



**FINAL PROJECT REPORT**

[bnhcrc.com.au](http://bnhcrc.com.au)

# **COST-EFFECTIVE MITIGATION STRATEGY FOR BUILDING RELATED EARTHQUAKE RISK**

**Final project report**

**Prof Michael Griffith**

University of Adelaide & Bushfire and Natural Hazards CRC





Version	Release history	Date
1.0	Initial release of document	14/04/2021



Australian Government  
Department of Industry, Science,  
Energy and Resources

**AusIndustry**  
Cooperative Research  
Centres Program

© Bushfire and Natural Hazards CRC 2021

All material in this document, except as identified below, is licensed under the Creative Commons Attribution-Non-Commercial 4.0 International Licence.

Material not licensed under the Creative Commons licence:

- Department of Industry, Science, Energy and Resources logo
- Cooperative Research Centres Program logo
- Bushfire and Natural Hazards CRC logo
- Any other logos
- All photographs, graphics and figures

All content not licenced under the Creative Commons licence is all rights reserved. Permission must be sought from the copyright owner to use this material.



**Disclaimer:**

The University of Adelaide and the Bushfire and Natural Hazards CRC advise that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, the University of Adelaide and the Bushfire and Natural Hazards CRC (including its employees and consultants) exclude all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

**Publisher:**

Bushfire and Natural Hazards CRC

April 2021

Citation: Griffith M (2021) Cost-effective mitigation strategy development for building related earthquake risk - final project report, Bushfire and Natural Hazards CRC, Melbourne.

Cover: Damage to 2-storey URM retail buildings in the Christchurch September 2010 earthquake. Source: MC Griffith



## TABLE OF CONTENTS

<b>ACKNOWLEDGMENTS</b>	<b>4</b>
<b>ABSTRACT</b>	<b>5</b>
<b>END-USER PROJECT IMPACT STATEMENT</b>	<b>7</b>
<b>END-USER TESTIMONIALS</b>	<b>8</b>
<b>INTRODUCTION</b>	<b>9</b>
<b>BACKGROUND</b>	<b>11</b>
<b>RESEARCH APPROACH</b>	<b>12</b>
Unreinforced masonry (URM) buildings	14
Limited ductile reinforced concrete (LDRC) buildings	15
<b>FINDINGS</b>	<b>17</b>
Cost-benefit analysis of retrofit of URM buildings	17
Limited ductility reinforced concrete buildings	18
<b>KEY MILESTONES</b>	<b>40</b>
<b>UTILISATION AND IMPACT</b>	<b>43</b>
Summary	43
Earthquake mitigation case study for regional town of York, WA	43
York earthquake building mitigation implementation project	45
Earthquake mitigation case study for metropolitan city of Melbourne, VIC	48
Earthquake design requirements for concrete structures	48
Accelerograms database for earthquake assessment in regions of low to moderate seismicity	49
Rapid vulnerability assessment of limited ductile reinforced concrete buildings	49
<b>CONCLUSION</b>	<b>51</b>
Next steps	51
<b>PUBLICATIONS LIST</b>	<b>53</b>
Peer-reviewed journal articles	53
Conference papers	54
Conference posters	57
Book chapters	58
Technical reports	58
<b>TEAM MEMBERS</b>	<b>59</b>
Researchers	59
CRC funded post-doc researchers (1.2 FTE)	59
Students (1.0 FTE)	59
End-users	59
<b>PUBLICATIONS LIST</b>	<b>61</b>
<b>APPENDIX A – DETAILS OF COSTING</b>	<b>62</b>



## ACKNOWLEDGMENTS

On behalf of the entire research team, I would like to acknowledge the support of the following organisations and individuals without whose assistance this project would not have been successful.

- Our employers (Geoscience Australia and Swinburne, Melbourne and Adelaide Universities) for allowing their members of the project team to provide substantial in-kind support to the project which amounted to approximately 4 FTE of staff time in each year of the project.
- DFES, WA – in particular Jackson Parker and Stephen Gray for their assistance with the York Implementation project and NDRP extension project.
- York Shire Council and their CEO Paul Martin in particular for their enthusiastic support for and involvement with York as a case study and implementation of seismic retrofit demonstration projects for several Shire buildings.



## ABSTRACT

This final report contains a summary of the research undertaken by the research team from four partner institutions towards the development of an evidence base to inform decision making on the mitigation of the seismic risk posed by the most vulnerable Australian buildings subject to earthquakes. Without this evidence base, it is impossible to make cost-effective and economically justifiable decisions by building owners and government officials on all matters concerning seismic strengthening of existing and design of new buildings. While the focus of this project is on buildings, many of the project outputs will also be relevant for other Australian infrastructure such as bridges, roads and ports, while at the same time complementing other 'Natural Hazards' CRC project proposals for severe wind and flood.

In order to achieve the overall project aim, work was undertaken on three complementary fronts to:

- 1) Understand the seismic vulnerabilities of existing unreinforced masonry (URM) and limited ductile reinforced concrete (LDRC) buildings and methods to address them through seismic retrofit;
- 2) Risk assessment of the building stock through development of an economic loss model with trial evaluations for a regional town (York, WA) and a metropolitan area (Melbourne); and
- 3) Advance an end-user focused research utilisation project in the area of community risk reduction. This is done through an Earthquake Mitigation Case Study for the historic town of York in Western Australia.

The first of the above components was researched in the Universities of Adelaide, Melbourne, and Swinburne. This work included investigations of existing building seismic capacities and development of building specific retrofit techniques. The second area was studied by Geoscience Australia and the work includes estimating direct and indirect losses associated with building damage and benefits from seismic retrofit. The delivery date for the Melbourne CBD trial evaluation was delayed due to Covid-19 impacts but the revised delivery date of March 2021 has been agreed by the CRC. The last component was conducted utilising the research findings in the two other areas in collaboration with the Western Australia Department of Fire and Emergency Services, York Shire Council and its residents.

Finally, using the new damage loss models and costings for seismically retrofitting buildings, recommendations are made for the development of seismic retrofit guidelines and policy based on the strong evidence base being developed by this CRC project team.

As a consequence, the project has been extremely successful with several end-users implementing the research outputs. York Shire Council has embarked on seismic retrofit of up to three buildings in the Shire as demonstrations to other building owners of the cost-effectiveness as well as helping to develop the local expertise amongst the building profession to implement these simple seismic strengthening techniques. The project has also resulted in a follow-on project in Western Australia to expand the building typologies from York to include three



additional typologies that are common in the rest of WA. The retrofit strategies for all nine typologies will be made publically available through web sites.



## END-USER PROJECT IMPACT STATEMENT

**Damien Pumphrey, Department of Fire and Emergency Services, WA**

Over the course of six years, this project has helped to build an evidence base to inform the emergency management sector and communities on strategies to mitigate the risk posed by earthquakes to seismically vulnerable buildings. The research has not only assisted DFES in building a stronger baseline knowledge of the seismic hazard in WA, it has also enhanced the department's awareness of those building types that are at greatest risk of collapse, with particular reference to heritage listed buildings.

I would like to take this opportunity to note the Shire of York for its involvement in this project, as I believe they were key to the many positive outcomes. While focused on the Shire of York, we anticipate the project outputs will be applicable to heritage buildings more broadly across the State, as well as assist in providing an evidence base for understanding risk to other infrastructure such as bridges, and water and gas pipelines from a multi-hazard perspective.

The results of the project have also been a catalyst for further projects which are focused on developing mitigation options and understanding seismic risk on a broader scale. DFES will look forward to engaging with and learning from these projects going forward.

The outputs from this project will not only help DFES in better preparing communities and providing a proportional response to earthquakes, they also demonstrate what can be achieved through a collaborative approach.



## END-USER TESTIMONIALS

**Dense Smythe, President, Shire of York, WA**

The South West Seismic Zone, which includes the Wheatbelt Region, has the highest seismic hazard in Australia. Earthquake was identified in the 2018 National Seismic Hazard Assessment as having the highest risk in terms of consequences for the Wheatbelt District with the impact on heritage buildings identified as catastrophic.

Nowhere would this effect be felt more than in York, where the nineteenth-century 'time-capsule' appearance of the main street, Avon Terrace, is the main tourism drawcard. It is unique as it remains virtually intact and unchanged since the early twentieth century.

At Meckering, 35km from York, an earthquake of measuring 6.9 on the Richter Scale occurred on 14 October 1968, one of the most significant in Australia in terms of the widespread damage to property and subsequent cultural upheaval. On that fateful day, York lost the Royal Hotel, damaged beyond repair and still a blank space on Avon Terrace. Numerous verandahs were destroyed, including those of the Imperial Hotel, which had to wait twenty years before replicas were made. The earthquake was even felt in Perth.

York is WA's oldest inland town and intangible benefits relate to the preservation of the significant value the building stock has to the community itself, the state and the nation due to its heritage value. York's heritage building stock is exceptional for a small country town and arguably second only to Fremantle in WA in the age, quantity and quality of its built heritage. There are 3 Heritage Precincts, 294 Heritage Places on the Shire of York's Heritage List [previously known as a Municipal Inventory] with 32 of these being classified as Grade A and on the State Heritage Register, with the York Town Hall being noted as nationally significant.

The research from Geoscience Australia and the University of Adelaide in this Bushfire and Natural Hazards CRC (BNHCRC) earthquake mitigation study on six York building types is of immense benefit to the town. The results will not only be useful for York, they will enable the refinement and adaptation of the retrofit information for wider application to similar buildings elsewhere in the State and nation.

It is a great example of what is possible when organisations work together for shared goals; to preserve life in natural disasters and preserve Australia's built heritage and the economies that depend on it.



## INTRODUCTION

This project arose out of the on-going research efforts by the group involving structural engineering academics at the Universities of Adelaide, Melbourne and Swinburne along with Geoscience Australia experts all working towards seismic risk reduction in Australia. Most of the research team are also actively involved in the revision to the Australian Earthquake Loads standard (AS1170.4) as well as being members of the Australian Earthquake Engineering Society which is a Technical Society of Engineers Australia. The devastating impact of the 2010 – 11 Christchurch earthquake sequence on the New Zealand economy (roughly 20% of NZ GDP) and society has further motivated this group to contribute to this CRC's aim of risk reduction through improved building resilience for all natural hazards in Australia.

This project specifically addresses the need for an evidence base to inform decision making on the mitigation of the risk posed by earthquakes on the most seismically vulnerable of Australian buildings – i.e. unreinforced masonry (URM) and limited ductile reinforced concrete (LDRC). While the focus of this project is on buildings, many of the project outputs will also be relevant for other Australian infrastructure such as bridges, roads and ports, while at the same time complementing other 'Natural Hazards' CRC project proposals for severe wind and flood.

Earthquake hazard has only been recognised in the design of Australian buildings since 1995. This failure has resulted in the presence of many buildings that represent a high risk to property, life and economic activity. These buildings also contribute to most of the post-disaster emergency management logistics and community recovery needs following major earthquakes. This vulnerability was in evidence in the 1954 Adelaide earthquake, the 1968 Meckering earthquake, the 1989 Newcastle earthquake of 1989, the 2010 Kalgoorlie/Boulder earthquake and with similar building types in New Zealand during the 2009-10 Christchurch earthquake sequence. With an overall building replacement rate of 2% nationally the legacy of vulnerable building persists in all cities and predominates in most business districts of lower growth regional centers.

The two most vulnerable building types that contribute disproportionately to community risk are unreinforced masonry (URM) buildings and limited ductility reinforced concrete (LDRC) structures. The damage to these will not only lead to direct repair costs but also to injuries, including fatalities and significant disruption to economic activity.

The following sections of this report include:

- Background – giving the context of seismic resistance design in Australia and Australia's earthquake hazard from a global perspective; scale.
- Research Approach – describes the methodology used to quantify the seismic resistance of existing URM and LDRC buildings and the population of such buildings and their exposure to the earthquake hazard;
- Findings of the research are presented next followed by a short description of the timeline for delivery of each of the key project milestones;.
- Utilisation and Impact of the research outputs; and.



- The report ends with a description of the project's Conclusions and recommendations for 'next steps'.



## BACKGROUND

Australia is a continent/country which has a relatively low level of seismic activity on a global scale. However, owing to the fact that the majority of buildings built before 1995 had no specific considerations for earthquake resistant design as well as being concentrated in a number of large metropolitan cities means that the economic impact of damage caused by a relatively small earthquake (say M6) occurring in close proximity of one of Australia's capital cities would be enormous. For example, the world reinsurance industry rates a moderate earthquake occurring near Sydney as one of the world's top-10 financial risks. The large percentage of unreinforced masonry (URM) and limited ductility reinforced concrete (LDRC) buildings in every one of Australia's capital cities is a major reason for this somewhat surprising conclusion.

For these reasons, the 'earthquake building resilience project' team has focused its attention on providing the evidence and developing the tools necessary for engineers and building officials to accurately assess the seismic resilience of their existing building stock, identify the most 'seismically at-risk' buildings, and determine the most cost-effective seismic strengthening strategies for each building type.



## RESEARCH APPROACH

As stated earlier, the aim of this project was to provide an evidence base to inform decision making on the mitigation of the seismic risk posed by the most vulnerable Australian buildings subject to earthquakes. Without this evidence base, it is impossible to make cost-effective and economically justifiable decisions by building owners and government officials on all matters concerning seismic strengthening of existing and design of new buildings. The scope of the project was confined to two most seismically vulnerable building types – unreinforced masonry (URM) and limited ductile reinforced concrete (LDRC) buildings. These building types were studied using numerical models which were first validated for accuracy using experimental data and damage statistics from previous earthquakes. In order to carry out the research the project was broken into a number of sequential sub-tasks aimed at providing:

- (i) a basis for understanding the current state of Australia's building stock with regard to earthquake loads and the state of the art in seismic retrofit options;
- (ii) developing risk and economic loss models, together with developing new retrofit options targeted at Australian environments;
- (iii) bringing these components together into a comprehensive Cost-Benefit Analysis of retrofit options; and
- (iv) communication of the findings through case studies, a national retrofit assessment program, and knowledge to be exploited in an "all natural hazards" decision support system.

This approach is shown schematically in Figure 1. Additional details for each task in Figure 1 are given below.

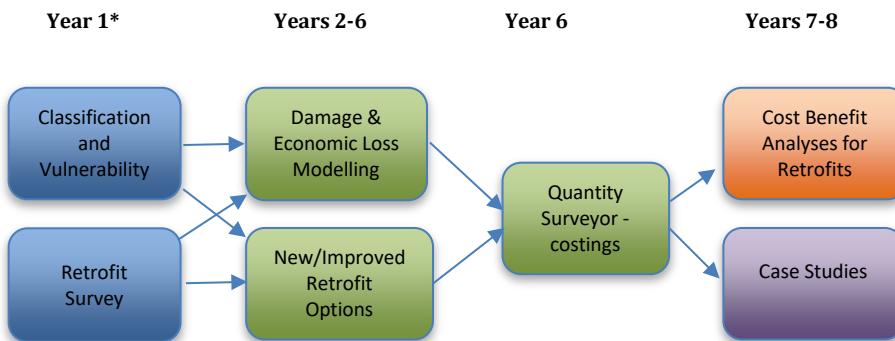


FIGURE 1. OVERVIEW OF THE RESEARCH PROGRAM APPROACH

\*Note – Years 1 and 8 are half-years only.

### Year 1: (Jan – June 2014)

Classification and Vulnerability – this involved classification of the most common construction types in Australia/NZ with respect to seismic vulnerability. Age of construction also taken into account.



Retrofit Survey – The current state of the art for seismic retrofit/strengthening of existing buildings was established with a view to its availability in Australia/NZ and any obvious gaps in capability were identified.

Plan experimental retrofit research – a research plan was developed to fill gaps identified in the Retrofit Survey work.

#### **Years 2-4: (July 2014 – Dec 2016)**

Damage Loss Modelling – This involved development of damage versus drift curves (i.e., fragility curves) for each construction type. Loss modelling was extended to include factors beyond just building repair/replacement costs such as casualties, loss of life, business interruption costs, other socio-economic impacts and costs. Fragility curves were also developed for several of the seismic retrofit techniques that were in place in Christchurch before the 2010/11 earthquakes. These provide the first picture of damage reduction that is possible through seismic retrofit applications.

#### **Years 2-6: (July 2014 – June 2018)**

New retrofit options – this involved work to develop specialised seismic retrofit techniques for the most vulnerable and widely used construction types identified in Year 1. This will involve some laboratory based testing to establish engineering properties needed for computer-based modelling of the various building types in 'as-is' and 'seismically strengthened' conditions.

#### **Years 4-6: (Jan 2017 – June 2019)**

Economic Loss Modelling – this involved extension of loss modelling to include factors beyond just building repair/replacement costs such as loss of life, business interruption costs, other socio-economic impacts and costs. Incorporate expanded economic loss modelling approach into: (1) format for use by Decision Support Research group; and (2) a seismic risk forecasting model that will allow government to better understand the seismic risk for their community.

#### **Years 7-8: (July 2019 – December 2020)**

Cost-benefit analysis for retrofit – in conjunction with accurate costing for the various retrofit techniques and economic loss modelling that includes the full socio-economic costs, an improved picture of the benefits for each retrofit technique will be incorporated into cost-benefit analysis models for use by the Decision Support Research group.

Case studies – York, WA and Melbourne, VIC were used as case studies representative of a regional town and a large metropolitan city using the new economic loss models. (As noted earlier, the Melbourne case study delivery date was revised to be the end of March 2021 and agreed to with the CRC management.) The new models were used to produce estimates of the economic losses that could be expected in Australian cities if no seismic retrofit work is undertaken and compared to the reduced losses for various levels of seismic strengthening and various earthquake intensities.

It is widely understood around the world that unreinforced masonry and low ductility reinforced concrete constructed buildings are the most vulnerable forms



of construction to earthquake induced vibrations. This is reflected in the Australian Earthquake Loading Code, AS 1170.4, which has the two smallest earthquake force reduction factors for URM and LDRC buildings. As these two building types comprise a significant portion of our building stock, this project has focused on them. The general approach to our research for them is described below.

## UNREINFORCED MASONRY (URM) BUILDINGS

The research approach for URM buildings was staged with two streams running in parallel.

As suggested by Figure 1, one stream focused on the existing URM building stock by first classifying URM structures into six representative **typologies** (refer Figure 2) and identifying the seismic **vulnerabilities** common to each typology. The vulnerabilities were represented by '**fragility curves**' (one curve for each of 5 damage ratios) which plotted the probability of exceedance versus earthquake peak ground acceleration (or velocity). A fragility curve was produced for each building vulnerability for the five damage ratios D1- D5 (being slight, moderate, extensive, near-collapse and complete collapse, respectively). The failure modes studied were the most vulnerable being out-of-plane collapse of parapets, chimneys, upper storey walls and gable end walls. The full range of fragility curves were reported previously to the CRC in Derakhshan and Griffith (quarterly report 2018). An example of a fragility curve for a 1m tall parapet on top of a 2-storey building is shown in Figure 3 where it can be seen that it predicts 50% probability that a small 0.067g PGA would occur which would cause extensive damage to a parapet with significant life safety risk. The damage expected for a range of different earthquake intensities and the economic losses for each earthquake scenario were calculated such that a quantity surveyor could cost the damage for use in cost-benefit analyses in the final stage.

