter has been found to be a relatively common form of construction even though its structural behaviour has received little to no previous research focus.
- Mechanical property tests on a range of common stone types, including small-size masonry specimens built in combination with typical historical mortar.
- Tests examining the efficiency of a range of retrofit options for strengthening stone masonry, including the use of fibre-reinforced polymer composites.
- Analysis of several notable case study buildings to determine their level of inherent seismic capacity before any retrofit, including Adelaide's St Peter's Cathedral which is pictured in Figure 11.

Figure 11. St Peter's Cathedral, Adelaide.

SUMMARY AND CLOSING REMARKS

In summary, a seismic risk case study of Adelaide's CBD has highlighted the significant risk posed by a moderate Mw 6.0 earthquake. Work is currently underway to quantify the financial savings possible through various seismic retrofit/strengthening options.

A recently completed study of four URM buildings suggests that various code provisions underestimate floor accelerations (i.e. height amplification factors) for buildings with rigid floors. The underestimation can be by more than 50% if elastic building response is considered. If some inelastic building response proportionate to the seismicity of Sydney or Melbourne is assumed, then the underestimation is reduced to about 48%. It was found that the peak floor accelerations in buildings with flexible diaphragms can be up to nearly 2 times greater than that in a building with rigid floors. Therefore, the code approaches need to be modified to address the need for accurate estimation of accelerations applied to non-structural URM components.

Finally, a comprehensive project is well underway to improve the seismic resilience of LDRC and URM buildings in Australia. Several case studies (York, WA and Melbourne's CBD) will be undertaken in conjunction with the CRC's end users to provide the evidence base needed for local governments and building authorities to justify any increases to the respective seismic design and/or retrofit requirements.

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