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EARTHQUAKE MITIGATION OF WA REGIONAL TOWNS

York Case Study: Final Report

Martin Wehner[1], Hyeuk Ryu[1], Michael Griffith[2], Mark Edwards[1], Neil Corby[1], Itismita Mohanty[1], Jaroslav Vaculik[2], Trevor Allen[1]

1 Geoscience Australia
2 University of Adelaide

THE UNIVERSITY OF ADELAIDE AUSTRALIA

Australian Government Geoscience Australia

SHIRE OF YORK

GOVERNMENT OF WESTERN AUSTRALIA

DFES Department of Fire & Emergency Services

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Geoscience Australia acknowledges the traditional custodians of the country where this work was undertaken. We also acknowledge the support provided by individuals and communities to access the country, especially in remote and rural Australia.

Cover: Undertaking the RICS survey in York. Source: Geoscience Australia

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EXECUTIVE SUMMARY

Earthquake hazard was not fully recognised in Australian building design until the mid-1990's. This oversight has resulted in a legacy of vulnerable buildings that can be readily damaged in moderate to severe Australian earthquakes. In particular, older unreinforced masonry (URM) buildings built with the architectural styles, materials and construction details used in the United Kingdom are particularly vulnerable. Australian earthquakes have highlighted the vulnerability of these building types. These include the Adelaide Earthquake of 1954, the Meckering Earthquake of 1968, the Newcastle Earthquake of 1989 and the Kalgoorlie Earthquake of 2010, all of which damaged pre WWII masonry buildings in particular. The proportion of the community building stock in this age and construction category can be quite significant in many low growth Australian regional towns and contribute disproportionately to the earthquake risk of a community. The damage to these buildings can also greatly add to emergency management logistics after a major earthquake and can impede the recovery of the community physically, economically and socially.

York is Western Australia's oldest inland town with many older masonry buildings that are particularly vulnerable to earthquakes. These legacy structures are greatly valued by the community and draw many visitors to the town, including those attending the large annual events hosted by York. They have great heritage value and many of the buildings are on the State and National heritage registers. The heritage precinct they create contributes significantly to York's economy, supporting the local businesses by the tourist spending they attract to the town. The risk posed by these buildings is exacerbated in York by the local seismic hazard, which is high compared to most other parts of Australia. Understandably, improving the resilience of these buildings is of interest to property owners, the community, the Shire of York, the Western Australian (WA) Department of Fire and Emergency Services (DFES) and the WA Department of Planning, Lands and Heritage (DPLH).

This document reports on a Bushfire and Natural Hazards Collaborative Research Centre (BNHCRC) utilisation project that has sought to develop information on the most effective means to address York's high risk buildings. It has also sought to develop a better understanding of the logistics that would be faced by emergency services and the local shire council in a rare, but credible, earthquake event. The utilisation project is entitled "Earthquake Mitigation of WA Regional Towns: York Case Study", and sits under the over-arching BNHCRC Project A9 "Cost-effective Mitigation Strategy Development for Building Related Earthquake Risk". The work commenced in January 2018 and was undertaken over a two year period. It involved the University of Adelaide and Geoscience Australia (GA) as the CRC research partners, and DFES and the Shire of York as the end users. The WA DPLH has also been a participant, though not a formal BNHCRC end user. The project had the following key components:

- Develop a building, business and demographic exposure database for York with the attributes collected tailored for modelling earthquake impact and for quantifying avoided consequences in economic terms.

- Examine the benefits and costs of retrofitting old URM buildings to improve the resilience of them to earthquake. This is to range in scale from individual households and businesses up to the community as a whole.
- Prepare earthquake impact scenarios suitable for emergency management planning by DFES and the Shire of York.

Significantly, the project has also examined how the scenario impacts and losses to the community would change over thirty years with different credible rates of implementation of retrofit measures.

The work required the development of the three fundamental risk elements of earthquake hazard, community exposure and building vulnerability. It also entailed the assessment of the economic loss measures associated with human injury, contents losses, rental income, commercial property leasing, and business activity. It also included the application of the semi-intangible value placed on human life to society. Each of these are described below:-

Earthquake Hazard

Western Australia arguably has the highest seismicity of any state in the country and has experienced more damaging earthquakes than any other over the last 120 years. This study has drawn upon the latest understanding of the WA earthquake hazard, utilising the recently released National Seismic Hazard Assessment (NSHA 2018) (Allen et al, 2018a). The bedrock hazard from this assessment shows York to have a hazard that is at the high end of "low" by global standards and high by Australian standards. The hazard is further amplified in York by the presence of the sediments deposited by the Avon River. These soil effects increase the hazard to all buildings on the main street of York and many of the town's heritage structures. The effects of soil amplification were assessed to increase the severity of shaking by approximately 50% and have been considered in the scenario and risk assessment work for York.

Community Exposure

Surveys were undertaken to define the community assets exposed to earthquake hazard. The survey work addressed the first project component and entailed three activities. In the first, the streetscape of the town was digitally photographed using a vehicle mounted camera system called the *Rapid Inventory Capture System* (RICS) developed by GA. Then, using available state government building data integrated into the *National Exposure Information System* (NEXIS) and best available imagery, a building exposure database was developed. This process included foot-printing of each buildings and database integration using a desktop software tool developed by GA called the *Field Data Analysis Tool* (FiDAT). Finally, a field survey activity was undertaken to inspect older heritage buildings by structural engineers, along with an economist led survey of almost all businesses in the town. In total 1,463 York buildings and 87 businesses were surveyed. Of the buildings, 307 were identified as being built of unreinforced masonry (URM) and of pre-WWII construction. In turn, of these URM buildings, 158 are heritage listed and approximately 85% of this subset are houses. Many of the town's businesses were found to be housed in old URM buildings as almost all those on the main street, Avon Terrace, are of this type. It was also noted that most businesses were small, locally based and appeared vulnerable to the major disruption that a large damaging earthquake would cause.

Human activity and household resilience were also assessed utilising several sources. For population exposure, pedestrian movement was captured through timed images taken in parallel to other field survey activity. This was augmented using United States population models, visitor information provided by the York Shire and images of major events in York. It was noted that the number of people in the business district during the week and on special events varied enormously. This variation was included in the probable human exposure model developed and for three earthquake timings of each of the three scenario earthquakes modelled. For household resilience the University of New England in NSW provided its *Australian Natural Disaster Resilience Index* for the Australian Bureau of Statistics (ABS) Statistical Area 2 (SA2) the Shire sits in. The index indicated the community of York sits in the lowest quartile of Australian SA2's, and is typical of smaller rural communities.

Building Vulnerability

In the building vulnerability assessment work the surveyed old URM building stock was categorised into six vulnerability classes that covered the majority of the York's older URM buildings. The classes were assessed to each have distinctly different overall structural vulnerability based on the architectural elements, number of storeys, layout of walls and use. For each of these a suite of retrofit measures were developed by the University of Adelaide to strengthen the most vulnerable features. These included the restraining of chimneys, gables, and parapets. It also entailed tying back the exterior walls to the first floor and roof level structures. The class selection sought to cover most of the vulnerable building stock but could not cover every type, particularly those less common or unique. The selection was validated with the End Users at a workshop held in York on the 9th August, 2018.

The physical vulnerability assessment for each of the building types entailed a series of tasks. Firstly, the increasing severities of earthquake damage typically experienced by each component type with increased shaking were identified and the associated repair strategies described. The overall box structure of the building walls (excluding the vulnerable components) was also treated as a final single component with a series of damage severities defined. This work formed the basis for a quantity surveying consultancy which entailed evaluating the cost of entirely reconstructing each building to current standard, the cost of effecting repairs to each component type for each damage level, and the cost of effecting each retrofit strategy to each building component as relevant. Finally, the overall vulnerability of each building type, with and without retrofit, was assessed through the development of fragility curves for each component and integrating these using a Monte Carlo simulation process. This process sampled uncertainties and generated the building vulnerably function for progressively more extensive applications of retrofit measures to the building.

Economics Cost Assessment

The economic assessment considered a broad range of measures. These ranged from the direct costs to property owner, building occupiers, and businesses through to health care costs and the partially intangible value placed on the loss of a human life. The aim was to provide scalable information on benefits versus cost to a range of decision makers and investors. Importantly, the measures where not comprehensive and so represent a lower bound to the actual avoided impacts mitigation achieves. For example, the cost of emergency response, clean-up and community recovery support were not considered. Neither was a macro-economic perspective developed to capture non-impacted businesses that would benefit from a stimulus in business activity such as in the construction industry, the supply of home appliances, soft furnishings and drapery.

Scenario Impacts and Risk

The study considered three earthquake scenarios having annual likelihoods of 1/500, 1/1,000 and 1/2,500 of causing the modelled bedrock shaking severity beneath York, or worse. These likelihoods correspond with a 10%, 5% and 2% chance, respectively, of being exceeded in the next 50 years. Three historical WA earthquakes were selected for the scenarios by moving the actual event epicentre to the required distance from York so as to generate the target bedrock shaking taken from NSHA 18. Selecting actual historical events rather than hypothetical ones was recommended at the 9^{th} August, 2018, workshop as it would provide a credibility measure to the community. For each event the injuries, Urban Search and Rescue (USAR) logistics and the economic losses within the scope of this study were assessed. These were also assessed for three human exposure times; nighttime, midday on a busy weekend and during a major festival event in York. The range of costs to the town of York were not comprehensive but those assessed were accumulated to give a total loss in each scenario event that ranged from $12m for the least severe to $73m for the most severe.

The damage, injuries and losses were then forecast 10, 20 and 30 years into the future using two rates of building retrofit that were agreed on at the 9^{th} August, 2018, workshop. The lowest rate was three buildings retrofitted every two years and the highest rate was double that. It was found that for the highest rate of retrofit the scenario losses for York reduced by 24% after 30 years. The emergency management logistics associated with casualties and urban search and rescue were reduced by a greater extent: between 50% and 100% depending on the particular scenario and its time of occurrence.

In a similar manner, the long term financial risk of York associated with earthquake hazard was evaluated for both building damage and contents losses. These were presented as an average annualised loss for the heritage building stock and for the entire town. They were also forecast decadally into the future for each of the two retrofit uptake strategies. For the highest uptake rate the financial risk reduced by 31% for the heritage building stock and by 17% across the entire York community.

Discussion and Outcomes

Earthquakes occur frequently in Australia with over 100 events greater than magnitude 3.0 (M_L) recorded within the Australian continent every year by Geoscience Australia. The smaller and more frequent events are typically non-damaging, whereas the less frequent larger events can be very damaging when they occur close to a community. This contrasts with severe weather related events where the more frequent events are still damaging and costly. This plays out in the economics of strengthening older structures where the benefits of avoided building damage and contents losses through retrofit for earthquake are not a full offset for the significant costs. Other avoided costs associated with business losses, lost wages, health care costs, and the value placed on human life, do increase the sum significantly but are not realised by the property owner. While not all avoided costs were considered, on balance this project has shown that the justification for retrofit based solely on a financial investment is difficult to demonstrate for York.

The current vulnerability assessed for each of the six building types indicated that the Type 4 structure (two storey commercial with high street front parapets) is the most vulnerable, whereas the vulnerability functions for the other five types are more clustered. The Type 1 single storey house was the least vulnerable of the six. The research has also shown that retrofit measures focused on the most vulnerable elements do reduce this vulnerability and significantly so if all measures are applied. However, the retrofit measures do not bring the building up to complying with the latest building standards called up in the National Construction Code (ABCB, 2019). Furthermore, the owner may not opt to implement the full suite of measures considered in this project due to limitations in funds or diminishing incremental return on investment with increased cost. This is because the deeper levels of retrofit with high implementation costs yield typically the lowest overall rates of return. Further, for the larger York buildings the cost of all retrofit measures can exceed $100,000. Retrofit can greatly reduce the risk from the more likely earthquake events, but does not mitigate all risk nor make the building earthquake proof. This needs to be clearly communicated to building owners.

What is clear from this study is that there are other considerations for the retrofit of buildings in York and similar communities. The consequences of inaction, particularly along the Avon Terrace heritage precinct, could be unacceptable to the community. If a rare earthquake, such as has already taken place close to York, occurred locally during a period of high public exposure there would be considerable loss of life. This research has shown that if a 2,500 year Return Period (RP) event (6.5 M_W) approaching the severity of the Meckering Earthquake occurring on a busy weekend in York would kill approximately 30 people with close parallels to the 2011 Christchurch Earthquake outcome for masonry structures (42 fatalities). If the same event occurred during a major festival with a closed off and crowded Avon Terrace, the death toll could approach 500.

Further, following a rare, but credible, earthquake the high value heritage streetscape is unlikely to be fully recovered. While businesses in less damaged premises may be able to recommence activity more quickly, the loss of tourism would be profound. All of this has relevance in the context of the resilience of York businesses and households. The field survey of businesses indicated that many are struggling and may lack the resilience to recover from the damage, disruption and business turnover losses a major earthquake would cause. Further, the Australian National Disaster Resilience Index for York and Beverley, focused largely on households, indicates a low resilience in the community to natural disasters. A rare earthquake would be difficult for the town to cope with pointing to the need for a broader view of the seismic risk issues of York.

Much can be learned from the program of building retrofit underway in New Zealand and the legislation that supports it. Under the NZ Building Act of 2004 and its recent amendment in 2016, buildings with one third current code capacity or less are classed as earthquake prone and need to be retrofitted or demolished. What may be informative to the Australian setting are the parameters that set the priorities and associated timelines for this work to be done. In the NZ process, higher priority is given to areas of New Zealand where the hazard is higher. Secondly, priority is linked to the consequences of damage in a rare earthquake. Buildings that could fall and block key transport or emergency services corridors and those that could cause major loss of life in pedestrian precincts have the highest priority with half the timeframe for action. The latter focus on avoided major loss of life and injury in particular may be informative to Australia. Avoiding a 2011 Christchurch Earthquake outcome caused by falling masonry could be the objective and that the priority building elements to avoid this outcome may be the minimum retrofit scope. The accelerated "Unreinforced Masonry Building Program" implemented in Wellington City following the 2016 Kaikoura Earthquake had the sole aim of avoiding casualties in a future earthquake.

The scenario outcomes with and without progressive retrofit have provided the York Shire Council measures of the expected reductions in consequences and losses to the communities. For the scenarios and loss measures considered, the loss reductions across the entire town for the highest uptake rate ranged from 23% to 24% after 30 years. While the reduction in the building physical damage severity was less noticeable, USAR logistics reduced by 58% up to 100%. Further, the reduction in the scenario injuries were even more significant. Deaths were reduced by 89% up to 100% for the 500 year RP event, by 82% up to 100% for the 1,000 year RP event, and by 63% up to 67% for the 2,500 year RP event. These un-retrofitted and retrofitted outcomes provide a basis for emergency management (EM) planning by both DFES and the Shire, giving credible metrics of events that are beyond present experience. They also illustrate that retrofit is not a short term campaign, but a sustained journey that progressively reduces the risk.

The strategies for providing drivers for this risk reduction activity can also be informed by the experience of some local governments in New Zealand. While the benefit of underpinning legislation is not available here in Australia, other factors were identified that could be considered as part of a forward strategy. These were:

- Risk awareness could be heightened through scenario modelling of expected impacts. They would increase awareness and may raise the expectations of tenants of their landlords to have safe premises and residences.
- Incentives may be needed to motivate retrofit behavior. This may be particularly the case in York where many building owners lack the resources to fully fund retrofit intervention measures.
- Prioritising retrofit activity could be done in areas of high hazard and potential consequences. These would include areas where falling masonry could cause major injuries and loss of life.

On the issue of prioritisation, the study has provided interesting insights on the benefit to investment cost for different decision makers. For an owner of an unrented building it is the lowest, but progressively increases for owner occupiers (contents losses included) to landlords, businesses and local government (avoided rents, proprietor income losses and lost wages) to state government (health care costs and societal cost of loss of human life). Particularly for the last category and buildings in pedestrian precincts, the increase in Benefit/Cost ratio is about 2.5 times. Heritage preservation objectives aside, this could be a justification for external incentives for retrofit initiatives.

An exciting aspect of this project has been the significant engagement of the BNHCRC End Users. DFES has been instrumental in facilitating the project in WA and the Shire of York has been strategic in its aim to proactively address the earthquake risk ahead of the next damaging event. In addition, the project has benefitted from a third informal WA participant in the DPLH which has a central interest in preserving the heritage structures of York. This alignment of interests has come together in a sequel to the BNHCRC project that is a successfully funded National Disaster Resilience Program (NDRP) project that will address the need for testing the utility of the retrofit strategies on buildings, expand the building type range for which information is available, and disseminate the learnings for earthquake risk reduction activity in the state and nationally. The retrofit work will be separately funded and managed through a linked parallel program funded through local and state government initiatives. This five partner collaboration seeks to inform the address of high risk buildings of this type in Australia ahead of a damaging earthquake. It also aims to support the development of an industry skill base to promote the uptake, effectiveness and affordability of retrofit measures.

Summary

The success of this project is greatly attributable to the alignment of six key factors. York has a high earthquake hazard by Australian standards, it has a high proportion of vulnerable masonry structures, the same structures are very valuable from a broader heritage perspective, the town's economy is very dependent on the visitors attracted to York to enjoy the older building stock, the town hosts many large annual events centred in its heritage precinct and the local stakeholders have been highly engaged and motivated to understand and address this risk.

The project has developed a range of retrofit measures for a suite of six URM building types. These measures have been demonstrated to reduce the physical vulnerability of each building. The project has also translated this vulnerability change into broader metrics that form an evidence base to inform decisions to retrofit.

The project has also demonstrated the benefit of retrofit through a virtual retrofit of the town. These benefits have included reduced post event logistics for emergency management and the Shire, reducing financial losses to building owners, businesses, the Shire and the State, and reducing injuries and fatalities. It has also demonstrated that retrofit reduces the long term financial cost of earthquake hazard, thereby making risk transfer through insurance uptake more affordable.

Finally, the project is informing the actual implementation of the retrofit activity in York through a succeeding project that is expected to refine and disseminate a broader range of information to inform retrofit activity in other high risk communities across WA and Australia.

END-USER STATEMENTS

Denese 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.

Steve Gray, *Department of Fire and Emergency Services, WA*

The collaboration and engagement of the project team has been pivotal in the success of this project. There are many actionable items that can be applied to support DFES in fulfilling its role as the agency responsible for earthquake in WA. Information on USAR 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 make informed decisions on earthquake mitigation strategies. The success and practicality of the recommendations has supported a follow on project to look at implementing some of these recommendations in York.

ACKNOWLEDGMENTS

The project gratefully acknowledges:

- The residents of York for their interest and willingness to partake in interviews during the surveys.
- The Shire of York, especially Paul Martin and Carol Littlefair for their support of the project, supplying aerial imagery of the town, supplying their inventory of heritage buildings in York, distributing project flyers (see Appendix D), and arranging meetings with local York associations.
- The WA Department of Fire and Emergency Services, especially Steve Gray for their logistics, support and facilitation of the project.
- The Department of Planning, Lands and Heritage, especially Harriet Wyatt for their engagement in this project and strategic contributions to shaping the succeeding project that will refine, broaden and disseminate the research to other users.
- To all the participants in the York Workshop of the 9th March, 2018, including representatives from Engineering Heritage, WA, and the Insurance Australia Group (IAG).
- To Insurance Australia Group (IAG) for the contribution of anonymous claims data for the Newcastle earthquake.

ABBREVIATIONS

AAL	Average Annualised Loss
ABS	Australian Bureau of Statistics
AEP	Annual Exceedance Probability
ANDRI	Australian Natural Disaster Resilience Index
ANZSIC	Australia and New Zealand Standard industrial Classification
AR-DRG	Australian Refined Diagnosis Related Groups
ASSCM	Australian Seismic Site Conditions Map
B/C	Benefit – cost ratio
BNHCRC	Bushfire and Natural Hazards Cooperative Research Centre
CEO	Chief Executive Officer
DFES	Department of Fire and Emergency Services, WA
DI	Damage Index (defined as Repair Cost / Replacement Cost)
DNZ	Destination Zones as defined by the Australian Bureau of Statistics
DPLH	Department of Planning, Lands and Heritage, WA
ED	Emergency Department
EM	Emergency Management
FiDAT	Field Data Analysis Tool
GA	Geoscience Australia
GA-BS	Geoscience Australia Business Survey in York
GEM	Global Earthquake Model Foundation
IAG	Insurance Australia Group
IHPA	Independent Hospital Pricing Authority
LGA	Local Government Authority
MDC	Masterton District Council, NZ
NDRP	National Disaster Resilience Program
NEP	National Efficiency Price
NHCDC	National Hospital Cost Data Collection
NSHA18	National Seismic Hazard Assessment, 2018
NSHM12	National Seismic Hazard Maps, 2012
NSW	New South Wales
PGA	Peak Ground Acceleration
PSHA	Probabilistic Seismic Hazard Assessment
RICS	Rapid Inventory Capture System
SA2	Statistical Area 2 defined by the Australian Bureau of Statistics https://www.abs.gov.au/websitedbs/D3310114.nsf/home/Australian+Statistical+Geography+Standard+(ASGS)
SEIFA	Socio-Economic Indicators for Areas developed by the ABS

SW	South West
SWSZ	South West Seismic Zone
UoA	University of Adelaide, SA
UMBP	Unreinforced Masonry Building Program,
URG	Urgency Related Groups
URM	Unreinforced Masonry
URML	Low Rise Unreinforced Masonry
USAR	Urban Search and Rescue
WA	Western Australia
WCC	Wellington City Council, NZ
1st	Single storey building
2st	Two storey building

INTRODUCTION

Earthquake hazard was only fully recognised for Australian building design in the early 1990's following the Newcastle Earthquake of 1989. This has resulted in a significant legacy of Australian buildings that are inherently more vulnerable to low to moderate earthquake generated ground motion. Having accessible knowledge of the most effective measures to retrofit older masonry buildings will enable and encourage the strengthening of buildings resulting in more resilient communities.

Western Australia has a region of elevated seismicity inland from Perth where there are located several older regional towns having a predominance of older unreinforced masonry (URM) buildings. In 1968 the town of Meckering was devastated by an earthquake (Gordon et al, 1980), which destroyed the town's URM building stock and damaged URM buildings in other neighbouring towns. The town of York, situated approximately 37km from the epicentre was also significantly damaged (Everingham et al, 1982). The combination of high hazard and vulnerability in this region points to a need for informed mitigation measures.

This project entailed undertaking a mitigation implementation study of York, Western Australia's oldest inland town, which has many valuable historical buildings that are vulnerable to damage by a large earthquake. This utilisation project sits beneath and draws upon the vulnerability and economic modelling research outcomes of the BNHCRC project "Cost-effective Mitigation Strategy Development for Building related Earthquake Risk". Utilising the outcomes of the project a range of mitigation strategies have been virtually applied to the town's URM buildings. This has enabled an assessment of the effectiveness of these interventions on community risk and emergency management (EM) logistics in the context of rare, but credible, earthquakes.

In this report the research and its outcomes are presented and discussed. Further, recommendations are made for future retrofit strategy implementation in York and more broadly in Western Australia. In particular, a new NDRP project is described that will build upon this BNHCRC project in testing the application of the measures in actual retrofit work undertaken in York. This BNHCRC project has been led by the University of Adelaide (UoA) with project partner Geoscience Australia (GA). The end users are the Shire of York and the WA Department of Fire and Emergency Services (DFES) with valuable contributions made by the WA Department of Planning, Lands and Heritage. Through the workshop activity reported there have also been valuable guidance from Engineering Heritage, WA, and the Insurance Australia Group (IAG).

PROJECT ACTIVITIES

The project team has undertaken project inception, engagement, data gathering, database development and modelling activities during the period October, 2016 to June, 2019. These are listed below.