(a) House	(b) Pub	(c) 1-storey row
(d) 2-storey row	(e) 2-storey institutional	(f) 2-storey free-standing

FIGURE 2. URM BUILDING TYPOLOGIES (YORK EXAMPLES)

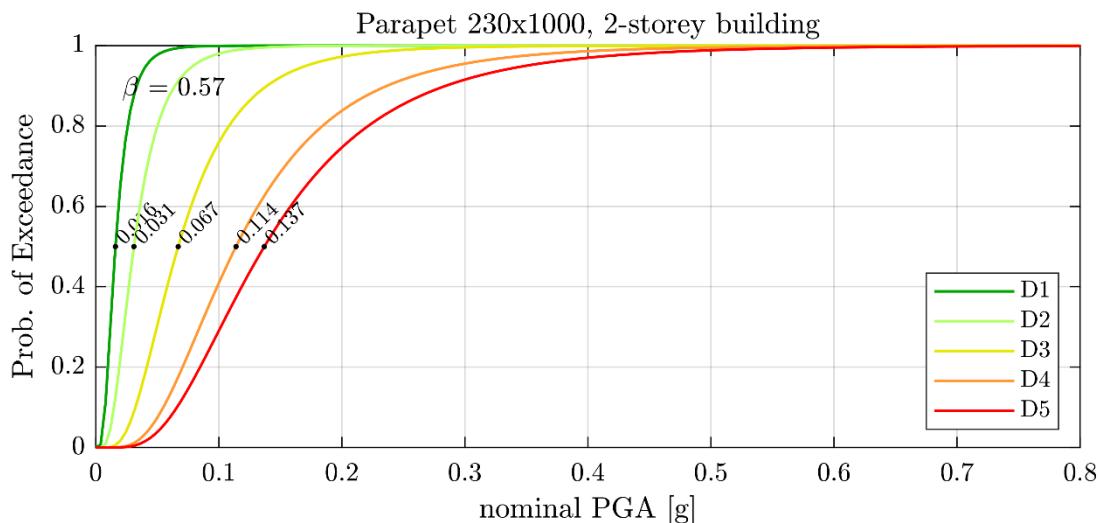


FIGURE 3. FRAGILITY CURVES FOR 1M TALL, 230MM THICK PARAPET

In the other parallel stream, seismic retrofit techniques for URM buildings were documented and where existing techniques were unsuited to Australian conditions, modified and/or new techniques were developed. The techniques appropriate for Australian URM buildings were then costed for use in the economic loss models and cost-benefit analyses for two case studies. The first case study was for a regional town, in this case the project team used York, WA. The second case study was for a major urban centre, in this case the project team used the Melbourne CBD.

## LIMITED DUCTILE REINFORCED CONCRETE (LDRC) BUILDINGS

The research program for limited ductile reinforced concrete (LDRC) buildings follow the general approach described above. This section summarises the approach adopted on the vulnerability assessment of the buildings and the evaluation of the retrofitted options.

A numerical approach has been adopted in the vulnerability assessment of limited ductile reinforced concrete buildings. Archetypal building models were used to represent two building types: i) reinforced concrete buildings that are mainly laterally supported by reinforced concrete walls; ii) reinforced concrete buildings are supported by reinforced concrete walls and frames. The buildings were selected to represent older RC buildings constructed in Australia prior to the requirement for seismic load and design to be mandated on a national basis. Standard guidelines and procedures (AS 3600:1988, AS 1170.2:1983, Building Code of Australia), and guidance from experienced practicing structural engineers were sought in the design of the archetypal buildings.

Finite element models were created for the archetypal buildings. To ensure that the models are able to represent the behaviour of limited ductile reinforced concrete elements, the results of the modelling were compared with results of experimental programs conducted by the project team and in published literature. Non-linear analyses used are the capacity spectrum method and non-linear time history analyses. A combination of multiple stripe analysis and cloud analyses were adopted in the construction of fragility curves.



Selection of ground motion excitations that are representative of Australian conditions was an important step in the vulnerability assessments. In this project, the approach adopted was to first collate bedrock excitations from a combination of historical records with characteristics that are representative of Australian earthquakes and stochastically generated records. Site analyses were then conducted to generate ground motion excitations on soil using the bedrock excitations and borehole records as input. The non-linear analyses of the buildings were conducted using the more onerous ground excitations on soil.



## FINDINGS

### COST-BENEFIT ANALYSIS OF RETROFIT OF URM BUILDINGS

It is of interest to note that this project team has incorporated direct and indirect costs into the Benefit-Cost Ratio (BCR) calculations used to determine the economic viability of seismic retrofit for existing buildings. The indirect also has included intangible values that, while significant, are challenging to quantify. For the York case study the cost of injury and loss of life to Society was included as a broader avoided cost. For the Melbourne case study the additional cost associated with lost building heritage value was further included. This involved a collaboration with the University of Western Australia BNHCRC research group in order to incorporate these intangibles as costs.

Normal BCR calculations for individual building projects only consider the benefits and costs directly related to the individual buildings, such as damage reduction and associated costs to repair. However, earthquake events that generate moderate or greater levels of ground shaking impact on every building structure within the epicentral region. Hence, it is possible for an entire central business district to be shut down for several weeks or longer due to damage to less than 25% of the buildings in the vicinity because of life safety issues due to falling hazards from the damaged (less seismically resilient) buildings. This was the situation in Christchurch after the 2010 September earthquake where no businesses could operate for many weeks due to damage to less than 20% of the buildings (almost all of which were URM construction). Furthermore, the community damage can be a loss in other ways through the loss of heritage structures and possible broader economic consequences through lost tourism. Hence, the work with the UWA team has brought into our calculations intangible costs associated with the value communities place on 'heritage buildings' in addition to other metrics such as business interruption costs, injuries and fatalities. Geoscience Australia has worked with the UWA researchers in refining their survey method based on the outcomes of the York case study to capture the level of willingness to pay to avoid loss of heritage, community disruption caused by loss of utilities, and the emotional stress associated with severe earthquake damage. The heritage value metrics developed have been subsequently applied to Melbourne in the study of the city's CBD precinct.

To date, even with the inclusion of cost of health care and the value of human life, we have not been able to generate BCR values above 1 to justify seismic retrofit even though a 2019 report by the National Institute of Building Sciences in the USA entitled "Natural Hazard Mitigation Saves" reports BCR values well in excess of 1 for much of western and central eastern USA where the seismicity is comparable to Australia's. Having noted that, the inclusion of these measures for York markedly increased the B/C ratios associated with economic loss from a maximum of 0.37 to a value of 0.88, highlighting the significance of these measures in more holistic decision making. Indeed, in 2018 the NZ government amended "The Building Act 2004" to specifically require all URM parapets (i.e. falling hazards) to be seismically restrained, or removed, within 12 months due to the life-safety hazard that they pose. The estimates of costs to strengthen parapets have been less than \$20,000 whereas the economic cost of one fatality



is estimated as \$4.3 million. The work on this project, which incorporates the UWA research outcomes, will be included in the Final Report on Case Study of Melbourne CBD Precinct (deliverable (3.2.1) ) which, as noted in the Introduction, will be delivered in March 2021.

## LIMITED DUCTILITY REINFORCED CONCRETE BUILDINGS

### Prioritisation strategy for seismic retrofitting of reinforced concrete buildings

An assessment involving a three-tiered approach for retrofitting methodology has been developed to evaluate the potential vulnerability of Australian RC buildings. The approach includes three levels of scan check. The first level of scan check involves a visual appraisal of buildings and can be conducted without any calculations. The level 2 scan check involves a simple computation to estimate seismic demands for comparison with buildings' capacity. The level 3 involves more rigorous seismic analyses. The purpose of a tiered approach is such that if a building passes level one, the building can be deemed safe, and it does not need to go through level 2 or level 3. Only a building that has not met level 1 and 2 checks need to go through the level 3 check.

The methodology is intended to provide guidance to relevant decision-makers on how a rapid assessment is to be conducted without detailed information about the buildings. The project focuses on assessing the vulnerability of RC buildings without adequate bracing and featuring non-ductile detailing; both are vulnerable features included in the section. However, it is outside the scope of the study to investigate and develop retrofitting measure for each vulnerable feature.

#### Level 1 scan check

Level 1 scan check is subdivided into two levels of scan checks, which are level 1.1 and 1.2 scan checks. Level 1.1 scan check is based on the overall height and characteristics of the building, which can be determined by inspection of the site or the design drawings if they are available. Likewise, it only involves a simple evaluation of the site and building, which does not contain any analytical or computation works. The acceptance criteria in level 1.1 scan check are listed in Table 1. Level 1.1 scan involves checking if the building has adequate lateral load resisting elements, and the building features any one of category A vulnerable features presented in Table 2. A building can be deemed safe if the building has adequate lateral load resisting elements that do not contain any feature of category A. Further checks are not required.

When the assessment does not satisfy the acceptance criteria of level 1.1 scan check, level 1.2 scan check will be applied. Level 1.2 scan check involves identifying if there are any vulnerable features of category A in Table 1 and more than one vulnerable features of category B in Table 2. If the building did not contain any vulnerable features of category A and not more than one vulnerable feature of category B in Tables 1 and 2, it can be deemed to pass level 1.2 scan check. Otherwise, the level 2 scan check is needed.



Item	Building height range	Acceptance criteria
1	Building height up to 8m	The building is not containing any features belonging to category A.
2	Building height more than 8m	Buildings have adequate lateral bracings and does not have any vulnerable features which are classified into category A. Adequately braced buildings can include the following buildings. For example, a braced building with external structural walls from the foundation to the roof of the building is symmetrically designed on the floor plan. A symmetric building plan with a minimum of two major core walls of the same dimensions and a clear distance between two major core walls to be approximately equal to the width of the building can be classified as adequately braced building.

TABLE 1. ACCEPTANCE CRITERIA IN LEVEL 1.1 SCAN CHECK

## Category A

Item	Vulnerable feature	Description	Category
1	Improperly braced building frame including frame with soft or weak-storey	An unstable building which does not contain structural walls to significantly contribute the building stability.	A
2	Fragile structural wall	The thickness of a structural wall is less than 150mm, which is generally consisting of only a single layer of longitudinal rebar located in the middle of the wall.	A
3	Unsecured or unfilled support floor	Lack of connection due to the improperly sealed gap between adjacent structural elements or limited seating width for supporting floor on adjoining structural wall or column.	A
4	Inadequate separation between buildings	The clear distance of setback from the boundary of the adjacent buildings that are more than 15m in height is less than 1% of the height of the taller building.	A
5	Lack of structural load path	The structure does not contain a complete, well-defined load path, which includes structural elements and connections that transfer the inertia forces associated with the foundation.	A
6	Geohazards including liquefaction issue, slope failure, and surface fault rupture	Liquefaction induced by an earthquake will happen when susceptible, saturated, loose, granular soil under the building is within the foundation soil at a depth of 15m. It could reduce the seismic performance of buildings. The building is not located sufficiently away to avoid potential earthquake-induced slope	A



		failure and rockfalls. Surface fault rupture is expected or anticipated at the building site.	
7	Hollow-core floors	Precast floor with hollow-core floors and top9ing on the top	A

### Category B

Item	Vulnerable feature	Description	Category
1	High axial load on columns	High axial load on the column represents a high compression index in any column $\geq 0.3$ , high strength concrete columns with concrete compressive strength ( $f_c'$ ) $\geq 50\text{MPa}$ .	B
2	Undersized column	Undersized columns with an aspect ratio of more than 15 or dimensions less than 400mm.	B
3	Columns are prone to shear failure due to the low aspect ratio, use of brick infill, captive or short column effect	A column with an aspect ratio of less than four is considered shear critical. Brick infill walls built around the adjoining RC columns can result in shear failure of the columns. There are columns at a story with a height/depth ratio is less than 50% of the normal height/depth ratio of the typical columns at the story of the building	B
4	Non-ductile detailing	It includes features with non-ductile reinforcement and reinforcement content below the minimum reinforcement requirement (minimum longitudinal ratio 0.01 for columns and 0.0025 for walls, minimum transverse reinforcement ratio 0.0009 for columns and 0.0025 for walls) and lack of continuity/anchorage between the beam-column connection or slab or foundation. Strong beams and weak columns are also classified as non-ductile detailing.	B
5	Vertical irregularities	Vertical irregularities include discontinuities in the lateral load resisting systems or gravity load transferring path such as the application of transfer beam, and abrupt changes in stiffness, strength and mass between adjacent stories.	B
6	Onerous site subsoil conditions	Onerous subsoil condition with the maximum depth of soil above bedrock more than 40 m. The site with this kind of feature will be classified as class D and E site, according to AS1170.4-2007.	B
7	Horizontal irregularities	A structural plan features asymmetry due to asymmetrical locations of structural elements such as structural walls or core walls within the	B



		floor plan and irregularities in mass distribution and floor shape.	
8	Mezzanine structure	There is an inadequate load path to transfer forces from the mezzanine to the main lateral load resisting system.	B
9	Deterioration of structural materials	There are clear signs of degradation of structural materials such as scaling, disintegration, erosion of reinforcement, delamination, spalling and cracking of the concrete	B
10	Inadequate wall anchorage and foundation dowels for the RC wall	Exterior concrete walls, which are relying on the diaphragm to provide the lateral support, are not anchored for out-of-plane forces at each diaphragm level with steel anchors, reinforcing dowels, or straps that are developed into the diaphragm. Wall reinforcement is not dowelled into the foundation with vertical bars that are at least equal in size and spacing to the vertical wall reinforcement above the foundation.	B
11	Topping slab	A continuous reinforced concrete topping slab with thickness less than 65mm when it is connected to the precast concrete diaphragm and less than 75 mm when it is not connected to the precast concrete diaphragm.	B

TABLE 2. CLASSIFICATION OF VULNERABLE FEATURES RC BUILDINGS

## Level 2 scan check

Level 2 scan check is performed to assess the torsional stiffness parameter and estimate drift demand of the building caused by an earthquake. The process involves linear elastic analyses such as dynamic analyses or equivalent static analyses. The drift demand obtained for critical structural elements will be compared with the drift capacity to decide if retrofitting is required. The Generalised Force Method (GFM) developed in recent years by the project team (Lumantarna et al., 2018; Khatiwada et al., 2020) can be used to replace the complex three-dimensional analyses.

One of the purposes of seismic retrofitting is to increase the torsional stiffness parameter of asymmetrical RC buildings. The torsional stiffness parameter is defined by the parameter ( $b_r$ ), which is the torsional stiffness divided by the radius of gyration ( $r$ ) of the building plan.

Parametric studies undertaken by the project team (Lam et al., 2016; Lumantarna et al., 2018, Lumantarna et al., 2019) reveal that buildings with  $b_r$  value less than 1.0 results in a high amplification of displacement demand of the building. A building can be deemed to have the  $b_r$  value to be greater than 1.0 if the core and shear wall systems are spread well away from the center of rigidity of the building, meeting one of the following criteria (Xing et al., 2019):

- More than four or more core/shear wall systems

A building with four or more shear wall systems can be deemed to have a  $b_r$  value greater than 1.0.



- Three core/shear wall systems

If a building has three core/ shear wall systems, a separation distance between the external two core/shear wall systems should be approximately equal to the building width. If two cores are located close to each other, the three core/shear wall systems can be classified as two core/shear wall systems.

- Two core/shear wall systems

If a building has two core/shear wall systems, a separation distance between the two core/shear wall systems should be larger than  $2r$  ( $r$  is the mass radius of gyration).

Otherwise, the value of  $b_r$  of the building can be determined by the following approach (Kathiwada et al., 2020).

If  $b_r$  is less than 1, the RC building can be classified to have low torsional stiffness and should be retrofitted. If  $b_r$  is equal or larger than 1, the maximum displacement on the critical elements can be calculated using linear dynamic analyses. Seismic retrofit is needed when the drift demand on the critical column exceeds the drift capacity. The drift capacity for a column can be calculated by applying the project team's recommendation based on empirical data from published literature (Raza et al., 2018).

If the drift demand on the critical structural element did not exceed the element's drift capacity, the building could pass the level 2 scan check and be deemed safe. RC building that does not pass the level 2 scan check can be deemed unsafe. Consequently, retrofitting is recommended for the building. Alternatively, a level 3 scan check can be performed.

The archetypal buildings for vulnerability assessment and the implementation of retrofitting strategy were selected based on some of the vulnerable features presented in this section. Hence, they have not passed levels 1 and 2 scan checks.

### Level 3 scan check

Level 3 scan check is a more rigorous analysis based on non-linear behaviour of RC buildings to check the conservative results from the level 2 scan check if it is necessary. Level 3 scan check involves non-linear time-history analyses or capacity spectrum analyses.

The focus of the Level 3 scan check has been put on the non-linear behaviour and failure risk of concrete columns. This is because the most common causes of failure of RC building, as discussed previously, are improperly braced building frame including frame with soft or weak-storey, high axial load on columns, undersized column, non-ductile detailing and columns that are prone to shear failure due to the low aspect ratio, use of brick infill, captive or short column effect. The failure of even just a single column can lead to progressive failure of the whole building due to the lack of structural load path.

However, the understanding of the post-peak non-linear behaviour of RC columns is limited to those made of normal-strength concrete, whereas high-strength concrete has become more and more common in recent decades. Hence, the project team decided to conduct an experimental program on high-



strength limited ductile RC columns in order to fill in this knowledge gap. Also, the non-linear behaviours of RC columns under realistic bi-directional earthquake actions and variation of axial loads have been investigated. The models developed from the test data have been incorporated as an important tool in the Level 3 scan check.

### Non-linear behaviour models of RC columns via an experimental program

A comprehensive experimental testing program comprising of 14 column specimens, representative of typical Australian construction practice, was conducted to evaluate the collapse performance of limited ductile HSRC columns during earthquakes. All the column specimens have a cross-section of 250 mm × 300 mm × 2550 mm. Two concrete grades are considered in this study 65 MPa and 100 MPa. The specimens are tested under three axial load ratios, 0.15, 0.3 and 0.45. All the specimens are designed with the same longitudinal ratio of 1.6 % with 6N16 bars. In order to investigate the influence of transverse reinforcement ratio on the drift performance of the HSRC column, the testing program considers three different transverse reinforcement ratios i.e. code compliant, under reinforced and over reinforced. Figure 4 presents the detailing of the code compliant RC column tested in this study.

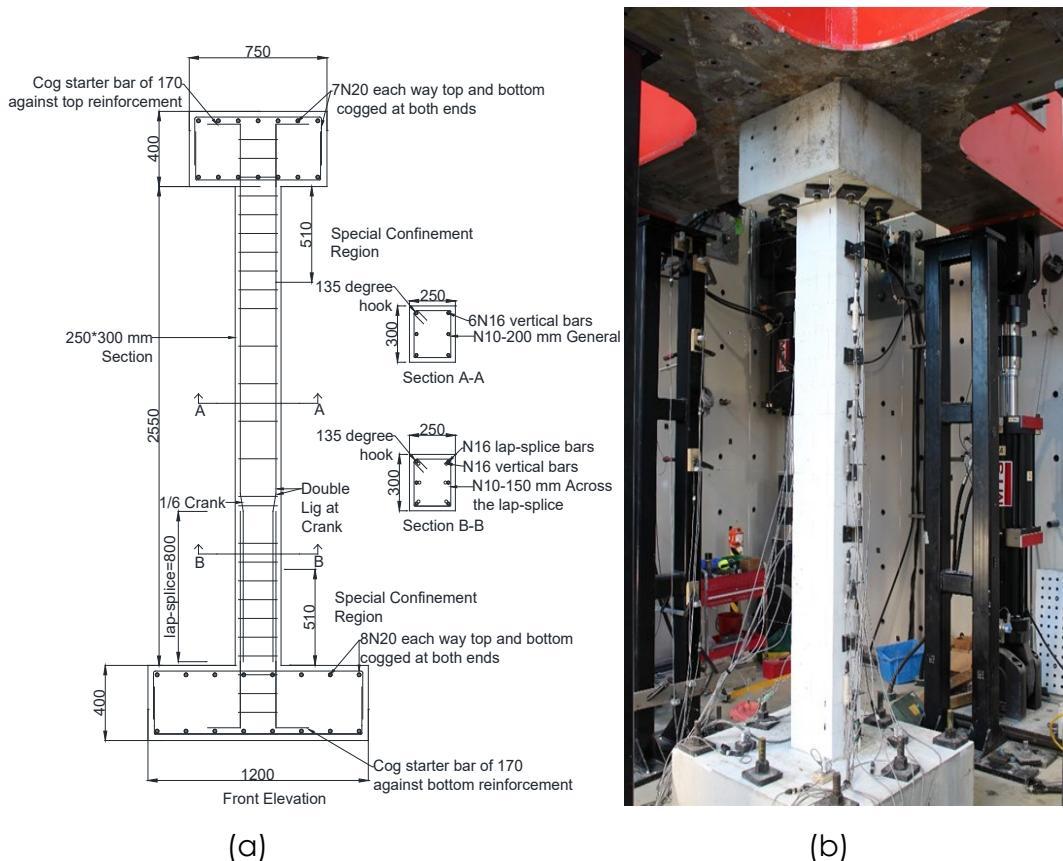


FIGURE 4. (A) DETAILS OF RC COLUMN SPECIMEN (DIMENSIONS IN MM), (B) SPECIMEN UNDER THE ADVANCED MULTI-AXIS SUBSTRUCTURE TESTING (MAST) SYSTEM IN THE SMART STRUCTURES LABORATORY AT SWINBURNE UNIVERSITY OF TECHNOLOGY, MELBOURNE, AUSTRALIA

The tests are conducted under the advanced Multi-Axis Substructure Testing (MAST) system in the smart structures laboratory at Swinburne University of Technology. The MAST system has a maximum vertical load capacity of  $\pm 4$  MN with four vertical actuators, each having a capacity of  $\pm 1$  MN. Similarly, the MAST



system is also equipped with two pairs of  $\pm 0.5$  MN horizontal actuators in each of the orthogonal directions for applying lateral loading in the horizontal directions.

