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COST-EFFECTIVE MITIGATION STRATEGY DEVELOPMENT FOR BUILDING RELATED EARTHQUAKE RISK

Annual project report 2015-2016

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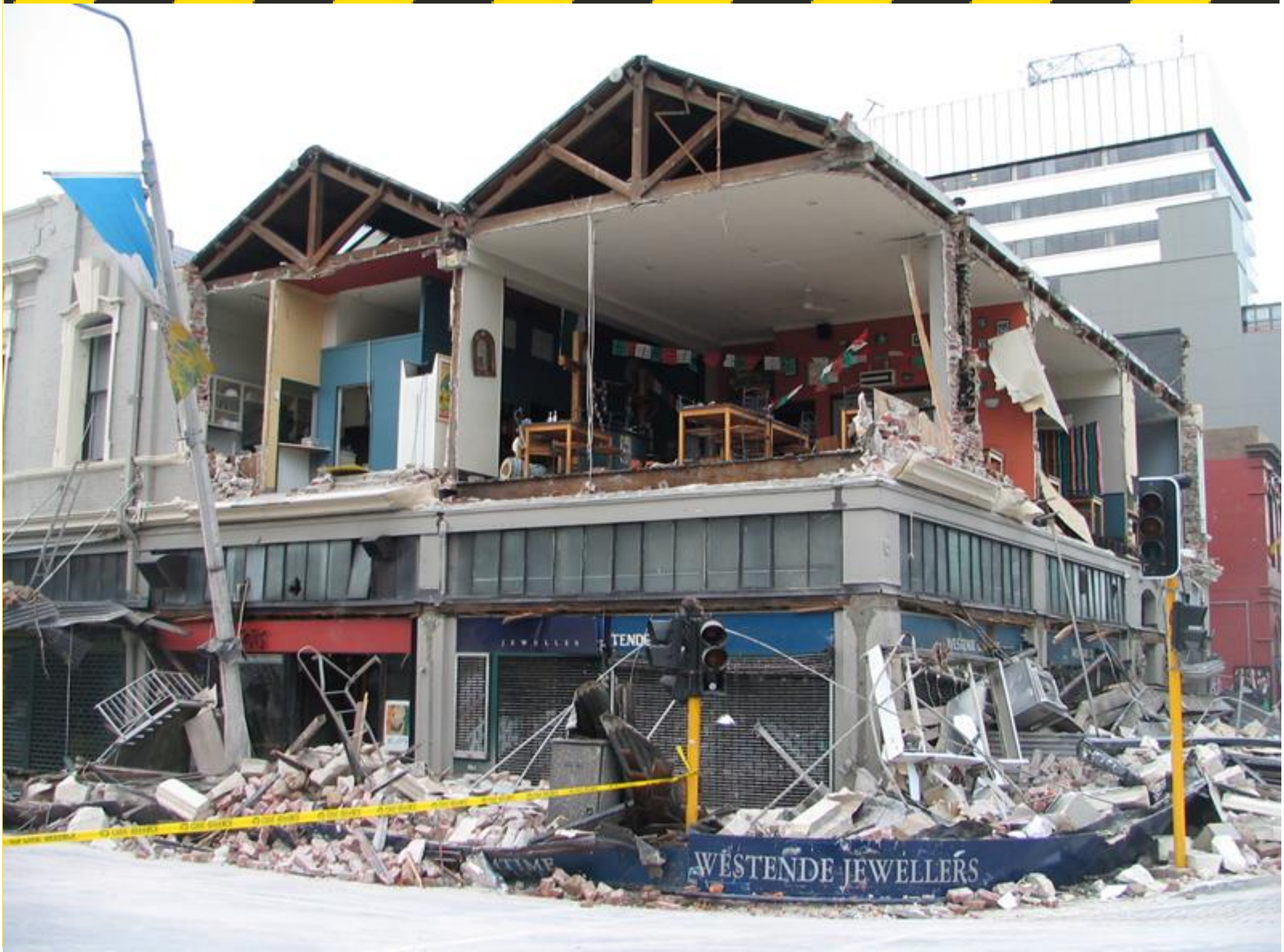

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Cover: Christchurch earthquake damage, Sept 2009, courtesy of MC Griffith

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EXECUTIVE SUMMARY

The seismic risk posed by earthquakes to buildings in our major cities in Australia is significant with the world insurance market rating a modest magnitude 6 earthquake occurring in Sydney to be in their world's top 10 of financial risks. A major reason for this is that Australia had not designed buildings for earthquake-induced forces until 1995, so a large portion of our building stock is seismically vulnerable. As demonstrated in Christchurch New Zealand in 2010-11, a magnitude 6 earthquake can have a devastating impact on a city and country (damage rebuild estimated at ~ 20% national GDP) even though buildings there have been designed for earthquakes for many decades.

