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COST-EFFECTIVE MITIGATION STRATEGY DEVELOPMENT FOR BUILDING RELATED EARTHQUAKE RISK

Annual report 2019-2020

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Cover: Dust clouds of the February 2011 Christchurch earthquake. Source: Gillian Needham

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EXECUTIVE SUMMARY

This annual report contains a summary of research undertaken by 4 partner institutions towards the development of cost-effective seismic retrofit methods for vulnerable Australian buildings in the 12-month period from July 2019 through June 2020.

Progress has been made in 4 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
3. advance an end-user focused research utilization project in the area of community risk reduction. This is done through an Earthquake Mitigation Case Study of the historic town of York in Western Australia
4. commencement of an End-User Utilisation Project with York Shire Council and the WA Department of Fire and Emergency Services through a Natural Disaster Resilience Program funded grant.

The first of the above components is being researched in the Universities of Adelaide, Melbourne, and Swinburne. This work includes investigation of existing building seismic capacities and development of retrofit techniques. The second area is being studied by Geoscience and the work includes estimating direct and indirect losses associated with building damage and benefits from seismic retrofit. The third component is being conducted utilizing 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. The last component only started at the end of 2019 but is extremely exciting. To date, the project team has identified several URM buildings in the York Shire to act as 'exemplars' for seismic retrofit. The first of these, the York Residency Museum building, has been seismically assessed, retrofit solutions recommended, local consultants (engineering and building contractors) have submitted a report and estimated costings for the rehabilitation work and Council is now in discussions with the contractor.

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.

END-USER PROJECT IMPACT STATEMENT

Stephen Gray, *Department of Fire and Emergency Services, Western Australia*

During the past 12 months significant progress has been made towards one of the proposed end-user projects. As detailed under "Conference and workshop attendance", researchers from GA and Adelaide have been working towards the WA-based end-user program.

Some of the engagement activities have included:

- briefing at the Australian Earthquake Engineering Society (AEES) conference in November 2018 and an accompanying tour of York township to inspect key buildings involved in the study
- submission of a joint abstract at the 2018 AFAC conference, with the end-user delegates being the speakers
- success in obtaining $250,000 grant from the National Disaster Resilience Program to facilitate implementation of the seismic strengthening of solutions developed for York by a broader audience across the entire state of Western Australia. This will necessitate expanding the scope of building typologies (six for York) by three to adequately cover the wider range anticipated across the state.

INTRODUCTION/BACKGROUND

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.

This project addresses 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 recognized 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 centers.

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

LOW DUCTILITY REINFORCED CONCRETE BUILDINGS

A 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. Also, axial load variation protocols were proposed based on the typical patterns of axial load variation observed in the numerical study.

The same numerical study was extended to study the typical patterns of bidirectional displacement path of the building columns under ground motion excitations. 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 that can be used in quasi-static testing of RC columns.

Large scale testing of reinforced concrete (RC) U-shaped walls was conducted by Dr Ryan Hoult at École Polytechnique Fédérale de Lausanne, Switzerland. While the walls were constructed and designed to current construction practices in Colombia, some of the detailing is similar to what is expected in the older RC building stock in Australia. Some of the initial results, which were presented at the 2019 Australian Earthquake Engineering Society (AEES) conference, showed that one of the plastic hinge length expressions that were derived from Dr Hoult's PhD work (funded by BNH CRC) correlated well to the experimental data. The plastic hinge lengths and corresponding plastic hinge expressions were ultimately used to derive fragility curves for RC buildings in Australia as part of his PhD research.

An assessment for retrofitting methodology involving a three-tiered approach was introduced. The assessment framework including a tiered approach was developed to evaluate the potential vulnerability of Australian RC buildings and to facilitate decision making in relation to the need for seismic retrofitting. The methodology and structural threshold values related to the vulnerable features introduced in the framework were also investigated to support the identification process of the method, which were presented in the 2019 Australian Earthquake Engineering Society (AEES) conference.

An archetypal Australian limited ductility reinforced concrete (RC) building, and the effect of some retrofitting options, were investigated, using push over analyses. Results of the structural behaviour before and after the retrofit, showing different levels of structural improvement, were presented in the paper "Development of Cost effective Mitigation Strategies for Limited Ductility RC Buildings" at the Australian Earthquake Engineering Society 2019 (AEES) conference. Future work will include the exploration of the structural behaviour of archetypal Australian limited ductility RC buildings under nonlinear time history analysis, with ground motions selected to match Australian seismicity, to study the structural behaviour before and after retrofit application.

YORK EARTHQUAKE BUILDING MITIGATION IMPLEMENTATION PROJECT

Researchers at GA and Adelaide have commenced work on the three year NDRP funded project "York Earthquake Building Mitigation Implementation Project" with the convening of both the Project Steering Committee and the Industry Reference Group. A presentation on the NDRP project to the WA Heritage Council and the Shire of York Council was accompanied by the outcomes of the BNHCRC utilisation project "Earthquake Mitigation Case Study for Regional Town of York, Western Australia". The first building for retrofit, the Shire's Residency Museum, was selected during a site visit on the 14th November as the first building for retrofit and the BNHCRC retrofit measures. Repair strategies have been developed and costs submitted by local design and construction professionals to the Council for their consideration in conjunction with the WA Heritage Council and NDRP steering committee. Council has given the project approval and allocated budget.