Another variable factor in this experimental program is the direction of loading. HSRC columns have not been tested under bi-directional cyclic loading so far and therefore this project makes an attempt to compare collapse drift performance of HSRC columns under uni-directional and bi-directional cyclic loading. Hence, seven specimens are tested under uni-directional cyclic loading while the remaining seven are tested under two different bi-directional cyclic loading protocols.

The specimens were subjected to loading protocols, representative of actual earthquake loading on columns, that were developed by rigorous numerical analysis. To this end, a case study building was subjected to ground motions that were scaled to design basis earthquake and maximum considered earthquake response spectrum levels of Australian Earthquake Standard. The typical patterns of bidirectional displacement path of the building columns under ground motion excitations were studied. A detailed statistical analysis of the bidirectional drift response history of the column was subsequently conducted, which led to the development of generalised bidirectional loading protocols, namely, Octo-Elliptical path, that can be used in quasi-static testing of RC columns.

Furthermore, an extended numerical study was conducted on a case study RC frame-wall building, representative of typical mid-rise RC structures constructed in Australia, to investigate the typical patterns and ranges of axial load variation that would be experienced by RC columns in Australian infrastructure during an earthquake. The underlying mechanism and the controlling parameters affecting axial load variation were studied in detail. Subsequently, a generalised expression was proposed for estimating axial load variation in RC columns in low to moderate seismic regions. Consequently, two axial load variation protocols namely, synchronous axial load variation and nonsynchronous axial load variation were also developed.

The proposed bidirectional and axial load variation protocols have been applied in tandem to investigate the capacity of the RC columns under varying triaxial loading in quasi-static testing conditions using the MAST system in the Smart Structures Laboratory at Swinburne University of Technology.

The model, therefore, could be used by structural design engineers in Australia to reliably predict the non-linear response of RC columns. The results of the experimental testing have been presented in a couple of conference and journal papers (Raza et al. 2018; Raza et al. 2019a; Raza et al., 2020a-d).

### Fragility curves for limited ductile reinforced concrete buildings

Studies have been undertaken by the project team to develop fragility curves for limited ductile reinforced concrete (RC) buildings typical of Australian constructions: i) fragility curves for RC buildings that are primarily supported by limited ductile RC shear walls (referred to **RC shear walled buildings** herein); ii) fragility curves for RC buildings that are supported by limited ductile RC walls and frames (referred to **RC framed buildings** herein). Archetypal buildings have been selected to represent low-, medium-, and high-rise buildings. The buildings are representative of older RC buildings constructed in Australia prior to the

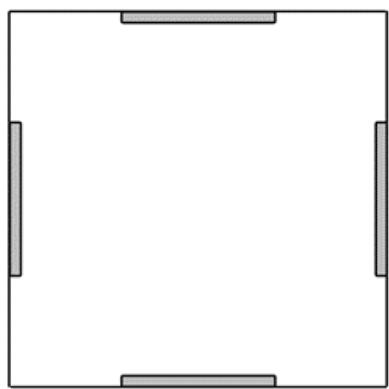


requirement for seismic load and design to be mandated on a national basis. Both building types will have more than two vulnerable features A and/or B as described in Table 2.

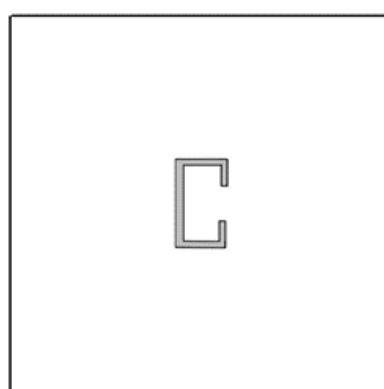
## Description of the buildings

### RC shear walled buildings

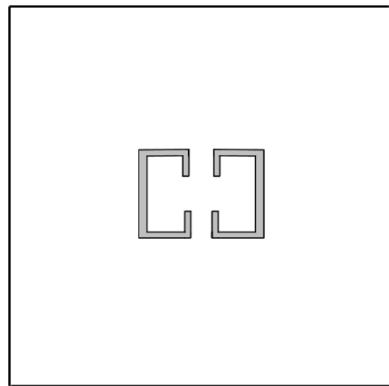
Four idealised reinforced concrete shear walled buildings, laterally supported by rectangular and/or RC walls, were used in the assessment. The four configurations considered are presented in Figure 5. The height of the buildings varies from 2-storey to 12-storey high. The type of RC shear wall configuration was selected for each building depending on the capability of the walls in resisting earthquake and wind load in accordance with Australian Standard (AS1170.4-2007; AS1170.2:2011). Full details are available in Hoult et al., (2018).



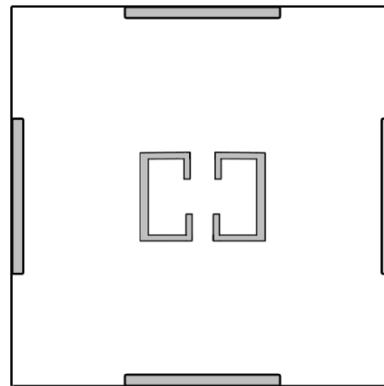
(a) Type 1



(b) Type 2



(c) Type 3



(d) Type 4

FIGURE 5. IDEALISED RC SHEAR WALLED BUILDINGS

### RC framed buildings

Three reinforced concrete buildings were assessed which are 2-storey, 5-storey and 9-storey high, representing low-, medium- and high-rise buildings. The buildings have been designed in accordance with AS 3600:1988 Concrete Structures Standard, AS 1170.2:1983 Wind Actions Standard, and guidance from experienced practicing structural engineers. The frames were designed as ordinary moment resisting frames (OMRFs). The core walls have low longitudinal



reinforcement ratio (approximately 0.23 %) with no confinement. The building plans are provided in Figure 6. The gravity load resisting system of the buildings constructed in the 1980s typically included perimeter frames with deep beams (600-900 mm deep) to satisfy fire design requirements, and band-beams or flat-slab floor systems with column spacing of 7.0 to 8.4 m. Hence for the buildings the typical column spacing of 8.4 m was adopted with perimeter beam depth of 650 mm.

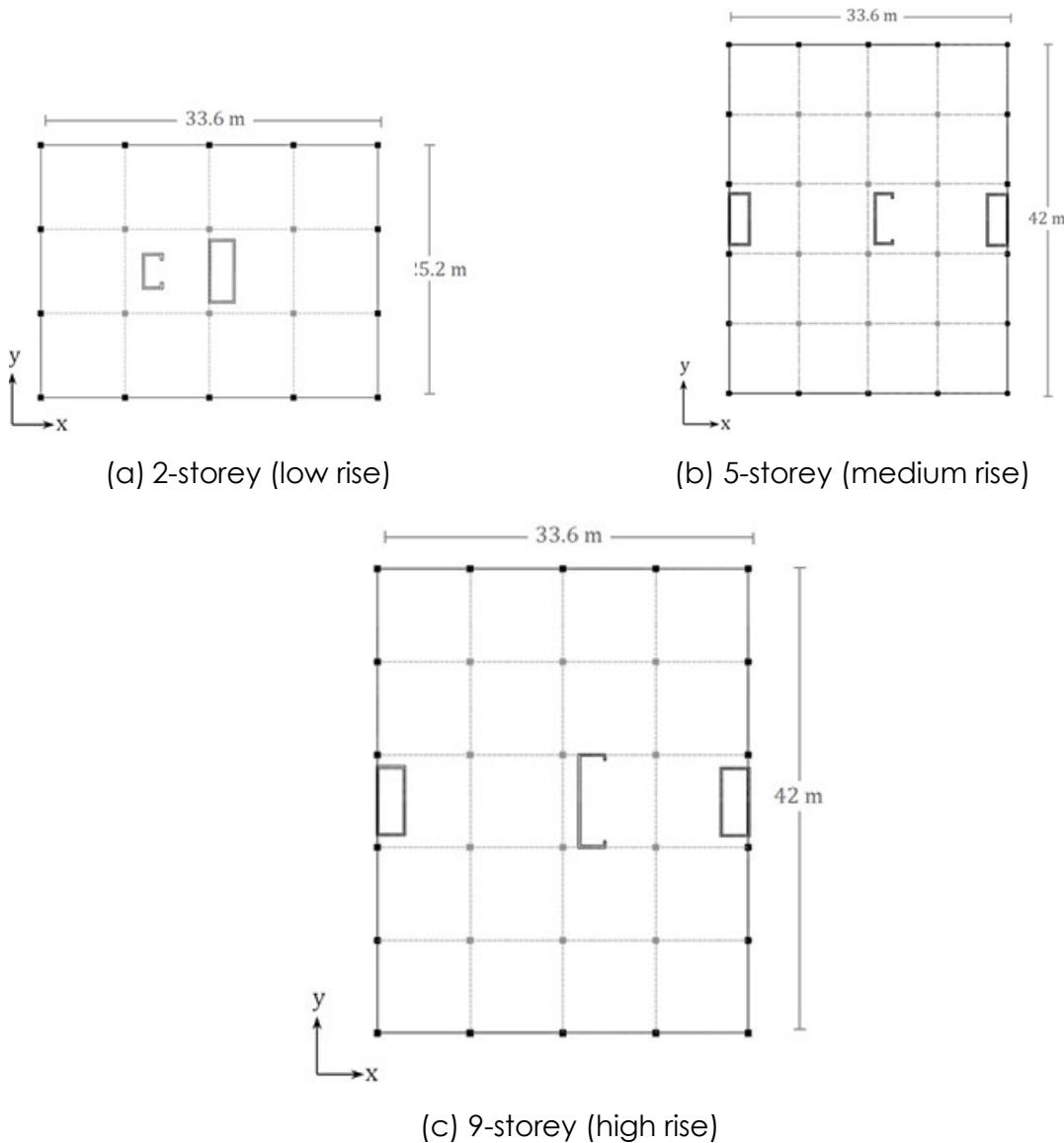


FIGURE 6. IDEALISED RC FRAMES BUILDINGS

### Analyses of the building models

The analysis to construct the fragility curves for the framed wall buildings were conducted based on the capacity spectrum method using ground motion inputs selected to represent the regions of low to moderate seismicity and Australian site conditions. A program in MatLab has been developed to undertake a large number of analyses, taking into account the variation in building models, the height of the buildings, and the detailing of the structural elements. The results from the capacity spectrum method were validated by



comparison of non-linear dynamic time history analysis conducted using SeismoStruct. Full details on the modelling approach and validation are available in Hoult et al. (2018). The analyses for the reinforced concrete framed buildings were conducted based on non-linear time history analyses using a finite element analysis package OpenSees. The three archetypal buildings were subject to ground motion excitations selected to represent Australian seismicity and site conditions. The buildings' structural elements were modelled using lumped plasticity elements, and the beam-column joint response was modelled using the scissor's model with rigid links approach. Rigid diaphragm was assumed for the analyses of reinforced concrete walled and framed buildings. Full details are available in Hoult et al., (2018), Amirsardari et al., (2020). The details of the modelling approach and the construction of fragility curves have been presented in the past report (Lumantarna et al., 2018).

Ground motion inputs selected in the analyses represent a wide range of intensity of Australian earthquakes. The records selected are a combination of: (i) stochastically generated records which is capable of producing ground motions that are representative of Australian earthquakes, and (ii) historical records with characteristics that are representative of Australian earthquakes, including shallow earthquakes with reverse fault mechanisms. Ground motions on soil were generated by using equivalent linear and non-linear site response program DEEPSOIL, using bore hole record of sites classified as class C and D soil site based on AS1170.4.

### Fragility Curves

Four performance levels were considered: i) slight damage (also often referred to as operational, serviceability or immediate occupancy limit state); ii) moderate damage (also often referred to as damage control or repairable damage limit state); iii) extensive damage (also often referred to as life safety limit state); and iv) complete damage (also often referred to collapse prevention limit state). A summary of the adopted performance levels is provided in Table 3.

#### (a) For RC shear walls buildings (Hoult et al., 2018)

<b>Performance limit</b>	<b>Primary structure</b>
<b>Slight Damage / Serviceability (S)</b>	Wall reaching a compressive strain of 0.001, or tensile strain of 0.005, whichever occurs first
<b>Moderate Damage/ Damage Control (DC)</b>	Wall reaching a compressive strain of 0.002, or tensile strain of 0.01, whichever occurs first
<b>Extensive Damage/ Life Safety (LS)</b>	Wall reaching ultimate rotational limit, corresponding to a compressive strain of 0.003, or tensile strain of $0.6\varepsilon_{su}$ , whichever occurs first
<b>Complete Damage/ Collapse Prevention (CP)</b>	NA



(b) For RC frames buildings (Amirsardari et al., 2020)

Performance level	Limits	Primary structure	Secondary structure	Non-structural limit
<b>Slight Damage / Serviceability (S)</b>		Wall reaching initial yield limit	Frame component reaching nominal yield rotational limit	ISD reaching 0.004
<b>Moderate Damage/ Damage Control (DC)</b>		Wall reaching a compressive strain of 0.002, or tensile strain of 0.015, whichever occurs first	Frame component reaching rotation which is at mid-point between yield and ultimate rotational limits	ISD reaching 0.008
<b>Extensive Damage/ Life Safety (LS)</b>		Wall reaching ultimate rotational limit, corresponding to a compressive strain of 0.004, or tensile strain of $0.6\varepsilon_{su}$ , whichever occurs first	Frame component reaches the rotation corresponding to shear failure	ISD reaching 0.015
<b>Complete Damage/ Collapse Prevention (CP)</b>	NA		Frame component reaches the rotation corresponding to 50 % reduction in ultimate lateral strength	ISD reaching 0.002

NA: Not applicable

ISD: Inter-storey drift

TABLE 3. SUMMARY OF THE ADOPTED PERFORMANCE LEVELS

The fragility curves for the RC buildings are presented in Figures 7 and 8. The figures indicate the probability of a certain damage limit state being exceeded for a given value of peak ground velocity (PGV). The fragility curve in the form of probability of exceedance will be converted to the damage factor in the next section. The results are presented for the onerous soil site class C and D (based on AS1170.4).

It was observed that when the RC walls reach a damage limit state, the damage generally occurs at the base of the walls. When the columns and beam-column joints reach a damage limit state, the failure is most likely to occur on the frame elements in the top storeys. For the complete damage level, the failure of the frame elements may occur at the top storeys (due to accumulation of damage which has occurred during earlier stages of loading). Alternatively, the failure of the elements may occur at the base of the building; especially for the columns, since columns with high axial load have significantly lower drift capacities.

The results show that RC frames buildings are more vulnerable than RC shear wall. The RC frames buildings were subjected to retrofitting measures in the following section.

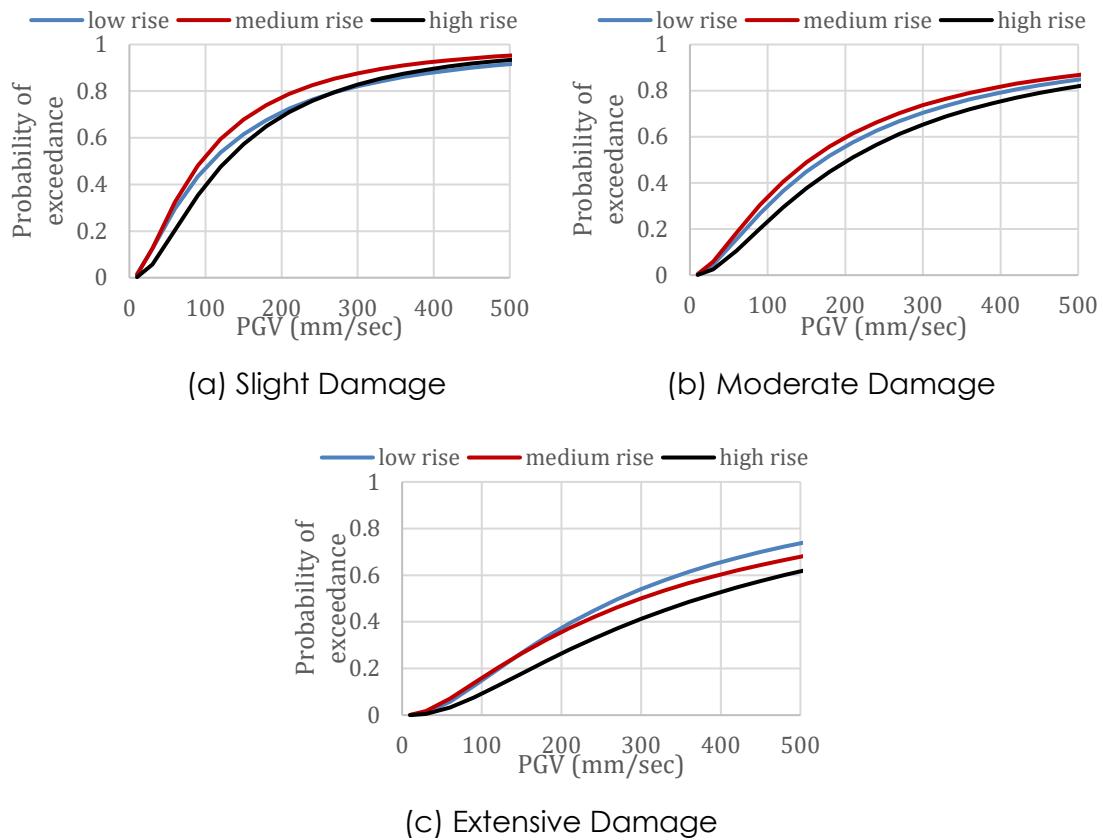


FIGURE 7. FRAGILITY CURVE FOR RC WALL BUILDINGS

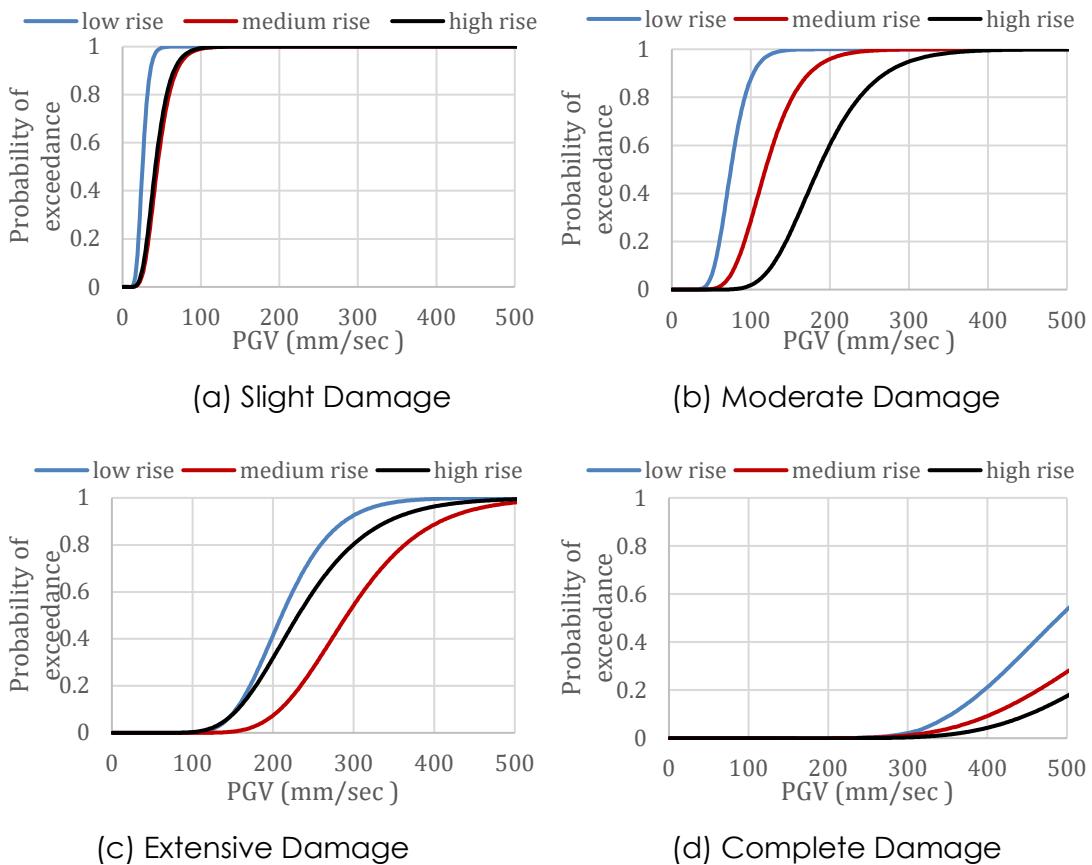


FIGURE 8. FRAGILITY CURVES FOR RC FRAMES BUILDING



## Retrofitting of limited ductile reinforced concrete buildings

### Review of strengthening techniques

The project considers global and retrofitting strategies to strengthen the limited ductile reinforced concrete buildings

Global retrofit strategies include providing additional lateral load resisting elements such as infill wall, shear wing wall, buttress walls, steel braced frames, external precast and prestressed concrete frames, energy dissipation and base isolation devices, to improve the strength and stiffness of the structure.