This project will investigate:

1) The relative vulnerabilities to earthquake shaking of the most common forms of building construction in Australia;

2) What earthquake retrofit techniques worked and what didn't work in Christchurch as a starting point to developing a 'menu' of economically feasible seismic retrofit techniques that could be used in Australian cities; and

3) With industry end-user support, conduct proof of concept tests on some of the most promising seismic retrofit techniques on buildings scheduled for demolition by the South Australian state government;

4) Use the new damage and economic loss models developed over the first 3 years of this project to undertake a seismic risk assessment case study of the Melbourne metro area. In conjunction with the new damage loss models and costings for seismically retrofitting buildings, make recommendations for the development of seismic retrofit guidelines and policy based on the strong evidence base developed.

5) Advance a series of end user focused research utilisation projects in the areas of improved building regulation, community risk reduction, design profession guidance and insurance industry engagement with their policy holders.

This information will then be fed into a 'decision support tool' being developed in the Bushfire and Natural Hazards CRC project "*Decision support system for assessment of policy and planning investment options for optimal natural hazard mitigation*" that will be used by end users to develop consistent national policies for the application of seismic design of new buildings and retrofit of existing buildings.

END USER STATEMENT

Leesa Carson, *Geoscience Australia, Commonwealth*
The most vulnerable building types to earthquake in our community are unreinforced masonry and low ductility reinforced concrete frames. The focus of the project this year has been in-situ testing of unreinforced clay brick masonry, thanks to the support of the South Australian Government who allowed access to houses that were planned for demolished. The project is also focused on three types of reinforced concrete structures, undertaking seismic vulnerability assessment.

At the October 2015 workshop and November 2015 RAF key project members engaged to re-focus the project team's attention to objectives of the project and identified end users, in particular industry groups, to engage with the project. The project team has revised the scope of the project with key end users to ensure that the project is aligned to achieve the desired practical outcomes.

Research aspects of the project are progressing with a number of publications and conference presentations on preliminary results.

The project has delivered its scheduled outputs. The progress report on economic loss modelling of earthquake damaged buildings has been submitted, however is being converted to a BNHCRC report for general release.

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 with Geoscience Australia experts all working towards seismic risk reduction in Australia. Most of the research team are 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 earthquakes in the Christchurch region on the New Zealand economy and society has further motivated this group to contribute to this CRC's aims of risk reduction for all natural hazards in Australia.

PROJECT BACKGROUND

The project will address the need for an evidence base to inform decision making on the mitigation of the risk posed by the most vulnerable Australian buildings subject to earthquakes. 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 Newcastle Earthquake of 1989, the Kalgoorlie Earthquake of 2010 and with similar building types in the Christchurch earthquake. 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 centres.

The two most vulnerable building types that contribute disproportionately to community risk are unreinforced masonry and low ductility reinforced concrete frames. The damage to these will not only lead to direct repair costs but also to injuries and disruption to economic activity.

This research project will draw upon and extend existing research and capability within both academia and government to develop information that will inform policy, business and private individuals on their decisions concerning reducing vulnerability. It will also draw upon New Zealand initiatives that make use of local planning as an instrument for effecting mitigation.

Findings from the New Zealand Royal Commission on the Christchurch earthquake will also be used and opportunities for insurance industry linkages will be explored such as with the Insurance Council of Australia Building Resilience Rating Tool development by the consultant Edge Environment (http://buildingresilience.org.au/). The latter aims, in part, to ultimately provide metrics to support insurance premium incentives but does not presently include earthquake.

WHAT THE PROJECT HAS BEEN UP TO

CONFERENCE AND WORKSHOP ATTENDANCE

AFAC'15 – Wade Lucas, Elisa Lumantarna, Ryan Hoult, Mark Edwards and Michael Griffith attended with 3 posters and papers (Elisa, Ryan and Bamang Setiawan) and an oral presentation by Ryan Hoult.

PCEE'15 - Researchers from all participating institutions (GA, Swinburne Uni, Melbourne Uni and Adelaide Uni) attended the 2015 Pacific Earthquake Engineering Conference in Sydney (held in parallel with the Australian Earthquake Engineering Society conference). As part of this event researchers involved in this project presented many papers on their work - the 3 presented papers relevant to this project and the CRC are listed below.

Project workshop (23 October) – a workshop of researchers was held in Melbourne at Swinburne University where each group presented overviews of the CRC related research conducted on each 'campus' up to that time. The workshop then revisited the original aims of the project and wrapped up by noting the progress made against each aim and clarified responsibilities for research deliverables amongst the project team. Finally, it foreshadowing potential revisions to the project's scope and issues to pursue in collaboration with end uses through follow-on research.

RAF'15 (November) – the Research Advisory Forum in Brisbane was attended by Michael Griffith, Mark Edwards and Hing-Ho Tsang. Good interaction with the other cluster groups and end users was achieved. Significantly, much discussion focused on identifying appropriate end users to facilitate the transfer of research outcomes to application in Australia.

IB^{2}MaC (June 2016) – the International Brick-Block Masonry Conference is held once every four years with Griffith and Derakhshan from the University of Adelaide attending this year to present 3 papers on their research into the seismic capacity of brick masonry construction.