- Project inception activities are detailed as follows:
  - Preliminary meeting with Paul Martin, Chief Executive Officer (CEO) of York Shire Council, Steve Gray (DFES), GA, and local DFES emergency managers at the York Shire office, 1 Joaquina St, York. The proposed scope of the project was discussed and refined based on the end user needs (25^{th} October, 2016).
  - Joint letter from DFES and the BNHCRC offering to undertake a mitigation case study on the town of York (23^{rd} March, 2017).
  - Letter from York Shire Council advising that the Council had passed a motion unanimously at its April meeting to participate in the case study project (12^{th} May, 2017).
  - Planning meeting with Paul Martin, CEO of York Shire Council, Steve Gray (DFES) and Mark Edwards of GA to discuss future project activities in the town of York and communication strategies to engage both business and residents (6^{th} June, 2017).
- Project team inception meeting at the University of Adelaide (UoA) (30^{th} November, 2017).
- Meetings between UoA and GA staff and:
  - Shire of York (11^{th} December, 2017).
  - York Society (12^{th} December, 2017).
  - York Business Association (12^{th} December, 2017).
- Two public outreach sessions held in York (11^{th} and 12^{th} December, 2017).
- Foot survey of York road bridges (12^{th} December, 2017).
- Digitisation of council register of heritage listed buildings in York (April 2018).
- RICS survey of York buildings on the 19^{th} and 20^{th} February, 2018.
- FiDAT interrogation of RICS imagery (March 2018).
- Foot survey of old non-residential URM buildings in York (9^{th} to 12^{th} April, 2018).
- Foot survey of York businesses (9^{th} to 12^{th} April, 2018).
- Detail survey of three buildings (St Patricks Church, Convent and Town Hall) from 9^{th} to 12^{th} April, 2018.
- Digitisation of survey records (May 2018).
- Engagement with end users through:

  - Meeting with Shire of York and local associations (11th to 12th December, 2017).
  - Project presentation by Steve Gray, DFES, to the Wheatbelt District Emergency Management Committee at Northam (16th November, 2017).
  - Project presentation by Steve Gray, DFES, to the DFES Research Committee (10th April, 2018).
  - Introduction of DFES personnel to foot survey techniques (11th April, 2018).
  - Interview by Mark Edwards of GA with local newspaper, the "Avon Valley Advocate", with ensuing article (Grierson, 2018) on 13th February, 2018.
  - Mark Edwards of GA was interviewed live by radio journalist Chris Ilsley of Perth Radio Station 6PR about the York project on 20th February, 2018
  - Project presentation by Steve Gray (DFES), to the State Emergency Management Committee's Risk Subcommittee in Perth (7th June, 2018).
  - Distribution of project flyer through the Council and the York Society to the public (December 2017 – June 2018).
- Project workshop in York, 9th August, 2018. Refer to Appendix A.
- Presentation at the 2018 AFAC and BNHCRC Conference by Steve Gray (DFES) and Paul Martin (Shire of York): *Community strategy development for reducing earthquake risk in WA*. 5-8 September, 2018, Perth, WA.
- Publication of Vaculik et al, 2018b.
- Publication of Edwards, 2018.
- Briefing of the Australian Earthquake Engineering Society Conference as part of a conference tour, 15th November, 2018.
- Tendering and commissioning (18th March, 2019) a contract with quantity surveyors Turner and Townsend to provide cost estimates for retrofit, repair and replacement of URM building types typical of the York exposure.
- Publication of Edwards et al, 2019a.
- Presenting project outcomes at the joint meeting of the York Shire Council and the Heritage Council of Western Australia in the Shire council chambers on the 14th November, 2019.
- Publication of Edwards et al, 2019b.
- Publication of Ryu et al, 2019.

PROJECT SCOPE

This project entails undertaking a mitigation strategy implementation study of the regional centre of York. It draws upon the vulnerability and economic modelling research outcomes for the BNHCRC project "Cost-Effective Mitigation Strategy Development for Building Related Earthquake Risk". Utilising the outcomes of the project a range of mitigation implementation strategies are virtually applied to the URM buildings in the town to assess their effectiveness of these interventions on community risk and EM logistics in a rare, but credible, earthquake. As part of this study:

- Building exposure data provided by the WA Government already integrated into Geoscience Australia's National Exposure Information System (NEXIS) was augmented through field survey activity.
- Business exposure has been defined to enable the assessment of the economic activity disruption.
- A suite of six common URM building types in York was identified and retrofit strategies were developed for each.
- The economics of effecting these retrofit measures to each building type and use was made in the context of the seismic hazard beneath York. This was undertaken considering stepwise increasing levels of earthquake mitigation.
- Assessment was made of the reduced economic losses to the York community for two levels of staged roll-out of the mitigation over a 30 year period.
- Selected detailed scenarios were developed for EM planning purposes.

NEW ZEALAND CONTEXT ON THE MITIGATION OF HIGH EARTHQUAKE RISK BUILDINGS

The understanding of the severity of natural hazards and how to design our built environment to be resilient to them has progressively improved over time. This has been the case for earthquake hazard and the improved knowledge has translated into more effective building regulations. However, building regulations typically are non-retrospective, though this has changed recently in New Zealand. Notwithstanding this, presently within both New Zealand and Australian communities there are buildings that are vulnerable to earthquake and represent a significant risk to people, households and economic activity. The most vulnerable type is older URM buildings and, given the common colonial heritage of both countries, the architectural forms and construction practices used to construct them are very similar to each other and impart similar vulnerabilities.

New Zealand is located on the boundary between the Pacific and the Australian tectonic plates, whereas Australia has an intra-plate setting within the Australian plate. Consequently the seismic hazard and risk associated with older buildings is much greater in New Zealand than Australia. New Zealand has moved to address earthquake prone buildings in the country through the *Building Act 2004* (Legislation 2020). This requires earthquake prone buildings to be identified by Local Government Authorities which, by definition, are buildings that have a capacity of one third or less that imparted by the provisions of the country's latest building regulations. The Act at the time did not, however, stipulate when these buildings needed to be addressed, either through retrofit or demolition. This has been recently addressed in the passing of the *Earthquake Prone Buildings Amendment Act 2016* which took effect on the 1st July, 2017 (MBIE 2020). The Act divides New Zealand into three regions of risk based on bedrock hazard and now requires:

- Earthquake prone buildings in high risk regions (e.g. Wellington) be demolished or strengthened in 15 years.
- Earthquake prone buildings in medium risk regions (e.g. Rotorua) be demolished or strengthened in 25 years.
- Earthquake prone buildings in low risk regions (e.g. Auckland) be demolished or strengthened in 35 years.
- If a building is in a priority class, the address of earthquake risk must be implemented in half the time. The two key high priority classes are pedestrian precincts where earthquake damage could cause major casualties and along main transport corridors where damage debris could disrupt emergency access and supply chains.

The Act, and its 2016 amendment, effectively now provides local governments in NZ with a stick to address, in a prioritised manner, URM and poorly detailed reinforced concrete buildings that contribute the most to the earthquake risk in New Zealand communities. The original Act nor its amendment does not, however, stipulate the level of retrofit in relation to current code requirements appropriate and any raising of the building resistance above 33% of current code would be deemed adequate under the Act.

Retrofit of earthquake prone buildings has been underway for some time in New Zealand and provide valuable insights for Australian retrofit program strategies. The Resilience Program of the Wellington City Council (WCC) is arguably the exemplar for other local governments in the country. The program commenced in 2009, has been running for 10 years, and had made considerable progress, even before the amendment of the Act in 2016. The WCC (Mendonca 2020) has:

- Surveyed 5,000 potentially earthquake prone buildings;
- Identified through more detailed investigation 1,000 that are earthquake prone in terms of the Building Act;
- Requires retrofit to 67% current code for owner occupied buildings, 80% for tenanted, and 100% for Council buildings;
- Offers incentives in the form of rates rebates and grants for some professional design services for retrofit measure;
- Has 600 remaining earthquake prone buildings as of March 2020;
- Has retrofitted 113 older URM buildings through an 18 month program called the Unreinforced Masonry Buildings Program (UMBP).

Masterton District Council (MDC) is a second local government example that has particularly benefitted from the amendment to the Act in 2016. MDC is a smaller local government with less resources than the WCC and has not been able to incentivise retrofit. While little progress had been made on earthquake prone buildings prior to July 2017, more recently they have reported (Soulley 2020):

- Priority areas have been identified as the main street of the central business district and the route of the State Highway through the city;
- 50 buildings have been identified as earthquake prone in these priority areas requiring retrofit or demolition within 7.5 years;
- Letters were sent to building owners soon after the Building Amendment Act took effect;
- Of these 96% of property owners have either strengthened the buildings, are in the process of acquiring engineering advice, or are engaging with the Council on a forward strategy;
- Work has commenced identifying earthquake prone buildings in the lower priority tier to be completed in 2021.

Collectively the experience of the two Local governments, both in the designated high risk area of New Zealand, provide the following learnings for the York project:

- Having enforceable retrospective legislation is very effective ("The Stick"). Recent discussions with a representative of the NZ Ministry of Business, Innovation & Employment (MBIE) (David Robson, 31 Oct 2019) has revealed that fines have subsequently been issued to some building owners due to their lack of compliance.
- Risk awareness of the community due to direct local experience of earthquake damage or other national disasters does positively influence uptake. It also provides a driver through tenants (residential and business) requiring safer buildings to rent or lease.
- Insurance has become a driver, not through incentives, but through the prospect of higher premiums if mitigation is not undertaken. Risk has not

been priced correctly and the recent earthquakes in New Zealand has highlighted this.
- Incentives, when provided, have been shown to be very effective ("The Carrot"). For the short term UMBP project in Wellington, incentives were found to be essential (Falcon Consulting 2019).

The New Zealand experience is informative to the Australian setting in the following areas:
- While enforceable retrospective legislation is very helpful, this is not available in Australia for any natural hazard. Other approaches to motivate retrofit behaviour are needed.
- Risk awareness is a challenge due to the limited damaging earthquake experience in Australia. Scenario modelling of expected impacts could be useful in communicating this risk to raise awareness and may raise the expectations of tenants to have safe premises and residences.
- As learned from the insurance industry at the 9th August workshop in York, currently the earthquake risk on York buildings is not based on local risk but on a larger regional risk. If it were to change to location based risk such as is done in Australia for severe wind, flood and bushfire, York property owners likely will face increased premiums.
- Incentives may be needed to motivate retrofit behavior.
- The NZ process of giving higher retrofit priority to areas of high hazard and consequences of damage may assist in targeting activity. In particular, the focus on avoiding major loss of life and injury through falling masonry could target the securing of elements that would potential cause this, thereby providing a minimum retrofit scope.

SEISMIC HAZARD IN THE YORK REGION

One of the fundamental uses of national-scale seismic hazard assessments is in national building codes and standards (e.g., Standards Australia, 2007). This section provides a summary of the seismicity and seismic hazard of the York region of Western Australia. York is located within the so-called Southwest Seismic Zone (SWSZ) of the Yilgarn Craton (Doyle, 1971) and in proximity to regions with historically high rates of seismicity. The Archaean rocks of the Yilgarn Craton are largely comprised granitoid-greenstone rocks which range in age from 3.0 billion and 2.6 billion years ago (Wilde et al., 1996).

HISTORICAL SEISMICITY

The distribution of historic earthquake epicentres in the southwest of Western Australia is not uniform, with a generally low level of seismicity being characteristic of much of the area (Figure 1). A relatively high level of seismicity is characteristic of a broad band crossing the south western corner. The SWSZ is one of the most seismically active regions in Australia (Leonard, 2008). Earthquake activity appears to have increased significantly since the 1940s (Leonard, 2008), and it has generated five of the nine known Australian historic surface ruptures; 1968 Meckering, 1970 Calingiri, 1979 Cadoux, 2007 Katanning, and 2018 Lake Muir (Gordon and Lewis, 1980; Lewis et al., 1981; Dawson et al., 2008; Clark et al., 2019).

The most well-known earthquake to have occurred in the SWSZ near York is the Meckering earthquake that occurred on the 14th of October, 1968 (Gordon and Lewis, 1980). The Meckering earthquake produced a 37 km-long arcuate surface rupture that locally reached up to approximately 2.3m in height (Clark and Edwards, 2018). The earthquake severely damaged the small town of Meckering and although twenty people were injured, thankfully, there were no fatalities. Extensive damage was also reported to public utilities and communications, including the Goldfields water supply pipeline, the Perth to Kalgoorlie Railway Line, and to the Great Eastern Highway (Gordon and Lewis, 1980).

NSHA 2018 BEDROCK HAZARD

Geoscience Australia has developed two probabilistic seismic hazard assessments for Australia. In 2012 GA released a national seismic hazard assessment that was intended to supersede the 1991 seismic design factors in the Australian loadings standard for building design (Burbidge, 2012; Leonard et al., 2013; 2014). The 2012 National Seismic Hazard Maps (NSHM12) used modern probabilistic methods, improved characterisation of tectonic region type and maximum earthquake magnitude (Leonard and Clark, 2011; Clark et al., 2014) and included Australian-specific ground-motion models (Somerville et al., 2009; Allen, 2012). In addition, the earthquake catalogue was augmented with a further 20 years of earthquake data (i.e. magnitudes and epicentres) relative to previous assessments used to inform the current earthquake loadings standard (Standards Australia 2007). Whilst a significant advance from its predecessor in terms of methods and data, the Standards subcommittee elected not to adopt the 2012-13 revision of the National Seismic Hazard Maps (NSHM12; Burbidge,

2012) to underpin seismic design provisions for AS1170.4 owing to the uncertainties associated with seismic hazard forecasts for Australia (as with any stable continental interior), as well as concerns that it did not reflect the view of the broader Australian seismological community.

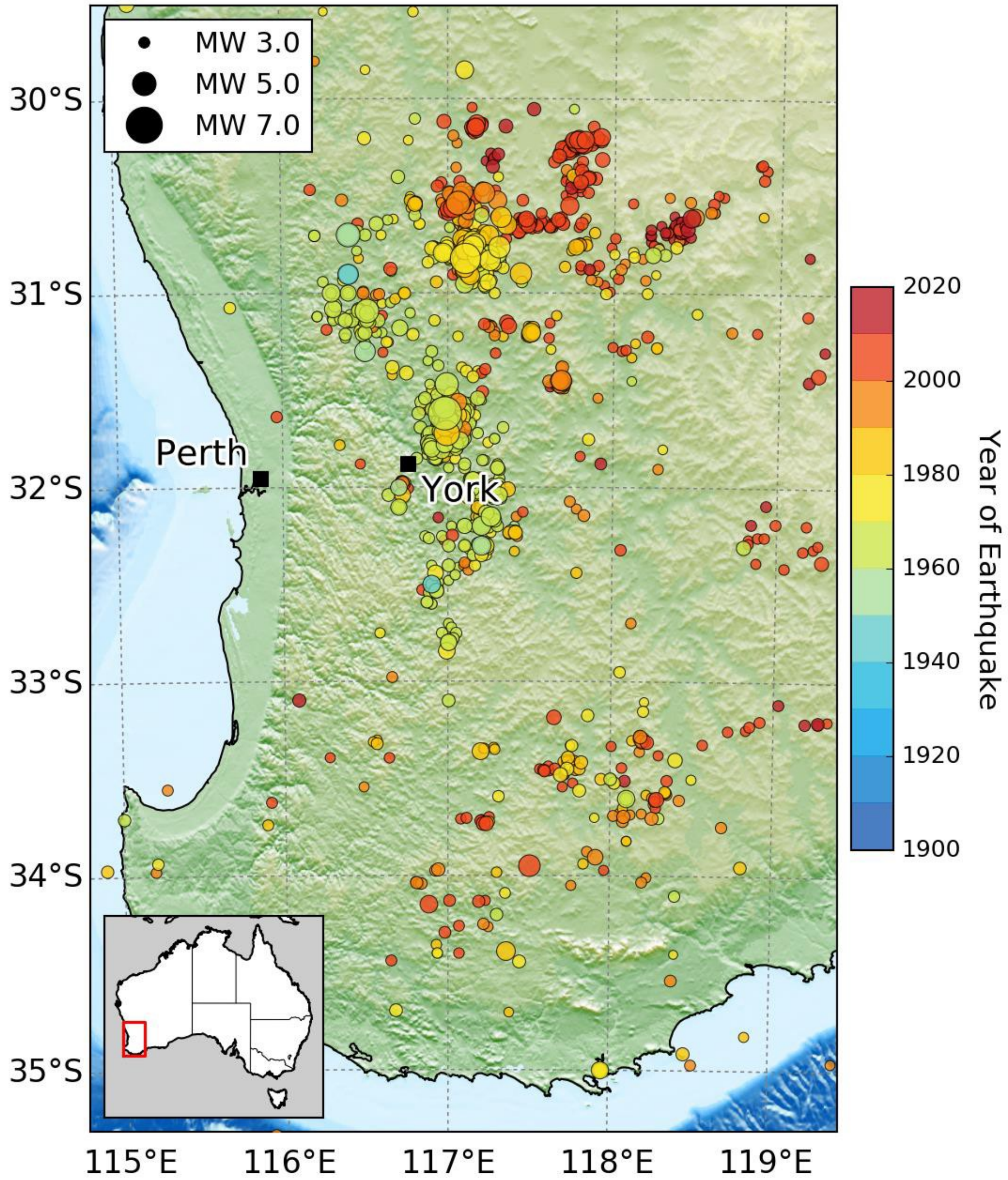


FIGURE 1 EARTHQUAKE EPICENTRES RECORDED IN THE SOUTHWEST OF REGION OF WESTERN AUSTRALIA BASED ON THE NSHA18-CATALOGUE (ALLEN ET AL., 2018). EPICENTRES ARE COLOUR-CODED BY THE YEAR OF THE EARTHQUAKE.

In 2018 Geoscience Australia, together with contributors from the wider Australian seismology community, produced an updated National Seismic Hazard Assessment (NSHA18), which updates the 2012 National Seismic Hazard Maps. Time-independent, mean seismic design values are calculated on Standards Australia's AS1170.4 Soil Class B_e (at V_{S30}=760 m/s) for the horizontal peak ground acceleration (PGA) and for the geometric mean of the spectral accelerations, Sa(*T*), for *T* = 0.1, 0.2, 0.3, 0.5, 1.0, 2.0 and 4.0 s.

Relative to the seismic hazard map in the AS1170.4 earthquake loading standard (Standards Australia, 2007), the NSHA18 update leverages advances in earthquake-hazard science in Australia and analogue tectonic regions over the last three decades. It offers many important advances over its predecessors, including:

- the calculation in a full probabilistic framework (Cornell, 1968) using the Global Earthquake Model Foundation's OpenQuake-engine (Pagani et al., 2014);
- consistent expression of earthquake magnitudes in terms of moment magnitude, M_W;
- inclusion of a national fault-source model based on the Australian Neotectonic Features database (Clark et al., 2016);
- use of structured expert elicitation workshops involving the Australian seismological community, to capture epistemic (i.e., modelling) uncertainty through the selection and weighting of multiple alternative:
    - source models;
    - magnitude-recurrence distribution types;
    - fault recurrence and clustering models;
    - maximum earthquake magnitudes for both fault and area sources; and
    - ground-motion models.
- the engagement of a science advisory panel, comprising internationally recognised experts in probabilistic seismic hazard assessment, to ensure global best practice and evidence-based science.

The NSHA18 shows that PGA values at the 1/500 annual exceedance probability (AEP) across Australia have decreased, on average, by 72% relative to the earthquake hazard factors provided for localities in the current earthquake loadings standard (Standards Australia, 2007). Additionally, the NSHA18 1/500 AEP PGA values are approximately half of those in the 2013 update of the NSHM12 (Leonard et al., 2013), with an average decrease of 48% at the communities listed in the current loadings standard. The key reasons for this decrease in seismic hazard factors are:

- the reduction in the rates of moderate-to-large earthquakes (approximately $M_W \geq 4.0$); firstly through the correction of pre-1990 local magnitude M_L estimates, and secondly, through the conversion of M_L to M_W (Allen et al., 2018a);
- increases in Gutenberg and Richter (1944) *b*-values, particularly in eastern Australia, owing to the M_L to M_W conversions, which decrease the rates of rare large earthquakes relative to more commonly observed moderate-magnitude earthquakes; and
- the use of modern ground-motion attenuation models that predict lower ground-motions and faster attenuation of PGA and other

spectral ordinates with increasing distance, and thus forecasting lower ground-motion hazard.

Whilst the seismic hazard estimated through the NSHA18 is lower than previous estimates at the 1/500 AEP, it is observed that the hazard increases at a faster rate at longer return periods (Allen et al., 2019). The PGA hazard curve calculated on AS1170.4 Soil Class B_e is compared to the currently specified hazard in the Australian loadings standard in Figure 2 which shows the NSHA18 hazard significantly lower at shorter return periods, but converging at longer one. The NSHA18 hazard curves was used for the benefit-cost analysis.

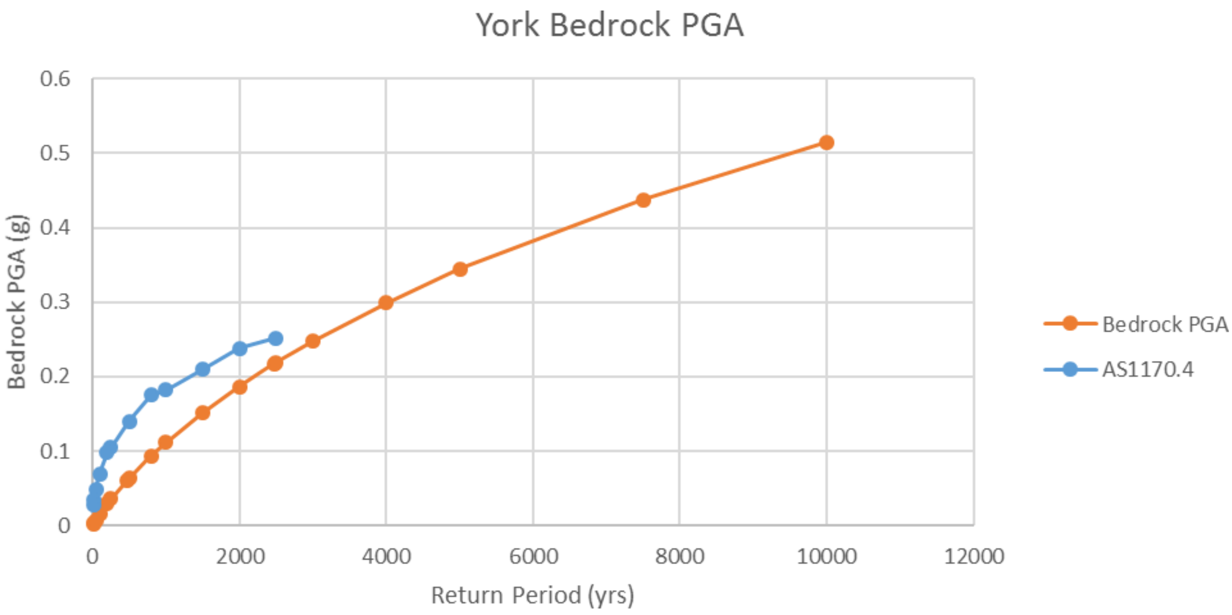


FIGURE 2 BEDROCK HAZARD CURVE FOR YORK EXTRACTED FROM NSHA18 (ALLEN ET AL, 2018) COMPARED TO THE HAZARD SPECIFIED IN AS 1170.4 FOR YORK(STANDARDS AUSTRALIA, 2007).