Local retrofit strategies focus on local structural elements such as reinforced concrete columns, beams and joints. The structural elements can be retrofitted by adding layers of material such as concrete jacketing, steel jacketing (or use of steel plate) and fibre-reinforced polymer (FRP) sheet.

A comprehensive review of the different strengthening and repair techniques for RC columns has also been conducted as part of the project. A review paper (Raza et al., 2019) has been written in this regard, which provides useful insights to practitioners and designers for the selection of appropriate strengthening and repair techniques to meet the desired retrofitting objectives. The various techniques have been broadly categorised into six different categories, RC/mortar jacketing; steel jacketing; externally bonded FRP jacketing; near-surface mounted FRP or steel reinforcement; shape memory alloy (SMA) wire jacketing; and hybrid jacketing. A summary of the benefits and drawbacks for each category of techniques has been summarised in Table 4 (Raza et al., 2019).

Strengthening Method	Benefits	Drawbacks
RC/Mortar Jacketing	Commonly used/available material	Expensive, labor intensive and time consuming due to formwork installation
	Familiarity of practicing engineers with the material	Change in cross-sectional size leading to change in stiffness and seismic demands
	Ability of RC to take any shape	Increase in ductility is small due to brittle nature of concrete
	Increases both strength and ductility	Disruption of occupancy
Steel Jacketing	Ductile and commonly used/available material	Expensive and labor intensive. Rusting and corrosion
	Excellent confinement leading to considerable increase in both strength and ductility	Change in cross-sectional size leading to change in stiffness and seismic demands
		Heavy weight



	Ease and speed of installation	
	Corrosion resistance	
	Minimum modification to geometry and aesthetics of structure	Costly material (but overall cost is low due to small cost of transportation and installation)
Externally Bonded FRP Jacketing	Minimum disruption of occupancy	Low efficiency (30–35%) due to debonding
	High durability, high strength-to-weight ratio	Poor properties on exposure to high temperature and wet environment
	Better work safety and minimum risk hazard	Increase in strength is relatively small
	Enhancement in both strength/ductility	
	Less prone to debonding	
	Minimum modification to geometry and aesthetics of structure	Costly material (but overall cost is low due to small cost of transportation and installation)
Near-Surface Mounted FRP or Steel Reinforcement	Less prone to mechanical impact and accidental damage due to protection by concrete cover	Comparatively more labor intensive in comparison to externally bonded FRP, but lesser than RC or steel jacketing
	Aesthetics of the structure remain unchanged	Not much increase in ductility
	Enhances strength considerably	
	Fast installation	
Shape Memory Alloy (SMA) Wire Jacketing	No need for adhesive	Costly material
	No danger of peel off	Ineffective composite action with concrete
	Super elastic and durable	Enhancement in strength is relatively small
	Increases both the strength and ductility	
	Fast installation	
	Minimum modification to geometry and aesthetics of structure	Costly material
Hybrid Jacketing	High durability	Comparatively labor intensive as it combines two different retrofitting techniques
	Significant enhancement in both strength and ductility	

TABLE 4. SUMMARY OF BENEFITS/DRAWBACKS OF THE DIFFERENT REPAIR AND STRENGTHENING TECHNIQUES

The six broad retrofitting and strengthening categories have been compared using six generic criteria, as follows: effect on strength; effect on ductility; effective on stiffness; cost of strengthening; aesthetics; and impact to occupants, which specifically, is the impact to the building occupants while the strengthening and repairing techniques are being undertaken. A matrix



summarising the performance of each technique for each category is presented in Table 5. Full details are provided in Raza et al. (2019).

Strengthening Method	Effect on Strength	Effect on Ductility	Effect on Stiffness	Cost of Strengthening	Aesthetics/Impact to Floorplan	Impact to Occupants
RC Jacketing	Increase	Increase	Unchanged/increased	Very high	Poor	Very high
Steel Jacketing	Significant increase	Significant increase	Unchanged/increased	Very high	Moderate	High
Externally Bonded FRP Jacketing	Increase	Significant increase	Unchanged	Moderate	Good	Moderate
Near-Surface Mounted FRP or Steel Reinforcement	Significant increase	Increase	Unchanged	Moderate	Good	High
Shape Memory Alloy (SMA) Wire Jackets	Increase	Increase	Decrease	High	Moderate	Moderate to high
Hybrid Jacketing	Significant increase	Significant increase	Unchanged/increased	High	Moderate	High to very high

TABLE 5. COMPARISON MATRIX OF DIFFERENT STRENGTHENING AND REPAIRING TECHNIQUES FOR RC COLUMNS

In conclusion, it was found that although the strength, ductility and drift capacity of the damaged columns can be recovered and even enhanced by repair, it is very difficult to fully restore the initial stiffness of the damaged column.

### Fragility curves of retrofitted limited ductile reinforced concrete buildings

Four retrofitting options have been investigated further in this project i) addition of bracing system; ii) addition of infill walls; iii) fibre reinforced polymer (FRP) jacketing; and iv) steel jacketing. Two-dimensional nonlinear capacity spectrum analyses were performed on a bare frame model and the frame models retrofitted by the four techniques respectively. Fragility curves were constructed for the reinforced concrete framed buildings that have been identified in the previous section to be the most vulnerable amongst limited ductile reinforced concrete buildings (Figure 6).

Case study office buildings with a floor plan of 12 m x 12 m (3 bays in each direction) were modelled as a plane frame in the finite element modelling software SpaceGass. The structural design of the buildings was based on the requirements in the 1980's in Melbourne. The size of the columns is 300 x 350 mm. Also, the span of the RC beams is 4 m and their size is 400 x 300 mm. The dead load is estimated to be 8 kPa for each floor and 6 kPa for the roof while the imposed loads were assumed as 3 kPa for each floor and 1 kPa for the roof.

The concrete strength was assumed to be N25 whilst the grade of the steel reinforcement is D500N. For the nonlinear analysis of the structure, the mean



values of the actual material properties as recommended by Priestley et al. (2007) were used as opposed to the characteristic values as required by AS 3600. The retrofitting techniques were then provided to the end bays, which are considered the most vulnerable in a building.

The steel bracing system as shown in Figure 9 used to retrofit the RC frame is the eccentric bracing consisting of chevron pattern and a vertical shear link. The steel member used for the brace members and the link is 150UB14.0 and the link is approximately 300 mm long attached centrally to the beam.

The material selected for the infill walls is concrete. As shown in Figure 10, the infill walls were modelled using the “equivalent diagonal strut” which functions as a compression brace. This is a simplified method widely used by researchers and engineers to model infill wall panels. The strut width should be one third of the diagonal length of the infill wall. The diagonal length of the infill wall in this case study is 5000 mm, therefore, the strut width was taken as 1700 mm. Also, the thickness of the strut is 300 mm.

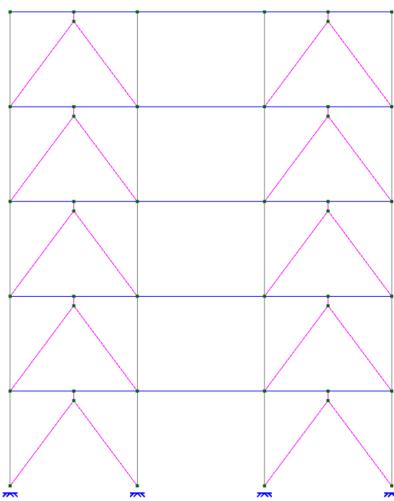


FIGURE 9. ECCENTRICALLY BRACED RC FRAME

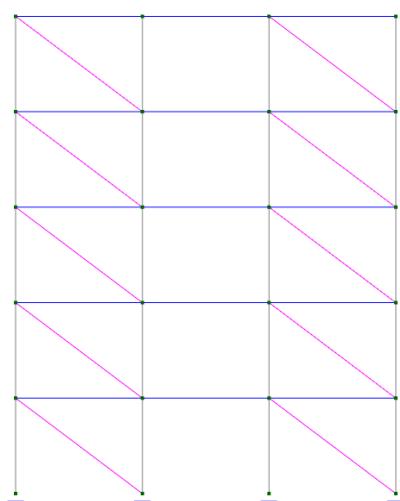


FIGURE 10. RC INFILLED FRAME

Steel jackets were modelled as two steel plates of 40mm x 300mm either side (in the plane of the lateral force) along the entire length of every first-storey column in order to mitigate the soft-storey and weak-storey effects. The steel jackets on the other sides of these columns (along out-of-plane faces) were not considered, since it was assumed that these elements would contribute negligible benefits to the seismic performance of the frame.

The use of FRP for the purpose of jacketing is becoming an attractive alternative. FRP jacketing employed for confining concrete will increase the strength and ductility of the column to which it is applied. A standardised model adapted from the American Concrete Institute (ACI) standard ACI440.2R was applied to estimate the improvement achieved from jacketing. By adopting three layers of FRP to jacket the concrete columns, an effective compressive strength of confined concrete,  $f'_{cc}$ , of 77.81 MPa can be achieved. This is an increase of 139% over the initial, unconfined concrete strength of 32.5 MPa. This value was introduced to model the capacity of the frame.

The fragility curves of the retrofitted RC framed buildings are compared with those of non-retrofitted RC framed buildings (from Figure 8). The fragility curves



for moderate damage and extensive damage states are presented in Figure 11 and 12, respectively.

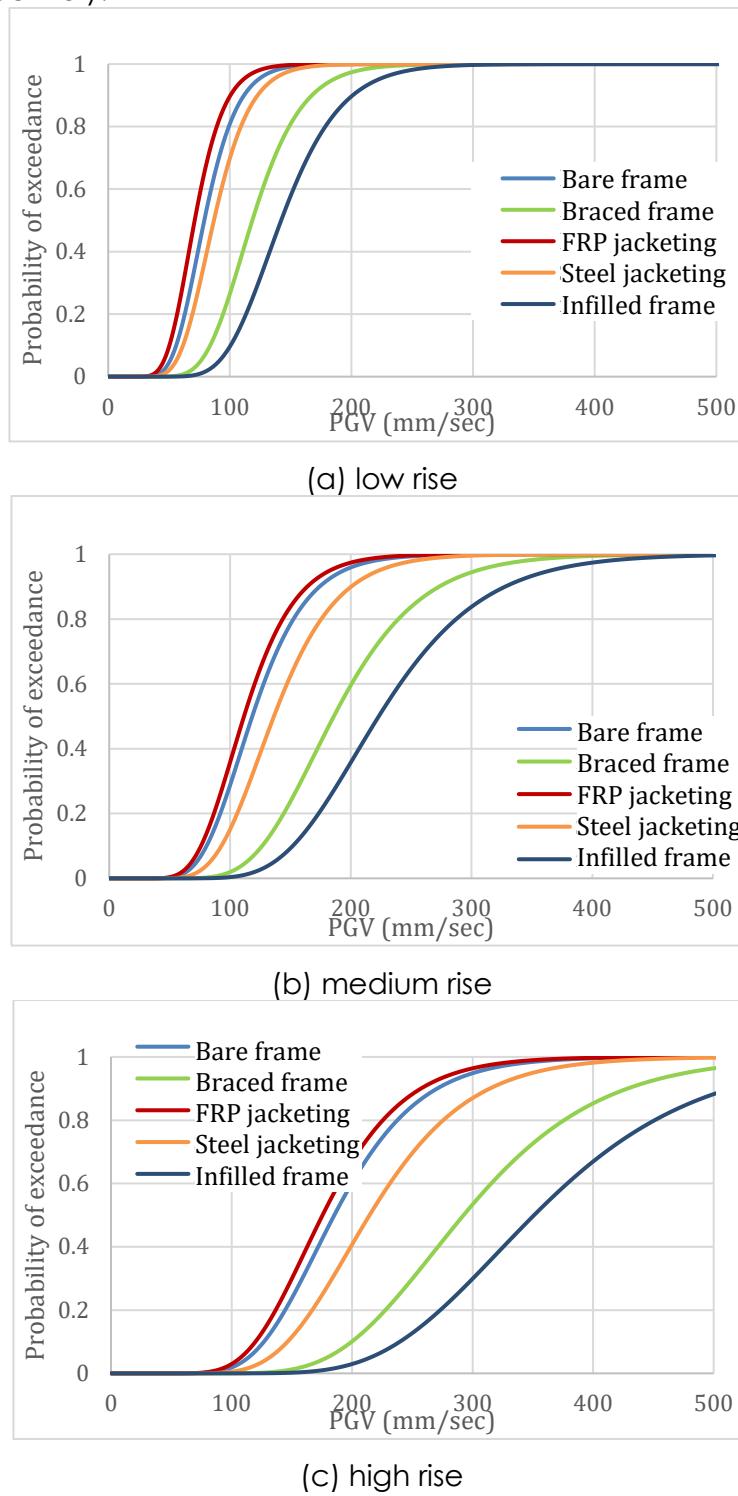


FIGURE 11. FRAGILITY CURVES FOR RETROFITTED RC FRAMED BUILDINGS, MODERATE DAMAGE

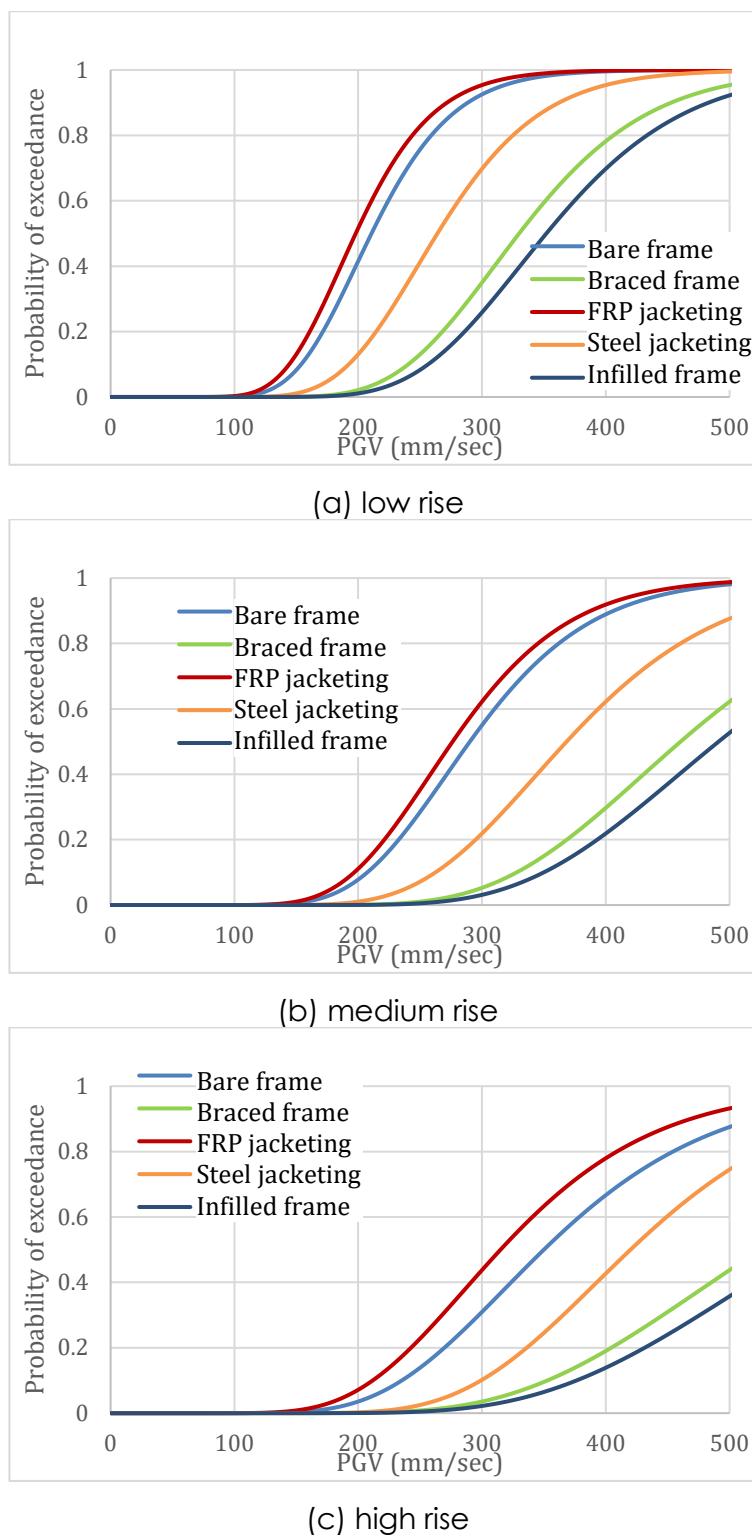


FIGURE 12. FRAGILITY CURVES FOR RETROFITTED RC FRAMED BUILDINGS, EXTENSIVE DAMAGE

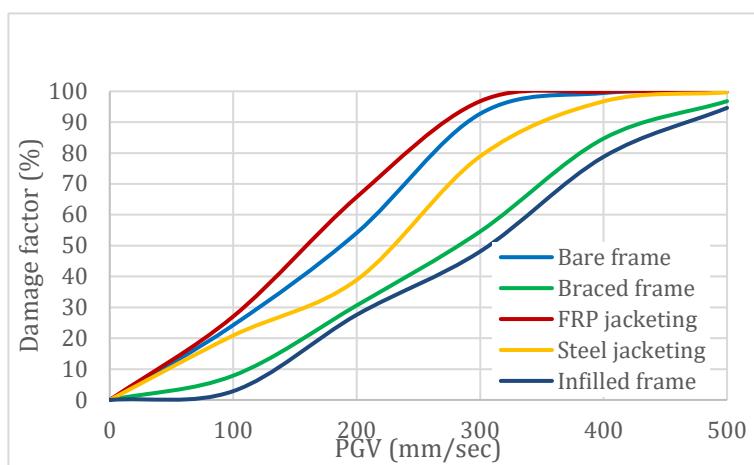
Four retrofitting techniques have been evaluated, the addition of bracing system, the addition of infill walls, fibre reinforced polymer (FRP) jacketing and steel jacketing. Comparison between the retrofitting options and the non-retrofitted RC frames buildings show that the infill walls provide the greatest benefit, followed by steel bracing. The addition of FRP and steel jacketing was found to have the least impact on the seismic performance of the RC frames.