IN-SITU TESTING OF UNREINFORCED CLAY BRICK MASONRY HOUSES

With the support of the Department of Planning, Transport and Infrastructure, South Australia, we have been allowed access to test 8 brick cavity walls and 3 chimneys in four houses that have since been demolished as part of the government's South Road Corridor project. Furthermore, the cyclonic wind hazard project researchers have also been able to collect data and test samples from these houses for their project. The results of our wall and chimney tests will be published in reports to the CRC as well as selected journal and conference papers in the coming year. We anticipate that we will be given similar access in the coming year to some small commercial buildings that will be demolished for road widening purposes. In these future tests, commercial organisations will be invited to apply their techniques as seismic strengthening options for us to test as 'proof of concept' demonstrations to the engineering profession to enhance rapid take-up of the technologies for seismic risk mitigation in the future.

REINFORCED CONCRETE STRUCTURES

Types of Buildings Considered

The project team decided that three broad types of reinforced concrete (RC) structures will be considered in the project:

1. Building with soft-storey that will collapse by column or beam-column joint failure, especially those without walls at the soft-storey level. They can be further classified into two construction types, namely, precast column and in-situ column.
2. Building with walls as major lateral load resisting systems, including singly-reinforced wall panels.
3. Building with both MRF and walls as lateral load resisting systems, including those with significant discontinuity (or offset) of gravitational load carrying elements.

Definition of Performance Levels for Vulnerability Assessment

Four structural damage levels, namely, Slight, Moderate, Extensive and Complete, are adopted. The definition and detailed description of each damage state have been consolidated from various seismic assessment guidelines (e.g., SEAOC, 1995; ASCE, 2000; ATC, 2003; CEN, 2004) with the considerations of Australian conditions, as summarised in the Table below.

Performance Level	***Terminology***	***Description***	***F-Δ Behaviour***
1	Slight Damage Immediate Occupancy Operational Serviceability	Minimal damage may be observed with this performance level, however the damage and subsequent repairs should not affect the operational capacity of the facility. Hairline cracks are expected. The structural response should be such that concrete compressive strains are within the elastic zone of the stress-strain curve and reinforcement tensile strains are associated with minimal inelastic behaviour.	Close to Linear Elastic Design Lateral Strength
2	Moderate Damage Repairable Damage Damage Control Damage Limitation	The structure has reached their yield capacity indicated by large cracks and some concrete spalling. The amount of damages is limited and the building is repairable following the event. Limited inelastic behaviour is allowed in both concrete and reinforcement.	Effective Yield True Yield Strength
3	Extensive Damage Life Safety No Collapse (EC8)	The structure has reached its ultimate lateral strength capacity indicated by large cracks, spalled concrete and buckled main reinforcement. The building is non-repairable following the event. Very serious damage may have occurred but the structure has not collapsed and loss of life should be prevented. Inelastic behaviour are expected in both concrete and reinforcement.	Peak Lateral Strength

4	Complete Damage Collapse Prevention Near Collapse Partial Collapse	The building has low residual lateral strength and stiffness. There could be excessive permanent lateral deformation or brittle failure of certain critical structural components, or loss of stability of part of the structure. Parts of the structure has collapsed or are in imminent danger of collapse. The degree or proportion of collapse depends on the robustness of the structure and the intrinsic properties of the construction materials.	Ultimate Drift

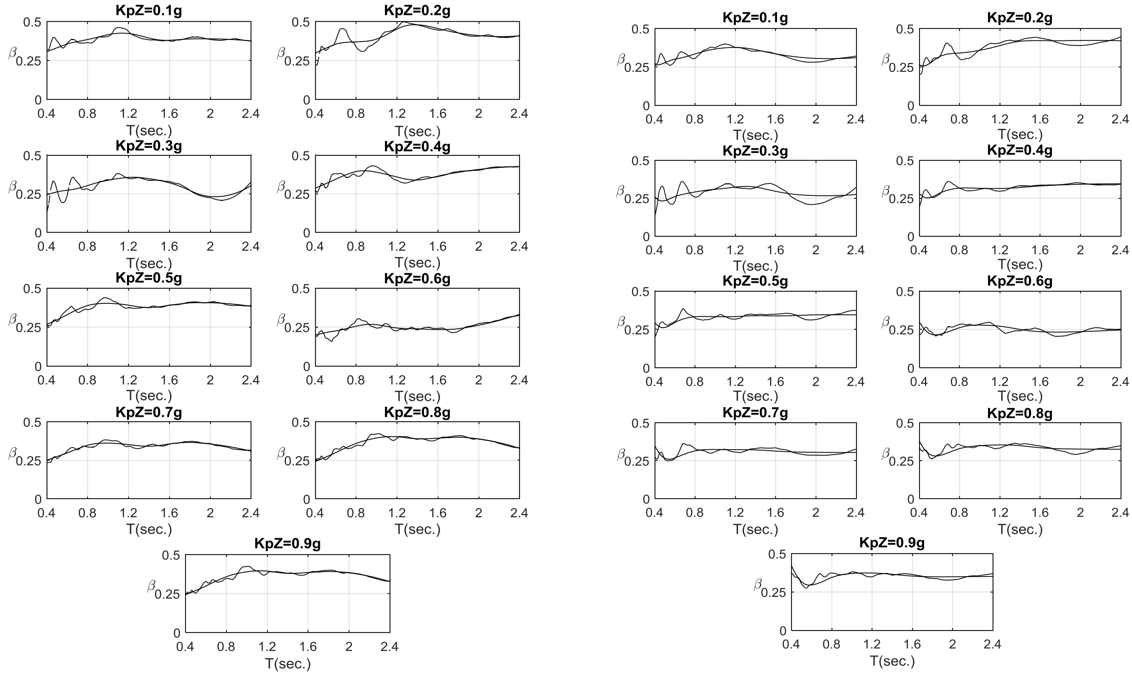
The associated inter-storey drift limits presented in the Table below are adopted in this study.