SITE SOIL EFFECTS ON BEDROCK HAZARD

It is well known that near-surface lithology can modify earthquake ground shaking at the Earth's surface and that sites underlain by soft sediments are more likely to experience significant amplification of ground shaking (Borcherdt, 1970). The Australian Seismic Site Conditions Map (ASSCM) uses information about surficial geology (or regolith) as a proxy for the potential behaviour of geological materials under the influence of seismic ground shaking, predominantly in the context of ground-motion amplification (McPherson, 2017).

Ground-motion hazard is commonly calculated for an engineering rock site class equivalent to a Soil Class B_e (at V_{S30}=760 m/s), as is the case for AS1170.4. According to McPherson (2017), the township of York is sited on mainly hard rocks including granite with fault systems which have observed geologically recent movements extending over an area of more than 200 km^2 around Meckering. Typically rock can be found at a depth of few metres or less, but near the Avon River soft deposits can reach a thickness of 10 metres or more. The influence of the soil on bedrock shaking at an individual building site as a result of soil thickness and stiffness is captured by assigning a Site Class. Figure 3 shows the expected site classes over the study area determined from McPherson (2017). The hazard parameter used in the fragility and vulnerability curves developed in this project is surface PGA which is typically higher than bedrock PGA due to the amplifying effects of overlying soils or regolith. The softer and deeper the regolith the greater the amplification. Most of the old URM buildings in York are on site class D regolith hence the bedrock PGA values were factored by 1.56 to produce a representative surface PGA hazard.

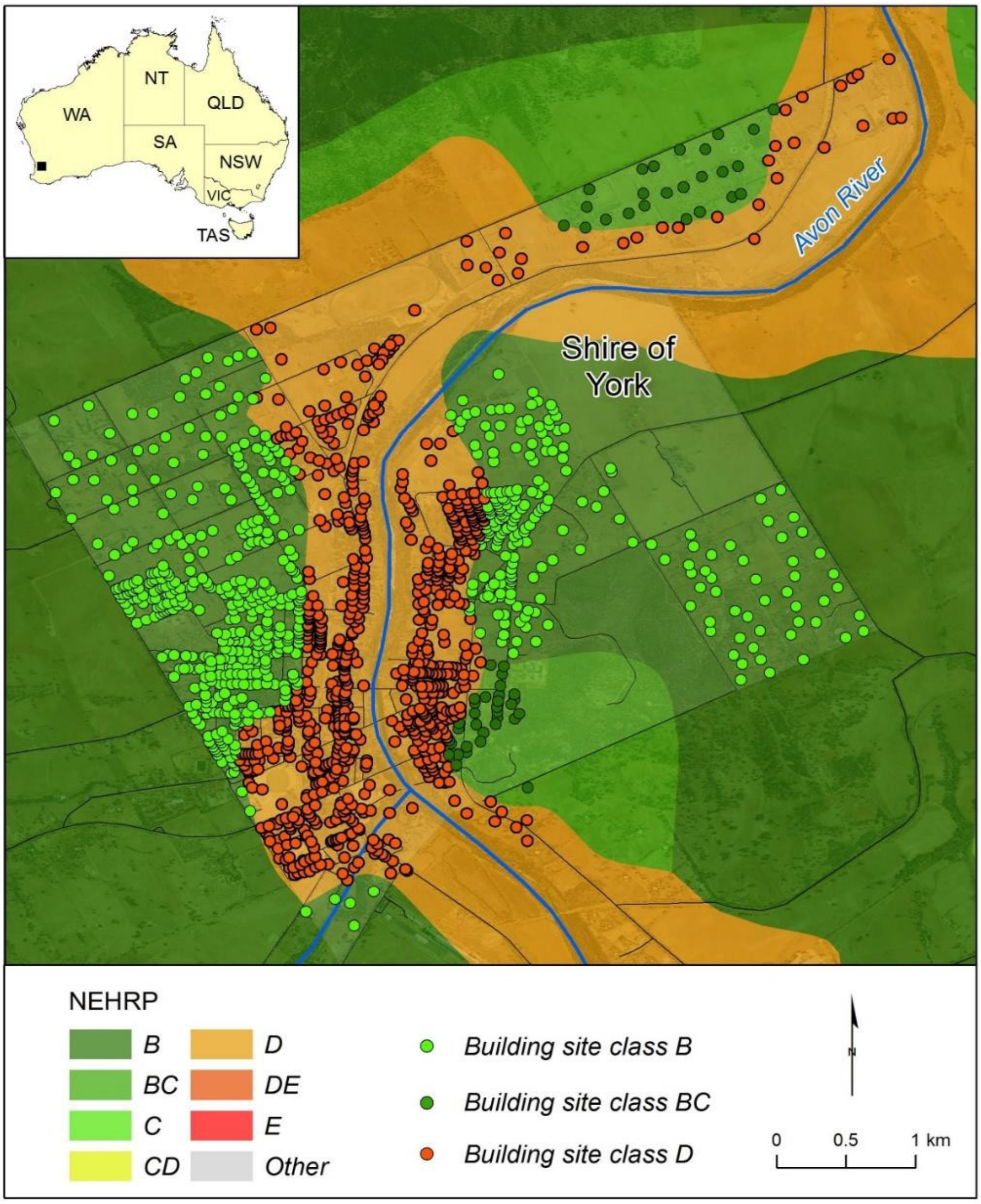


FIGURE 3 SITE CLASSES OVER THE STUDY AREA WITH SITE CLASSES ASSIGNED TO EACH BUILDING

ANALYTICAL TOOLS, MODELS AND INDICES USED

SCENARIO AND RISK MODELLING

Natural hazard risk is the combination of the local hazard, the assets of value and the vulnerability of these assets to the hazard being considered. Each of these elements are illustrated in Figure 4. Using this impact and risk framework the three elements can be brought together numerically to assess the expected consequences of a severe natural event. Further, by considering the full range of possible natural hazard events the individual consequences assessed for each can aggregated into a measure of risk.

The impact and risk metrics can be narrow or they can be progressively broadened. For the financial sector (e.g. insurance industry) the lens is narrower with a focus on the risk of damage to buildings, fit-outs, plant, and contents. It can also include business interruption losses and temporary accommodation costs if these are within the cover of an insurance policy. More holistically, impact and risk can consider injuries, deaths, wage losses, rental income losses, cost of health care, cost of emergency response and clean-up, etc. In this project a broad impact and risk focus has been adopted to cover a wide range of metrics of interest to the various stakeholders involved.

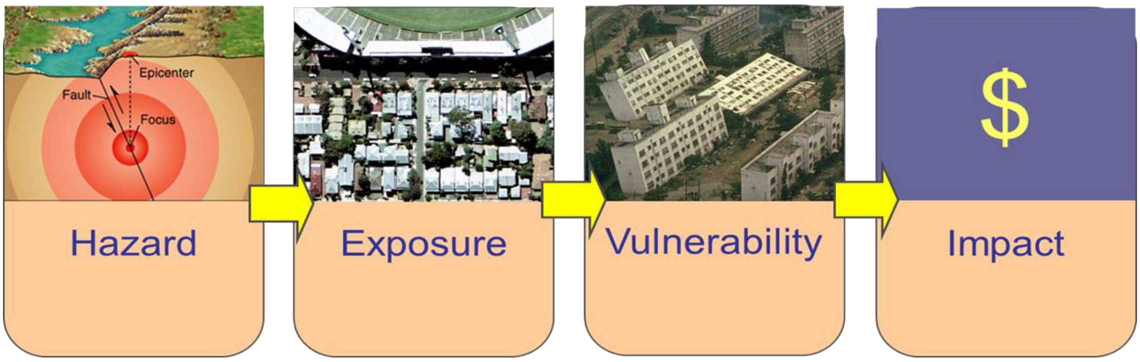


FIGURE 4. NATURAL DISASTER IMPACT AND RISK ASSESSMENT FRAMEWORK ILLUSTRATING THE COMBINATION OF HAZARD, EXPOSURE AND VULNERABILITY INFORMATION IN A QUANTITATIVE MANNER TO ASSESS COMMUNITY RISK.

OPENQUAKE

The integration of the elements of the risk framework for earthquake has been undertaken for this project using *OpenQuake*. The *OpenQuake*-engine is a seismic hazard and risk modeling software developed by the Global Earthquake Model Foundation (GEM) (Pagani et al., 2014) that is based in Pavia, Italy. The software is developed within a rigorous, test-driven framework and is designed to be both modular and flexible. Because of the open-source nature, users have access to peer-reviewed methods and models soon after their release and can also contribute back to the development project with their own enhancements. The community-driven development environment promoted by GEM is ensuring that the software remains current and supports the needs of its users.

AUSTRALIAN NATIONAL DISASTER RESILIENCE INDEX (ANDRI)

ANDRI was recently developed by the University of New England, New South Wales (NSW), under a project within the Bushfire and Natural Hazard Collaborative Research Centre (BNHCRC). It is a top-down measure of community level resilience assessed in a nationally consistent manner. It comprises eight sub-indices based on 77 indicators, that are "rolled up" under "Coping" and "Adaptive Capacity" themes. The final index is the combination of these two. The hierarchal structure of the index is illustrated in Figure 5 and a more detailed description of it and the eight themes is contained in Appendix B.

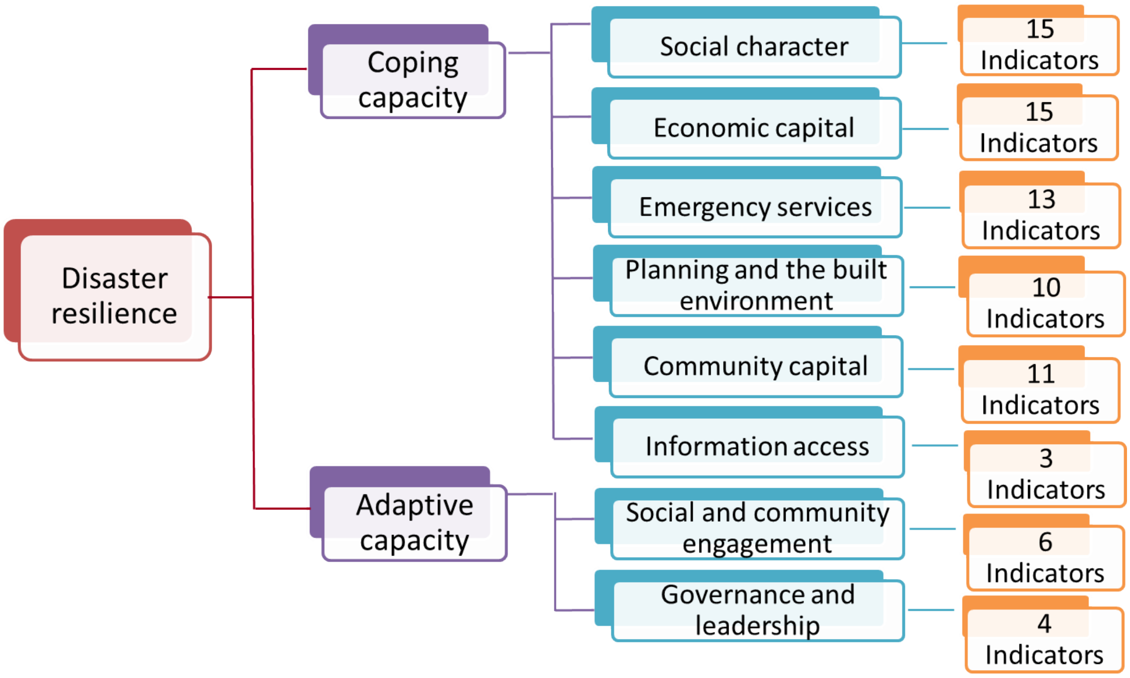


FIGURE 5 HIERARCHAL STRUCTURE OF THE AUSTRALIAN NATURAL DISASTER RESILIENCE INDEX.

ANDRI has similarities to the Australian Bureau of Statistics (ABS) Socio-Economic indices for Areas (SEIFA) because both draw heavily on ABS statistics derived from the five yearly national Census. Given the development timeframe of ANDRI, the index relates to the 2011 Census and the ABS geographical boundaries used for it. It is, however, broader as it includes other indicators that are related to resilience related measures. The overall ANDRI index ranges from 0.3 (low resilience) to 0.7 (high resilience). Its utility is in enabling a comparison between SA2's and classifies them into five types based on the similarities in the mix of the eight ANDRI sub-indices. The typologies are presented in Figure 6 as a cluster analysis of all SA2's in Australia. The typologies give insights into the strengths, weaknesses and needs of communities exposed to severe natural hazard events.

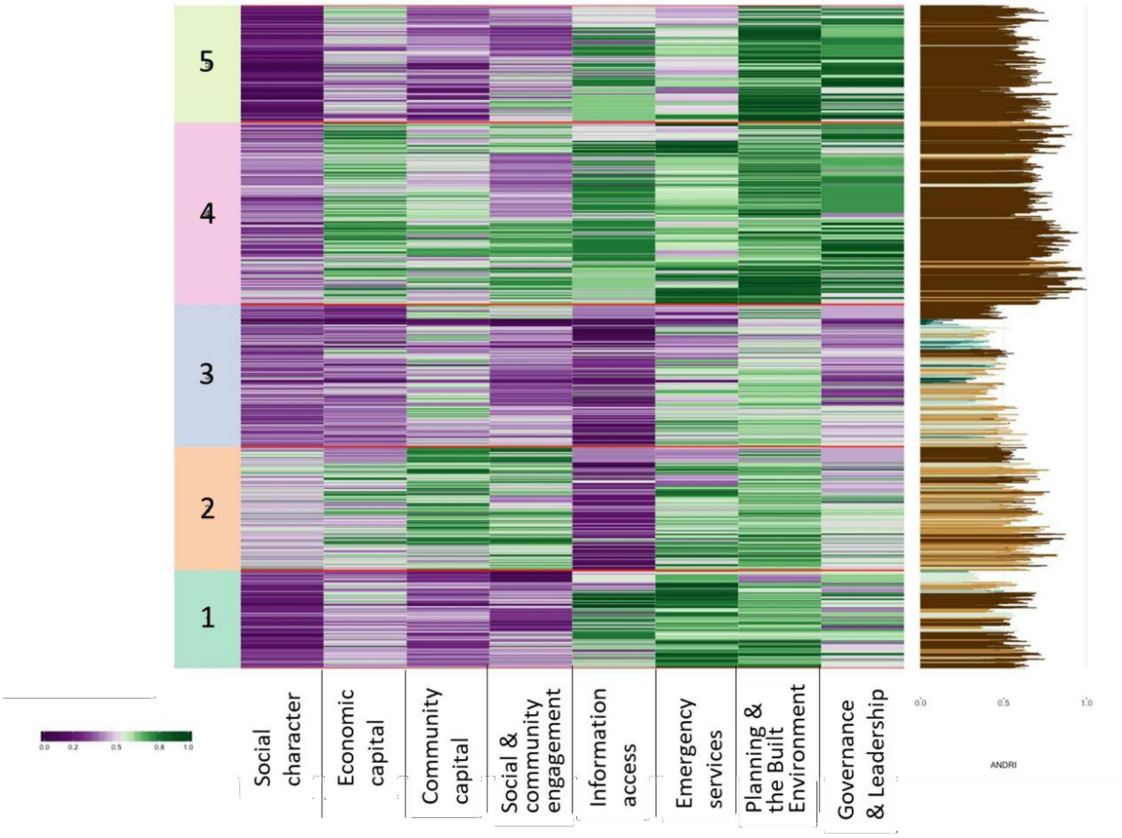


FIGURE 6 CLUSTERING OF THE AUSTRALIAN NATURAL DISASTER RESILIENCE INDEX SUB-INDICES OF SA2 ACROSS AUSTRALIA AND THE CATEGORISATION OF THE RELATIVITY BETWEEN THEM INTO FIVE CLASSES.

It should be noted that, as ANDRI is top down, it can only elucidate the local factors influencing disaster resilience as captured by the national indicators. It may not be correct in every way for an individual community. Further, the geographical scale of the SA2 areas can be large in rural areas and sometimes covers several communities as well as the farming properties around them. Finally, the index is particularly focused on household resilience as a subset of communities rather than the community as a whole. The ANDRI reporting in Appendix B indicates that York is in the lower quartile of SA2 areas nationally and falls into Typology Group 3.

YORK COMMUNITY EXPOSURE

Existing exposure databases are available for buildings in York, namely: Landgate (https://www0.landgate.wa.gov.au/) data for residential properties, integrated into GA's National Exposure Information System (NEXIS) (Nadimpalli, 2007) and the Shire of York Heritage Inventory. Existing exposure information available to the project from NEXIS is shown in Figure 7 and Figure 8. The existing exposure databases contain attributes such as age, building use, roof material and wall material. Whilst these are useful for the project, more detailed exposure information was required to enable the project to calculate building replacement costs, seismic upgrade costs, repair costs in the event of earthquake damage and costs incurred by businesses due to earthquake damage.

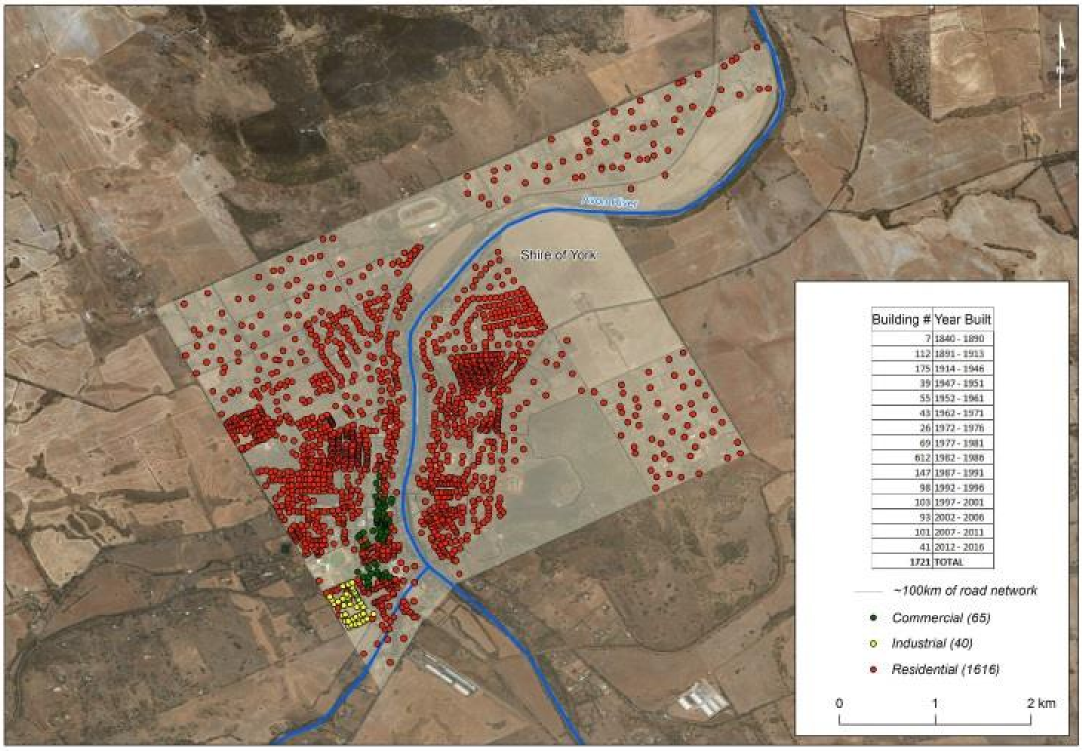


FIGURE 7 EXISTING NEXIS INFORMATION AVAILABLE TO THE PROJECT – YORK BUILDINGS BY USAGE.

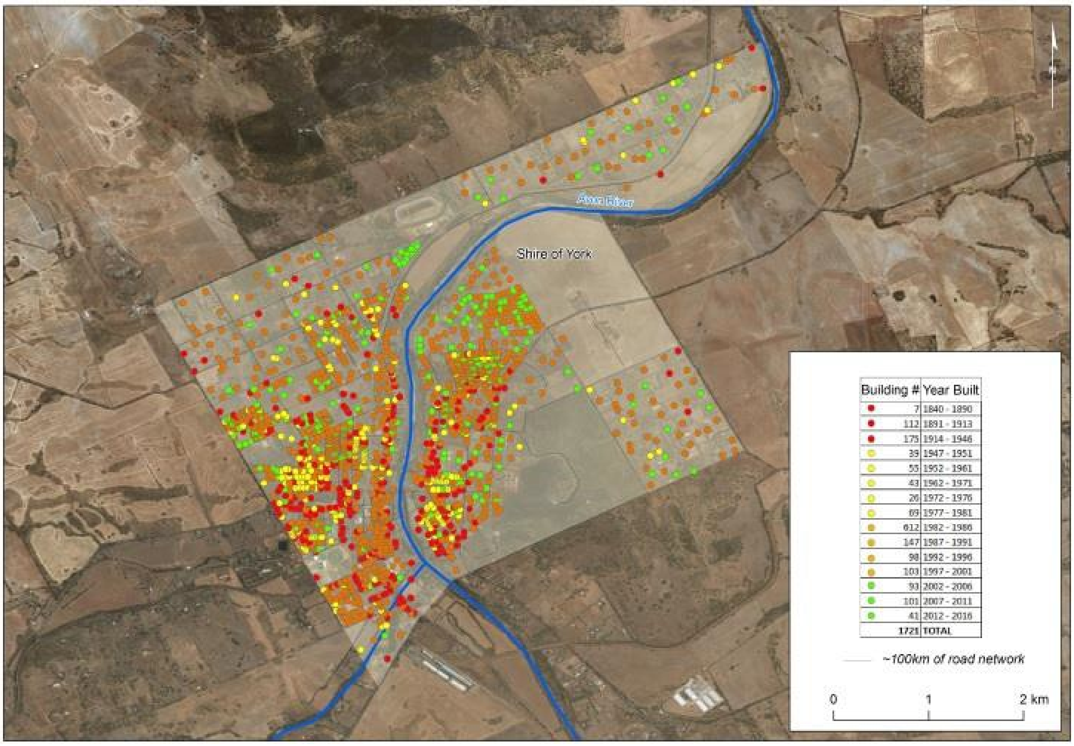


FIGURE 8 EXISTING NEXIS INFORMATION AVAILABLE TO THE PROJECT – YORK BUILDINGS BY AGE.

For the purposes of the project the detailed exposure information was required at the resolution of individual buildings. A feature of Australian URM buildings, mostly built prior to WW2, is a variety of architectural forms. Architectural features such as chimneys, parapets, storey heights and construction materials all affect a building's vulnerability to earthquake and hence its repair cost in the event of earthquake damage. Further, the presence and form of such features will influence the type and necessity of earthquake upgrade works appropriate for an individual building.

Knowledge of the nature of businesses in York was also required so that estimates of earthquake impact on them, including direct loss due to damaged premises, loss of custom and loss of staff, could be made.

Additionally, some knowledge of the distribution of the exposed human population with time was desired so that estimates of injuries from earthquake events could be made.

Surveys were undertaken to capture the three types of exposure information noted above. For each survey, a data dictionary was prepared that gave details for each attribute to be captured with examples and explanatory notes. The surveys are discussed in detail in the following section.

BUILDING SURVEY

The capture and collation of building exposure information for the buildings in York presented the largest task for the project. Two levels of information were required:

- Collection of a range of attributes for all buildings in York; and

- Collection of more detailed information for the URM buildings in York.

To achieve this aim a two stage building survey was designed. Firstly, a coarse survey of all York buildings using GA's Rapid Inventory Collection System (RICS) (Geoscience Australia, 2011) with subsequent interrogation of the captured images, aerial imagery and internet resources using GA's in-house Field Data Analysis Tool (FiDAT) software (Geoscience Australia, 2013) was completed.