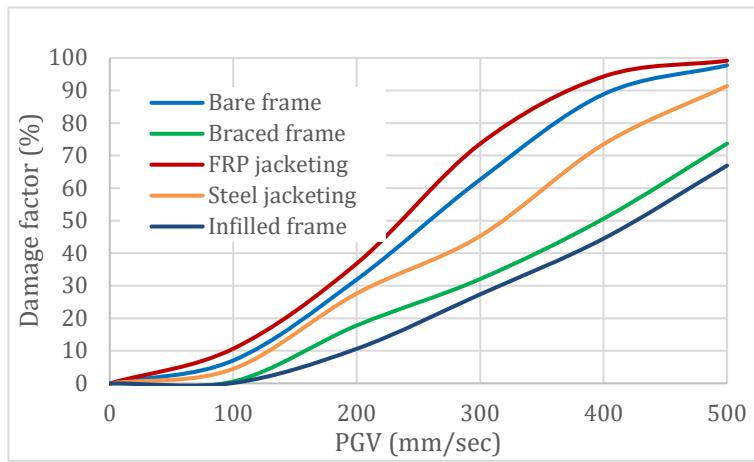
## Vulnerability assessment of retrofitted limited ductile reinforced concrete buildings

The mean vulnerability curves were constructed out of the fragility curves by the probability of a building sustaining a damage state and the cost for a given damage state (the cost is presented in terms of damage factor, which is the % of repair to replacement ratio).

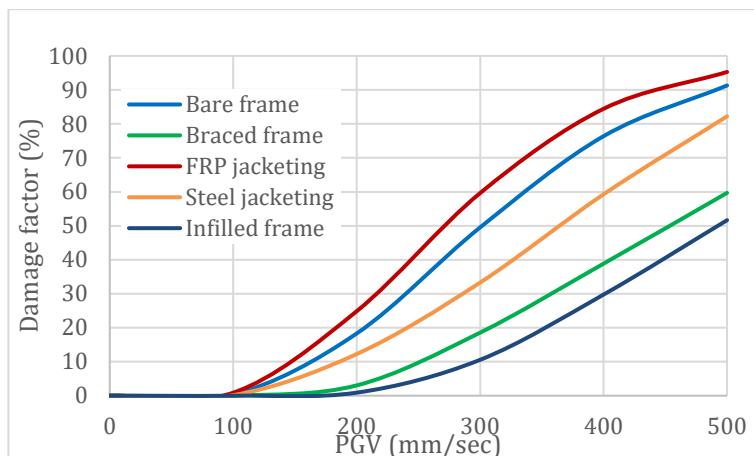
The Vulnerability curves were constructed for two damage states, moderate and extensive damage, based on fragility curves presented in Figures 9 and 10. The values of cost, in terms of damage factor %, were 30% and 100%, for moderate and extensive damage, respectively. These values were adopted from a study conducted by the project team (Menegon et al., 2019). The vulnerability curves are presented in Figure 13.



(a) low rise



(b) medium rise



(c) high rise

FIGURE 13. VULNERABILITY CURVES FOR RETROFITTED RC FRAMES

### Cost analysis of the retrofitted options

The four retrofitting options have been analysed: i) addition of bracing system; ii) addition of infill walls; iii) fibre reinforced polymer jacketing; and iv) steel jacketing. Each technique has been costed separately. For costing purpose, all bays have been considered to have non-structural stud partitions with plasterboard on either side, a 200 mm suspended slab separating each floor and access is considered to be good with no issues regarding bringing in materials.

#### **Technique One: Eccentric Bracing System**

The eccentric bracing system requires the demolition of the non-structural elements within the frame permanently to make room for the bracing system.

The steel members will then be installed by 2 to 3 people, hand tools and a jack to hold the members in place while installing. Drilling into the structural members and attaching them using hold-down bolts will be required.

Full reinstatement of the stud partition wall with plaster either side can be completed to hide the seismic retrofit.

#### **Technique Two: RC Infill Walls**

RC walls are usually constructed based on in-situ pours. Literature suggests that precast concrete walls can be used, although limited access would make it difficult to be adopted from a constructability standpoint.

RC walls require the demolition of any partitions or other non-structural elements within the bay. To install the RC wall, starter bars will be installed into the column and the beam by drilling into the concrete and inserting epoxy prior to installing the starter bars. Reinforcement will then be placed as per the retrofitting requirements. Formwork will be erected, and the concrete pumped in and vibrated. The concrete can be pumped through holes drilled into the roof slab if required.

Once the RC infill wall has been installed, the wall will be patched for any defects and tied into the existing column. The wall will then be painted to match the aesthetics of the building.



### **Technique Three: FRP Jacketing**

FRP is considered a niche technique in Australia as not many contractors are able to complete the work. As the work is specialised, the industry is not very competitive at the moment compared to techniques such as steel jacketing which can be completed by most competent construction companies. FRP can be installed if the equipment and contractors are available.

FRP jacketing requires the local demolition of non-structural partitions directly adjacent to the column to expose the member. 3 m has been assumed to be removed on all sides of the column for the entire height of the bay. FRP jacketing was considered for the entire height of the column and was wrapped three times. FRP will be installed using a FRP rig and a crew of 2 or 3 people.

Once the FRP jacket has been installed, the area will be reinstated. The stud partitions will be built back up to the column that was exposed for the retrofit installation. The area will then be patched for any defects and the area painted to tie back into the existing aesthetics.

### **Technique Four: Steel Jacketing**

Steel jacketing involves a relatively simpler installation compared to FRP.

Steel jacketing requires local demolition of non-structural partitions directly adjacent to the column to expose the member. 3 m has been assumed to be removed on all sides of the column for the entire height of the bay.

Steel jacketing for the entire height of the column on all sides was considered in the costing. Completing this with a single steel plate for each side was considered to be very difficult if not impossible due to the self weight of the steel plates and assuming no access directly above the member for a crane. Therefore, the plates will be brought in smaller manageable sections of 0.5 m – 1.0 m lengths. The plates will be installed by a team of three using hand tools and a platform. On-site welding will be necessary.

Once the steel jacket has been installed, the area will be reinstated. The stud partitions will be built back up to the column that was exposed for the retrofit installation. The area will then be patched for any defects and the area painted to tie back into the existing aesthetics.

### **Cost summary**

The costing was completed per bay using the standardised techniques outlined above. It was found that eccentric bracing was the cheapest, whereas FRP jacketing was the most expensive. A summary of the costs is shown in Table 6. The breakdown of the cost can be found in the appendix of this report. It was found that the most expensive component for each of the retrofitting techniques is the cost of materials. The steel jacketing and the FRP jacketing were priced as being installed to the entire column. They can be installed to a smaller part of the column which would significantly reduce the cost.



<b>Retrofit Solution</b>	<b>Adelaide</b>	<b>Brisbane</b>	<b>Melbourne</b>	<b>Perth</b>	<b>Sydney</b>
Eccentric Bracing	\$3,895	\$3,835	\$3,644	\$4,653	\$4,206
RC Infill Wall	\$16,011	\$15,513	\$16,156	\$17,068	\$17,956
FRP Jacketing	\$26,187	\$26,370	\$26,240	\$26,024	\$26,124
Steel Jacketing	\$19,470	\$19,326	\$18,891	\$20,128	\$19,705

TABLE 7. SUMMARY OF COSTING (PER BAY)



## KEY MILESTONES

The key milestones for this project were:

June 2014:

- Report on retrofit options survey and gap analysis
- Report on building classification and vulnerability attributes

December 2014:

- Literature review of fragility curve data for damage loss modelling

June 2015:

- Progress report on retrofit experiments
- Progress report on damage loss modelling

December 2015:

- Draft journal paper No.1
- Preliminary report on economic loss modelling

March 2016:

- Progress report on retrofit experiments
- Draft journal paper No. 2

June 2016:

- Progress report on economic and damage loss models
- Review of project aims against current needs and recommendations for scope change as required

September 2016:

- Final report on 1<sup>st</sup> stage damage loss models
- Two posters and conference papers for BNH CRC conference

December 2016:

- Final report on retrofit experiments
- Draft journal paper No. 3

March 2017:

- Draft journal paper No. 4

September 2017:

- Progress report on pushover analysis of classes of URM buildings
- Final report on LDRC building drift-damage relationship
- Poster for BNH CRC conference

December 2017:



- Final report on URM building drift-damage relationship
- Draft journal paper on URM building drift-damage relationship
- Final report on fragility curves for LDRC buildings
- Draft journal paper on fragility curves for as-built LDRC buildings
- Report on business resilience models

March 2018:

- Progress report on fragility curves for URM buildings
- Report on costing of URM building repair

June 2018:

- Final report on fragility curves for URM buildings
- Progress report on retrofit methods for LDRC buildings
- Reporting on economic framework and precinct cordon model

September 2018:

- Final report on fragility curves for retrofitted URM buildings
- Report on costing of URM building retrofit
- Draft journal paper on fragility curves for URM buildings

December 2018:

- Progress report on retrofit tests for LDRC buildings
- Final report on fragility curves for as-built and retrofitted URM buildings

March 2019:

- Draft journal paper on case study of URM buildings retrofit in CBD
- Final report on testing retrofitted LDRC buildings
- Report on costing of LDRC building repair

June 2019:

- Report on costing LDRC building retrofit
- Reporting on economic evaluation of mitigation strategies at building level
- Final report on the fragility curves for retrofitted LDRC buildings
- Draft journal paper on retrofit options and experimental program

September 2019:

- Final report on vulnerability of as-built and retrofitted LDRC buildings
- Progress report on case study of CBD precinct (Melbourne)
- Draft journal paper on fragility curves for retrofitted LDRC buildings
- Poster for BNH CRC conference



December 2019:

- Completion of the Case Study CBD Precinct Cost-Benefit Analysis

June 2020:

- Synthesis report summarising all project activities

September 2020:

- Poster for BNH CRC conference

December 2020:

- Final report
- Final report on Case Study of Melbourne CBD precinct; was due in December 2019 quarter but has been delayed to March 2021.



## UTILISATION AND IMPACT

### SUMMARY

This project has already seen significant evidence of community utilisation and impact of its research. This is best exemplified by York Shire Council's strategy to use seismic retrofit techniques to strengthen several 'exemplar' buildings in its jurisdiction to demonstrate the 'how to' of seismic retrofit and to give local consultant engineers/builders and architects experience in doing this type of work on heritage listed construction so that future work on other similar building typologies in the York Shire council can be undertaken with confidence. While the program has the first Shire owned building progressing, the extent of retrofit implementation in York will be determined by the ability to source cost-sharing funding and to motivate property owners to participate.

The retrofit information is intended to be rolled out across the rest of the state (WA) by courtesy of the National Disaster Resilience Program grant which intends to extend the York project to cater for an additional 3 heritage building typologies that were poorly represented in the York Shire.

Further, it is expected that the expertise gained by the research team will be increasingly called upon by heritage building owners across the rest of the country who are dealing with similar issues of seismically vulnerable heritage construction and susceptibility to heavy damage from low-to-moderate earthquake shaking anywhere in the country.

### EARTHQUAKE MITIGATION CASE STUDY FOR REGIONAL TOWN OF YORK, WA

#### Output description

The key outcomes of the project are:

- Foremost, the study has demonstrated strong stakeholder engagement to focus the project to their information needs. It has also benefitted from sustained contributions from the end-users in facilitating the research and sharing the outcomes.
- The project has also engaged a broader stakeholder group beyond the formal end-users to include the WA Department of Planning, Lands and Heritage, the Heritage Council of WA, Heritage Engineers and the Insurance Australia Group.
- The risk posed by all building types in the town of York has been assessed and the effectiveness of mitigation measures virtually applied to the most vulnerable subset has been examined. This has been at the scale of individual buildings up to the entire community of York.
- The project has also developed scenario outcomes for EM planning by state agencies and local government. These can be used to plan and prepare for the next damaging earthquake in the region, thereby promoting more effective response and recovery.



- The project has identified the importance that reduction of earthquake casualties afforded by retrofit plays in the assessment of the benefits of these measures.
- The project has integrated the research outcomes of another BNHCRC project (led by the University of New England) that has developed the *Australian National Disaster Resilience Index*. Further, it has secured the stakeholder support and community engagement for a second project studying the non-market values placed on community heritage buildings.
- The project has published five conference papers (Vaculik et al, 2018b; Edwards, 2018; Edwards et al, 2019a; Ryu et al, 2019 and Edwards et al, 2019b), one international and one as part of a keynote address.
- The project has also paved the way for a succeeding project that will study the implementation of the retrofit measures developed, broaden the mitigation evidence base to three other common vulnerable building types, and refine the information provided on all nine. Significantly, it will result in information becoming widely available and used to support mitigation efforts in other WA communities and nationally.

### **Extent of use**

- The project output acted as a catalyst for the Shire of York to proceed with seismically retrofitting a small selection of URM buildings in York as part of a subsequent NDRP funded project examining the implementation of seismic retrofit to heritage URM buildings in WA. The subsequent project is reported in the following sections.

### **Utilisation potential**

- The impact and USAR information developed during the project will allow DFES to conduct capability analysis and the scenarios will enable the development of plans that take into account risk reduction measures, preparedness, proportional response and recovery. The sections on component mitigation strategies, retrofit scenarios and mitigation strategies – implementation costs has provided something tangible to enable people and organisations to make informed decisions on earthquake mitigation strategies.
- The vulnerability curves for URM buildings using in conjunction with the earthquake hazard in other localities will inform future earthquake impact and risk studies such as the Melbourne Case Study reported below.

### **Utilisation impact**

- As noted above, several seismically vulnerable buildings in York are expected to be seismically strengthened with workshops and publicity events planned to promote the economic viability of seismic strengthening in WA.
- As noted above the vulnerability curves are being used in the Melbourne Case Study reported on below.



## Utilisation and impact evidence

1. Awarded \$250,000 grant by National Disaster Resilience Programme to extend the scope of the York Earthquake Mitigation Study to cover additional building typologies for all of Western Australia and assist with seismic retrofit demonstration project for York Heritage Museum.
2. Vaculik, J and Griffith, MC (2019). "Out-of-plane fragility of URM parts and components based on time-history analysis – comparison to simplified force-based approaches," Proceedings, Australian Earthquake Engineering Society Conference, Newcastle, Paper No. 62.
3. Edwards, M, Wehner, M, Ryu, H, Griffith, MC and Vaculik, J (2019). "Modelling the vulnerability of old URM buildings and the benefit of retrofit," Proceedings, Australian Earthquake Engineering Society Conference, Newcastle, Paper No. 2.
4. Ryu, H., Edwards, M., Wehner, M., Gray, S., Griffith, M., Vaculik, J., Corby, N. and Allen, T. (2019). "Earthquake Management Logistics for York, WA, Pre and Post Mitigation" Proceedings, AEES Conference, Newcastle, NSW.
5. Vaculik, J, Griffith, MC, Wehner, M & Edwards, M (2018). "Seismic assessment of URM buildings in a heritage-listed township," Proceedings, Australian Earthquake Engineering Society Conference, Perth.
6. Gray, S., Martin, P., Edwards, M., Griffith, M.C. and Derakhshan, H. (2018). "Community strategy development for reducing earthquake risk in Western Australia," Proceedings, AFAC, Perth, Sept 5-8, 2019.

## YORK EARTHQUAKE BUILDING MITIGATION IMPLEMENTATION PROJECT

### Output description

York is West Australia's oldest inland town with many older (heritage listed) masonry buildings which are particularly vulnerable to earthquake ground shaking (Edwards et al, 2019). Furthermore, the earthquake hazard in York is high compared to most other parts of Australia. Given that the economic prosperity of the York Shire relies significantly on the tourism that is generated by the preponderance of heritage buildings in the township, protection of these structures from future damaging earthquake shaking is of high importance. Hence, the York Shire Council has embarked on a multi-year project to increase the town's resilience against the effects of a future earthquake and study the utility of the measures developed through the CRC. This involves the Shire Council promoting seismic strengthening measures in several of the important masonry buildings in York as demonstration projects for the local community and to give local engineers and building contractors first-hand experience with seismic retrofit projects. It is anticipated that by showing that relatively simple structural interventions are inexpensive to implement the demonstrated implementation of retrofit information will motivate other building owners to follow suit.

### Extent of use

- An expected total of three demonstration buildings will be seismically assessed and strengthened in York to demonstrate the range of retrofit techniques that can be used and implemented by local contractors (refer Vaculik et al 2018). The three building types will include the first, a single



storey free-standing building typical of domestic construction in the late 1800s to early/mid 1900s. The second building type will likely be a multi-storey (2 or 3 storey) commercial building on the main street which may have parapets, chimneys and gable end walls. The third building type may be a larger community building, hall or church where the walls may need some strengthening and improved connections between the walls and roof structure.

### **Utilisation potential**

- It is anticipated that use of this expertise will be communicated to the wider population of Western Australia, including other regional communities, through the Natural Disaster Resilience Program funded project which will support work by this research team to extend the range of unreinforced masonry buildings most vulnerable to earthquake to other types that are common in WA but not already covered in the York project scope.
- It is expected that eventually this work will be applicable in most Australian communities given the comparatively uniform age and construction of heritage buildings across the continent. An example of this is the "Earthquake Risk and Mitigation Assessment in Tasmania" project that has been most recently funded under the National Partnership Agreement on Disaster Risk Reduction. The proposal will look at the earthquake risk in Hobart and will apply the BNHCRC and NDRP research outcomes in a virtual retrofit of high risk buildings in the central city. The 12 month project will commence on the 1<sup>st</sup> July 2021 and will focus on masonry buildings in high pedestrian exposure business precincts.
- Clearly, the expertise developed by the researchers in the project team will be sought by the engineering profession and heritage building owners. For example, the Anglican diocese in Adelaide has sought advice from two south Australian members of the research team (Prof M Griffith and Dr J Vaculik) to improve the seismic resilience of St Peters Cathedral in Adelaide. The project is well underway with a number of major structural elements already being strengthened (refer Griffith et al, 2018).

### **Utilisation impact**

- As noted above, several seismically vulnerable buildings in York are being seismically strengthened with workshops and publicity events planned to promote the economic viability of seismic strengthening in WA.
- Similarly, this expertise is increasingly being sought and utilised in other parts of Australia as noted above for St Peters Cathedral in Adelaide.

### **Utilisation and impact evidence**

1. Griffith, MC, Vaculik, J, Klenke, A and McBean, P (2018). "Seismic upgrade of heritage masonry – a case study of St Peter's Cathedral in Adelaide," Proceedings, Australian Earthquake Engineering Society Conference, Perth, Paper No. 60.



2. Vaculik J, Griffith, MC, Edwards, M and Wehner, M (2018). "Seismic assessment of unreinforced masonry buildings in a heritage-listed township," Proceedings, Australian Earthquake Engineering Society Conference, Perth, Paper No. 59.
3. Edwards, M, Wehner, M, Ryu, H, Griffith, MC and Vaculik, J (2019). "Modelling the vulnerability of old URM buildings and the benefit of retrofit," Proceedings, Australian Earthquake Engineering Society Conference, Newcastle, Paper No. 2.

**Press Releases, courtesy of York local press and Geoscience Australia**

**Page 8. The YORK & DISTRICTS COMMUNITY MATTERS - September 2020**

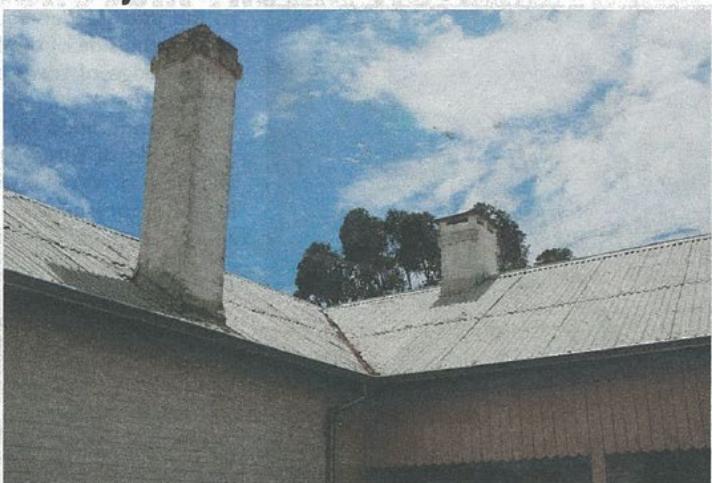
## SHAKE, RATTLE AND ROLL!

Thanks to a grant from the Department of Planning Lands and Heritage matched by funding from the Shire of York we hope that the chimneys – and other structures – of the Residency Museum will soon be able to survive any shaking and rattling due to future earthquakes.

The Museum will be the pilot project for study and practical application of earthquake mitigation building works under a Natural Disaster Resilience Program (NDRP) Grant. This project acknowledges the funding contribution of the Commonwealth Government of Australia and support from the WA State Emergency Management Committee. Support has also been provided by the Department of Fire and Emergency Services.