Performance Level	***Terminology***	***Damage Index****	***Transient Drift Limit (%)***	***Permanent Drift Limit (%)***	ε_c	ε_s
1	Slight Damage	< 10%	0.5 or for NSC 0.4 (brittle) 0.7 (ductile)	Negligible	0.001	0.005
2	Moderate Damage	5 – 30%	1.5	0.5	0.002	0.01
3	Extensive Damage	20 – 60%	Varying with Axial Load Ratio, 2.5 if not specified	1.0	0.003 – 0.004	0.02
4	Complete Damage	> 40%	-	-	0.005	0.03

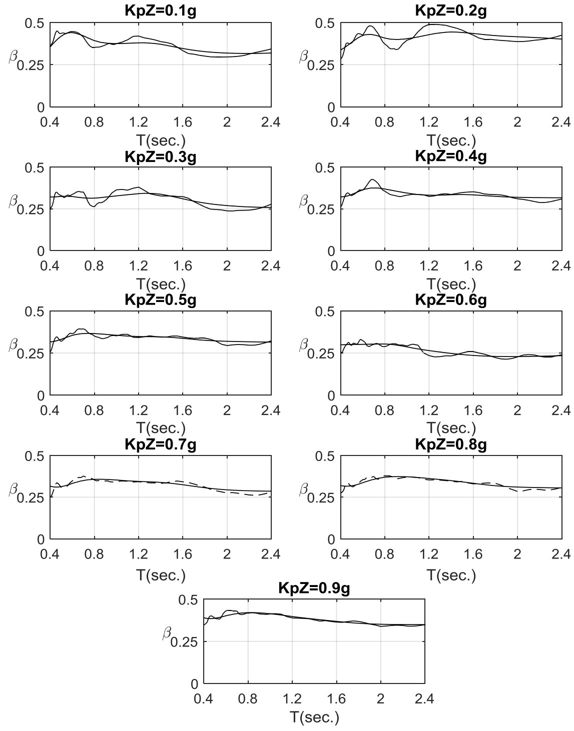
* Damage Index (DI) is defined as the repair to replacement cost ratio. Structural and non-structural damages are included.

Study on Uncertainty Measures in Fragility Functions

A study has been conducted to produce estimates of standard deviation values for fragility functions representing the total dispersion arising from record-to-record variability. Earthquake excitations were generated based on magnitude and epicentral distance combinations that produce a wide range of kp Z values on rock. The earthquake ground motions on rock were generated using program GENQKE (Lam et al., 2000). The program SHAKE (Ordonez, 2013) was used to generate accelerograms that are representative of earthquake excitations on class C and D sites in accordance with AS1170.4-2007 (Standards Australia, 2007). Four representative soil profiles were used to simulate the earthquake excitations on site class C and D. The standard deviation values associated with record-to-record variability are presented in Figure 1.



(a) Rock site (b) Site class C



(c) Site Class D

Figure 1 Record to record dispersion factor (β_D)

Seismic Vulnerability Assessment

Seismic vulnerability assessments are being conducted on the three broad types of RC structures. Recent progresses are summarised as follows:

1. **Buildings with soft-storey**. Fragility curves representing the probability of collapse of typical pre-cast RC columns have been constructed. A lognormal cumulative distribution function is presented in Equation (1):

$$P(C|PDD) = \Phi\left(\frac{\ln(PDD)-\ln(\overline{PDD})}{\beta}\right) \qquad (1)$$

The peak displacement demand (*PDD*) was used to represent the ground motion intensity parameters. The fragility curves for four different sizes of pre-cast columns are presented in Figure 2. The fragility functions have been combined with the ground motion recurrence relationships by Sommerville et al. (2013) for calculation of the 50-year collapse and cumulative collapse risk (Figure 3) of the columns. The studies on in-situ RC column are on-going.