Secondly, a follow-up door to door foot survey was undertaken to capture those exposure attributes that could not be determined during the RICS survey. During this second survey a more detailed inspection of three York URM buildings (the Town Hall, St Patrick's Church and the Convent School) was also undertaken. The intention of this activity was to capture detailed knowledge of the construction details of York URM buildings. However, typical access limitations such as internal finishes and inability to enter roof spaces precluded this aim from being fully achieved.

Each activity is described in detail below. The building exposure database developed as part of this survey exercise was provided to the Shire of York for their reference and augmentation.

RICS Survey

This survey was undertaken on the 19th and 20th February, 2018. A vehicle with roof mounted high-resolution cameras was driven along all York streets recording images at a rate of approximately four frames per second for both sides of the street. The captured images were loaded into the FiDAT software that associated each building with the closest RICS images. The FiDAT software enables users to then examine the most appropriate RICS images together with aerial imagery, and any other imagery available and record various building attributes.

The attributes captured for each building in York are shown on the RICS Survey Form in Appendix C. These attributes are shaded green on the Foot Survey Form in Appendix C.

The RICS survey captured building attributes for 1,463 buildings in York which are shown in Figure 9. Of the surveyed buildings, 307 buildings were identified as URM buildings of interest to the project which are shown in Figure 10. Typically these could be easily identified due to the presence of masonry chimneys as these are an architectural feature that is characteristic of the building vintage of interest. The residential subset of the URM buildings was excluded from detail foot survey follow-up out of consideration for the occupants' privacy.

Foot Survey

The follow-up foot survey was undertaken from the 9th to the 12th April, 2018 together with the Business Survey. This survey aimed to record all the non-shaded attributes shown on the foot survey form in Appendix C, typically those attributes pertaining to interior features and those features not visible from the road. Teams of two people, one recording business attributes and the other recording building attributes, walked from door to door through York visiting businesses and all the non-residential URM buildings identified in the RICS survey. In total, the foot survey recorded attributes for 47 buildings.

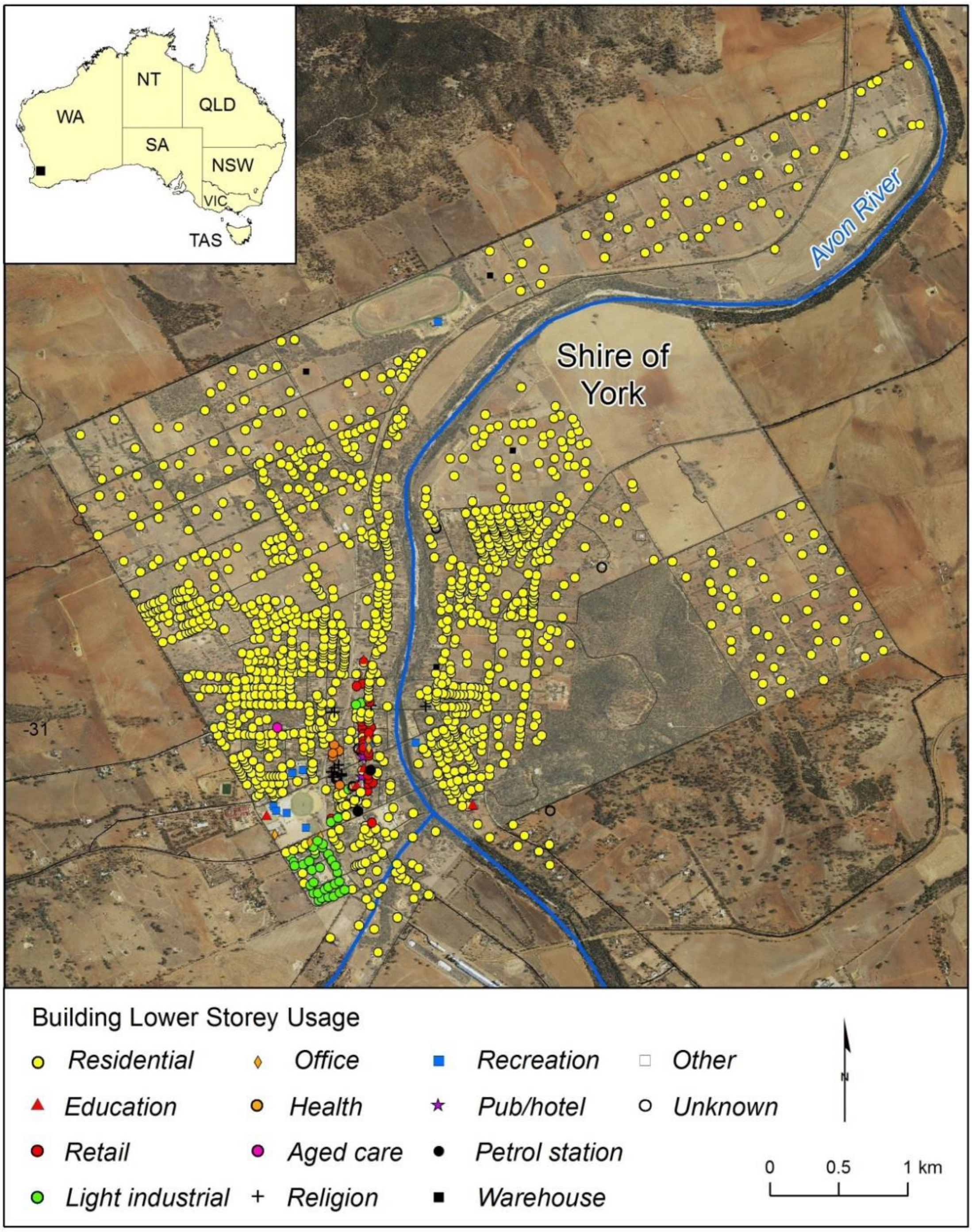


FIGURE 9 BUILDINGS IN YORK CAPTURED DURING THE RICS SURVEY CATEGORISED BY USAGE.

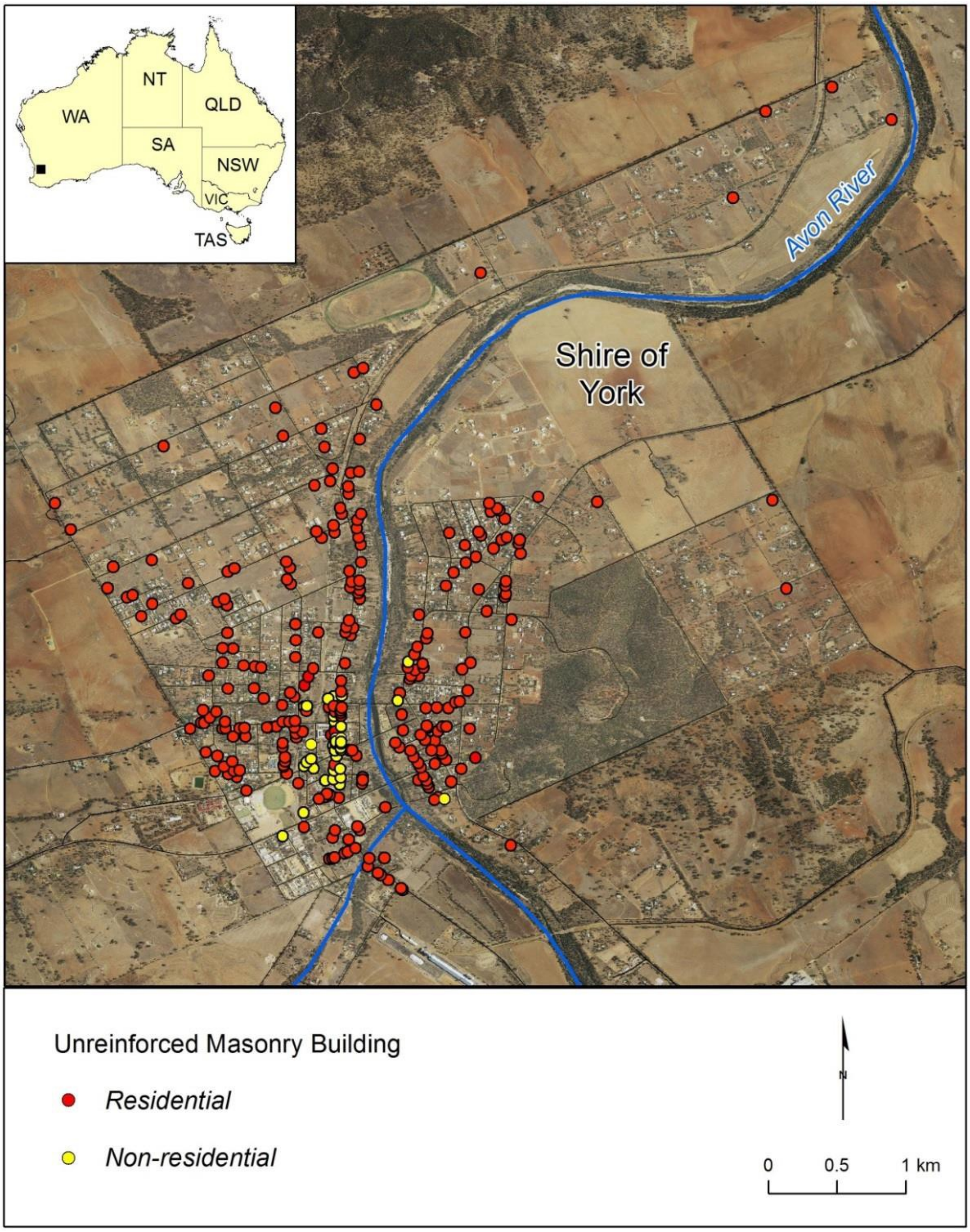


FIGURE 10 URM BUILDINGS IN YORK IDENTIFIED FROM THE RICS IMAGERY. BUILDINGS SELECTED USING AGE BRACKET AND HAVING A MASONRY LOWER STOREY WALL MATERIAL.

BUSINESS SURVEY

The business survey was undertaken from the 9th to the 12th April, 2018. The survey was designed to collate earthquake related business exposure information in the town. Information on business type, structure, age, trading times, business size, number of employees, business income, and business expenditure was included. The survey was also specifically aimed to collect information on the value of assets and liabilities of the business to enable an estimation of business interruption loss in the event of an earthquake scenario. Additionally, the survey was designed to collect information on insurance coverage for disaster, level of owner's preparedness against earthquake and flood and details of some flood exposure information such as floor dimensions, floor finish, fit-out quality and the vertical distribution of fit-out, machinery and products values in the building. The business survey form is included in Appendix C.

The survey collected information on 87 businesses in the town. The businesses are mostly retail businesses. Of the 87 surveyed businesses, 61 provided data about the number of employees. Of the 61, 34 businesses are small businesses and the remaining 27 are sole traders. The business survey was not successful in obtaining information on business income/expenditure or the value of assets/liabilities of the business. While some businesses did provide some of this information, many of the business owners, or the staff present at the time of survey, were unwilling to share this information due to its commercial-in-confidence nature.

HUMAN ACTIVITY

In addition to damage to buildings and impacts on businesses, the project also estimated casualties from earthquakes. In a streetscape dominated by low-rise URM buildings many casualties may potentially arise from people in the street being impacted by falling masonry. To have an understanding of the spatial distribution of people in the main street of York by time of day photographs of the main streetscape were taken at mid-morning, midday and evening times during the course of one normal business day. Counting of cars and pedestrians in each photograph enabled an estimation of the likely population in the street on a typical day. Figure 11 is an example of an evening shot

FIGURE 11 EXAMPLE STREETSCAPE IMAGE TAKEN IN THE EVENING.

It was also noted from the Shire of York that the street population can increase significantly during a major event hosted by York. The town hosts several of these annually in which the main street is closed and effectively turned into a mall. The Shire provided the summary of events held in 2019 and the corresponding visitor centre numbers as summarised in Table 1. The visitor centre numbers are a relatively small portion of those that were in the centre of town on that day that can number in the thousands. Figure 12 is of the annual motorcycle festival that illustrates both the number and congestion of people in the main street during this event.

TABLE 1 SUMMARY OF VISITORS TO YORK VISITOR CENTRE DURING MAJOR EVENTS HOSTED IN YORK IN 2019.

Festival/Major Event	Event Day	Visitor Centre Numbers
York Motorcycle Festival	Saturday, 13th April	456
	Sunday, 14th April	1,322
Easter Fair	Saturday, 20th April	574
	Sunday, 21th April	675
York Motor Show	Sunday, 1st September	327
York Agricultural Show	Saturday, 7th September	425
York Medieval Fayre	Sunday, 29th September	1,059
York Festival	Saturday, 28th September	590
	Sunday, 29th September	1,059
	Monday, 30th September	1,030
	Saturday, 5th October	1,210
	Sunday, 6th October	652
	Saturday, 12th October	707
	Sunday, 13th October	508

In addition, as York draws visitors to the town based on its heritage nature and boutique shops, the town can become very busy on weekends. It is a pleasant drive from Perth and on a weekend the town can have several hundred visitors. During the survey activity it was noted that the presence of people on the main street during the day increased gradually towards the weekend.

FIGURE 12 AVON TERRACE DURING THE YORK MOTORCYCLE FESTIVAL IN YORK (CREDIT: YORK MOTORCYCLE FESTIVAL).

BUILDING VULNERABILITY

Vulnerability curves in terms of Damage Index (DI) versus ground shaking beneath the building were required. The DI is factored by the building replacement cost to determine damage loss resulting from the ground shaking in an earthquake event. These were produced for each generic building type for its current or 'unretrofitted' state and also for each retrofit scenario considered. A retrofit scenario is a set of upgrade works applied to a building type to increase its resilience to earthquake actions. The upgrade works can range from retrofit of just one component (e.g. bracing chimneys) to full retrofit of all components. Several retrofit scenarios were selected for each generic building type to explore the variability in benefit-cost of undertaking a range of retrofit works.

BUILDING VULNERABILITY TYPE SELECTION

The architectural and structural features of the old URM buildings in York were assessed to determine a limited number of generic building types that were representative of the more common building types encountered in York and represented the range of architectural features commonly encountered in older URM buildings in country towns. The selection of generic building types was discussed and consensus reached on them at the 9th August, 2018, workshop in York. Minutes of the workshop are contained in Appendix A. With the exception of several unique buildings such as churches, The Mill and the Town Hall, almost all of York's URM buildings fell into one of these adopted classes. Table 2 describes the six generic building types identified for the project team to use in its development of assessment methodology and seismic strengthening options.

TABLE 2 GENERIC BUILDING TYPES.

Type	Description	Usage	Example photo	Frequency
1	Single storey URM	Residential		219
2	Two storey URM with bedrooms and bathrooms on the upper storey, kitchen, bar, dining room and bathrooms on ground floor	Pub		5

Type	Description	Usage	Example photo	Frequency
3	Single storey URM split into 5 tenancies	Commercial		12
4	Two storey URM with apartments on the upper floor and two commercial tenancies on ground floor	Commercial		3
5	Two storey institutional URM with apartment on upper floor	Post Office		2
6	Two storey URM with small rooms	Bank		5

BUILDING VULNERABILITY ASSESSMENT PROCESS

To produce a vulnerability curve for each generic building type, a process was adopted that sampled the fragility of each major component of the building and computed the repair cost for the set of component damage states. The process was repeated many times for each hazard magnitude to capture the variability in component fragility. The components of the URM buildings that were considered vulnerable to earthquake are:

- Chimneys (squat, medium and slender),
- Parapets (short and tall),
- Gable walls,
- 1 storey URM 'boxes',

- 2 storey URM 'boxes'.

The term 'box' is used to describe that portion of a URM building other than vulnerable roof level URM components (chimneys, parapets and gable walls). Typically the 'box' consists of external URM walls, internal URM walls, timber floor structure and timber roof structure.

The process for a single building type is outlined in Figure 13. It was repeated for each generic building type in its current or 'un-retrofitted' state and also for each retrofit scenario. As a result of its Monte Carlo sampling, it produces a scatter of damage indices at each hazard magnitude which was averaged to produce a single vulnerability curve for the generic building type in question. Note that not every generic building type included each component type. The components considered for each generic building type are shown in Table 3.

TABLE 3 URM COMPONENTS MODELLED IN EACH GENERIC BUILDING TYPE.

Generic building type	1	2	3	4	5	6
Components	Squat chimneys Gable walls 1 storey 'box'	Medium chimneys Low parapets 2 storey 'box'	Low parapets 1 storey URM walls	Medium chimneys Tall parapets 2 storey 'box'	Slender chimneys 2 storey 'box'	Medium chimneys Low parapets 2 storey 'box'

The process of independantly sampling the fragility curves for each component within a building can lead to an illogical set of component damage states. For example, if the building 'box' was sampled to be in a 'Collapse' damage state and chimneys were sampled to be in 'None' or 'Slight' damage state; the set of damage states is illogical as if the main building is collapsed then the roof-level components cannot be undamaged. To overcome this issue, a table of logical damage states was constructed (Table 4)and if the set of sampled component damage states did not match the logical damage states then the sample was discarded.

TABLE 4 PERMISSABLE DAMAGE STATE COMBINATIONS.

Building 'box' damage state	**Permissable roof level component damage states**		
	Chimneys	**Parapets**	**Gable walls**
D1 (slight cracking)	Any	Any	Any
D2 (major cracking)	Any	Any	Any
D3 (near collapse)	Any	Any	Any
D4 (partial collapse)	D4, D5	D4, D5	D4, D5
D5 (full collapse)	D5	D5	D5

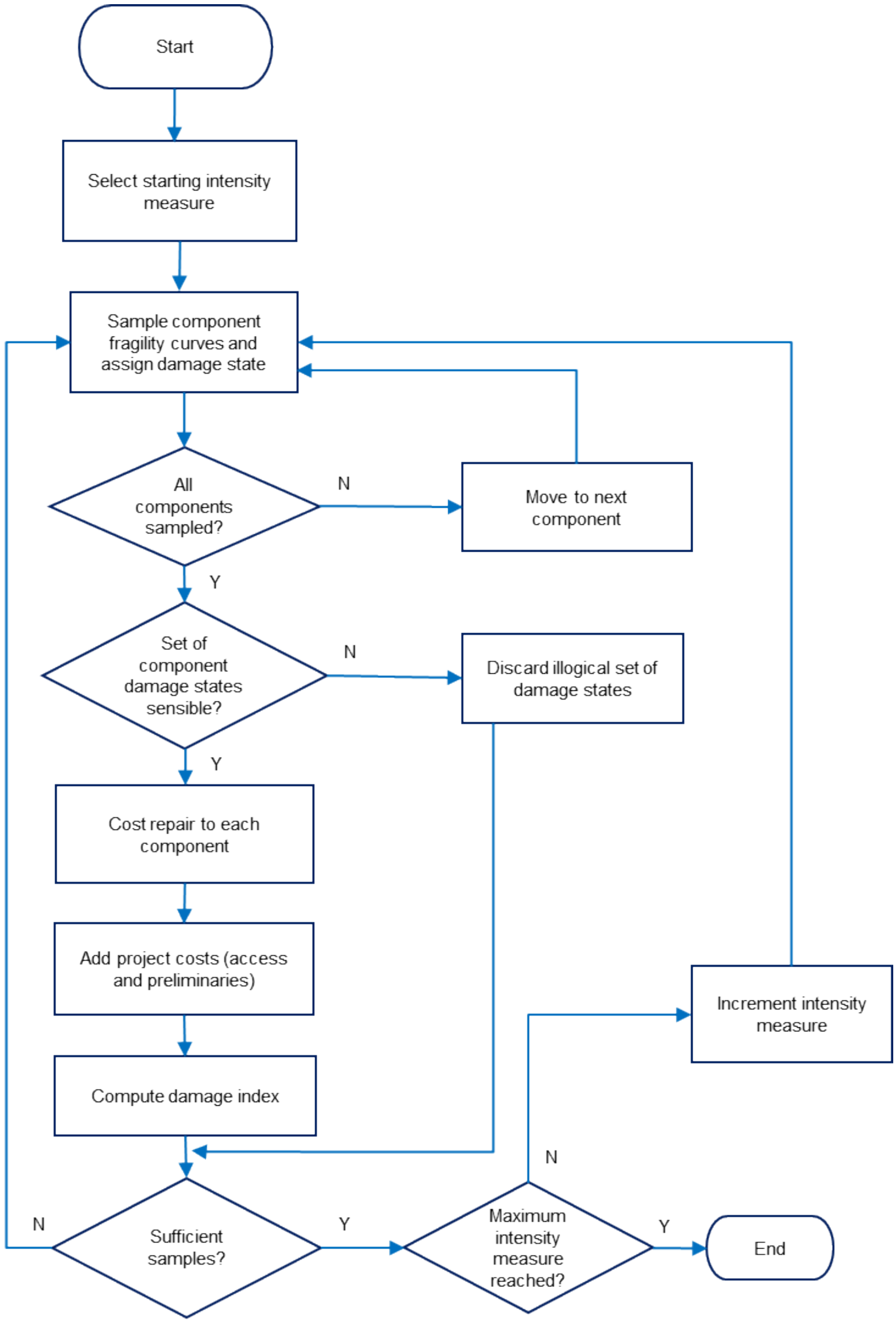


FIGURE 13 PROCEDURE USED TO GENERATE BUILDING VULNERABILITY CURVES FROM COMPONENT FRAGILITY CURVES.

COMPONENT FRAGILITIES

Fragility curves for each component type, both current state and retrofitted, were developed via numerical modelling and, where damage data was available, calibrated using damage observed following the Christchurch 2010 and 2011 earthquakes. The modelling procedures used are described in detail in Derakhshan and Griffith (2018) and Vaculik and Griffith (2018) for the building boxes and Appendix F for roof level URM components. The numerical modelling for the building box components produced four damage states. Based on descriptions of the damage states, similar values were assigned to Damage States 3 and 4 so that fragility curves were available for five damage states similar to the roof level components. A summary of the fragility curve parameters used to define the cumulative log-normal fragility curves is provided in Table 5 and Table 6 for each component type.

TABLE 5 FRAGILITY CURVE PARAMETERS FOR CURRENT STATE URM BUILDING COMPONENTS.

State	Current Unretrofitted State									
Damage State	D1		D2		D3		D4		D5	
Component	Median	Beta	Median	Beta	Median	Beta	Median	Beta	Median	Beta
Chimney squat 1st	0.039	0.57	0.078	0.57	0.162	0.57	0.242	0.57	0.294	0.57
Chimney squat 2st	0.03	0.57	0.061	0.57	0.128	0.57	0.195	0.57	0.248	0.57
Chimney medium 1st	0.034	0.57	0.068	0.57	0.145	0.57	0.19	0.57	0.282	0.57
Chimney medium 2st	0.029	0.57	0.058	0.57	0.126	0.57	0.169	0.57	0.232	0.57
Chimney slender 1st	0.031	0.57	0.064	0.57	0.125	0.57	0.168	0.57	0.276	0.57
Chimney slender 2st	0.028	0.57	0.056	0.57	0.115	0.57	0.156	0.57	0.234	0.57
Gable wall	0.012	0.7	0.021	0.7	0.065	0.7	0.089	0.7	0.121	0.7
Parapet 1m 1st	0.035	0.7	0.068	0.7	0.134	0.7	0.221	0.7	0.269	0.7
Parapet 1m 2st	0.024	0.7	0.047	0.7	0.101	0.7	0.172	0.7	0.207	0.7
Parapet 2m 1st	0.023	0.7	0.044	0.7	0.088	0.7	0.130	0.7	0.205	0.7
Parapet 2m 2st	0.020	0.7	0.041	0.7	0.080	0.7	0.118	0.7	0.181	0.7
1st box	0.170	0.45	0.301	0.45	0.400	0.45	0.400	0.45	0.532	0.45
2st box	0.100	0.45	0.250	0.45	0.300	0.45	0.300	0.45	0.530	0.45

TABLE 6 FRAGILITY CURVE PARAMETERS FOR RETROFITTED URM BUILDING COMPONENTS.