The 1968 Meckering earthquake illustrated the vulnerability of unreinforced masonry (URM) buildings by destroying the town of Meckering and causing significant damage to older buildings in neighbouring towns, including York. Essentially all heritage buildings are URM and this project is designed to research and provide reliable information on the most effective retrofit measures for high risk URM buildings to inform strengthening programs, reduce risk and promote more resilient communities.

The grants from the Department of Planning Lands and Heritage will ensure this significant heritage building, the last



above: Two chimneys at the Residency Museum, York;  
image courtesy Quoin Consulting Heritage Engineers

remaining part of York's 1850's Convict Depot, is retrofitted in accordance with the latest research by GeoScience Australia and the University of Adelaide. General conservation works are also being undertaken to preserve the building and ensure it survives other natural hazards well into the future. The Museum is a State Heritage Listed Place and you can find out more about the history of this fascinating heritage site on the State Heritage Office database, InHerit <http://inherit.stateheritage.wa.gov.au/public>

Using a simple keyword search you can find the 35 State Heritage Listed Places of York, or the 227 included on the Shire's Heritage List. The website lists hundreds of heritage places all over Western Australia and is great fun and really easy to use.

Specialist Heritage Engineers are currently assessing the Residency Museum and it is hoped that works will start later this year. Opportunities will be provided for the public to find out more about the practical application of strengthening work to heritage buildings.



### Local government initiative to reduce earthquake risk in York



Australian Government  
Geoscience Australia

Earthquake hazard was not fully recognised in Australian building design until the mid-1990s and this oversight has resulted in a legacy of vulnerable community buildings that can be readily damaged in Australian earthquakes.

In particular, older unreinforced masonry buildings, common in many regional towns, are vulnerable to earthquakes. Damage to these can add to emergency management logistics and impede community recovery by local governments physically, economically and socially.

York is Western Australia's oldest inland town with many older buildings that are greatly valued by the community. These draw many visitors to the town to enjoy the heritage precinct they create, and this tourism contributes significantly to the economy of York Shire through visitor spending.



York Town Hall constructed in 1911



Shire Residency Museum built circa 1852

Improving the resilience of the heritage buildings is of interest to property owners, the community, the Shire of York and the Western Australian (WA) government.

The Shire of York has been a key partner in a recent two year Bushfire and Natural Hazards Collaborative Research Centre (BNH CRC) utilisation project undertaken collaboratively by Geoscience Australia and the University of Adelaide.

It has developed information on the most effective means to address York's high risk buildings and has developed a better understanding of the logistics that would be faced by emergency services and the local shire council in a rare earthquake event. The project has also projected the earthquake risk of York considering various uptake rates for mitigation.

It is the first community level retrofit study for earthquake undertaken in Australia and has illustrated that community level risk reduction targeted on the most vulnerable buildings is a decadal journey that can be effective in making communities more resilient.

The project has now transitioned to a sequel project funded under the WA Natural Disaster Resilience Program, in which actual mitigation work on heritage buildings is being studied to improve the retrofit information available in York. This will expand the range of building types considered to a total of nine that are common in regional towns more widely.

The three year project commenced in 2019 and the first building under consideration is the Shire's Residency Museum. This was formerly the superintendent's residence for the local convict depot.

While retrofitting a community is a journey that needs to be sustained, the Shire of York has commenced theirs that will lead to a more earthquake resilient shire.



bushfire & natural  
HAZARDS CRC



Australian Government  
Department of Industry,  
Innovation and Science

Business  
Cooperative Research  
Centres Programme



from Australia New Zealand Emergency Management Committee – “On the Radar”, Edition 18, August-September 2020.

## EARTHQUAKE MITIGATION CASE STUDY FOR METROPOLITAN CITY OF MELBOURNE, VIC

### Output description

This work has been delayed but is well underway. A delivery date of March 2021 has been agreed with the BNH CRC management.

## EARTHQUAKE DESIGN REQUIREMENTS FOR CONCRETE STRUCTURES

### Output description

The study conducted by the project team on the fragility assessment of limited ductile reinforced concrete buildings has identified detailing practice for reinforced concrete walls and frames that result in the vulnerability of the structural elements, causing their brittle failure. The outcomes of this study have contributed to the addition of detailing requirements in the Australian Standard for Concrete Structures AS3600:2018 Chapter 14 on Earthquake Design Requirements. The project team was part of the working group tasked with development of a Chapter addressing seismic design in the Standard.



### **Utilisation impact**

The design provision applies to the design of limited and moderately ductile concrete buildings post-2018.

## **ACCELEROGrams DATABASE FOR EARTHQUAKE ASSESSMENT IN REGIONS OF LOW TO MODERATE SEISMICITY**

### **Output description**

The project involving fragility assessment using incremental dynamic analysis requires ground motion excitations that are representative of Australian conditions. Obtaining ground motions that are representative of seismic conditions in regions of low to moderate seismicity can be challenging due to lack of local data. As a part of the study, the project team developed a database of ground motions based on scaled recorded and generated excitations for regions of low to moderate seismicity where indigenous strong motion data are lacking.

### **Utilisation potential**

The database will be made publically available. Hence, there is a potential uptake by practising engineers who may need to perform dynamic analysis in the design and assessment of structures as required by the Standard. Currently, the use of the Equivalent Static Analysis following AS1170.4 is restricted to regular low to medium-rise buildings. The standard requires dynamic analysis to be performed on the majority of multi-storey buildings.

## **RAPID VULNERABILITY ASSESSMENT OF LIMITED DUCTILE REINFORCED CONCRETE BUILDINGS**

### **Output description**

As a part of the studies to evaluate retrofitting options for limited ductile reinforced concrete buildings, a rapid assessment method has been developed to evaluate relative vulnerabilities of existing concrete buildings. The method is based on a tiered approach involving visual inspection and simple calculations (without requiring detailed structural information). The method is useful in prioritisation strategy for retrofitting of limited ductile reinforced concrete buildings.

### **Utilisation potential**

- The research outcome can be promoted for use by the insurance industry to develop a property insurance policy for different building types and location. Parameters for classifying buildings and their site conditions need to be simplified to enable laypersons to make judgements. Hence additional work may be necessary to tailor for the specific needs of the insurance industry.
- The Australian Building Code Board requires existing buildings to be re-evaluated for code compliance should there be significant modifications



or extension work. The developed methodology can be used to inform building owners the likely costs of achieving that compliance and help develop an optimal retrofit solution on a case by case basis.

- Whilst the project is primarily targeted at existing buildings, the developed methodology is potentially useful in the design of new buildings as well in the preliminary phase of design of seismically sensitive buildings (to costing design alternatives). The research outcome can assist designers, architects and building owners to quickly identify if a building is seismically sensitive without doing complex engineering calculations.



## CONCLUSION

### NEXT STEPS

There are four areas in which the earthquake resilience research group will be focusing on in the immediate future and medium term as follow-on activities as 'utilisation outcomes' of the CRC. These are:

1. Complete deliverable (3.2.1) of the Melbourne Case Study. The scope of this activity was expanded to include the expertise from the BNHCRC UWA project and the use of their 'intangible values' in "Value Tool of Natural Hazards". This will utilise new CRC research by the UWA as part of their ongoing CRC research to assess the value that residents place on the heritage buildings in their community. The new delivery date for this work is March 2021.
2. Committee work for Standards Australia on:
  - a. Australian Loading Code, Part 4: Earthquake Loads AS 1170.4;
  - b. Australian Masonry Structures Code, AS 3700; and
  - c. Australian Concrete Structures Code, AS 3600.
3. A significant utilisation of our project's research findings is the York, WA utilisation of the seismic retrofit strategies for unreinforced masonry buildings. The physical retrofit work is expected to be funded jointly by the Shire of York and WA's Department of Planning, Lands and Heritage. The research on the implementation will be through a National Disaster Resilience Program grant of \$250,000. This 3-year project commenced in July 2019 and has already identified the first demonstration project – the York Residency Museum building. It has been seismically assessed with retrofit options proposed and a local consultant has already investigated and submitted a proposal and fee to carry out the necessary work. Council has agreed with the work proposal which should be completed within the next 6 months, Covid-19 issues permitting. Further work along these lines will continue with a second demonstration building project identified for seismic assessment, retrofit and corresponding fee submission.
4. It is the expectation that the researchers from this project will document the full range of seismic retrofit solutions that have been developed by their research with indicative costings. This work will not be completed before the end of the CRC in December 2020; most likely this would take place before the end of 2021 as part of their normal professional activities through 'in-kind' contributions to the CRC after the fact.
5. Many of the researchers in the earthquake building resilience project team will have opportunities to advise practicing engineers tasked with improving the seismic resilience of existing buildings throughout the nation. As noted earlier, Professor Griffith and Dr Vaculik have consulted on several seismic retrofit projects already – St Peter's Cathedral in Adelaide and previously on Sydney's Central Rail Station's clock tower. It is anticipated that insurance companies will require building owners to ensure their properties meet a



minimum level of earthquake resistance to qualify for insurance cover. This will trigger a significant demand for the expertise developed over the course of this CRC-funded project.

6. Finally, the research team is committed to draft a 'Seismic Retrofit Guidelines' document for use by professionals in Australia that would be relevant for limited ductile concrete and unreinforced masonry (brick and/or stone) buildings in all states and territories. This document will be an extension of the final report of outcomes from the NDRP funded project that grew out of this CRC supported project. It is hoped that this document could be put out for comment by Standards Australia and Engineers Australia's Structural College by the end of 2021.



## PUBLICATIONS LIST

### PEER-REVIEWED JOURNAL ARTICLES

- 1 Hoult, R.D., Goldsworthy, H.M., Lumantarna, E. (2015). "Relationship between longitudinal reinforcement ratio and ductility in RC walls," *Magazine of Concrete Research*.
- 2 Hoult, R.D., Lumantarna, E., Goldsworthy, H.M. (2015). "Spectral Shape Factors for Low-to-Moderate Seismic Regions," *Soil Dynamics and Earthquake Engineering*.
- 3 Kafle, B., Lam, N.T.K., Lumantarna, E., Gad, E.F., Wilson, J.L. (2015). "Overturning of precast RC columns in conditions of moderate ground shaking," *Earthquakes and Structures*. Vol. 8, no. 1, p. 1-18.
- 4 Lam, N.T.K., Tsang, H. H., Lumantarna, E., Wilson, J.L. (2015). "Local intraplate earthquake considerations for Singapore," *The IES Journal Part A: Civil and Structural Engineering*, pp. 1-9.
- 5 Sivanerupan, S., Wilson, J., Gad, E., Lam, N.T.K. (2014). "Drift performance of point fixed glass façade systems," *Advances in Structural Engineering*. Vol. 17, no. 10, pp. 1481-1495.
- 6 Wibowo, A., Wilson, J.L., Lam, N.T.K., Gad, E.F. (2014). "Drift capacity of lightly reinforced concrete columns," *Australian Journal of Structural Engineering*. Vol. 15, no. 2, pp. 131-150.
- 7 Wibowo, A., Wilson, J.L., Lam, N.T.K., Gad, E. F. (2014). "Drift performance of lightly reinforced concrete columns," *Engineering Structures*. Vol. 59, pp. 522-535.
- 8 Oehlers, D.J., Visintin, P., Lucas, W. (2015). Fundamental mechanics governing FRP retrofitted RC beams with anchored and prestressed FRP plates. *ASCE Journal of Composites for Constr.* 10.1061/(ASCE)CC.1943-5614.0000710, 04016047.
- 9 Oehlers, D.J., Visintin, P. and Lucas, W. (2016) Flexural Strength and Ductility of FRP-Plated RC Beams: Fundamental Mechanics Incorporating Local and Global IC Debonding *J. Compos. Constr. (ASCE)*, 20(2), 04015046.
- 10 Hashemi, M.J., Tsang, H.H., Al-Ogaidi, Y., Wilson, J.L., Al-Mahaidi, R. (2017). Collapse Assessment of Reinforced Concrete Building Columns through Multi-Axis Hybrid Simulation. *ACI Structural Journal*, 114(2):437-449.
- 11 Tsang, H.H., Wilson, J.L., Lam, N.T.K., Su, R.K.L. (2017). A Design Spectrum Model for Flexible Soil Sites in Regions of Low-to-Moderate Seismicity. *Soil Dynamics and Earthquake Engineering*, 92:36-45.
- 12 Lam, N.T.K., Wilson, K.L, Lumantarna, E. (2016). Simplified elastic design checks for torsionally balanced and unbalanced low-medium rise buildings in lower seismicity regions, *Earthquakes and Structures*, 11(5), 741-77
- 13 Hoult, R.D., Lumantarna, E., Goldsworthy, H.M. (2016). Soil amplification in low-to-moderate seismic regions, *Bulletin of Earthquake Engineering*, 1-19.
- 14 Sorrentino, L, D'Ayala, D., de Felice, G., Griffith, M.C., Lagomarsino, S. and Magenes, G. (2017). "Review of out-of-plane seismic assessment techniques applied to existing masonry buildings," *International Journal of Architectural Heritage*, doi:[10.1080/15583058.2016.1237586](https://doi.org/10.1080/15583058.2016.1237586)
- 15 Lumantarna, E., Mehdipanah, A., Lam, N., Wilson, J. (2018), Chapter 4, Structural Analysis, in *Guideline on Design of Buildings and Structures in Low-to-Moderate Seismicity Countries*, CNERC.
- 16 Hoult, R., Goldsworth, H and Lumantarna, E. (2018), "Fragility Functions for RC Shear Wall Buildings in Australia," *Earthquake Spectra*.
- 17 Raza, S., Tsang, H.H. and Wilson, J.L (2018). "Unified Models for Post-Peak Failure Drifts of Normal- and High-Strength RC Columns," *Magazine of Concrete Research*, 70(21), 1081-1101.
- 18 Hoult, R. D., Goldsworthy, H. M., & Lumantarna, E. (2018). Plastic hinge analysis for lightly reinforced and unconfined concrete structural walls. *Bulletin of Earthquake Engineering*, 16(10), 4825-4860.
- 19 Hoult, R., Goldsworthy, H., & Lumantarna, E. (2018). Plastic hinge length for lightly reinforced rectangular concrete walls. *Journal of Earthquake Engineering*, 22(8), 1447-1478.
- 20 Zabihi, A., Tsang, H.H., Gad, E.F., Wilson, J.L. (2018). Seismic Retrofit of Exterior RC Beam-Column Joint using Diagonal Haunch. *Engineering Structures*, 174:753-767.
- 21 Howlader, M.K., Masia, M. & Griffith, M.C. (2019). "In-plane shear testing of unreinforced masonry walls and comparison with FEA and NZSEE predictions," *International Journal of Masonry Research and Innovation*.
- 22 Menegon, S. J., Tsang, H. H., Lumantarna, E., Lam, N. T. K., Wilson, J. L., & Gad, E. F. (2019). Framework for seismic vulnerability assessment of reinforced concrete buildings in Australia. *Australian Journal of Structural Engineering*, 20(2), 143-158.
- 23 Amirsardari, A., Rajeev, P., Lumantarna, E., & Goldsworthy, H. M. (2019). Suitable intensity measure for probabilistic seismic risk assessment of non-ductile Australian reinforced concrete buildings. *Bulletin of Earthquake Engineering*, 1-23.
- 24 Raza, S., Khan, M. K. I., Menegon, S. J., Tsang, H.-H., Wilson, J. L. (2019). Strengthening and Repair of Reinforced Concrete Columns by Jacketing: State-of-the-Art Review. *Sustainability* 11(11), 3208.
- 25 Tsang, H.H. (2019). Innovative Upscaling of Architectural Elements for Strengthening Building Structures. *Sustainability*, 11(9), 2636.
- 26 Liu, X., Tsang, H.H., Wilson, J.L. (2019). Seismic Retrofit of Precast Soft-Storey Building using Diagonal Steel-Shape Memory Alloy Bracing Device: Numerical Investigation. *Advances in Structural Engineering*, 22(3):802-817.
- 27 Zabihi, A., Tsang, HH, Gad, EF & Wilson, JL (2019). "Design procedure for seismic retrofit of RC beam-column joint using single diagonal haunch," *Structural Engineering and Mechanics* 71(4), 341-350.



- 28 Tang, Y., Lam, N., Tsang, H. H., & Lumantarna, E. (2019). "Use of Macroseismic Intensity Data to Validate a Regionally Adjustable Ground Motion Prediction Model," *Geosciences*, 9(10), 422.
- 29 Derakhshan, H., Walsh, K.Q., Ingham, J.M., Griffith, M.C. and Thambiratnam, D.P. (2019). "Seismic fragility assessment of non-structural components in unreinforced clay brick masonry buildings," *Earthquake Engineering and Structural Dynamics*, 2019;1–16. <https://doi.org/10.1002/ege.3238>.
- 30 Tang, Y., Lam, N., Tsang, H. H., & Lumantarna, E. (2020). "An adaptive ground motion prediction equation for use in low-to-moderate seismicity regions", *Journal of Earthquake Engineering*, 1-32.
- 31 Howlader, MK, Masia, MJ and Griffith, MC (accepted 2/2/2020). "Numerical Analysis and Parametric Study of Unreinforced Masonry Walls with Arch Openings under Lateral In-Plane Loading," *Engineering Structures*, Vol. 208, <https://doi.org/10.1016/j.engstruct.2020.110337>
- 32 Vaculik, J, Visintin, P, Lucas, W and Griffith, MC (2020). "Durability of near-surface-mounted FRP-to-clay brick masonry retrofits under environmental exposure," ASCE, *Journal of Composites for Construction*, 24(1): 04019058.
- 33 Howlader, M.K., Masia, M. and Griffith, M.C. (2020). "In-plane shear testing of unreinforced masonry walls and comparison with FEA and NZSEE predictions," *International Journal of Masonry Research and Innovation*, 5(1):47–66.
- 34 Derakhshan, H., Nakamura, Y., Griffith, M.C. and Ingham, J. (2020). "Suitability of height amplification factors for seismic assessment of existing unreinforced masonry components," *Journal of Earthquake Engineering*, <https://doi.org/10.1080/13632469.2020.1716889>
- 35 Derakhshan, H., Nakamura, Y., Griffith, MC and Dhanasekar, M (2020). "Simplified calculation of roof accelerations in existing low-rise symmetric unreinforced masonry buildings with flexible diaphragms," *Bulletin of Earthquake Engineering*, (2020) 18:3383–3400, <https://doi.org/10.1007/s10518-020-00823-1>.
- 36 Howlader, MK, Masia, MJ and Griffith, MC (2020). "In-plane response of perforated unreinforced maonsry walls under cyclic loading – experimental study," ASCE, *Journal of Structural Engineering*, 146(6): [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0002657](https://doi.org/10.1061/(ASCE)ST.1943-541X.0002657).
- 37 Raza, S., Menegon, S. J., Tsang, H.H., Wilson, J. L. (2020a), "Force-displacement behaviour of limited ductile high-strength RC columns under bidirectional earthquake actions." *Engineering Structures*, vol. 208
- 38 Raza, S., Menegon, S. J., Tsang, H.H., Wilson, J. L. (2020b), "Collapse performance of limited ductile high-strength RC columns under uni-directional cyclic actions," *Journal of Structural Engineering*, Vol. 146(10), Article number 4020201, doi:10.1061/(ASCE)ST.1943-541X.0002772.
- 39 Raza, S., Menegon, S.J., Tsang, H.H. and Wilson, J.L., (2020c), "Axial Load Variation of Columns in Symmetrical RC Buildings Subject to Bidirectional Lateral Actions in Regions of Low to Moderate Seismicity", *Journal of Earthquake Engineering*, 1-29 doi:10.1080/13632469.2020.1772151.
- 40 Raza, S., Tsang, H.H., Menegon, S. J., Wilson, J. L. (2020d), "Generalized Loading Protocols for Experimentally Simulating Multi-Directional Earthquake Actions on Building Columns in Regions of Low to Moderate Seismicity," *Journal of Structural Engineering* (Under Review).
- 41 Hoult, R. D., Goldsworthy, H. M., & Lumantarna, E. (2020). Plastic hinge length for lightly reinforced C-shaped concrete walls. *Journal of Earthquake Engineering*, 24(7), 1083-1114.
- 42 Amirsardari, A., Lumantarna, E., Rajeev, P., & Goldsworthy, H. M. (2020). Seismic Fragility Assessment of Non-ductile Reinforced Concrete Buildings in Australia. *Journal of Earthquake Engineering*, 1-35.
- 43 Tang Y, Lam NTK, Tsang HH (2020) "A Computational Tool for Scaling Strong Motion Accelerograms Incorporating Regional Crustal Conditions" *Seismological Research Letters*
- 44 Yacoubian M, Looi D, Lam NTK, Wilson J (2020), "Seismic Response Modification Factors for buildings featuring a gravity transfer system by Incremental Dynamic Analyses", *Journal of Earthquake Engineering* (under review)
- 45 Tiwari R, Lam, NTK (2020), "Modelling of Seismic Actions in Earth Retaining Walls and Comparison with Shaker Table Experiment ", *Journal of Earthquake Engineering* (under review)
- 46 Hu Y, Lam NTK, Menegon S, Wilson J (2020), "The Selection and Scaling of Ground Motion Accelerograms For use in Stable Continental Regions" *Journal of Earthquake Engineering* (under review).
- 47 Lam, N., Tsang, H-H., Lumantarna, E. (accepted 2020, in press). "An Adaptive Ground Motion Prediction Equation for Use in Low-to-moderate Seismicity Regions," *Journal of Earthquake Engineering*.