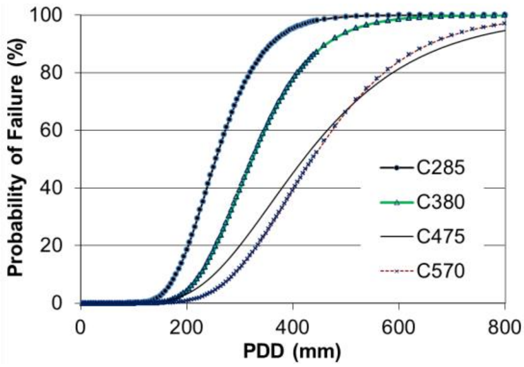
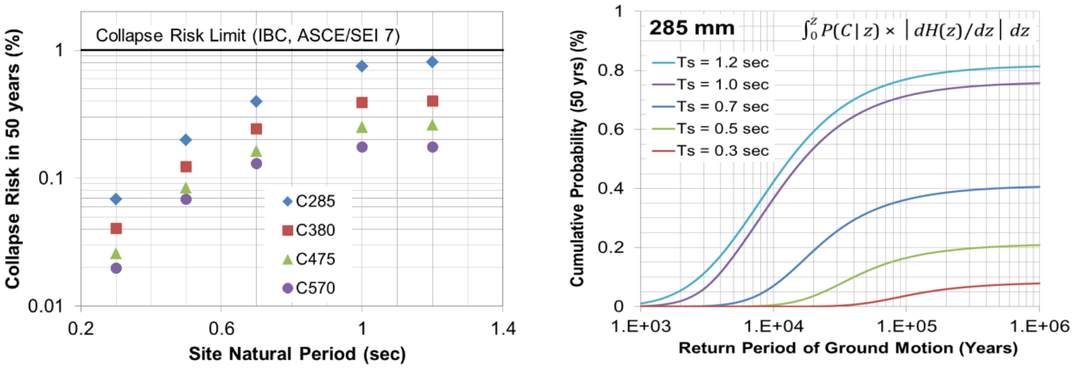


Figure 2 Collapse fragility functions for precast RC columns of different sizes



(a) Collapse risk

(b) Cumulative collapse risk

Figure 3 Collapse risk in a notional design life of 50 years on five different soil sites (different site period Ts)

2. **Buildings with walls as major lateral load resisting systems**. The studies on reinforced and precast concrete walls are on-going. Large-scale laboratory testings have been done on RC core walls, with the considerations of different construction methods. The left panel of Figure 4 below shows the failure mode of RC core wall with construction joints between precast wall panels, whilst the right panel shows the failure mode of cast in-situ monolithic RC core wall.

   Numerical modelling of RC wall buildings is currently being carried out. Seismic vulnerability assessment and collapse risk assessment will be conducted in the next phase of the research.