State	Retrofitted State									
Damage State	D1		D2		D3		D4		D5	
Component	Median	Beta	Median	Beta	Median	Beta	Median	Beta	Median	Beta
Chimney squat 1st	0.0975	0.57	0.195	0.57	0.405	0.57	0.605	0.57	0.735	0.57
Chimney squat 2st	0.06	0.57	0.122	0.57	0.256	0.57	0.39	0.57	0.496	0.57
Chimney medium 1st	0.0816	0.57	0.1632	0.57	0.348	0.57	0.456	0.57	0.6768	0.57
Chimney medium 2st	0.058	0.57	0.116	0.57	0.252	0.57	0.338	0.57	0.464	0.57
Chimney slender 1st	0.0713	0.57	0.1472	0.57	0.2875	0.57	0.3864	0.57	0.6348	0.57
Chimney slender 2st	0.0532	0.57	0.1064	0.57	0.2185	0.57	0.2964	0.57	0.4446	0.57
Gable wall	0.031	0.7	0.055	0.7	0.169	0.7	0.232	0.7	0.314	0.7
Parapet 1m 1st	0.087	0.7	0.170	0.7	0.336	0.7	0.551	0.7	0.672	0.7
Parapet 1m 2st	0.041	0.7	0.080	0.7	0.172	0.7	0.293	0.7	0.352	0.7
Parapet 2m 1st	0.087	0.7	0.170	0.7	0.336	0.7	0.551	0.7	0.672	0.7
Parapet 2m 2st	0.041	0.7	0.080	0.7	0.172	0.7	0.293	0.7	0.352	0.7
1st box	0.238	0.45	0.421	0.45	0.559	0.45	0.559	0.45	0.745	0.45
2st box	0.140	0.45	0.350	0.45	0.420	0.45	0.420	0.45	0.742	0.45

Figure 14 shows the comparison between an empirical vulnerability curve for older URM with those derived from the numerically modelled fragility curves for one and two storey old URM buildings. The empirical curve was derived from:

- aggregated loss data from the Newcastle 1989 earthquake (Maqsood et al, 2016 and Ryu et al, 2013);
- costing of surveyed earthquake damage following the 2010 Kalgoorlie earthquake (Edwards et al, 2010); and
- a heuristic data point (DI = 0.9 at MMI IX) from the Meckering earthquake (Everingham et al, 1982).

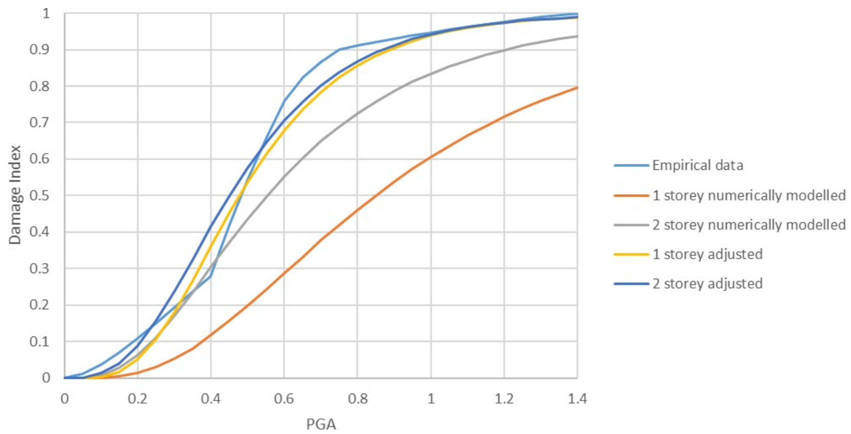


FIGURE 14 VULNERABILITY CURVES OF UN-RETROFITTED BUILDINGS DERIVED FROM EMPIRICAL DATA, NUMERICALLY MODELLED VULNERABILITY CURVES WITHOUT ADJUSTMENT, AND ADJUSTED VULNERABILITY CURVES.

It was found that the modelled curves were substantially more resilient than the vulnerability described by the empirical curve. To address this discrepancy, the numerically derived fragility curves for the building 'boxes' component were adjusted so that the resulting overall building vulnerability curves more closely matched the empirical curve. The ratios of medians between fragility curves for different damage states were maintained. Further, the fragility curves for two storey old URM buildings were adjusted so that the resulting vulnerability curve for two storey old URM buildings was 25% more vulnerable than that for the single storey old URM buildings between hazard values of 0.0 and 0.5g. This reflects a trend observed in the Kalgoorlie damage survey data that showed two storey buildings being more vulnerable than single storey buildings at MMI V and VI. The values in Table 5 and Table 6 reflect the adjustments described above.

COMPONENT FAILURE TYPES

A description of each damage state and consequential repair work was developed for each component type. This description enabled the cost of repair to be developed from a detailed breakdown of repair work. An example is shown in Table 7.

TABLE 7 EXAMPLE OF DESCRIPTION OF COMPONENT DAMAGE STATE AND REQUIRED REPAIR. BWK DENOTES BRICKWORK.

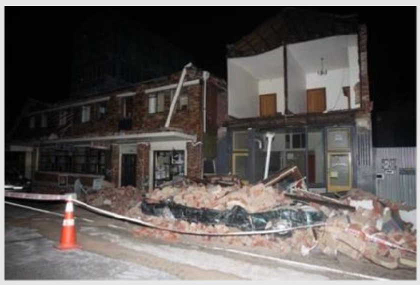
Component	Damage State	Description of Damage State	Repair
Chimney (slender)	D1	Slight cracking	Scaffold from roof level for access Epoxy inject cracks Remove scaffold
	D2	Major cracking	Scaffold from roof level for access Dismantle bwk (assume half chimney height) Reconstruct bwk Remove scaffold
	D3	Near Collapse with residual offset	Scaffold from roof level for access Dismantle bwk (full chimney) Reconstruct with new bricks Remove scaffold
	D4	Near collapse with major spalling/cracks and sliding with large permanent offsets and some bricks onto roof without significant collateral damage	Scaffold from roof level for access Dismantle bwk (full chimney) Reconstruct with new bricks Remove scaffold
	D5	Full or partial collapse through roof sheeting, battens and ceiling to floor below	Remove chimney, roof and ceiling debris from floor and roof Prop roof structure from floor Repair roof sheeting and battens Repair lath and plaster ceiling Clean-up at floor level Scaffold from roof level for access Reconstruct with new bricks Remove scaffold

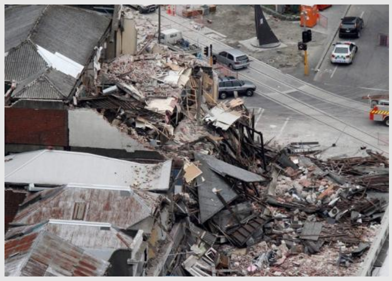
For the main part of each generic building type (i.e. that part of the building that excludes chimneys, gable walls and parapets), a more detailed breakdown of repair work was developed on a component by component basis for each damage state. An example is provided in Appendix E.

BUILDING DAMAGE SCENARIOS AND REPAIR COSTING

Five damage states were identified for each component. For the 1 storey and 2 storey building 'boxes' damage states 3 and 4 are similar in physical expression. Descriptions of the damage states are provided in Table 8.

TABLE 8 DAMAGE STATE DESCRIPTIONS.

Damage State	Description of damage state for parapets, chimneys and gable walls	Description of damage state for building 'boxes' with example photographs	
D1 Slight / minor cracking	Slight cracking	Narrow cracking in masonry at some window and door corners. Fine cracks along cornice - wall joins. Cracks in masonry repairable via epoxy injection and refinishing. Cracks in plaster elements repairable by filling and painting.	
D2 Moderate cracking, attainment of peak load capacity	Major cracking	Wide cracking in masonry requiring local demolition to sound masonry and reconstruction. Some windows require replacing. Heavy fittings dislodged requiring refixing and repair.	
D3 Fully formed out-of-plane collapse mechanism, widening of cracks	Near collapse, out-of-plane failure mechanism visible	Partial failure of external masonry with whole portions, i.e. whole walls, collapsed or on verge of collapsing but building still standing. Severe cracking of internal masonry. Significant consequential damage to finishes. Heavy fittings dislodged requiring refixing and repair. Damage to water supply pipework and other building services. Theoretically repairable but demolition more likely.	
D4 Near collapse, major spalling and/or sliding along cracks	Near collapse with major spalling/cracks and sliding with large permanent offsets and some bricks onto awning/roof without significant collateral damage	Partial failure of external masonry with whole portions, i.e. whole walls, collapsed or on verge of collapsing but building still standing. Severe cracking of internal masonry. Significant consequential damage to finishes. Heavy fittings dislodged requiring refixing and repair. Damage to water supply pipework and other building services. Theoretically repairable but demolition more likely.	

Damage State	Description of damage state for parapets, chimneys and gable walls	Description of damage state for building 'boxes' with example photographs	
D5 Total collapse	Full or partial collapse through awning to street below	Collapse of most of building. Remaining portions to be demolished and all debris removed and building reconstructed. Repair impractical.	

The replacement cost for each generic building type was estimated using rates provided in Turner and Townsend (2012). Repair cost estimates for each component type from each damage state, together with estimated costs for access and preliminaries were obtained from Turner and Townsend, 2019. The cost estimates are summarised in Table 9 and Table 10. Costs for parapets are presented for the longest length of parapet encountered amongst the generic building types. In establishing the repair cost for an individual building, the repair cost was adjusted for the actual length of each segment of parapet considering the segment's damage state.

TABLE 9 GENERIC BUILDING TYPES REPLACEMENT COSTS.

Generic building type	1	2	3	4	5	6
Replacement cost	$714,000	$2,509,000	$1,519,000	$1,837,000	$1,770,000	$1,225,000

TABLE 10 COMPONENT REPAIR COSTS.

Component	Component repair cost from damage state ($)				
	Damage state1	Damage state 2	Damage state 3	Damage state 4	Damage state 5
Squat chimney	620	1,140	1,510	1,510	2,020
Medium chimney	620	1,290	1,830	1,830	4,880
Slender chimney	1,110	2,340	3,440	3,440	6,490
Short parapet	2,590	12,400	14,800	14,820	75,600
Tall parapet	4,000	24,700	29,600	29,640	90,700
Gable wall	1,480	2,060	3,220	3,220	3,220
Generic building type 1 'box'	6,660	51,500	180,100	180,100	508,900
Generic building type 2 'box'	20,300	193,000	529,600	529,600	1,859,600
Generic building type 3 'box'	16,800	143,500	422,600	422,600	1,142,100
Generic building type 4 'box'	56,600	249,000	632,400	632,400	1,316,200
Generic building type 5 'box'	29,700	139,000	446,500	446,500	1,277,100
Generic building type 6 'box'	36,400	123,000	256,300	256,300	879,700

Note that the costs in Table 10 do not include costs for access (scaffolding), preliminaries or profit. These costs were added to the sum of repair cost for a combination of component damage states to establish a total repair cost for a building whose components were in a variety of damage states. Where a building 'box' was in Damage State 5, repair costs for all other components were set to zero as their repair is, of necessity, included in the full rebuild cost. Where the building 'box' was required to be scaffolded for repair, the access cost for roof-level components was set to zero. The logic used to establish the building repair cost incorporating the above issues is summarised in Figure 15.

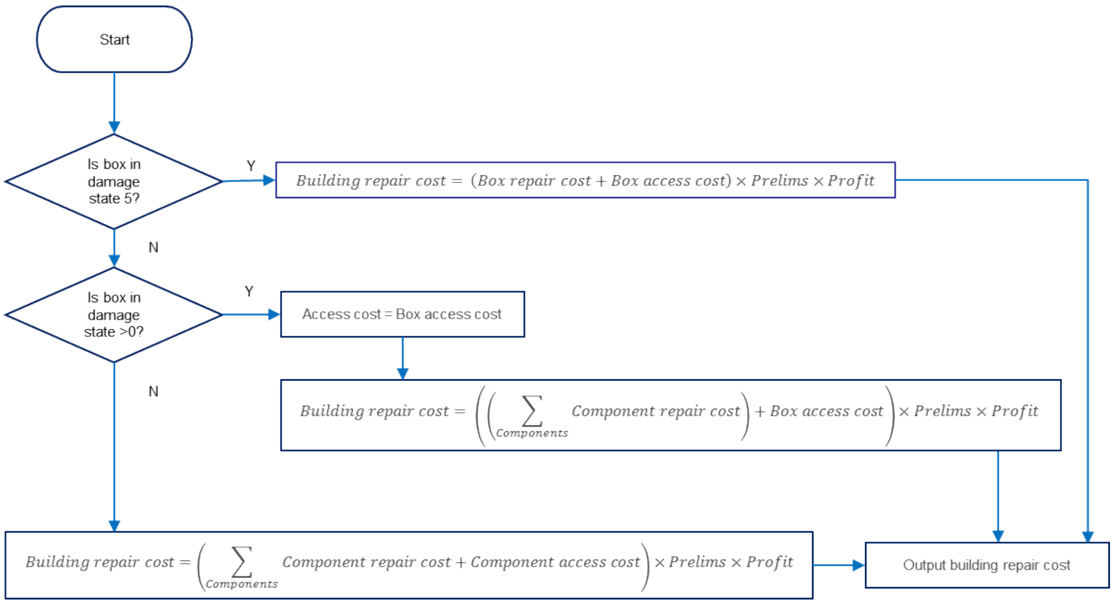


FIGURE 15 LOGIC USED TO ESTIMATE BUILDING REPAIR COST.

BUILDING DAMAGE REPAIR TIMES

Building Damage Repair Times

Whilst the time from a damaging earthquake to commencement of repair is unknown, an estimate is required of the time taken to undertake repairs for purposes of costing repair work. In the absence of supporting data, the periods set out in Table 11 were assumed for actual construction time.

TABLE 11 ASSUMED CONSTRUCTION TIME FOR REPAIR OF EARTHQUAKE DAMAGE.

Damage State	Assumed Construction Time
Damage State 1	1 month
Damage State 2	1 month
Damage State 3	2 months
Damage State 4	2 months
Damage State 5	12 months

Disruption Time

In order to estimate the economic loss, resulting from a building being unusable following earthquake damage, an estimate of the period from the earthquake to the building being restored to full functionality (known as the disruption time) is required. The disruption time serves as input to estimate Rental Losses, Wage Losses and Proprietor Losses.

To estimate the disruption time, claims data from the 1989 Newcastle earthquake were analysed to arrive at the relationship between time to settlement (equated to disruption time) and claim ratio (equated to damage index). In the analysis, very short settlement times with high claim ratios were discarded as these were thought to represent write-off behavior. Similarly, very long settlement times with low claim ratios were also discarded as these were thought to represent claims with some unknown problem that caused lengthy delays in settlement.

The results of the analysis are presented in Figure 16 where the blue line represents the average time to settlement in each claim ratio interval and the dashed line is a fitted curve that was subsequently used in economic analysis.

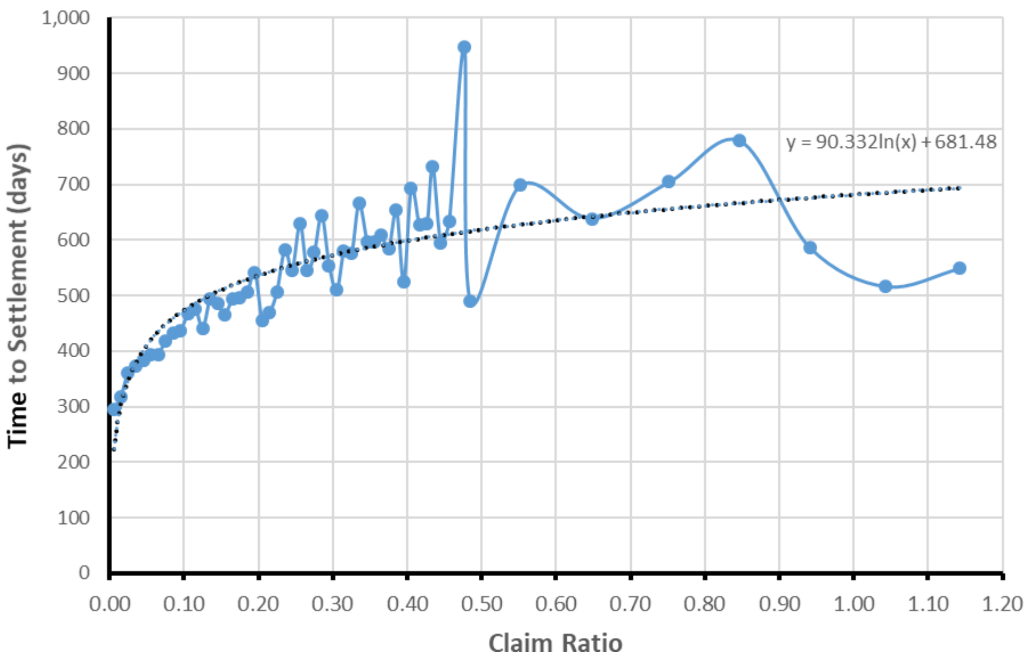


FIGURE 16 DISRUPTION TIME ESTIMATE FROM NEWCATSLE EARTHQUAKE CLAIMS DATA.

COMPONENT MITIGATION STRATEGIES

Retrofit work to upgrade components of URM buildings was identified and documented with illustrative sketches and photographs where available. This enabled cost estimates for the installation of retrofit to be prepared for each retrofit scenario discussed below. The retrofit work to each component type is briefly described in Table 12.

TABLE 12 RETROFIT DESCRIPTION FOR EACH COMPONENT TYPE.

Component	Description of Retrofit
Squat chimney Height = 1.4m Plan dimensions 460 x 805mm	Brace chimney to roof structure at roof level and ceiling level using additional timber. Include for: • necessary access from floor level, • temporary removal of roof sheeting and reinstatement.
Medium height chimney Height = 2.0m Plan dimensions 460 x 805mm	Brace chimney to roof structure at 2/3 height and at eaves level using galvanised structural steelwork. Include for: • necessary access from roof level, • temporary removal of roof sheeting and reinstatement.

Component	Description of Retrofit
Slender chimney Height = 4.0m Plan dimensions 600 x 720mm	Brace chimney to roof structure at 2/3 height and at eaves level using galvanised structural steelwork. Include for: • necessary access from roof level, • temporary removal of roof sheeting and reinstatement.
Parapet Height = 1m above roof level	Brace parapet to roof structure at 2/3 height and at eaves level using structural steel. Include for: • necessary access from roof level (access to roof level costed separately), • temporary removal roof sheeting and gutter and reinstatement.
Parapet Height = 2m above roof level	Brace parapet to roof structure at 2/3 height and at eaves level using structural steel. Include for: • necessary access from roof level (access to roof level costed separately), • temporary removal roof sheeting and gutter and reinstatement.
Gable wall Height above eaves= 2.5m to apex	Connect gable wall to roof new timber back-structure fixed to existing timber roof structure. Allow: • 10 M16 chemical anchors at ceiling level. • 10 M16 chemical anchors at eaves level. • 6 M16 chemical anchors to body of gable wall. Include for: • Installation of timber backing members, • Structural steel brackets, • Temporary removal of roof sheeting and reinstatement, Note: access from ground level to eaves costed separately.
External URM walls 40m of wall to floor connection (joists perpendicular to wall) 25m of wall to floor connection (joists parallel to wall) 40m of wall to roof connection (rafters perpendicular to wall) 25m of wall to roof connection (rafters parallel to wall)	Connect external masonry walls to first floor timber structure (joists perpendicular and parallel to external wall). Include for: • Removal and reinstatement of 600m width of floorboards for access, • Refinishing of floorboards after reinstatement. Connect external masonry walls to timber roof structure (roof framing perpendicular and parallel to external walls). Include for: • Removal of roof sheeting for access, • Reinstatement of roof sheeting. Note: access from ground level to eaves costed separately.

RETROFIT SCENARIOS

For each generic building type, the components of the building that are particularly vulnerable to earthquake were identified are summarized in Table 3. Retrofit scenarios were identified for each building type where a 'scenario' denotes retrofit to a set of building components. For each building type, a scenario was identified for retrofit of each possible combination of components as shown in Table 13. To limit the retrofit scenarios to a manageable number it was assumed that retrofitting was applied to all components of a given type. For example, if a scenario included chimney retrofit it was assumed that all the chimneys would be retrofitted.

TABLE 13 RETROFIT SCENARIOS. "NA" DENOTES THIS COMPONENT TYPE DOES NOT EXIST IN THE GENERIC BUILDING TYPE, "Y" DENOTES THE COMPONENT TYPE IS RETROFITTED IN THE PARTICULAR SCENARIO AND "N" DENOTES THE COMPONENT TYPE IS NOT RETROFITTED IN THE PARTICULAR RETROFIT SCENARIO.

Retrofit scenario	Generic Building Type	Description	Number of storeys	Retrofit to component				
				Chimneys	Parapets	Gable walls	1 storey 'box'	2 storey 'box'
1	1	1 storey residence	1	Y	NA	N	N	NA
2	1	1 storey residence	1	N	NA	Y	N	NA
3	1	1 storey residence	1	N	NA	N	Y	NA

Retrofit scenario	Generic Building Type	Description	Number of storeys	Retrofit to component				
				Chimneys	Parapets	Gable walls	1 storey 'box'	2 storey 'box'
4	1	1 storey residence	1	Y	NA	Y	N	NA
5	1	1 storey residence	1	Y	NA	N	Y	NA
6	1	1 storey residence	1	N	NA	Y	Y	NA
7	1	1 storey residence	1	Y	NA	Y	Y	NA
8	2	2 storey pub	2	Y	N	NA	NA	N
9	2	2 storey pub	2	N	Y	NA	NA	N
10	2	2 storey pub	2	N	N	NA	NA	Y
11	2	2 storey pub	2	Y	Y	NA	NA	N
12	2	2 storey pub	2	Y	N	NA	NA	Y
13	2	2 storey pub	2	N	Y	NA	NA	Y
14	2	2 storey pub	2	Y	Y	NA	NA	Y
15	3	1 storey commercial	1	NA	Y	NA	N	NA
16	3	1 storey commercial	1	NA	N	NA	Y	NA
17	3	1 storey commercial	1	NA	Y	NA	Y	NA
18	4	2 storey commercial	2	Y	N	NA	NA	N
19	4	2 storey commercial	2	N	Y	NA	NA	N
20	4	2 storey commercial	2	N	N	NA	NA	Y
21	4	2 storey commercial	2	Y	Y	NA	NA	N
22	4	2 storey commercial	2	N	Y	NA	NA	Y
23	4	2 storey commercial	2	Y	N	NA	NA	Y
24	4	2 storey commercial	2	Y	Y	NA	NA	Y
25	5	2 storey institutional	2	Y	NA	NA	NA	N
26	5	2 storey institutional	2	N	NA	NA	NA	Y
27	5	2 storey institutional	2	Y	NA	NA	NA	Y
28	6	2 storey bank	2	Y	N	NA	NA	N
29	6	2 storey bank	2	N	Y	NA	NA	N
30	6	2 storey bank	2	N	N	NA	NA	Y
31	6	2 storey bank	2	Y	Y	NA	NA	N
32	6	2 storey bank	2	N	Y	NA	NA	Y
33	6	2 storey bank	2	Y	N	NA	NA	Y
34	6	2 storey bank	2	Y	Y	NA	NA	Y

MITIGATION STRATEGIES – IMPLEMENTATION COSTS

The description and associated sketches enabled cost estimates of retrofit to be calculated for each retrofit scenario described in Table 13. Estimated rates for retrofit to each component were obtained from Turner and Townsend (2019). The rates were then adjusted for the quantity of retrofit required for each generic building type and estimated costs for access and preliminaries added. The cost of retrofit for each retrofit scenario is set out in Table 14.