## CONFERENCE PAPERS

- 1 Dizhur, D., Griffith, M.C. and Ingham, J.M. (2014). "Improvement of unreinforced masonry wall panels shear strength using NSM CFRP strips," Proceedings, 9th International Masonry Conference, Guimaraes, Portugal, 7-9 July 2014, 13p.
- 2 Derakhshan, H., Griffith, M.C. and Ingham, J.M. (2014). "A numerical model to assess the dynamic response of out-of-plane loaded one-way spanning URM walls connected to flexible diaphragms," Proceedings, 9th International Masonry Conference, Guimaraes, Portugal, 7-9 July 2014, 11p.
- 3 Hashemi, M. J., Al-Ogaidi, Yassamin, K. F., Wilson, J., Abdouka, K. (2014). "Collapse simulation of multi-story RC buildings through hybrid testing," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria.
- 4 Hashemi, M. J., Tsang, H. H., Menegon, S., Rajeev, P., Wilson, J. (2014). "Modelling 3D limited-ductile RC frame structures for collapse risk assessment," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria.



- 5 Hoult, R.D., Goldsworthy, H.M., Lumantarna, E. (2015). "Seismic assessment of non-ductile reinforced concrete C-shaped walls in Australia," Paper presented at the Eighth International Structural Engineering and Construction Conference, Sydney, Australia.
- 6 Hoult, R. D., Goldsworthy, H.M., Lumantarna, E. (2015). "Improvements and difficulties associated with the seismic assessment of infrastructure in Australia," Paper presented at the Australasian Fire and Emergency Service Authorities Council (AFAC) 2015 conference, Adelaide, South Australia.
- 7 Hoult, R.D., Goldsworthy, H.M. and Lumantarna, E. "Seismic Performance of Typical C-Shaped Reinforced Concrete Shear Cores in Australia," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria.
- 8 Hoult, R.D., Amirsardari, A., Sandiford, D., Lumantarna, E., Goldsworthy, H.M., Gibson, G. and Asten, M. "The 2012 Moe Earthquake and Earthquake Attenuation in South Eastern Australia," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria.
- 9 Hyeuk, R., Wehner, M. and Edwards, M. "Proposed Australian Building Stock Categorisation for Bushfire and Natural Hazards CRC Earthquake Project," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria
- 10 Lumantarna, E., Lam, N., Tsang, H.H., Wilson, J., Gad, E. and Goldsworthy, H. "Review of Methodologies for Seismic Vulnerability Assessment of Buildings," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria.
- 11 Nakamura, Y., Magenes, G. and Griffith, M. "Comparison of pushover methods for simple building systems with flexible diaphragms," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria.
- 12 Setiawan, B., Jaksa, M.B., Griffith, M.C. and Love, D. (submitted March 2015). "An Investigation of Local Site Effects in Adelaide: Learning from the Past," 6th International Conference on Earthquake Geotechnical Engineering, 1-4 November 2015, Christchurch, New Zealand.
- 13 Shahi, R., Lam, N.T.K., Gad, E.F., Saifullah, I., Wilson, J.L., Watsou, K. (2014). "Choice of intensity measure in incremental dynamic analysis," Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Victoria.
- 14 Tsang, H.H., Wilson J.L., Lam, N.T.K. (2015). Recommended Site Classification Scheme and Design Spectrum Model for Regions of Lower Seismicity. Proceedings of the Tenth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Pacific, 6-8 November 2015, Sydney, Australia.
- 15 Lam, N.T.K , Lumantarna, E., Goldsworthy, H., Tsang, H.H., Wilson, J.L., and Gad, E. (2015) Drift Demand Prediction of Gravitational Load Carrying Reinforced Concrete Frames in Australia Proceedings of the Tenth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Pacific, 6-8 November 2015, Sydney, Australia.
- 16 Goldsworthy, H.M., McBain, P., Somerville, P. (2015). Mitigation of seismic hazard in Australia by improving the robustness of buildings Proceedings of the Tenth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Pacific 6-8 November 2015, Sydney, Australia.
- 17 Derakhshan, H., Lucas, W., Griffith M. (2016). Flexural retrofit of brick cavity walls, 16th International Brick and Block Masonry Conference, Padua, Italy, 26 Jun 2016 - 30 Jun 2016.
- 18 Lucas, W., Visintin, P., Griffith, M.C. (2016). Long-term environmental effects on FRP-masonry bond. International Brick and Block Masonry Conference, Padua, Italy, 26 Jun 2016 - 30 Jun 2016.
- 19 Griffith MC, Derakhshan H, Vaculik J, Nakamura Y. (2016)."Recent developments in the seismic assessment of masonry buildings". Australian Earthquake Engineering Conference, Melbourne, 25 Nov 2016 - 27 Nov 2016. Editors: Anderson S . Proceedings of Australian Earthquake Engineering Conference.
- 20 Nakamura, Y., Derakhshan, H., Sheikh, H., Griffith, M., Ingham, J. (2016) Investigation of equivalent frame modelling for seismic analysis of unreinforced masonry building with flexible diaphragms. 24th Australasian Conference on the Mechanics of Structures and Materials (ACMSM24), 6-9 Dec 2016, Perth, Australia (Received F. Stan Shaw Award for best paper).
- 21 Mehdipanah, A. ; Lumantarna, E. ; Lam, N. T. K. ; Goldsworthy, H. ; Tsang, H. H. ; Wilson, J. L. ; Gad, E. ; 2016. Seismic vulnerability assessment of irregular reinforced concrete buildings in Australia, Mechanics of Structures and Materials XXIV: Proceedings of the 24th Australian Conference on the Mechanics of Structures and Materials (ACMSM24), Perth, Australia, 6-9 December 2016 / Hong Hao & Chunwei Zhang (eds.), pp. 1645-1651.
- 22 Zabihi, A. ; Tsang, H. H. ; Gad, E. ; Wilson, J. L. ; 2016. Analytical development of seismic retrofit technique for RC beam-column joint using single diagonal haunch, Mechanics of Structures and Materials XXIV: Proceedings of the 24th Australian Conference on the Mechanics of Structures and Materials (ACMSM24), Perth, Australia, 6-9 December 2016 / Hong Hao & Chunwei Zhang (eds.), pp. 1687-1692
- 23 Tsang, H. H. ; Lumantarna, E. ; Lam, N. T. K. ; Wilson, J. L. ; ; 2016. Annualised collapse risk of soft-storey building with precast RC columns in Australia, Mechanics of Structures and Materials XXIV: Proceedings of the 24th Australian Conference on the Mechanics of Structures and Materials (ACMSM24), Perth, Australia, 6-9 December 2016 / Hong Hao & Chunwei Zhang (eds.), pp. 1681-1686
- 24 Zabihi, Alireza ; Tsang, Hing-Ho ; Gad, Emad F. ; Wilson, John L. ; 2016. Retrofitting RC beam-column joint in australia using single diagonal haunch, Australian Earthquake Engineering Society 2016 Conference, Melbourne, Australia, 25-27 November 2016, paper no. 378
- 25 Lumantarna, E. ; Mehdipanah, A. ; Lam, N. ; Tsang, H. H. ; Wilson, J. ; Gad, E. ; Goldsworthy, H. ; 2016. Seismic vulnerability assessment of asymmetrical reinforced concrete buildings in Australia, Australian Earthquake Engineering Society 2016 Conference, Melbourne, Australia, 25-27 November 2016, paper no. 379
- 26 Tsang, H. H. ; Menegon, S. J. ; Lumantarna, E. ; Lam, N. T. K. ; Wilson, J. L. ; Gad, E. F. ; Goldsworthy, H. ; 2016. Framework for seismic vulnerability assessment of reinforced concrete buildings in Australia, Australian



- Earthquake Engineering Society 2016 Conference, Melbourne, Australia, 25-27 November 2016, paper no. 377
- 27 Lam, Nelson ; Tsang, Hing-Ho ; Looi, Daniel ; Lumantarna, Elisa ; Wilson, John ; 2016. Seismic hazard modelling for Malaysia, Australian Earthquake Engineering Society 2016 Conference, Melbourne, Australia, 25-27 November 2016, paper no. 386
- 28 Tang, Yuxiang ; Lam, Nelson ; Lumantarna, Elisa ; Tsang, Hing Ho ; 2016. Generation of synthetic earthquake accelerograms based on up-to-date seismological ground motion models, Australian Earthquake Engineering Society 2016 Conference, Melbourne, Australia, 25-27 November 2016, paper no. 336.
- 29 Mehdipanah, A. ; Lam, N.;Lumantarna, E. 2016. Analytical simulation of limited ductile RC beam-columns. Australian Earthquake Engineering Society 2016 Conference, Melbourne, Australia, 25-27 November 2016.
- 30 Derakhshan, H., Lucas, W. D., Griffith, M. C. (2017). 'Two-way cavity clay brick walls tested in-situ', 16th World Conference on Earthquake Engineering, 9-13 Jan, 2017, Santiago, Chile.
- 31 Menegon, S., Wilson, J., Lam, N., Gad, E. (2017). 'Experimental testing of limited ductile reinforced concrete building cores', 16th World Conference on Earthquake Engineering, 9-13 Jan, 2017, Santiago, Chile.
- 32 Hashemi, M.J., Tsang, H.H., Rajeev, P., Al-Mahaidi, R., Wilson, J.L., Gad, E. F.(2017). 'Reliable Collapse Risk Assessment through Hybrid Simulation', 16th World Conference on Earthquake Engineering, 9-13 Jan, 2017, Santiago, Chile.
- 33 Derakhshan, H., Nakamura, Y., Goldsworthy, H., Walsh, K.Q., Ingham, J.M., and Griffith, M.C. (2018). "Peak floor accelerations in unreinforced masonry buildings with flexible diaphragm", 10<sup>th</sup> Australasian Masonry Conference (10AMC), 11-14 February, Sydney.
- 34 Griffith, M.C., Derakhshan, H., Vaculik, J., Giaretton, M., Dizhur, D., Ingham, J. M. (2017). "Seismic Performance Expectations for Australian Unreinforced Masonry Buildings", Australian Earthquake Engineering Society (AEES) Conference, 24-26 November, Canberra.
- 35 Hoult, R. D., Goldsworthy, H. M., & Lumantarna, E. (2017). Seismic performance of lightly reinforced and unconfined c-shaped walls. In *Australian Earthquake Engineering Society 2017 Conference*.
- 36 Hoult, R. D., Goldsworthy, H. M., & Lumantarna, E. (2017). Seismic Assessment of the RC building stock of Melbourne from rare and very rare earthquake events. In *Australian Earthquake Engineering Society 2017 Conference*.
- 37 Amirsardari, A., Goldsworthy, H. M., Lumantarna, E., & Rajeev, P. Seismic fragility curves for limited ductile RC Buildings including the response of gravity frames. In *Australian Earthquake Engineering Society 2017 Conference*.
- 38 Mehdipanah, A., Lumantarna, E., & Lam, N. T. Methods of Structural Analysis of Buildings Incorporating Higher Modes Effects. In *Australian Earthquake Engineering Society 2017 Conference*.
- 39 Lumantarna, E., Mehdipanah, A., Lam, N., Wilson, J. (2017), "Methods of structural analysis of buildings in regions of low to moderate seismicity", 2017 World Congress on Advances in Structural Engineering and Mechanics, Seoul, Korea.
- 40 Yacoubian, M., Lam, N., Lumantarna, E., (2017), "Simplified design checks of buildings with a transfer structure in regions of lower seismicity", 2017 World Congress on Advances in Structural Engineering and Mechanics, Seoul, Korea.
- 41 Vaculik, J, Griffith, MC, Wehner, M & Edwards, M (2018). "Seismic assessment of URM buildings in a heritage-listed township," Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 42 Vaculik, J, Howlader, M, Masia, M, Ingham, J and Griffith, MC (2018). "Seismic capacity of heritage masonry buildings in Australia – a progress report," Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 43 Raza, S., Menegon, S.J., Tsang, H.H. & Wilson, J.L. (2018). "Experimental Testing of Limited Ductile High-Strength Reinforced Concrete Columns under Bi-Directional Cyclic Actions," Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 44 Raza, S., Menegon, S.J., Tsang, H.H., Wilson, J.L. (2018). "Experimental Testing Program to Investigate the Collapse Drift Capacity of Limited Ductile High-strength RC Columns," Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 45 Tsang, H.H., Daniell, J.E., Wenzel, F., Wilson, J.L. (2018). "The Risk of Being Killed by Earthquakes in Melbourne: A Preliminary Study," Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 46 Del Rey Dastillo, E., Kanitkar, R., Smith, S., Griffith, M.C. and Ingham, J.M. (2019). "Fan-to-sheet failure mode of FRP anchors," Proceedings, FRPRCS 14, Belfast, Ireland, June.
- 47 Tsang, HH, Daniell, JE and Wenzel, F (2018). "Earthquake safety requirements based on individual and societal fatality risk," Proceedings, European Earthquake Engingeering Conference, Thessaloniki, Greece.
- 48 Raza, S., Menegon, S.J., Tsang, H.-H., Wilson, J. L. (2018). "Experimental Testing Program to Investigate the Collapse Drift Capacity of Limited Ductile High-Strength RC Column", Proceedings of the 25th Australasian Conference on the Mechanics of Structures and Materials, ACMSM25, Brisbane, Australia.
- 49 Tang, Y., Lam, N., Tsang, H.-H. (2018). "A Review of GMPEs that Have Been Proposed for Use in South-eastern Australia by Comparison with MMI Data", Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 50 Hu, Y., Lumantarna, E., Lam, N., Menegon, S., Wilson, J. (2018), "Development of a Soil Site Ground Motion Database for Australian Seismic Structural Design", Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 51 Lumantarna, E., Lam, N., Tsang, H.-H., Wilson, J., Gad, E., Goldsworthy, H. (2018), "Fragility Curves for Limited Ductile Reinforced Concrete Buildings", Proceedings, Australian Earthquake Engineering Society Conference, Perth.
- 52 Howlader, M.K., Masia, M.J. and Griffith, M.C. (2019). "Parametric study of the behaviour of perforated



- URM walls under in-plane loading and comparison with NZSEE strength prediction formula," Proceedings of the 13th North American Masonry Conference, Salt Lake City, Utah, 16-19 June.
- 53 Raza, S., Menegon, S. J., Tsang, H. H., Wilson, J. L (2019d). "Experimental assessment of high-strength RC columns under different bi-directional loading protocols", Proceedings of the 2019 Pacific Conference on Earthquake Engineering, SkyCity, Auckland, New Zealand, 4-6 April 2019.
- 54 Gray, S., Martin, P., Edwards, M., Griffith, M.C. and Derakhshan, H. (2018). "Community strategy development for reducing earthquake risk in Western Australia," Proceedings, AFAC, Perth, Sept 5-8, 2019.
- 55 Raza, S., Tsang, H.H., Menegon, S. J., Wilson, J. L. (2020). "Experimental testing of limited ductile RC columns under varying triaxial loading protocols", 8th International Conference on Advances in Experimental Structural Engineering (8th AESE), Christchurch, New Zealand.
- 56 Ryu, H., Edwards, M., Wehner, M., Gray, S., Griffith, M., Vaculik, J., Corby, N. and Allen, T. (2019). "Earthquake Management Logistics for York, WA, Pre and Post Mitigation" Proceedings, AEES Conference, Newcastle, NSW
- 57 Raza, S., Tsang, H.H., Menegon, S. J., Wilson, J. L. (2019). "Influence of loading history on the drift capacity of limited ductile reinforced concrete columns", Proceedings, AEES Conference, Newcastle, NSW.
- 58 Lumantarna, E., Lam, N.T.K., Wilson, J. (2019). "Predicting Maximum Displacement Demand of Asymmetric Reinforced Concrete Buildings", Proceedings, AEES Conference, Newcastle, NSW.
- 59 Xing, B., Lumantarna, E., Lam, N.T.K., Menegon, S. (2019). "Prioritisation strategy for seismic retrofitting of reinforced concrete buildings in Australia", Proceedings, AEES Conference, Newcastle, NSW."
- 60 Hu, Y., Lam, N.T.K., Menegon, S. (2019). "Ground Motion Accelerograms for Nonlinear Time History Analysis in Low-to-Moderate Seismicity Regions", Proceedings, AEES Conference, Newcastle, NSW.
- 61 Alazem, R., Lumantarna, E., Lam, N.T.K., Menegon, S. (2019). "Development of Cost-effective Mitigation Strategy for Limited Ductile Reinforced Concrete Buildings", Proceedings, AEES Conference, Newcastle, NSW.
- 62 Hoult, R., Appelle, A., Almeida, P. P., Beyer, K. (2019). "Experimental Tests of Thin RC U-shaped Walls with a Single Layer of Reinforcement", Proceedings, AEES Conference, Newcastle, NSW.
- 63 Menegon, S.J., Wilson, J. L., Lam, N.T.K., Gad, E.F. (2019). "Review of confinement requirements for the seismic design of rectangular RC walls in Australia", Proceedings, AEES Conference, Newcastle, NSW.
- 64 Tsang, H.H., Daniell, J.E., Wenzel, F., Wilson, J. L. (2019). "How Safe is Safe Enough? Melbourne Case Study", Proceedings, AEES Conference, Newcastle, NSW.
- 65 Edwards, M., Wehner, M., Ryu, H., Griffith, MC and Vaculik, J (2019). "Modelling the vulnerability of old URM buildings and the benefit of retrofit," Proceedings, Australian Earthquake Engineering Society Conference, Newcastle, Paper No. 2.
- 66 Nie, Y., Sheikh, A., Griffith, MC, Visintin, P and Vaculik, J nd (2019). "The application of mixed-mode de-cohesion criteria in masonry finite element analysis," Proceedings, Australian Earthquake Engineering Society Conference, Newcastle, Paper No. 60.
- 67 Vaculik, J and Griffith, MC (2019). "Out-of-plane fragility of URM parts and components based on time-history analysis – comparison to simplified force-based approaches," Proceedings, Australian Earthquake Engineering Society Conference, Newcastle, Paper No. 62.
- 68 Burton, C., Vaculik, J., Visintin, P., Griffith, MC and Sheikh, A (2019). "Pull out capacity of chemical and mechanical anchors in clay masonry under quasi-static, cyclic and impact loading," Proceedings, Australian Earthquake Engineering Society Conference, Newcastle, Paper No. 63.
- 69 Lam, N. (2019). "Earthquake engineering in areas away from tectonic plate boundaries". Proceedings, Computational Mechanics and Simulation, IIT Mandi, India.
- 70 Lumantarna E, Lam N, Menegon S, Wilson J (2020), "Simplified approach for multi-storey asymmetrical buildings in regions of low to moderate seismicity". Australasian Structural Engineering Conference 2020.
- 71 Alazem R, Lumantarna E, Lam N, Menegon S (2020), "Modelling Techniques for Seismic Analysis of Limited Ductility RC Buildings", Proceedings of Australian Earthquake Engineering Society Conference
- 72 Xing B, Lumantarna E, Lam N, Menegon S (2020), "Evaluation of torsional effects on reinforced concrete buildings due to the excitation of an earthquake", Proceedings of Australian Earthquake Engineering Society Conference

## CONFERENCE POSTERS

- 1 Setiawan, B., Jaksa, M., Griffith, M., and Love, D. (2015) Application of the single microtremor method to Adelaide's regolith. Australasian Fire and Emergency Service Authorities Council (AFAC) Conference, 1-3 Sep 2015, Adelaide, South Australia.
- 2 Lumantarna, E., Tsang, H.H., Lam, N.T.K., Wilson, J., Gad, E., and Goldsworthy, H. (2015) Seismic vulnerability assessment of buildings in Australia. Australasian Fire and Emergency Service Authorities Council (AFAC) Conference, 1-3 Sep 2015, Adelaide, South Australia.
- 3 Hoult, R., Goldsworthy, H., Lumantarna, E. (2015) Seismic assessment and design philosophy of reinforced concrete walls in Australia. Australasian Fire and Emergency Service Authorities Council (AFAC) Conference, 1-3 Sep 2015, Adelaide, South Australia.
- 4 Lumantarna, E., Mehdipanah, A., Lam, N.T.K., Tsang, H.H., Wilson, J., Gad, E., Goldsworthy, H. (2016). "Seismic vulnerability assessment of irregular reinforced concrete buildings in Australia". Poster presented at the Australasian Fire & Emergency Service Authorities Council (AFAC) conference, Brisbane, Australia, 30 Aug – 01 Sep 2016.
- 5 Hoult, R., Goldsworthy, H., Lumantarna, E. (2016). "Secondary cracking for a ductile performance in reinforced concrete walls". Poster presented at the Australasian Fire & Emergency Service Authorities Council (AFAC) conference, Brisbane, Australia, 30 Aug – 01 Sep 2016.