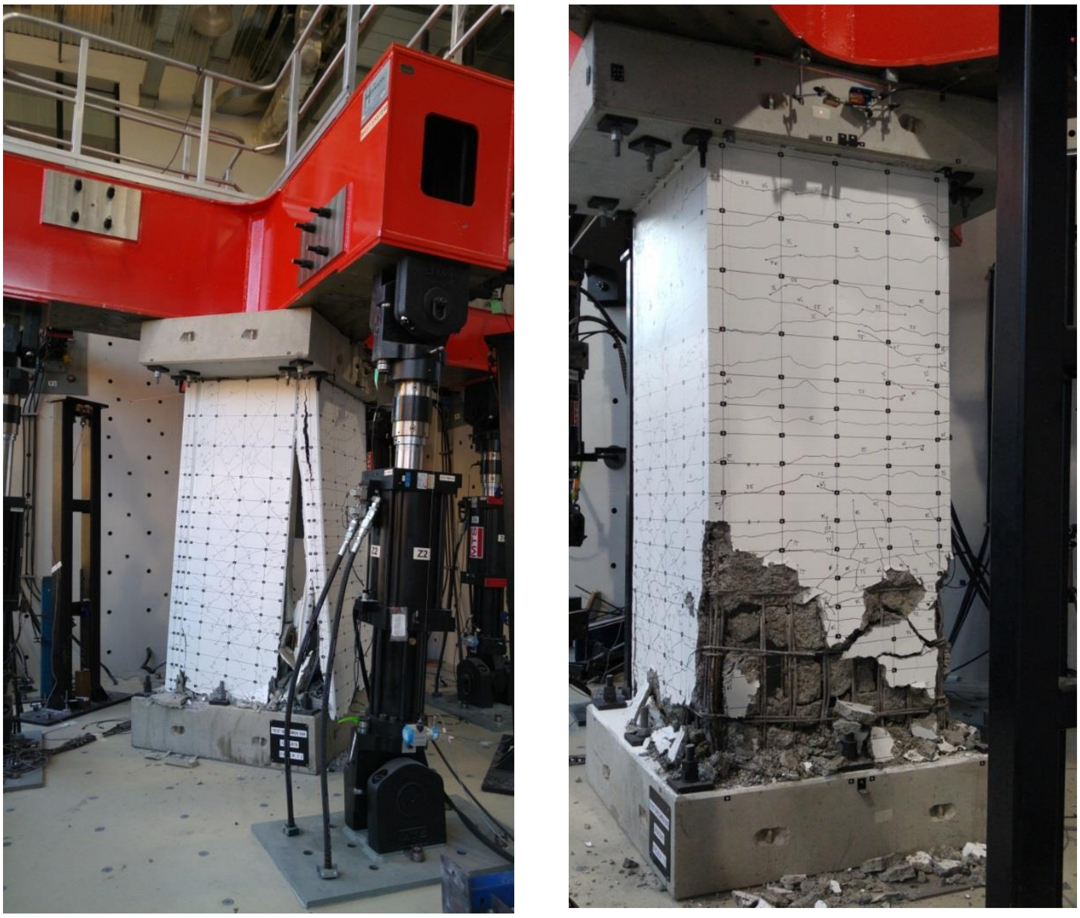


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Figure 4 (left) Failure mode of RC core wall with construction joints between precast wall panels, (right) failure mode of cast in-situ monolithic RC core wall

3. **Buildings with both RC walls and moment resisting frames as lateral load resisting systems**.

A simplified method of dynamic analysis of multi-storey buildings has been developed based on generalised mode shapes. Parametric studies on multi-storey buildings supported by reinforced concrete cores and frames including those with discontinuities of the gravitational load carrying elements based on 75 case study buildings (based on three building plans), with varying extent of moment resisting frames contribution to the lateral resistance of the buildings and discontinuities of the columns in the buildings, have been conducted to test the robustness of the developed method. The method has been extended to account for multi-storey buildings with plan asymmetry by incorporating factors which account for the effects of torsion.

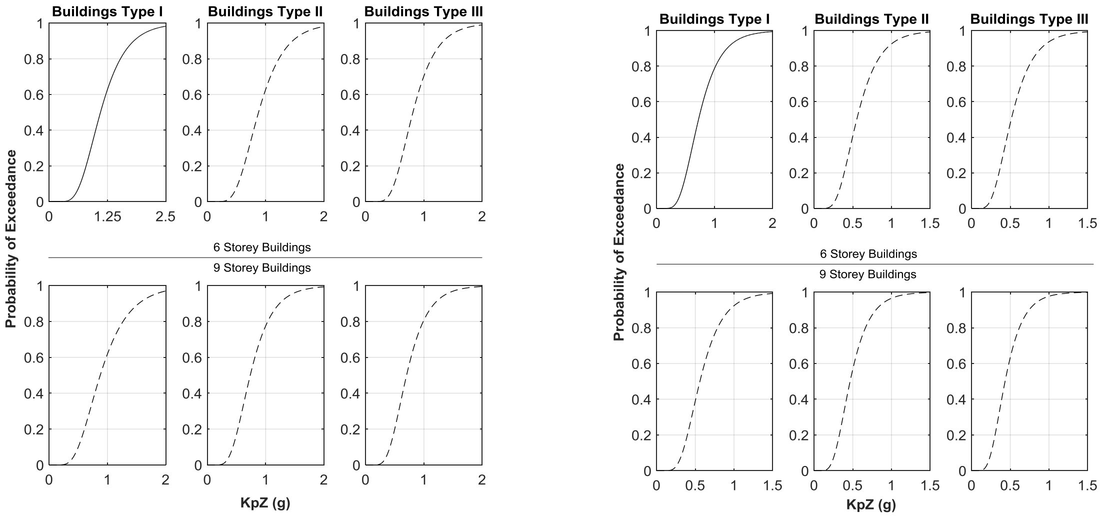
The fragility function for the buildings is defined by Equation (2):

$$P\left(DS \geq ds_i | k_p Z\right) = \varphi\left(\frac{\ln\left(k_p Z\right) - \ln\left(\overline{k_p Z}\right)}{\beta}\right) \qquad (2)$$

The parameter $k_p Z$, where k_p is the probability factor for the annual probability of exceedance and Z is the hazard factor, was adopted to represent the ground motion intensity.

Fragility curves have been constructed representing the probability of slight and moderate damage of the buildings being exceeded. The inter-storey drift limits of 0.5% and 1.5% for the slight and moderate damage state, respectively, in accordance with Vision2000 recommendation (SEAOC, 1995). The fragility curves for the moderate damage limit state are presented in Figure 5.

The studies are currently being extended to account for other damage states (extensive and complete damage) and buildings with plan asymmetry.



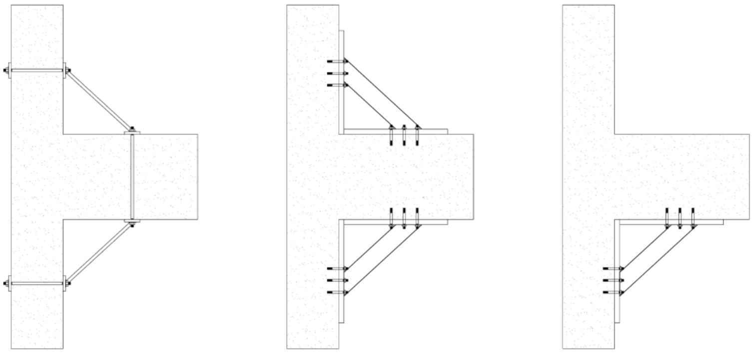
(a) Site Class C
(b) Site Class D

Figure 5 Probability of exceedance – moderate damage limit state (1.5%)

Seismic Retrofitting of RC Beam-Column Joint

It has been found that exterior beam-column joint is typically the weakest link in a limited-ductile RC frame structure. Hence, seismic retrofitting may be needed for this type of buildings.