BENEFIT-COST RATIO CALCULATIONS

It is of interest to note that collaboration with the University of Western Australia BNH CRC research group is under way to incorporate intangible costs into the Benefit-Cost Ratio (BCR) calculations often used to determine the economic viability of seismic retrofit of existing buildings. Normal BCR calculations for individual building projects only consider the benefits and costs directly related to the individual building. 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 region 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. Furthermore, the community damage can be a loss in other ways through the loss of heritage structures and possible broader economic consenquences through lost tourism. Hence, the work with the UWA team will attempt to bring into our calculations intangible costs associated with the value community's place on 'heritage buildings' in addition to other metrics such as business interruption costs, injuries and fatalaties. Geoscience Australia has worked with the UWA researchers in refining their survey instrument 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. To date, 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. Work continues on this project which will incorporate the UWA research outcomes into the deliverable (3.2.1) Final Report on Case Study of Melbourne CBD Precinct in December 2020.

SEISMIC RETROFITTING OF LDRC BUILDINGS

In the January-March 2020 quarter, the focus on the development of a simple method to determine the elastic radius ratio of multi-storey buildings (a parameter indicating the torsional rigidity of buildings). Multi-storey buildings with a low value of elastic radius ratio (less than 1.0) have been shown from earlier studies to be vulnerable in an earthquake. The reinforced concrete frames at the edge of the building can be subjected to high amplification of displacement demand. The robustness of the developed method was tested by comparison with results of dynamic analyses of realistic multi-storey building models. The developed method allows for the elastic radius ratio of the buildings to be calculated using simple static analysis.

In this quarter, vulnerability studies based on incremental dynamic analyses are conducted on case study reinforced concrete building. The reinforced concrete buildings have been identified by the tiered methodology previously developed by the research team to be vulnerable.

Analytical studies are currently being carried out to develop a tiered methodology to assess the potential vulnerability of buildings in seismic conditions and the need for retrofitting. A number of buildings are being analysed to test the robustness of the methodology. Further analyses are currently being conducted on RC buildings that have been identified to be vulnerable in order to describe failure mechanisms and the extent of damage that could occur to their structural elements. Experimental testing at Swinburne on the fully fastened single haunch retrofitting system is ongoing. An experimental program is also currently underway at Swinburne to investigate the force deformation behaviour of high strength columns subjected to two-directional loading. This work is reported in their final report on Testing of Retrofitted LDRC Buildings (deliverable 2.3.2) and a Progress report on costings of LDRC building report (deliverable 2.3.3). The costing work will be finalised with assistance from quantity surveyors at GA in Canberra.

KEY MILESTONES

The key milestones for this project in 2019-2020 were:

- Final report on vulnerability for as-built and retrofitted LDRC buildings. This was completed and delivered in the September quarter.
- Progress report on the case study for the Melbourne CBD precinct; delivered in the September quarter.
- Draft journal paper on fragility curves for retrofitted LDRC buildings; actually submitted and published as "Framework for seismic vulnerability assessment of reinforced concrete buildings in Australia," by Menegon, SJ, Tsang, HH, Lumantarna, E, Lam, NTK, Wilson JL and Gad, EF in Australian Journal of Structural Engineering (20(2): 143-158.
- Poster for 2019 BNH CRC conference; delivered by Saim Raza as "Collapse performance of limited ductile high-strength reinforced concrete columns in earthquakes."
- Final report on Case Study of Melbourne CBD precinct; was due in December 2019 quarter but has been delayed to December 2020 (refer agreed variation from John Bates, letter dated 18 June 2020).

UTILISATION AND IMPACT

SUMMARY

This project has already seen evidence of community utilization 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 development is intended to be rolled out across the rest of the state (WA) by courtesy of the National Disaster Resilienc Program grant which intends to extend the York project to cater for an additional 3 heritage building typologies that were not applicable to 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.

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 hoped that use of this expertise will be communicated to the wider population of West Australia, including other regional communities, through the Natural Disaster Resilience Program funded project which will support work by this research team to extend the types of 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 of the Australian communities given the comparatively uniform age and construction of heritage buildings across the continent.
- 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 upgreade 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

NEXT STEPS

There are four areas in which the earthquake resilience research group will be focusing on in the immediate future (next 6 months of the BNH CRC) and medium term as follow-on activites as 'utilisation outcomes' of the CRC. These are:

1. Complete our deliverable (3.2.1) of the Melbourne Case Study. The scope of this activity was expanded to include the expertise from the BNH CRC UWA project and the use of their 'intangible values' in "Value Tool of Natural Hazards". This will utilize 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 December 2020.
2. A significant utilization of our project's research findings is the York, WA utilization 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 wil 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 Musuem building. It has been seismically assessed with retrofit options proposed and a local consultant has already investigate and submitted a proposal and fee to carry out the necessary work. Council has agreed with the work proposal which might be completed within the next 6 months, Covid-19 issues permitting. Further work along these lines will continue with a second demonstration project identification for seismic assessment, retrofit and corresponding fee submission.
3. 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 activites through 'in-kind' contributions to the CRC after the fact.
4. Finally, the research team is commited to draft a 'Seismic Retrofit Guidelines' document for use by professionals in Australia that would be relevant for non- ductile concrete and unreinforced masonry (brick and/or stone) buildings in all states and territories. 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

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2 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

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PROJECT TEAM MEMBERS (CRC SUPPORT NOTED IN BRACKETS)

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
Swinburne University:	Prof J Wilson, Prof E Gad, Dr 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 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

Leesa Carson (Geoscience Australia), Stephen Gray (DFES, WA)

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