## BOOK CHAPTERS

- 1 Lumantarna, E., MehdiPanah, A., Lam, N., Wilson, J. (2018), Chapter 4, Structural Analysis, in Guideline on Design of Buildings and Structures in Low-to-Moderate Seismicity Countries, CNERC.
- 2 Raza, S, Tsang, HH, Menegon, SJ, Wilson, JL (2019). "Seismic performance assessment of reinforced concrete columns in regions of low to moderate seismicity," In: Resilient Structures and Infrastructure, (Eds.) Noroozinejad Farsangi, E, Takewaki, I, Yang, TY, Astaneh-Asl, A & Gardoni, P, Springer Nature, Singapore, pp 269-286.

## TECHNICAL REPORTS

- 1 Edwards, M., Itismita, M., Hyeuk, R., Wehner, M. (2016). Preliminary Report on Economic Loss Modelling. Report No. 164.2016 (May). Published by Bushfire and Natural Hazards CRC.
- 2 Griffith, M., Lucas, W. (2016). Economic Loss Modelling of Earthquake Damaged Buildings. Report No. 2016.158 (February). Published by Bushfire and Natural Hazards CRC.
- 3 Lucas, W., Derakhshan, H., Griffith, M. (2016). Draft report on in-situ testing in unreinforced masonry buildings in Adelaide (1327, 1357, 1443 and 1451 Main South Road). School of Civil, Environmental, and Mining Engineering. University of Adelaide.
- 4 Mohanty, I., Edwards, M., Hyeuk, R., Wehner, M. (2016). "Final Report on Economic Loss Modelling". Published by Bushfire and Natural Hazards CRC (September 2016). Melbourne. Australia.
- 5 Derakhshan, H., Lucas, W., Visintin, P., Griffith, M. (2016). "Final Report on Seismic Retrofit Tests of URM Cavity Walls". Published by Bushfire and Natural Hazards CRC (December 2016). Melbourne. Australia.
- 6 Derakhshan, H., Lucas, W., Griffith, M. (2017). "Final Report on In-situ Testing in Unreinforced Masonry Buildings in Adelaide (1327, 1357, 1443 and 1451 Main South Road)". School of Civil, Environmental, and Mining Engineering. University of Adelaide.
- 7 Mohanty, I., Edwards, M., Hyeuk, R., Wehner, M. (2018). "Final report on business resilience models". Submitted to Bushfire and Natural Hazards CRC (February 2018). Melbourne. Australia.
- 8 Lumantarna, E., Tsang, H.H. (2017). "Final report on limited ductile reinforced concrete buildings drift-damage relationships". Published by Bushfire and Natural Hazards CRC (October 2017). Melbourne. Australia.
- 9 Lumantarna, E., Tsang, H.H., Goldsworthy, H., Lam, N., Gad, E., and Wilson, J. (2018). "Final report on fragility curves for limited ductile reinforced concrete buildings". Submitted to Bushfire and Natural Hazards CRC (February 2018). Melbourne. Australia.
- 10 Derakhshan, H., Griffith, M. (2018). "Final Report on drift-damage relationships for unreinforced masonry buildings". Submitted to Bushfire and Natural Hazards CRC (February 2018). Melbourne. Australia.
- 11 Derakhshan, H., Griffith, M. (2018). "Final Report on fragility curves for unreinforced masonry buildings". Submitted to Bushfire and Natural Hazards CRC (June 2018). Melbourne. Australia.
- 12 Wehner, M, Ryu, H, Griffith, M, Edwards, M, Corby, N, Mohanty, I, Vaculik, J and Allen, T (2020). "Earthquake mitigation of WA regional towns – York Case Study: Final Report," BNH CRC Report, 192p.



## TEAM MEMBERS

### RESEARCHERS

University of Adelaide:	Prof M Griffith (Project Leader), Prof M Jaksa, Assoc Prof AH Sheikh, Dr MMS Ali, Dr A Ng, Dr P Visintin
University of Melbourne:	Prof NTK Lam, Assoc Prof Helen Goldsworthy (retired)
Swinburne University:	Prof J Wilson, Prof E Gad, Assoc Prof HH Tsang
Geoscience Australia:	Mr M Edwards, Dr H Ryu, Mr M. Wehner

### CRC FUNDED POST-DOC RESEARCHERS (1.2 FTE)

University of Adelaide:	Dr Hossein Derakhshan/Dr Jaroslav Vaculik
University of Melbourne:	Dr E Lumantarna

### STUDENTS (1.0 FTE)

University of Adelaide:

- Yu Nie: Nonlinear finite element analysis of URM walls
- Chris Burton: Seismic retrofit of URM parapets

University of Melbourne:

- Bin Xing: Prioritisation strategy for seismic retrofitting of limited ductile reinforced concrete buildings in Australia
- Raneem Al Azeem: Seismic retrofit options for limited ductile RC buildings

Swinburne University:

- Scott Menegon: Seismic collapse behaviour of non-ductile RC walls
- Yassamin K Faiud Al-Ogaidi: FRP retrofit for non-ductile RC frames
- Alireza Zabihi: Seismic retrofit of RC beam-column joints
- Saim Raza: Collapse behavior of high-strength reinforced concrete columns in low to moderate seismic regions

### END-USERS

End-user organisation	End-user representative	Extent of engagement (Describe type of engagement)
Geoscience Australia	Leesa Carson	High level of engagement



Department of Fire and Emergency Services, WA	Damien Pumphrey	High level of engagement
York Shire Council	Paul Martin	High level of engagement



## PUBLICATIONS LIST

- 1 Multi-Hazard Mitigation Council (2019). "Natural Hazard Mitigation Saves," Principal Investigator K. Porter National Institute of Building Sciences, Washington, DC, [www.nibs.org](http://www.nibs.org).
- 2 ASCE [American Society of Civil Engineers] (2014). Seismic evaluation and retrofit of existing buildings. ASCE 41-13, Reston, Virginia.
- 3 AS [Australian Standards] (2007). AS 1170.4-2007 *Structural design actions, Part 4: Earthquake actions in Australia*. Sydney: Standards Australia.
- 4 Zabihi, A. et al., 2016a. Analytical development of seismic retrofit technique for RC beam-column joint using single diagonal haunch. In Mechanics of Structures and Materials: Advancements and Challenges. CRC Press, pp. 1687–1692.
- 5 Zabihi, A. et al., 2016b. Retrofitting RC beam-column joint in Australia using single diagonal haunch. In 2016 Australian Earthquake Engineering Society's (AEES) annual conference.
- 6 New Zealand Ministry of Business, Industry and Employment, 2018. "Guidance - Securing parapets and facades on unreinforced masonry buildings".



## APPENDIX A – DETAILS OF COSTING

Eccentric Bracing														
DETAIL	Qty	Unit	Rate					Cost					Comments	References
			Adel.	Bris.	Mel.	Per.	Syd.	Adel.	Bris.	Mel.	Per.	Syd.		
<b>Demolition</b>														
Demolition of stud partition with plasterboard both sides	11	sqm	\$14.20	\$10.35	\$12.55	\$14.70	\$13.15	\$156.20	\$113.85	\$138.05	\$161.70	\$144.65		Pg. 206. 2016 Rawlinson's Construction Handbook Ed 34
Disposal of General Waste	0.5	tonne	\$50.00	\$80.00	\$120.00	\$90.00	\$340.00	\$25.00	\$40.00	\$60.00	\$45.00	\$170.00	Accounts for disposal of demolished partition wall and further construction waste.	Pg. 213. 2016 Rawlinson's Construction Handbook Ed 35
<b>Installation</b>														
Drilling for hold-down bolts to connect bracing system to the existing structural component	540	10mm	\$2.35	\$2.00	\$2.10	\$3.35	\$3.00	\$1,269.0	\$1,080.0	\$1,134.0	\$1,809.0	\$1,620.0	Costs were accounted for 16 150mm long hold-down bolts for each beam/column joint and 4 150mm long hold down bolt for the shear connection.	
High Strength Steel Friction Bolts - M20 x 150mm	36	no.	\$3.30	\$3.30	\$3.30	\$3.30	\$3.30	\$118.80	\$118.80	\$118.80	\$118.80	\$118.80		Pg. 286. 2016 Rawlinson's Construction Handbook Ed 35



Supply and erect 150 UB 14.0	0.10	t	\$4,950	\$5,550	\$4,850	\$6,050	\$5,250	\$495.00	\$555.00	\$485.00	\$605.00	\$525.00		Pg. 247. 2016 Rawlinson's Construction Handbook
Reinstatement (Optional)													Reinstatement is able to completely cover the retrofit technique. It is not required in all cases.	
Stud Framed Wall - 100 x 50mm Studs @ 600mm c/c	11	sqm	\$42.20	\$60.60	\$49.40	\$54.10	\$61.60	\$464.20	\$666.60	\$543.40	\$595.10	\$677.60		Pg. 133. 2016 Rawlinson's Construction Handbook
Insulation R1.5	11	sqm	\$13.55	\$16.25	\$14.85	\$15.75	\$17.00	\$149.05	\$178.75	\$163.35	\$173.25	\$187.00		Pg. 134. 2016 Rawlinson's Construction Handbook
Plasterboard 1 x 13mm thick (Not Fire-rated)	22	sqm	\$36.80	\$32.00	\$29.40	\$35.20	\$21.20	\$809.60	\$704.00	\$646.80	\$774.40	\$466.40		Pg. 135. 2016 Rawlinson's Construction Handbook
Painting (Two coats, water repelling)	22	sqm	\$18.55	\$17.20	\$16.10	\$16.85	\$13.50	408.1	378.4	354.2	370.7	297		Pg. 442. 2016 Rawlinson's Construction Handbook

Totals:      \$3,895      \$3,835      \$3,644      \$4,653      \$4,206

RC Infill Wall														
DETAIL	Qty	Unit	Rate					Cost					Comments	References
			Adel.	Bris.	Mel.	Per.	Syd.	Adel.	Bris.	Mel.	Per.	Syd.		
Demolition														



Demolition of stud partition with plasterboard both sides	11	sqm	\$14.20	\$10.35	\$12.55	\$14.70	\$13.15	\$156.2	\$113.8	\$138.0	\$161.7	\$144.6		Pg. 206. 2016 Rawlinson's Construction Handbook Ed 34
Disposal of General Waste	0.5	tonne	\$50.00	\$80.00	\$120.0	\$90.00	\$340.0	\$25.00	\$40.00	\$60.00	\$45.00	\$170.0	Accounts for disposal of demolished partition wall and further construction waste.	Pg. 213. 2016 Rawlinson's Construction Handbook Ed 35
Installation													Reinforcement details will change depending on the strength required. For the model, One layer of SL81 and N20 round bar at 200mm c/c	
Steel Mesh SL81	11	sqm	\$19.45	\$22.40	\$25.00	\$19.60	\$23.40	\$213.9	\$246.4	\$275.0	\$215.6	\$257.4		Pg. 247. 2016 Rawlinson's Construction Handbook
N20 Round Bar	4.39	t	\$2,150	\$2,140	\$2,205	\$2,155	\$2,315	\$9,438	\$9,394	\$9,679	\$9,460	\$10,162		Pg. 247. 2016 Rawlinson's Construction Handbook
Drilling for Stater Bars (200mm c/c) to connect to existing	1000	10mm	\$2.35	\$2.00	\$2.10	\$3.35	\$3.00	\$2,350	\$2,000	\$2,100	\$3,350	\$3,000		



Stater Bars (200mm c/c) to connect to existing	0.02	t	\$2,150	\$2,140	\$2,205	\$2,155	\$2,315	\$43.00	\$42.80	\$44.10	\$43.10	\$46.30		
Formwork Installation for wall (200/300mm Thick)	11	sqm	\$194.0	\$189.0	\$214.0	\$193.0	\$220.0	\$2,134	\$2,079	\$2,354	\$2,123	\$2,420		Pg. 245. 2016 Rawlinson's Construction Handbook
Reinforced Concrete wall 130 - 300mm thick (Delivery and Placement of concrete)	4	cum	\$303.0	\$299.0	\$278.0	\$317.0	\$359.0	\$1,212	\$1,196	\$1,112	\$1,268	\$1,436		Pg. 235. 2016 Rawlinson's Construction Handbook
Additional for 32Mpa	4	cum	\$7.55	\$5.40	\$9.70	\$7.55	\$5.40	\$30.20	\$21.60	\$38.80	\$30.20	\$21.60		Pg. 236. 2016 Rawlinson's Construction Handbook
<b>Reinstatement</b>														
Painting (Two coats, water repelling)	22	sqm	\$18.55	\$17.20	\$16.10	\$16.85	\$13.50	\$408.1	\$378.4	\$354.2	\$370.7	\$297.00		Pg. 442. 2016 Rawlinson's Construction Handbook

**Totals:**    \$16,011    \$15,513    \$16,156    \$17,068    \$17,956

<b>FRP Jacketing</b>														
DETAIL	Qty	Unit	Rate				Cost				Comments		References	



			Adel.	Bris.	Mel.	Per.	Syd.	Adel.	Bris.	Mel.	Per.	Syd.		
<b>Demolition</b>														
Demolition of stud partition with plasterboard around column (4 walls in model)	34	sqm	\$14.2	\$10.3	\$12.5	\$14.7	\$13.1	\$482.80	\$351.90	\$426.70	\$499.80	\$447.10	Further demolition of the plasterboard is required but simple to remove by hand.	Pg. 206. 2016 Rawlinson's Construction Handbook Ed 34
Disposal of General Waste	0.5	tonne	\$50.0	\$80.0	\$120	\$90.0	\$340	\$25.00	\$40.00	\$60.00	\$45.00	\$170.00	Accounts for disposal of demolished partition wall and further construction waste.	Pg. 213. 2016 Rawlinson's Construction Handbook Ed 35
<b>Installation</b>														
Supply and Install CFRP 150mm thickness (Wrapped 3 times)	91	m	\$220	\$220	\$225	\$215	\$225	\$20,020	\$20,020	\$20,475	\$19,565	\$20,475	FRP wrappings has been modelled to be wrapped 3 times for the whole length of the columns. CFRP wrapping most commonly comes in 150mm strips.	Pg. 249. 2016 Rawlinson's Construction Handbook Ed 35
<b>Reinstatement</b>														



Stud Framed Wall - 100 x 50mm Studs @ 600mm c/c	34	sqm	\$42.2	\$60.6	\$49.4	\$54.1	\$61.6	\$1,434.8	\$2,060.4	\$1,679.6	\$1,839.4	\$2,094.4		Pg. 133. 2016 Rawlinson's Construction Handbook Ed 35
Insulation R1.5	34	sqm	\$13.5	\$16.2	\$14.8	\$15.7	\$17.0	\$460.70	\$552.50	\$504.90	\$535.50	\$578.00		Pg. 134. 2016 Rawlinson's Construction Handbook Ed 35
Plasterboard 1 x 13mm thick (Not Fire-rated)	68	sqm	\$36.8	\$32.0	\$29.4	\$35.2	\$21.2	\$2,502.4	\$2,176.0	\$1,999.2	\$2,393.6	\$1,441.6		Pg. 135. 2016 Rawlinson's Construction Handbook Ed 35
Painting (Two coats, water repelling)	68	sqm	\$18.5	\$17.2	\$16.1	\$16.8	\$13.5	1261.4	1169.6	1094.8	1145.8	918		Pg. 442. 2016 Rawlinson's Construction Handbook Ed 35

Totals:    \$26,187    \$26,370    \$26,240    \$26,024    \$26,124

Steel Jacketing														
DETAIL	Qty	Unit	Rate					Cost					Comments	References
			Adel.	Bris.	Mel.	Per.	Syd.	Adel.	Bris.	Mel.	Per.	Syd.		
Demolition														
Demolition of stud partition with plasterboard around column (4 walls in model)	34	sqm	\$14.20	\$10.35	\$12.55	\$14.70	\$13.15	\$482.80	\$351.90	\$426.70	\$499.80	\$447.10	Further demolition of the plasterboard is required but simple to remove by hand.	Pg. 206. 2016 Rawlinson's Construction Handbook Ed 34



Disposal of General Waste	0.5	tonne	\$50.00	\$80.00	\$120.0	\$90.00	\$340.0	\$25.00	\$40.00	\$60.00	\$45.00	\$170.00	Accounts for disposal of demolished partition wall and further construction waste.	Pg. 213. 2016 Rawlinson's Construction Handbook Ed 35
Installation														
Supply and Installation of steel Plates	6.1	t	\$1,325	\$1,300	\$1,300	\$1,385	\$1,325	\$8,082	\$7,930	\$7,930	\$8,448	\$8,082	The steel jacket has been modelled to cover the entire column with 40mm plates.	Pg. 282. 2016 Rawlinson's Construction Handbook Ed 35
On-Site Welding (12mm Fillet Weld)	50.2	m	\$104.0	\$100.5	\$103.5	\$104.0	\$119.0	\$5,220	\$5,045	\$5,195	\$5,220	\$5,973	The plates will have to procure in smaller sections as full-length sections would be too heavy and difficult to install. Assumed that the plate will be procured in three lengths to meet	Pg. 287. 2016 Rawlinson's Construction Handbook Ed 35



														height of the column.	
<b>Reinstate ment</b>															
Stud Framed Wall - 100 x 50mm Studs @ 600mm c/c	34	sqm	\$42.20	\$60.60	\$49.40	\$54.10	\$61.60	\$1,434	\$2,060	\$1,679	\$1,839	\$2,094		Pg. 133. 2016 Rawlinson's Construction Handbook Ed 35	
Insulation R1.5	34	sqm	\$13.55	\$16.25	\$14.85	\$15.75	\$17.00	\$460.70	\$552.50	\$504.90	\$535.50	\$578.00		Pg. 134. 2016 Rawlinson's Construction Handbook Ed 35	
Plasterboa rd 1 x 13mm thick (Not Fire-rated)	68	sqm	\$36.80	\$32.00	\$29.40	\$35.20	\$21.20	\$2,502	\$2,176	\$1,999	\$2,393	\$1,441		Pg. 135. 2016 Rawlinson's Construction Handbook Ed 35	
Painting (Two coats, water repelling)	68	sqm	\$18.55	\$17.20	\$16.10	\$16.85	\$13.50	1261.4	1169.6	1094.8	1145.8	918		Pg. 442. 2016 Rawlinson's Construction Handbook Ed 35	

Totals:      \$19,470      \$19,326      \$18,891      \$20,128      \$19,705