Amongst all available options, the use of diagonal haunch element has been considered as a desirable seismic retrofit option for preventing brittle failure of the joint. Previous research has been focused on implementing double haunches (Figure 6a&b), whilst the performance of using single haunch element (Figure 6c) as a less-invasive and more architecturally favourable retrofit option has not been investigated. Hence, the feasibility of using single haunch system for retrofitting RC beam-column joint is explored in this study. Analytical development of the technique is being done and its effectiveness on the changes in the shear demand at the joint is studied.



(a) (b) (c)

Figure 6 Schematic diagrams of various haunch retrofit solutions: (a) Externally Clamped Double Haunch Retrofitting System (ECDHRS); (b) Fully Fastened Double Haunch Retrofitting System (FFDHRS); (c) Fully Fastened Single Haunch Retrofitting System (FFSHRS)

ONGOING RESEARCH

A summary of the research undertaken over the previous year is outlined below.

- An analytical study has been undertaken to determine rock hazards and generalised response spectra on rock for varying return periods. The generalised response spectra have been determined based on probabilistic seismic hazard assessment employing five Ground Motion Prediction Equations (GMPEs) developed worldwide.
- A detailed study has been conducted to investigate the effects of local site conditions on ground shaking. Parameters investigated include shear wave velocity on site, depth of soil to bedrock and the intensity of ground motion. Soil response spectra have been proposed for various site conditions based on correlations between initial site properties and site response parameters.
- A simplified method to estimate drift demands of irregular buildings is currently being developed based on the developed rock and site response spectra. The irregularities are quite common features in existing building stock and can be in a form of plan asymmetry and vertical irregularities (e.g., vertical irregularity caused by discontinuity in load resisting elements or non-structural elements such as masonry infills).
- Studies on lightly reinforced concrete walls are being conducted. Experimental works have been undertaken in Swinburne's state-of-the-art Smart Structures Laboratory to assess the global out-of-plane buckling and the local buckling of vertical reinforcement failure mechanisms of RC walls, and the general instability failures of lightly reinforced RC walls. Analytical study is currently being undertaken to develop a model which provides estimates of the plastic hinge length and displacement capacity of the RC walls, and a force-displacement backbone curve for the wall.
- Studies are being conducted on reinforced concrete frames. Experimental works consisting of quasi-static cyclic test and pseudo dynamic simulation test have been conducted in Swinburne's state-of-the-art Smart Structures Laboratory to assess drift capacity of corner columns of multi-storey of ordinary moment resisting frames. Analytical studies have also been undertaken to model force-displacement curve and displacement capacity of the moment resisting frames, which takes into account the component capacity of beams, columns, and beam-column joints within the non-ductile moment resisting frames.
- A review of vulnerability assessment for damage loss modelling has been undertaken. Studies are being conducted to construct fragility and vulnerability curves for a selected RC building type.
- An in-depth progress report into the economic loss modelling of earthquake damaged buildings has been prepared and submitted to the CRC as part of the 3rd quarter deliverables. At the request of the CRC this deliverable is being converted to BNHCRC report format for publication/general release.

- Experimental work into the seismic retrofit of masonry elements is ongoing. The experimental plan developed in the 1st quarter of 2014-2015 and subsequently finalised in the 2nd quarter has now entered production. The program has been slightly delayed due to substandard material properties of key components that were supplied by a 3rd party. This issue has now been resolved and new components received. The first test specimen is currently undergoing instrumentation and testing should take place in early August. Subsequent specimens will be tested over the following months.
- Research in ongoing to produce new URM building fragility curves that properly address the non-structural building damage that is linked with significant economic loss as evidenced by 2010-2011 Canterbury earthquake swarm

PROJECT REVISION – REVISED SCOPE AND GOING FORWARD

Following the October 2015 Workshop a number of industry groups were engaged as part of the development of a research utilisation plan. In particular, four end user projects were scoped with key partners. An overview of each is presented below:-

Professional Design Guide for Earthquake Mitigation Implementation:-

The Steel Reinforcement of Australia (SRIA) recently developed and published a professional guide for designing reinforced concrete buildings. They are now progressing with the preparation of a further guide for structural design associated with the redevelopment of existing buildings. The SRIA see a logical progression is to develop a further professional design manual for the retrofit of existing reinforced concrete buildings for earthquake. This manual would utilise the research of this project for both reinforced concrete and brick. Further, it would entail the engagement of other key industry partners. Building on the engagement of the SRIA, a workshop is being arranged for the end of August with the SRIA, the Concrete Institute of Australia (CIA), the Cement and Concrete Association of Australia (CCAA), the National Precast Concrete Association of Australia (NPCAA) and Think Brick to scope out this work.