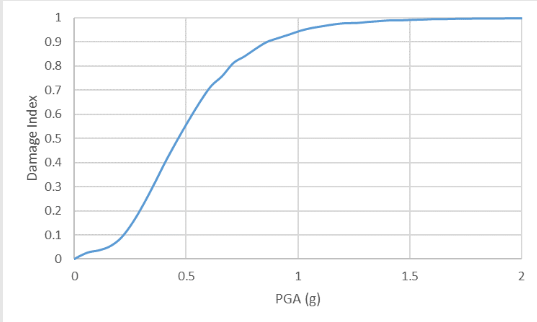
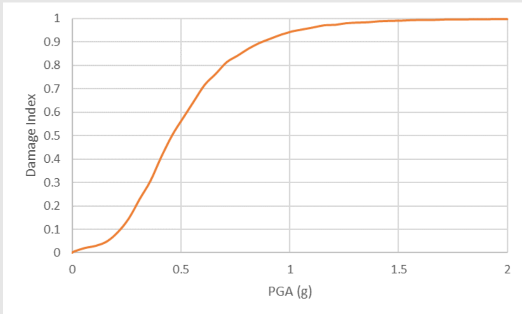
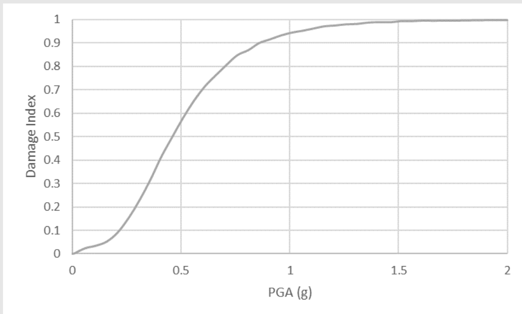
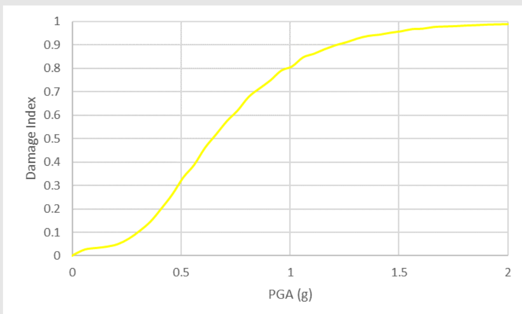
TABLE 14 ESTIMATED COST TO INSTALL RETROFIT FOR EACH RETROFIT SCENARIO.

Retrofit scenario	Generic Building Type	Description	Number of storeys	Retrofit cost
1	1	1 storey residence	1	$11,800
2	1	1 storey residence	1	$15,900
3	1	1 storey residence	1	$27,200
4	1	1 storey residence	1	$26,100
5	1	1 storey residence	1	$34,100
6	1	1 storey residence	1	$39,000
7	1	1 storey residence	1	$45,800
8	2	2 storey pub	2	$24,800
9	2	2 storey pub	2	$47,900
10	2	2 storey pub	2	$74,700
11	2	2 storey pub	2	$69,500
12	2	2 storey pub	2	$89,900
13	2	2 storey pub	2	$103,300
14	2	2 storey pub	2	$118,500
15	3	1 storey commercial	1	$24,500
16	3	1 storey commercial	1	$40,600
17	3	1 storey commercial	1	$58,900
18	4	2 storey commercial	2	$16,300
19	4	2 storey commercial	2	$24,000
20	4	2 storey commercial	2	$89,900
21	4	2 storey commercial	2	$30,700
22	4	2 storey commercial	2	$104,500
23	4	2 storey commercial	2	$96,600
24	4	2 storey commercial	2	$111,200
25	5	2 storey institutional	2	$12,900
26	5	2 storey institutional	2	$56,900
27	5	2 storey institutional	2	$63,300
28	6	2 storey bank	2	$21,800
29	6	2 storey bank	2	$32,800
30	6	2 storey bank	2	$53,000
31	6	2 storey bank	2	$51,300
32	6	2 storey bank	2	$72,200
33	6	2 storey bank	2	$65,200
34	6	2 storey bank	2	$84,400

UNMITIGATED AND MITIGATED BUILDING VULNERABILITY

The process described above produced the vulnerability curves for each unmitigated generic building type and each retrofit scenario shown in Table 15 to Table 20.

TABLE 15 GENERIC BUILDING TYPE 1 VULNERABILITY CURVES.

Retrofit scenario	Description	Vulnerability curve
-	No upgrade	
1	Chimneys only	
2	Gable walls only	
3	1 storey 'box' only	

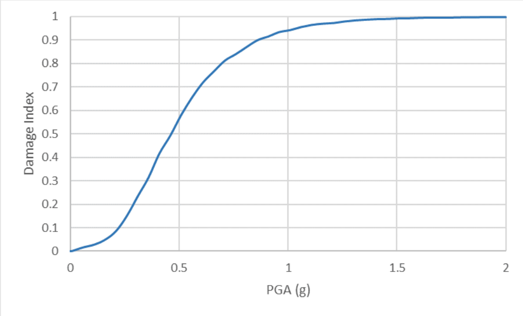
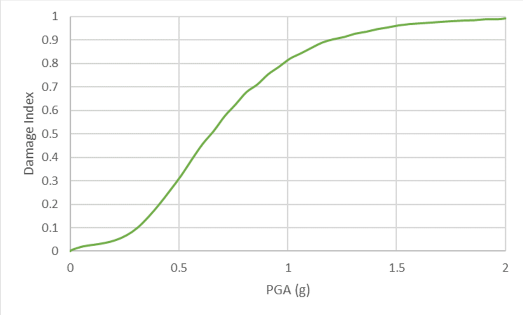
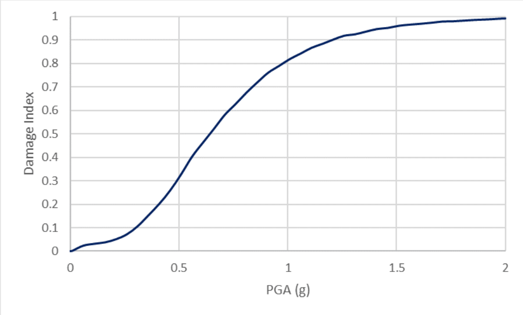
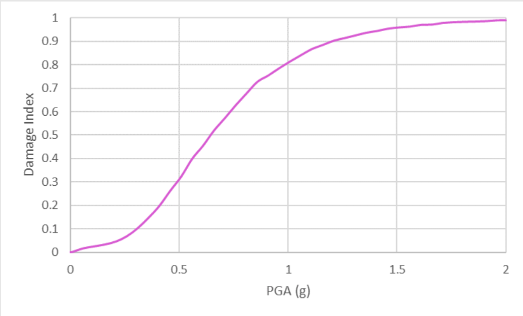
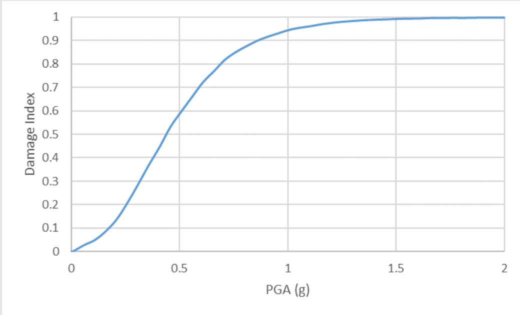
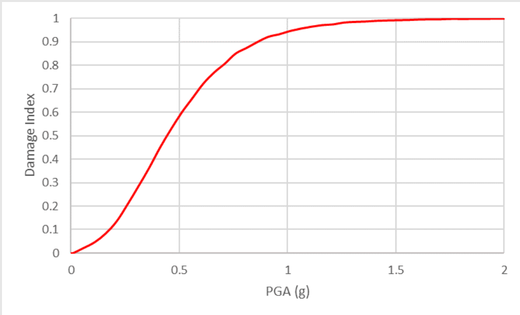
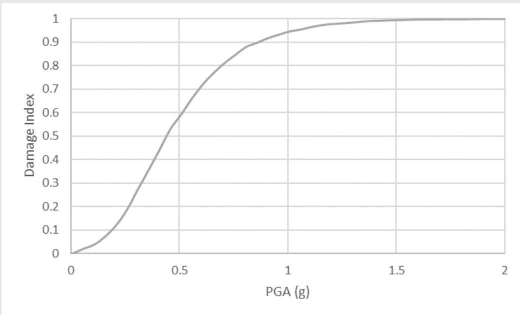
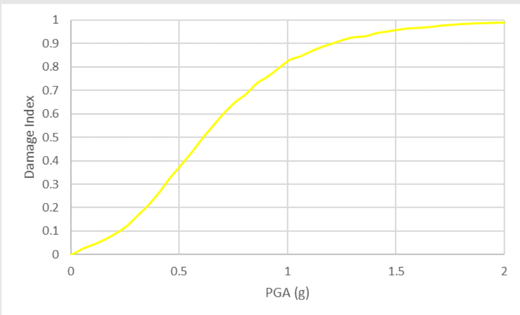
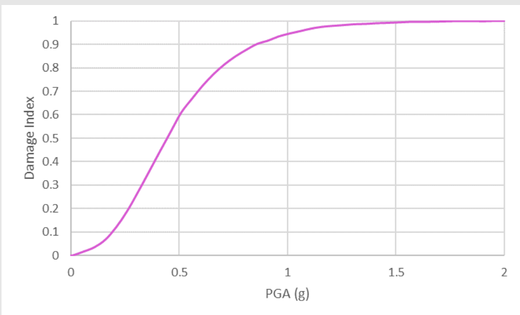
Retrofit scenario	Description	Vulnerability curve
4	Chimneys and gable walls	
5	Chimney and 1 storey 'box'	
6	Gable walls and 1 storey 'box'	
7	Full retrofit	

TABLE 16 GENERIC BUILDING TYPE 2 VULNERABILITY CURVES.

Retrofit scenario	Description	Vulnerability curve
-	No upgrade	
8	Chimneys only	
9	Parapets only	
10	2 storey 'box' only	
11	Chimneys and parapets	

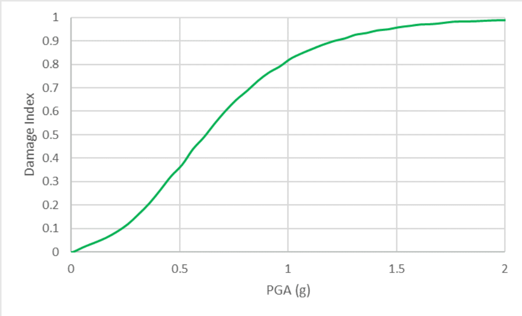
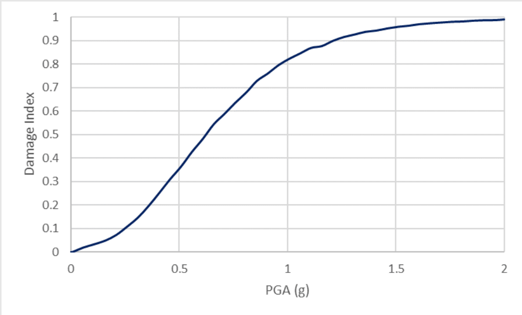
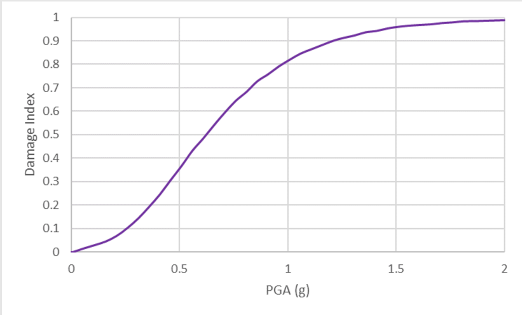
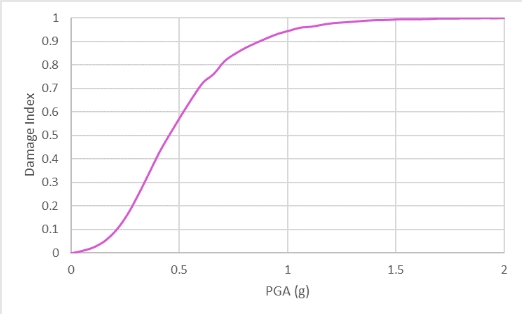
Retrofit scenario	Description	Vulnerability curve
12	Chimney and 2 storey 'box'	
13	Parapets and 2 storey 'box'	
14	Full retrofit	

TABLE 17 GENERIC BUILDING TYPE 3 VULNERABILITY CURVES.

Retrofit scenario	Description	Vulnerability curve
-	No upgrade	

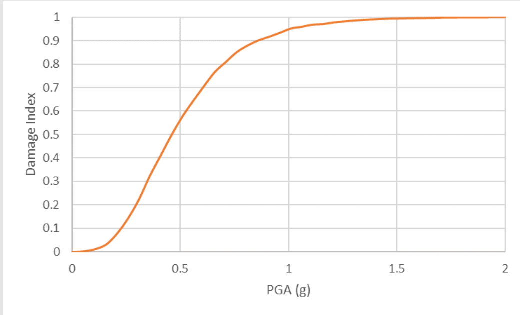
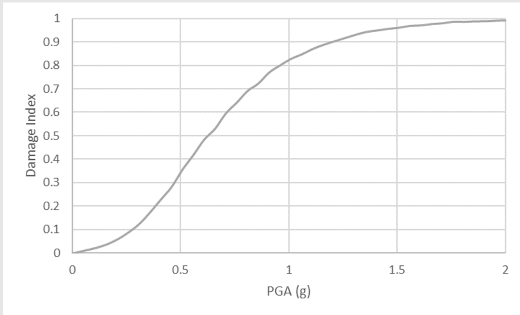
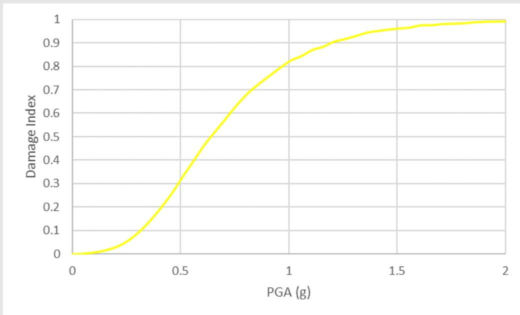
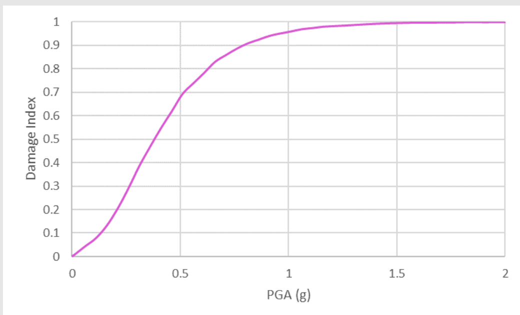
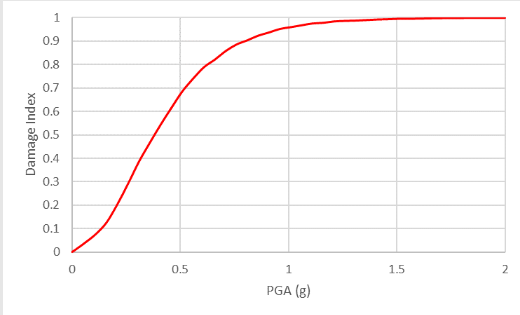
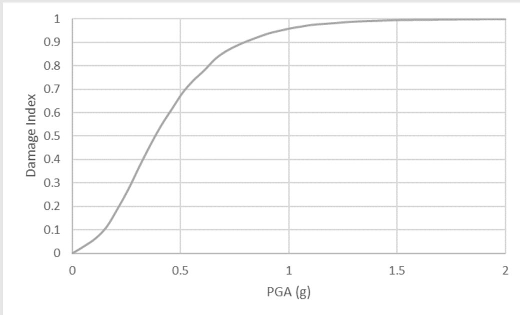
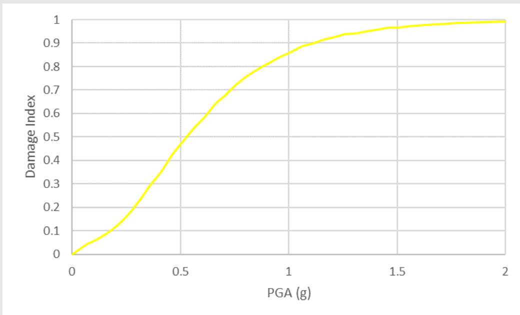
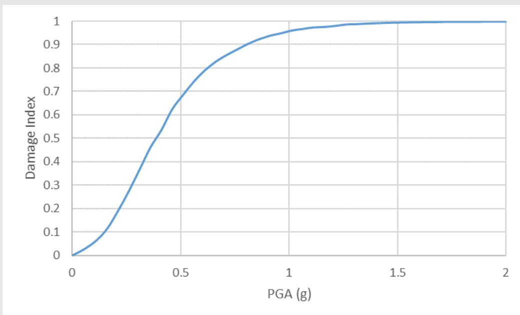
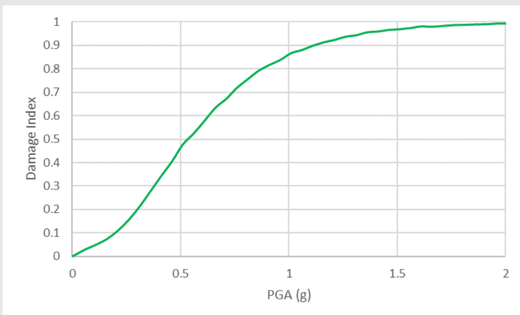
Retrofit scenario	Description	Vulnerability curve
15	Parapets only	
16	1 storey 'box' only	
17	Full retrofit	

TABLE 18 GENERIC BUILDING TYPE 4 VULNERABILITY CURVES.

Retrofit scenario	Description	Vulnerability curve
-	No upgrade	

Retrofit scenario	Description	Vulnerability curve
18	Chimneys only	
19	Parapets only	
20	2 storey ‘box’ only	
21	Chimneys and parapets	
22	Parapets and 2 storey ‘box’	

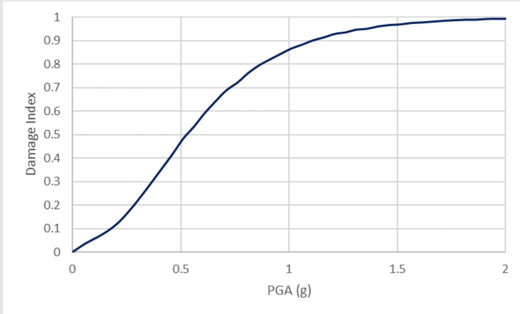
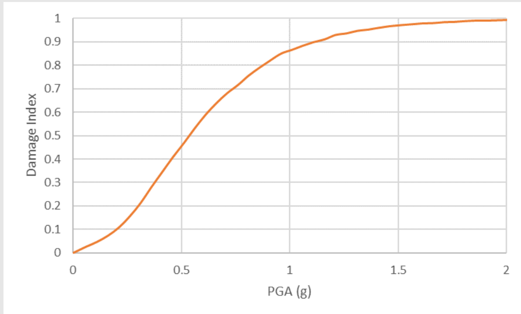
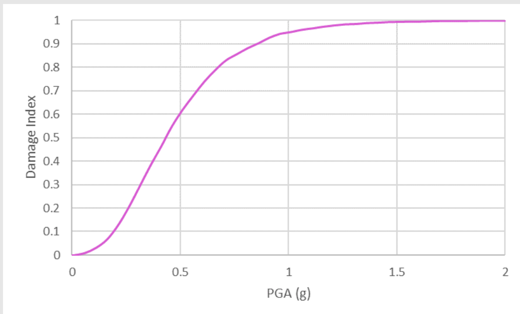
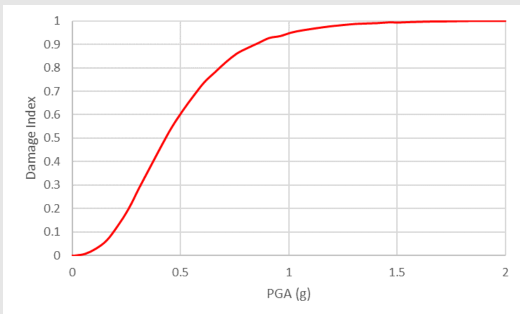
Retrofit scenario	Description	Vulnerability curve
23	Chimneys and 2 storey 'box'	
24	Full retrofit	

TABLE 19 GENERIC BUILDING TYPE 5 VULNERABILITY CURVES.

Retrofit scenario	Description	Vulnerability curve
-	No upgrade	
25	Chimneys only	

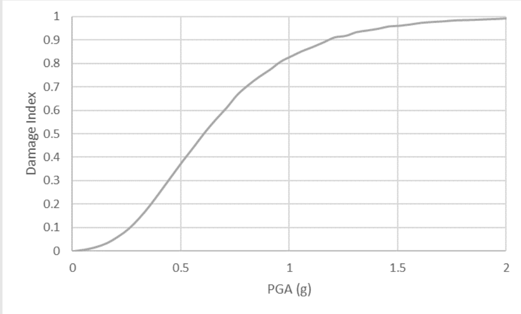
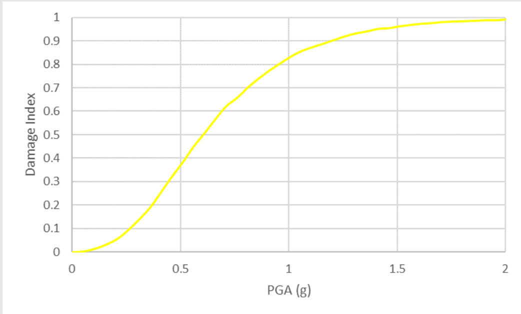
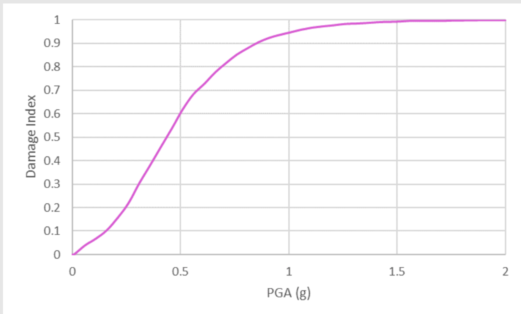
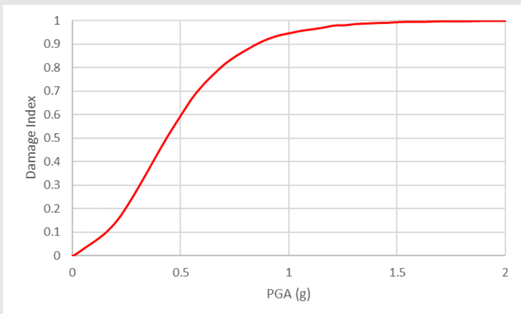
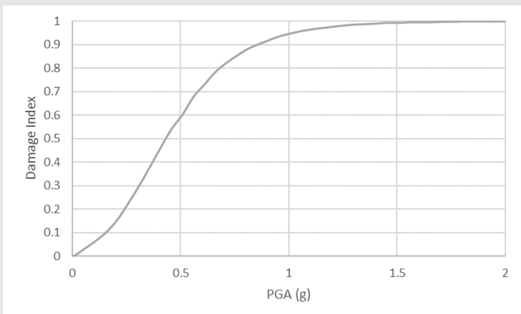
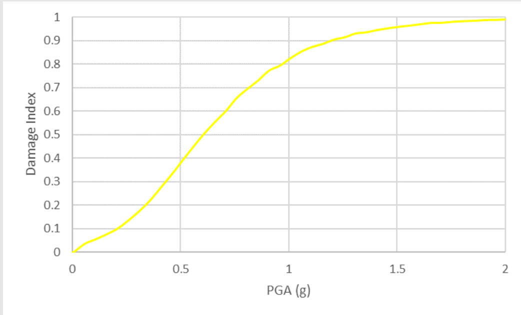
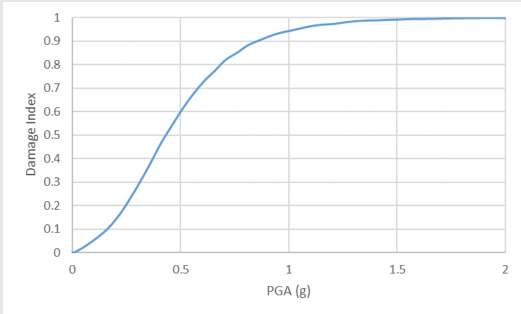
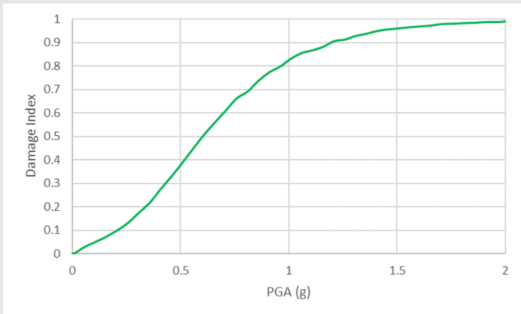
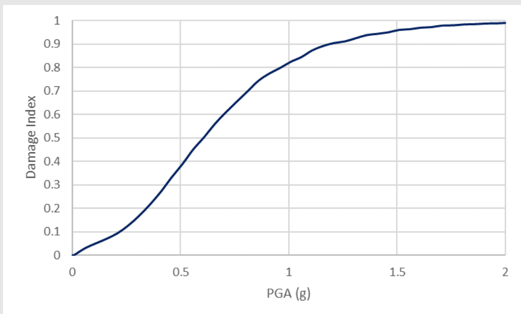
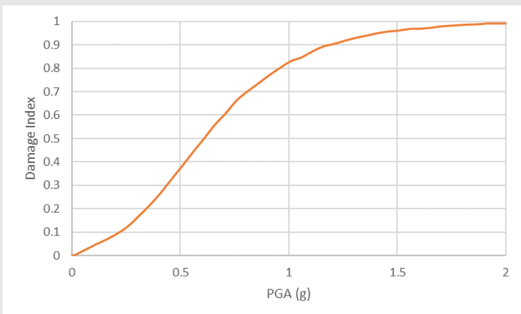
Retrofit scenario	Description	Vulnerability curve
26	2 storey 'box' only	
27	Full retrofit	

TABLE 20 GENERIC BUILDING TYPE 6 VULNERABILITY CURVES.