Holistic Risk Assessment of Regulatory Requirements for Earthquake Design:-

The vulnerability and economic modelling components under development in this project have utility for developing information for the Australian building regulator, the Australian Building Codes Board (ABCB). The capabilities, once developed, can inform the future development of future earthquake design regulations for new construction, as well as retrofit of existing.

This project would use the economic modelling capability to examine the residual risk associated with current building regulations and incremental benefits of designing for rarer events. Unlike wind design, building design philosophy for earthquake under the current standard implies a greater level of damage related loss for a design level event than for the equivalent wind. This is because the building is typically designed to undergo inelastic deformation in the design level event. This damage can come as surprise to the owner of a code compliant building, as shown by the Christchurch Earthquake of 2011. With the move to reducing the cost of natural disasters and making communities more resilient, the project will develop a more holistic performance based design framework that reflects broader societal expectations and examine the incremental benefit associated with avoided costs of design for rare earthquake events.

The second aspect of this project is to develop information to support the optimal minimum design hazard for Australia. The hazard map in the current hazard (Standards Australia, 2007) is under review and will be updated by the standards sub-committee drawing upon research being developed by Geoscience Australia. This research has shown a typically reduced hazard for Australian capital cities but has also highlighted the uncertainty of local hazard values. This research will utilise the economic modelling framework developed to inform the attribution of a minimum design level for Australian buildings and will feed directly into a regulatory impact statement for the ABCB.

Finally, in this research utilisation project Australian life safety issues associated with collapse prevention will be examined. Australian intraplate seismicity results in greater increases in hazard with decreasing likelihood than found in tectonic plate boundary countries. While the design processes for building in plate boundary countries provide adequate assurance of collapse prevention in rare events, that this is achieved in Australia is not clear. One facet of this project is to examine how effectively current building regulation in Australia prevents total building collapse and gross loss of life, such as seen in Christchurch. Further, it will examine options for future regulatory development to averting this outcome.

Adaptation of Earthquake Research to Mitigation Metrics for the Insurance Industry:-

This project will adapt the mitigation outputs for earthquake to provide metrics of the effectiveness of various mitigation options for the range of building types considered. The primary implementation will be to support the future development of the Building Resilience Rating Tool developed by the Insurance council of Australia to enable the resilience measures to be adjusted to capture building owner investment in earthquake mitigation. Similar products may be developed for similar customer oriented decision making tools for Suncorp.

PUBLICATIONS LIST (JULY 2015 - JUNE 2016)

REPORTS

- 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.
- Griffith, M., Lucas, W. (2016). Economic Loss Modelling of Earthquake Damaged Buildings. Report No. 2016.158 (February). Published by Bushfire and Natural Hazards CRC.
- 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

JOURNAL PAPERS

- 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.
- 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.

CONFERENCE PAPERS

- 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.
- 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.
- Goldsworthy, H.M., McBean, 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.
- 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.

- 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.

- Hoult, R., Goldsworthy, H.M., Lumantarna, H., (2015). Seismic assessment of non-ductile reinforced concrete C-shaped walls in Australia. 8th International Structural Engineering and Construction Conference Sydney, Australia.

- Hoult, R., Goldsworthy, H.M., Lumantarna, H., (2015). Improvements and difficulties associated with the seismic assessment of infrastructure in Australia. Australasian Fire and Emergency Service Authorities Council (AFAC) Conference, 1-3 Sep 2015, Adelaide, South Australia.

CONFERENCE POSTERS

- 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.

- 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.

- 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.

PROJECT TEAM MEMBERS (CRC SUPPORT NOTED IN BRACKETS)

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- Yunita Idris: FRP retrofit of non-ductile RC columns

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REFERENCES

1. American Society of Civil Engineers (2000). Prestandard and commentary for the seismic rehabilitation of buildings. FEMA-356, Washington, D.C.
2. Applied Technology Council (2003). Preliminary evaluation of methods for defining performance, ATC58-2, Redwood City, CA.
3. EN 1998-1 .2004. *Eurocode 8: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings,* BSI.
4. Lam, N., Wilson, J., Hutchinson, G. (2000), "Generation of synthetic earthquake accelerograms using seismological modelling: a review", Journal of earthquake engineering 4(3): 321-354.
5. Ordónez, G.A. (2013), *SHAKE2000: A computer program for the 1-D analysis of the geotechnical earthquake engineering problem*.
6. SEAOC (1995), Vision 2000: Performance Based Seismic Engineering of Buildings, San Francisco, April 1995
7. Somerville, P., Bayless, J., Skarlatoudis, A., Thio, H.K. (2013) Assessment of seismic design motions at low probabilities: comparing Australia and New Zealand. In: *Proceedings of the Australian Earthquake Engineering Conference*, Hobart, Tasmania, Australia, November 15-17, 2013.
8. Standards Australia (2007). AS 1170.4-2007 *Structural design actions, Part 4: Earthquake actions in Australia*. Sydney: Standards Australia.