Retrofit scenario	Description	Vulnerability curve
-	No upgrade	
28	Chimneys only	
29	Parapets only	

Retrofit scenario	Description	Vulnerability curve
30	2 storey 'box' only	
31	Chimneys and parapets	
32	Parapets and 2 storey 'box'	
33	Chimneys and 2 storey 'box'	
34	Full retrofit	

HUMAN CASUALTY AND SURVIVABILITY MODELS

Earthquakes cause injuries and fatalities. In particular, URM buildings have been observed to cause casualties. During the Christchurch earthquake sequence, 39 people died as a result of URM building failures. Of these, 35 were outside the buildings (Moon et al, 2014). Clearly the benefit of reduced casualties arising from retrofit must be taken into account in any benefit-cost calculation.

EARTHQUAKE INDUCED INJURIES

Population Estimates

For this project the casualty modelling followed the HAZUS methodology (FEMA, 2006). In this method, indoor and outdoor populations are established and casualty numbers are predicted as percentages of each population with the magnitude of the percentages of population in each injury severity level dependent on the building damage state.

Data Sources

Data sources used for establishing York populations were:

1. Counts of people and cars in Avon Terrace during surveys and in Google Streetview. Table 21 shows the count data gathered in York from a variety of sources.
2. Observations made during visits to York
3. ABS data:

   ABS (2016) contains 2016 census data summaries which are useful for applying the HAZUS population formulas in Chapter 13 of the HAZUS Earthquake Technical Manual.
4. HAZUS:

   Chapter 13 of the HAZUS Earthquake Technical Manual provides guidance on assigning numbers of people to the interiors of buildings, classified by usage, and outdoor areas.

TABLE 21 SURVEYED OUTDOOR POPULATION IN AVON TERRACE, YORK.

Time	April 2018 Survey people	April 2018 Survey vehicles	Jan 2010 Streetview people	Jan 2010 Streetview cars	Jan 2015 Streetview people	Jan 2015 Streetview cars	2008 Streetview people	2008 Streetview cars	Mean people	Mean cars
9:00	10	20							10	20
12:00	20	18	31	42			21	19	24	26.3
17:00	17	20			15	22			16	21

An earthquake can occur at any time of day or night with equal probability. Therefore, the project requires a time-weighted average population for each generic building type. Generic Building type 1 is a residential house while types 2 to 6 are commercial buildings. For each building type a population estimate was made for daytime (8am to 6pm, a period of 10 hours) and night time (6pm to 8am, a period of 14 hours).

Indoor population estimates

Residential buildings (Generic Building type 1)

The ABS data records an average Census night number of people per house as 2.2. The night time population was therefore set to this number, assuming very nearly the entire population is at home.

The daytime residential population was estimated as follows:

The total ABS population:	3,606
Less the number of people in full-time employment:	986
Less the number of people in part time employment/2:	253
Less the number of children of school age:	587
TOTAL - People at home:	1,780

This population was distributed over 1,639 houses in the York ABS area which yields a mean daytime population of close to 1 person per house.

Commercial buildings (Generic Building types 2 to 6)

The indoor population estimates in Table 22 were constructed from observations made during visits to York.

TABLE 22 ESTIMATED INDOOR POPULATIONS FOR EACH GENERIC BUILDING TYPE FROM OBSERVATIONS.

Generic Building type	Usage	Daytime population		Night time population
		Staff	Customers	
2	Pub	5	20	3
3	1st Retail	6	4	0
4	2st Retail	6	8	2.2
5	Post Office	2	2	2.2
6	Bank	4	2	0
Mean daytime commercial indoor population per building		11.8		

An estimate was also made using the HAZUS indoor population method for commercial buildings as follows.

Total 2:00pm population in commercial buildings =

$$[0.99\times0.98\times COMW]+[0.8\times0.2\times DRES]+[0.8\times HOTEL]+[0.8\times VISIT].$$

Where:

COMW is the number of people employed in the commercial sector

DRES is the daytime residential population calculated as above

HOTEL is the number of people staying in hotels in the study area

VISIT is the number of regional residents who do not live in the study area

For the purposes of the calculation,

COMW was estimated from ABS data as the half the number of people who nominated 'Manager' as employment + the number of people who nominated 'Professional' as employment + half the number of people who nominated 'Clerical' as employment + the number of people who nominated 'Sales' as employment.

HOTEL was estimated as the number of hotel rooms available in York × 0.30 occupancy × 1.2 people per room on average.

VISIT was estimated as the number of houses in the York ABS area but outside the study area times the average number of people per house × 0.10.

The above logic yielded:

COMW = (257 / 2)+(184)+(162 / 2)+120 = 513

DRES = 1780

HOTEL = 38×0.3×1.2 = 14

VISIT = (1639–1298)×2.2×0.1 = 0.75

Hence, the total 2:00pm population in commercial buildings was estimated to be 853. It is assumed these are distributed over 87 surveyed businesses and there is one business per building. This yields a mean indoor population per building of 9.8 people which agrees well with the figure from observations in Table 22.

Thus the indoor populations for the six generic building types are as set out below.

TABLE 23 HAZUS ESTIMATED INDOOR POPULATIONS FOR EACH GENERIC BUILDING TYPE.

Generic Building type		Usage	Daytime population	Night time population	Mean population
1		Residence	1	2.2	1.7
2		Pub	25	3	12.2
3		1st Retail	10	0	4.1
4		2st Retail	14	2.2	7.1
5		Post Office	4	2.2	3.0
6		Bank	6	0	2.5

Outdoor population estimates

The outdoor population for night time was set to zero based on observations made during visits to York.

The outdoor population for Residential buildings during daytime was set to zero based on observations made during visits to York.

The outdoor population for commercial buildings during daytime was estimated by estimating the population density along Avon Terrace (the main commercial street in York) based on observations and comparing that derived using the HAZUS method.

Table 21 shows an average midday weekday pedestrian population of 24 people. Allowing for a 212m long section of Avon Terrace as the section of road along which the observations were made, and also along which the bulk of the old URM commercial buildings are located, this yields an average density of 0.57 people per metre of footpath.

The HAZUS technical manual determines the outdoor population for commercial buildings as:

$[0.01 \times 0.98 \times COMW] + [0.2 \times 0.2 \times DRES] + [0.2 \times VISIT] + [0.5 \times (1 - PRFIL) \times 0.05 \times POP]$

Where the terms are as defined above and

POP is the total population in the census district

PRFIL is the factor representing the proportion of commuters who travel by car, taken as 0.85 for rural areas.

The values of the variables were taken as above except for:

POP = 3,606 from the ABS data.

Hence the total 2:00pm population outside commercial buildings is estimated to be 104 people. These people will be visiting commercial businesses in addition to those located along the stretch of Avon Terrace where the old URM buildings are located. Hence, the 104 people were distributed along three times as much street length yielding an average pedestrian density of 0.082 people per metre.

Adjusted Outdoor Population for Weekends and Festivals

The street population in York is highly variable. There is a distinct rise in population on weekends and additionally the town hosts several festivals during the year, some of which involve closing Avon Terrace to traffic and turning it into a pedestrian precinct. This behaviour is not accounted for in the figures discussed above. Allowance for higher populations during weekend days and festival days was made as described below.

Major Festivals

For the major annual festivals listed in Table 1, the number of peak days are:

- York Motorcycle Festival (1 day)
- York Medieval Fayre (1 day)
- York Festival (3 days)

Using photographs of Avon Terrace during the York Motorcycle Festival with the 19m wide street closed and crowded with people from side to side, it was estimated:

Maximum of 0.83 people/m^2 x 9.5m half street width = 8.0 people/m per side of street.

Minor Festival Days

For the major annual festivals listed in Table 1, there were other festival days during the event that had reduced but significant number of visitors. The number of days with lower visitors numbers are:

- York Motorcycle Festival (1 day)
- Easter (2 days)
- Motor Show (1 day)

- Agricultural Show (1 day)
- York Festival (4 days)

Assuming that the footpaths were populated to same density as the street on major festival days, but with the main street open to traffic, it was estimated:-

Maximum of 0.83 people/m^2 x 3.5m wide footpaths = 2.9 people/m per side of street.

Weekends

Assuming 150 people per side of street, it was estimated that:

Maximum 150 people / 207m of street = 0.72 people/m per side of street.

Weekdays

Estimate based on GA counts of streetscape photos and HAZUS estimates with ABS census data as described above:

Maximum 0.082 people/m per side of street.

For festival and weekend days the population variation during the day was assumed as shown in Figure 17.

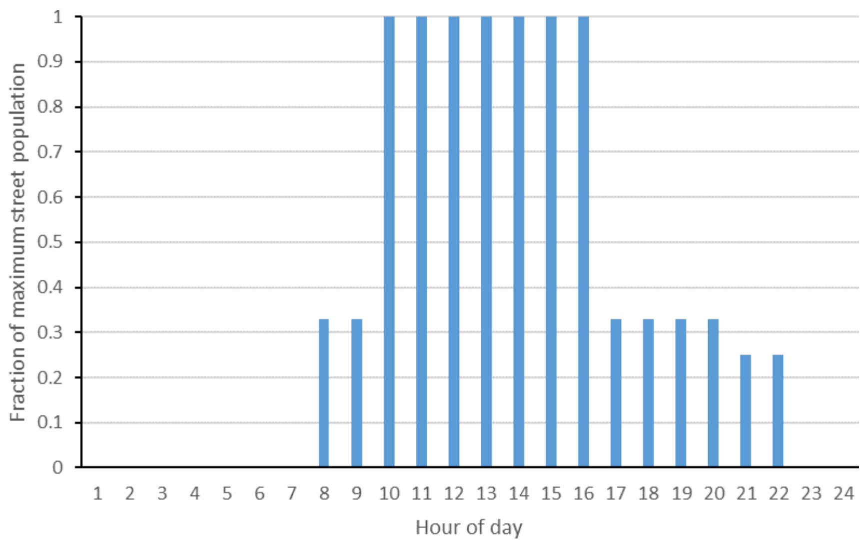


FIGURE 17 FRACTION OF MAXIMUM STREET POPULATION WITH TIME OF DAY.

The results of the above process yielded the values in Table 24. The mean figure compares favourably with Dutch data reported in Taig and Pickup (2016).

TABLE 24 ESTIMATED STREET POPULATION ON AVON TERRACE.

Event	Maximum population /m /side of street	Mean over 24 hours population /m/side of street	Number of days per year	Mean population /m / side of street per year
Major festival	8.000	2.83	5	14.16
Minor festival	2.900	1.06	9	9.56
Weekend	0.720	.255	90	22.95
Weekday	0.082	.034	261	8.87
			Sum	55.54
			Mean for year	0.152

This is converted to an outdoor population for each generic building type based on the length of its street frontage as given in Table 25.

TABLE 25 ESTIMATED OUTDOOR POPULATION FOR EACH GENERIC BUILDING TYPE.

Generic Building Type	Usage	Street Frontage (m)	Maximum daytime outdoor population	Mean outdoor population
1	Residence	29.6	0	0
2	Pub	44.0	352	6.7
3	1st Retail	25.0	200	3.8
4	2st Retail	19.0	152	2.9
5	Post Office	19.3	152	2.9
6	Bank	26.2	210	4.0

Casualty Rates

Table 26 shows the casualty rates for low-rise URM (URML) buildings extracted from FEMA, 2006.

TABLE 26 CASUALTY RATES FROM FEMA, 2006 EXPRESSED AS PERECNTAGES OF EXPOSED POPULATION IN EACH CASUALTY SEVERITY LEVEL. THE FIGURES FOR COMPLETE DAMAGE STATE ASSUME 15% OF BUILDINGS IN THAT DAMAGE STATE ARE COLLAPSED AND 85% ARE NOT.

Damage State	Indoor population Casualty Severity Level				Outdoor population Casualty Severity Level			
	1	2	3	4	1	2	3	4
None	0	0	0	0	0	0	0	0
Slight	0.05	0	0	0	0	0	0	0
Moderate	0.35	0.4	0.001	0.001	0.15	0.015	0.0003	0.0003
Severe	2	0.2	0.002	0.002	0.6	0.06	0.0006	0.0006
Complete	14.5	4.7	0.767	1.517	5	2	0.4	0.6

The outdoor casualty rates in Table 26 are extremely low. These were reviewed against photographs of damaged URM buildings in Christchurch, 2011 which showed the size and extent of fallen masonry. Hence, revised casualty rates for outdoor populations were adopted as given in Table 27. The figures in Table 27 take into account estimated values for:

- for each damage state the proportion of buildings where masonry collapses into the street; and
- the proportion of exposed people in each casualty severity level allowing for the ability of people in the street to effectively move during earthquake shaking to escape falling masonry.

TABLE 27 HEURISTIC OUTDOOR CASUALTY RATES ADOPTED FOR THE PROJECT (PERCENTAGE OF EXPOSED POPULATION IN CASUALTY SEVERITY LEVEL BY BUILDING DAMAGE STATE).

Building damage State	Proportion of buildings with masonry fallen into street (%)	Proportion of outdoor population in each casualty severity level if masonry falls into the street (%) Casualty Severity Level				Proportion of outdoor population in each casualty severity level (%) Casualty Severity Level			
		1	2	3	4	1	2	3	4
None	0	5	5	10	60	0	0	0	0
Slight	0	5	5	10	60	0	0	0	0
Moderate	25	5	5	10	60	1.25	1.25	2.5	15
Severe	75	5	5	10	60	3.75	3.75	7.5	45
Complete	90	5	5	10	60	4.5	4.5	9	54

The casualty severity levels in Table 26 and Table 27 are described in FEMA, 2006 and reproduced in Table 28.

TABLE 28 DESCRIPTION OF CASUALTY SEVERITY LEVEL.

Injury Severity Level	Injury Description
Severity 1	Injuries requiring basic medical aid that could be administered by paraprofessionals.
Severity 2	Injuries requiring a greater degree of medical care and use of medical technology such as X-rays or surgery but are not expected to progress to a life threatening status.
Severity 3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously.
Severity 4	Instantaneously killed or mortally injured

The building damage state was derived from the building vulnerability curve as defined in Table 29.

TABLE 29 DAMAGE INDEX RANGES FOR DAMAGE STATES.

Building Damage State	Range of Building Damage Index
None	DI <= 0.02
Slight	0.02 < DI <= 0.1
Moderate	0.1 < DI <= 0.3
Severe	0.3 < DI <= 0.6
Complete	0.6 < DI <= 1.0

URBAN SEARCH AND RESCUE

The Urban Search and Rescue (USAR) logistics assessment focused on URM buildings. This assessment considered people within the internal environments of building and those in the adjacent environment of the Avon Terrace pedestrian precinct. The assumed probabilities of the three levels of entrapment for each environment are summarised in Table 30. The internal environments likelihoods corresponded with those used previously in scenario modelling for DFES. The external environments were heuristically estimated to provide an indicative measure of the logistics involved.

TABLE 30 URBAN SEARCH AND RESCUE CONDITIONAL PROBABILITIES OF ENTRAPMENT.

Environment	Damage Measure	Building Type/ Injury Severity	Probability of Entrapment	Conditional Probability of Entrapment Level		
				Light	Deep	Heavy
Building Interior	Building Collapse	Single story URM	0.40	0.67	0.33	0.0
		Low Rise URM	0.40	0.60	0.25	0.15
Pedestrian Precinct	Injury Caused by Falling Masonry	Severe Injury	0.50	0.80	0.20	0.0
		Mortally Injured or Dead	0.90	0.78	0.22	0.0

SCENARIO IMPACTS

SCENARIOS

The scenarios developed for emergency management were scaled to match the recently released national scale assessment for bedrock hazard, NSHA18 (Allen et. al., 2018b). This probabilistic seismic hazard assessment (PSHA) included many refinements to the earlier assessment and provides the likelihood of hazard severity on bedrock as defined in AS1170.4:2018 for Soil Class Be. The hazard level it estimates for York is lower than that specified in the earthquake loading standard for building design, AS1170.4 (Standards Australia 2007) and the previous hazard assessment by GA (Leonard et al., 2013). Notwithstanding this, the estimated hazard for York is higher than for any major city in Australia.

Three ground motion likelihoods were selected for the scenario events based on the recommendations of the 9th August, 2018, stakeholder workshop. The magnitude and depth of the scenario events corresponded with the historical events presented in Table 31 as these earthquakes have credibility with the local community. The Meckering earthquake of October, 1968, caused significant damage to York with one hotel subsequently demolished as a result of the earthquake damage it sustained. The epicentre of each scenario was relocated to simulate the severity of ground motion at the centre of York that matched the peak ground acceleration (PGA) value at the selected rarity from NSHA18. The ground motion fields were simulated using the OpenQuake-engine (Version 3.6; Pagani et al., 2014). A single ground motion field for each of the scenario events was generated by taking a weighted average of the simulated mean ground motions through adopting the same logic tree of ground motion models used in NSHA18.

TABLE 31 SELECTED SCENARIO EVENTS.

Scenario Event	Return Period (years)	Historical Events	Magnitude (M_w)	Depth (km)	Epicentre (Long, Lat)	Distance from York (km)	PGA (g)
1	500	Calingiri (10th March 1970)	5.03	15	116.650, -31.755	18.8	0.059
2	1,000	Lake Muir (16th Sep 2018)	5.30	2	116.934, -31.820	17.5	0.102
3	2,500	Meckering (14th Oct 1968)	6.58	10	117.057, -31.906	27.4	0.199

MITIGATION TAKE-UP SCENARIOS

The rate of uptake of retrofit has a clear bearing on the overall progressive change to the vulnerability and risk of a community like York. It will also have a direct bearing on the emergency management logistics and economic costs sustained in the future for the same event. The modelled retrofit rate needs to realistically reflect the ability of both State and local government to incentivise this behaviour and the willingness of building owners to invest in this way. Insurance can have a role by recognising risk reduction achieved through these measures and reflecting this in premiums.

At a workshop convened in York on the 9th August, 2018, practical limits to uptake rates were discussed and two uptake rates, or "Retrofit Schemes", were selected for study. Retrofit Scheme I involved an uptake rate that was a modest single heritage building per year in the town and a single non-heritage building every second year. Retrofit Scheme II considered an uptake rate double that of Retrofit Scheme I. The higher uptake rate was considered to be a realistic outcome that could be expected with strong incentivisation. These rates were assumed uniform with time and are summarised in Table 32. The application of retrofit, however, was not totally uniform with a greater focus on Avon Terrace rather than buildings elsewhere in York.

TABLE 32 TWO RETROFIT SCHEMES CONSIDERED FOR YORK.

Retrofit Regime	Building Category	Aggregated Number of Buildings to Be Retrofitted		
		Over 10 years	Over 20 years	Over 30 years
Retrofit Scheme I	Heritage-listed	10	20	30
	Other	5	10	15
Retrofit Scheme II	Heritage-listed	20	40	60
	Other	10	20	30

DIRECT IMPACTS

The impacts on the town of York from the selected scenario events were estimated for four metrics: 1) monetary loss from necessary repair of physical damage to buildings and contents; 2) number of damaged buildings; 3) number of casualties; and 4) USAR logistics.

Table 33, Table 34 and Table 35 set out the estimated building damage loss for the scenarios and how these would be moderated over 30 years with the two Retrofit Schemes. The reduction in loss is larger for heritage-listed buildings than for the overall population of community buildings due to the larger proportion of buildings retrofitted and the typically greater vulnerability of these older URM buildings. For Event 3 the heritage building stock is predicted to have a 35% reduction in damage repair cost after 30 years under Retrofit Scheme II.

TABLE 33 ESTIMATED BUILDING DAMAGE LOSS FOR THE SCENARIO EVENT 1 (M AUD).

Building Group	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
All	7.69	7.45	7.05	6.71	7.35	6.67	6.20
Heritage-listed	3.34	3.17	2.84	2.52	3.10	2.67	2.24

TABLE 34 ESTIMATED BUILDING DAMAGE LOSS FOR THE SCENARIO EVENT 2 (M AUD).

Building Group	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
All	15.25	14.78	14.03	13.46	14.65	13.40	12.61
Heritage-listed	6.10	5.74	5.09	4.54	5.67	4.82	4.08

TABLE 35 ESTIMATED BUILDING DAMAGE LOSS FOR THE SCENARIO EVENT 3 (M AUD).

Building Group	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
All	43.95	42.43	40.15	38.38	41.98	38.38	36.09
Heritage-listed	16.72	15.53	13.57	11.85	15.26	12.93	10.79

Table 36, Table 37, and Table 38 set out the estimated contents loss for the scenarios and how these would be moderated over 30 years with the two Retrofit Schemes. Like the building damage loss, the reduction in contents loss is larger for heritage-listed buildings than for the overall population of community buildings. For Event 3 the heritage building stock is predicted to have a 37% reduction in content loss after 30 years under Retrofit Scheme II.

TABLE 36 ESTIMATED CONTENTS LOSS FOR THE SCENARIO EVENT 1 (M AUD).

Building Group	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
All	3.75	3.47	3.26	3.05	3.40	2.99	2.70
Heritage-listed	2.04	1.79	1.61	1.40	1.77	1.52	1.24

TABLE 37 ESTIMATED CONTENTS LOSS FOR THE SCENARIO EVENT 2 (M AUD).

Building Group	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
All	7.57	7.00	6.62	6.27	6.92	6.17	5.67
Heritage-listed	3.96	3.46	3.10	2.76	3.43	2.95	2.47

TABLE 38 ESTIMATED CONTENTS LOSS FOR THE SCENARIO EVENT 3 (M AUD).

Building Group	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
All	21.48	19.81	18.93	17.86	19.54	17.66	16.28
Heritage-listed	10.65	9.19	8.39	7.34	9.11	8.07	6.72

Table 39, Table 40 and Table 41 set out the estimated number of damaged buildings for the scenarios for all York buildings, while Table 42, Table 43 and Table 44 set out the estimated number for heritage-listed building subset. Like the building damage loss, the reduction in number of damaged buildings is larger for heritage-listed buildings than the overall population of community buildings. The reduction in the total number of damaged buildings for all York buildings is approximately 14% for Scenario Event 1, and decreases to 1% for the Scenario Event 3. The reduction for heritage-listed buildings is approximately 23% for Scenario Event 1, and decreases to 3% for the Scenario Event 3. These results are partly due to fact that the proposed retrofit schemes are not designed to be fully compliant with current code. Therefore the benefit of the retrofit becomes smaller for the scenarios with the strongest shakings.

TABLE 39 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT 1 FOR ALL BUILDINGS.

Damage State	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
Slight	243	240	237	230	232	223	210

		Retrofit Scheme I			Retrofit Scheme II		
Damage State	Unretrofitted	10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
Moderate	2	2	2	2	2	1	1
Extensive	0	0	0	0	0	0	0
Complete	0	0	0	0	0	0	0
Total	245	242	239	232	234	224	211

TABLE 40 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT 2 FOR ALL BUILDINGS.

		Retrofit Scheme I			Retrofit Scheme II		
Damage State	Unretrofitted	10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
Slight	443	440	437	433	436	429	421
Moderate	17	16	16	15	16	14	13
Extensive	2	2	2	1	2	1	1
Complete	0	0	0	0	0	0	0
Total	462	458	455	449	454	444	435

TABLE 41 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT 3 FOR ALL BUILDINGS.

		Retrofit Scheme I			Retrofit Scheme II		
Damage State	Unretrofitted	10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
Slight	776	777	778	779	778	782	785
Moderate	153	151	149	148	150	145	142
Extensive	20	19	18	17	18	17	15
Complete	6	6	6	6	6	5	5
Total	955	953	951	950	952	949	947

TABLE 42 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT 1 FOR HERITAGE-LISTED BUILDINGS.

		Retrofit Scheme I			Retrofit Scheme II		
Damage State	Unretrofitted	10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
Slight	93	91	90	86	86	80	72
Moderate	1	1	1	1	1	1	0
Extensive	0	0	0	0	0	0	0
Complete	0	0	0	0	0	0	0
Total	94	92	91	87	87	81	72

TABLE 43 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT 2 FOR HERITAGE-LISTED BUILDINGS.

		Retrofit Scheme I			Retrofit Scheme II		
Damage State	Unretrofitted	10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
Slight	118	116	115	113	113	108	104
Moderate	6	5	5	4	5	4	3
Extensive	1	1	1	1	1	1	0
Complete	0	0	0	0	0	0	0
Total	125	122	121	118	118	112	107

TABLE 44 ESTIMATED NUMBER OF DAMAGED BUILDINGS FOR THE SCENARIO EVENT 3 FOR HERITAGE-LISTED BUILDINGS.

Damage State	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
Slight	104	105	106	107	106	108	111
Moderate	31	30	29	28	29	26	24
Extensive	10	9	8	7	8	8	6
Complete	3	3	3	2	3	2	2
Total	148	147	146	144	146	144	143

Table 45, Table 46 and Table 47 summarise indoor casualty estimates for the four injury severity levels defined in the HAZUS methodology (FEMA, 2006) where the injury severity level 4 corresponds to fatality. Table 48, Table 49 and Table 50 below summarise the corresponding outdoor casualty estimates using the HAZUS methodology. The populations used for each environment in the casualty modelling reflects the comparatively low nighttime population and not the situation when York hosts large events with the town crowded during the day.

TABLE 45 ESTIMATED INDOOR CASUALTIES FOR THE SCENARIO EVENT1.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0

TABLE 46 ESTIMATED INDOOR CASUALTIES FOR THE SCENARIO EVENT2.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
1	1	1	1	1	1	1	1
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0

TABLE 47 ESTIMATED INDOOR CASUALTIES FOR THE SCENARIO EVENT3.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
1	4	4	4	4	4	4	3
2	2	2	2	2	2	2	1
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0

TABLE 48 ESTIMATED OUTDOOR CASUALTIES FOR THE SCENARIO EVENT 1.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
4	0	0	0	0	0	0	0

TABLE 49 ESTIMATED OUTDOOR CASUALTIES FOR THE SCENARIO EVENT2.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	2	1	1	1	1	1	0

TABLE 50 ESTIMATED OUTDOOR CASUALTIES FOR THE SCENARIO EVENT3.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
1	1	1	0	0	1	0	0
2	1	1	0	0	1	0	0
3	2	1	1	1	1	1	1
4	9	7	6	4	7	5	3

Table 51, Table 52 and Table 53 present the numbers of casualties If an earthquake were to occur during the peak of a major festival. They also present how the substantial numbers are modelled to reduce through retrofit.

TABLE 51 ESTIMATED OUTDOOR CASUALTIES FOR THE SCENARIO EVENT 1 DURING A MAJOR FESTIVAL.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
1	2	1	1	0	1	1	0
2	2	1	1	0	1	1	0
3	3	2	1	1	2	1	0
4	18	13	9	4	13	7	2

TABLE 52 ESTIMATED OUTDOOR CASUALTIES FOR THE SCENARIO EVENT 2 DURING A MAJOR FESTIVAL.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
1	7	5	4	2	5	3	1
2	7	5	4	2	5	3	1
3	15	11	8	5	11	6	3
4	89	65	46	28	63	35	16

TABLE 53 ESTIMATED OUTDOOR CASUALTIES FOR THE SCENARIO EVENT 3 DURING A MAJOR FESTIVAL.

Injury Severity Level	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
1	41	32	26	19	32	22	15
2	38	30	24	18	30	20	14
3	83	65	52	39	63	43	29
4	496	387	310	232	378	259	176

URBAN SEARCH AND RESCUE LOGISTICS

The estimated numbers for each of the three levels of USAR entrapment are summarised in Table 54 for each scenario event. The logistics are for York today and for three future times based on the higher Retrofit Strategy II.

TABLE 54 URBAN AND SEARCH AND RESCUE LOGISTICS FOR YORK IN PRESENT STATE AND AFTER RETROFIT.

Scenario Event	Scenario Timing	Entrapment Level	Time in Retrofit Program				Percentage Reduction after 30yrs
			Day 0 (Unretrofitted)	10 years	20 years	30 years	
1 500 year Return Period	Night-time	Light	0	0	0	0	NA
		Deep	0	0	0	0	NA
	Busy Weekend	Light	1	1	0	0	100
		Deep	0	0	0	0	NA
	Festival Event	Light	14	10	5	1	93
		Deep	4	3	2	0	100
2 1,000 year Return Period	Night-time	Light	1	1	1	0	100
		Deep	0	0	0	0	NA
	Busy Weekend	Light	4	3	1	1	75
		Deep	1	1	0	0	100
	Festival Event	Light	68	49	27	12	82
		Deep	19	14	8	4	79
3 2,500year Return Period	Night-time	Light	7	5	4	3	57
		Deep	2	2	1	1	50
	Busy Weekend	Light	23	18	12	9	61
		Deep	6	5	3	2	67
	Festival Event	Light	380	290	199	135	64
		Deep	108	82	56	38	65

It was found that there are essentially no entrapments for the 500 year RP Scenario 1 event and un-retrofitted York for a nighttime or busy weekend exposure. The logistics start to emerge for Scenario 1 during a busy festival event with large crowds. For Scenarios 2 and 3 the USAR logistics climb and are very significant for Scenario 2 during a festival event. This is consistent with the high death toll predicted and several of the 8 seriously injured people who are expected to be heavily entrapped are likely to succumb to their injuries, adding to this toll. The extremely rare combination of Scenario Event 3 occurring during a crowded festival yields major logistics for USAR. What is also evident is that retrofit is very effective in eliminating or reducing these logistics. For Scenarios 1 and 2 the logistics are reduced by over 75%. For Scenario 3 the logistics are reduced by about 67%.

ECONOMICS

The economic costs associated with a severe Australian earthquake were assessed for this research using the methodology developed by Mohanty et al, (2018). Table 55 presents a typology of the earthquake related economic losses that have been identified for potential inclusion. In the table there are two broad categories of earthquake related economic costs: the direct and the indirect economic costs. Overall, economic costs due to building related business interruptions, can be classified into both the direct and indirect components.

TABLE 55 TYPES OF EARTHQUAKE RELATED ECONOMIC LOSSES.

Cost Category	Type of Costs	Components of Costs
Direct	Tangible	Building Repair and Replacement Cost
		Building Contents Cost
		Business Interruption Cost
		Health care Cost
		Emergency Management Cost
		Clean-up Cost
Indirect	Tangible	Business Interruption Cost
		Casualty related loss of productivity
	Intangible	Injury or disability related quality of life loss (pain and suffering, psychological distress)
		Other quality of life loss (reduced job opportunities, access to schools and public services, participation in community life, recreational activities)

On the basis of available data and the methodological developments so far, the cost components in this economic assessment are presented in Figure 18. The figure illustrates how the scenario ground motion is translated through a value chain aligned to the impact framework to the economic measures shown in the yellow boxes. Specifically these are:

- Building damage loss;
- Contents loss, including plant and fit-out of businesses;
- Rental and commercial lease losses;
- Wage losses;
- Proprietor income losses;
- Health care costs; and
- Societal value of human life associated with deaths.

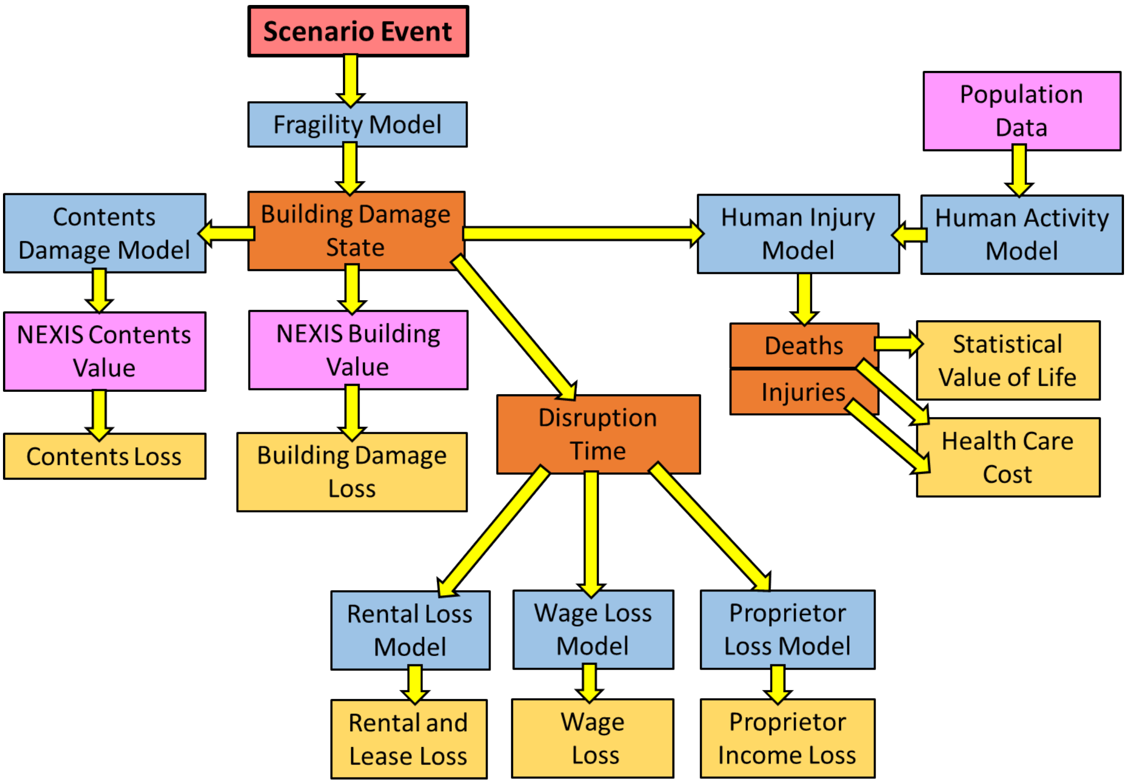


FIGURE 18 ECONOMIC MODELLING FRAMEWORK WITH THE ECONOMIC MEASURES QUANITFIED SHOWN IN YELLOW.

Earthquakes also affect infrastructure, nature reserves and recreational facilities that, apart from causing ripple effects in terms of direct and indirect business interruption costs, also involve important intangible costs to a community. These have not been considered in this research.

The evaluation of each of these economic measures is described briefly below.

BUSINESS INCOME LOSS

This section presents the methodology, data sources and the estimated values of the wage/salary income loss and the proprietor income loss to owner/managers of incorporated/unincorporated enterprises. These are major components of the business income loss in the Shire of York for an earthquake scenario event.

Wage/Salary Income Loss

The proprietary income and the wage/salary income loss can be estimated as a function of (1) number of proprietors/ employees within a building; (2) the average estimated income of proprietors/employees by employment type and industry classification; and (3) the overall time taken to resume the business following an earthquake by industry classification and building damage state.

Methodology

The methodology for estimating wage/salary income loss in the Shire of York involved the following steps:

1. Estimate the average wage/salary incomes of employed people in York using the 2017 Census of Population and Housing (ABS, 2017; hereafter referred to as the 'Census') based on their employment types comprising: full time and part time along with the industry of employment.
2. Apply these average wage/salaries in each category to the number of employees at each individual business at the resolution of individual buildings using matching industry and employment categories from the GA-BS. This enables estimation of wage/salary and proprietary income by employment types and industry classification.
3. Estimating the business interruption period during which the business is expected to be unable to operate for each earthquake scenario using the damage severity expressed as the damage index and the claim resolution time derived from claims data for the 1989 Newcastle Earthquake.
4. Estimating the wage/salary income loss for an individual business at the resolution of individual buildings based on the business interruption period and the damage state probabilities.
5. Aggregating the wage/salary income loss values for each individual business over the study area.

Data Sources

There is no census of wage/salary information available in Australia at the resolution of individual buildings. The GA Business Survey (GA-BS), conducted as part of this research, provides information on usage, employment and economic activity at individual building level. The Census contains information on wages /salaries in the local area categorised by employment type and industry classification. This research combined information from the Census with the GA-BS (conducted in 2018) to estimate the wage/salary income loss and the proprietary income loss at the resolution of individual buildings.

The scenario impacts can be effectively mapped to the GA-BS. The impact modelling simulates the probability of damage states for individual buildings. That is, the probability that a specific building (of known type) would be in a particular damage state for an individual scenario. The GA-BS contains information on the number of employees by their employment category at resolution of individual buildings, such as full time or part time. The surveyed employment categories match the Australian and New Zealand Standard Industrial Classification (ANZSIC). The Census contains information on the total weekly income (in ranges) for people aged 15 years and above. The Census income information is available by ANZSIC classification of employment and employment type; the latter classifies people as employed working full-time, part-time or away from work. The Census also contains information on status of employment that separates employees from owners and managers of incorporated/unincorporated enterprises.

Industry Classification

The Census uses the Australian and New Zealand Standard Industrial Classification (ANZSIC) 2006 (1292.0) (ABS, 2006) that have been jointly devised by the Australian Bureau of Statistics and Statistics NZ. This classification is a hierarchical classification with four levels, namely; Divisions (the broadest level), Subdivisions, Groups and Classes (the finest level). At the 'Divisional' level it provides a broad overall picture of the economy and is suitable for the publication of summary tables in official statistics. Where an individual business entity can be classified by more than one ANZSIC code, the ANZSIC identifier must reflect the primary (or most significant) industry that best describes the individual business entity's main economic activity. In total, there are 19 divisions specified under ANZSIC. They are:

1. Agriculture, Forestry and Fishing;
2. Mining;
3. Manufacturing;
4. Electricity, Gas, Water and Waste Services;
5. Construction;
6. Wholesale Trade;
7. Retail Trade;
8. Accommodation and Food Services;
9. Transport, Postal and Warehousing;
10. Information Media and Telecommunications;
11. Financial and Insurance Services;
12. Rental, Hiring and Real Estate Services;
13. Professional, Scientific and Technical Services;
14. Administrative and Support Services;
15. Public Administration and Safety;
16. Education and Training;
17. Health Care and Social Assistance;
18. Arts and Recreation Services; and
19. Other Services.

The data gathered by the GA-BS indicates the businesses in the town of York are primarily in the Retail Trade category – number seven.

Status in Employment

Status in Employment classifies a person's type of employment status such as owner/managers or employees, for their main job in the week prior to census night. This attribute is applicable to all persons aged 15 years or older who list their employment status as 'employed'. Status in Employment contains detailed information as to whether the incorporated/unincorporated enterprise has employees or not, as listed below:

1. Employees;
2. Owner managers of incorporated enterprise with employees;
3. Owner managers of incorporated enterprise without employees;
4. Owner managers of unincorporated enterprise with employees ;
5. Owner managers of unincorporated enterprise without employees;
6. Contributing family workers; and
7. Not stated.

For estimating proprietary income loss, categories 2 and 3 were combined into one category. Similarly, categories 4 and 5 were also combined into one category. The Census reports the number of people whose Status in Employment is categorised as "not stated". These were proportionately redistributed amongst other known categories. This redistribution was based on the relative frequency of the values of the known categories, so the not stated values were extrapolated out to other valid values (Cassells et al. 2010).

Income Categories

The Census does not provide information on the absolute income of an individual/household. Instead it records the income level of people aged 15 years and over and presents personal weekly income in ranges. For this analysis discrete values are required instead of ranges hence the mean income values were assigned to each range reported by the Census. The total personal weekly income ranges in the Census with their mean values are presented in Table 56.

TABLE 56 THE TOTAL PERSONAL WEEKLY INCOME RANGES IN CENSUS WITH THEIR MEAN VALUES.

Personal Weekly Income Ranges in Census (Equivalent Annual Income)	Mean Weekly Incomes
Negative income	0
Nil income	0
$1-$199 ($1-$10,399)	$100
$200-$299 ($10,400-$15,599)	$250
$300-$399 ($15,600-$20,799)	$350
$400-$599 ($20,800-$31,199)	$500
$600-$799 ($31,200-$41,599)	$700
$800-$999 ($41,600-$51,999)	$900
$1,000-$1,249 ($52,000-$64,999)	$1125
$1,250-$1,499 ($65,000-$77,999)	$1375
$1,500-$1,999 ($78,000-$103,999)	$1750
$2,000 or more ($104,000 or more)	$2500

The Census reported "*Not Stated*" values and these numbers were pro-rated and added into other income categories.

Both the Census and the GA-BS contain information on employment by the Australian and New Zealand Standard Industrial Classification (ANZSIC). In facilitating data matching between the two data sets, the ANZSIC industry divisions were combined into the three broad industry sector categories of primary, secondary and tertiary industries (for details refer Mohanty et al, 2017).

Proprietary Income loss

Both the Census and the GA-BS identify employed persons based on their status of employment such as employees separate from the business owners and managers of incorporated/unincorporated enterprises. Using the similar methodology as that used for wage/salary income losses, the proprietary income losses were independently estimated for the businesses and for Shire of York.

Estimating Income Loss

The following section describes the step by step methodology and presents the results for the earthquake related wage/salary and proprietors income loss in the Shire of York in the event of an earthquake scenario.

The total personal weekly income ranges and the corresponding mean values in the Census are presented in Table 56. The mean weekly income values in each income bracket and the number of people earning in that bracket are multiplied and the total weekly income in that wage bracket was estimated for the Shire of York. These figures were further aggregated by employment, labour force and industry division and the total incomes in those specific categories calculated. The average income in each category of employment and industry were subsequently estimated by averaging across those categories.

Table 57 presents the estimates of average wage/salary income for employees in the Shire of York. Table 58 presents the estimates of average income in the category of proprietary income for owner/managers of incorporated/unincorporated enterprises.

TABLE 57 ESTIMATED WEEKLY AVERAGE WAGES/SALARIES IN THE SHIRE OF YORK BY INDUSTRY, EMPLOYMENT AND LABOUR FORCE STATUS, 2017 CENSUS OF POPULATION AND HOUSING.

Industry of Employment	Status of Employment	Labour Force Status	Total Income	Number of Employed Persons	Average Income
Accommodation and Food Services	Contributing family worker	full-time	1,350	3	450
Accommodation and Food Services	Employee	away from work	2,100	8	262
Accommodation and Food Services	Employee	full-time	19,190	25	768
Accommodation and Food Services	Employee	part-time	22,050	55	401
Administrative and Support Services	Contributing family worker	part-time	0	5	0
Agriculture, Forestry and Fishing	Contributing family worker	full-time	8,670	18	481
Agriculture, Forestry and Fishing	Contributing family worker	part-time	674	3	225
Agriculture, Forestry and Fishing	Employee	away from work	4,875	3	1,625
Agriculture, Forestry and Fishing	Employee	full-time	43,480	37	1,175
Agriculture, Forestry and Fishing	Employee	part-time	10,040	14	717
Arts and Recreation Services	Employee	part-time	2,300	4	575
Construction	Employee	full-time	8,550	9	950
Education and Training	Employee	full-time	50,480	34	1,485
Education and Training	Employee	part-time	28,600	36	795
Electricity, Gas, Water and Waste Services	Employee	full-time	19,490	14	1,390
Electricity, Gas, Water and Waste Services	Employee	part-time	1,050	3	350
Financial and Insurance	Employee	part-time	2,175	3	725

Industry of Employment	Status of Employment	Labour Force Status	Total Income	Number of Employed Persons	Average Income
Services					
Health Care and Social Assistance	Employee	full-time	48,250	47	1,027
Health Care and Social Assistance	Employee	part-time	49,740	65	765
Inadequately described	Employee	full-time	4,500	4	1,125
Inadequately described	Employee	part-time	1,050	3	350
Other Services	Employee	part-time	2,300	4	575
Professional, Scientific and Technical Services	Employee	full-time	14,000	10	1,400
Professional, Scientific and Technical Services	Employee	part-time	14,500	14	1,030
Public Administration and Safety	Employee	full-time	37,100	25	1,480
Public Administration and Safety	Employee	part-time	8,070	11	734
Retail Trade	Contributing family worker	part-time	2,250	5	450
Retail Trade	Employee	full-time	30,480	33	924
Retail Trade	Employee	part-time	26,100	51	512
Transport, Postal and Warehousing	Employee	full-time	12,500	8	1,560
Transport, Postal and Warehousing	Employee	part-time	675	3	225
Wholesale Trade	Employee	full-time	26,600	14	1,900
Wholesale Trade	Employee	part-time	2,700	3	900

TABLE 58 AVERAGE WEEKLY PROPRIETARY (OWNER/MANAGERS) INCOME IN THE SHIRE OF YORK BY INDUSTRY, EMPLOYMENT AND LABOUR FORCE STATUS.

Industry of Employment	Status of Employment	Labour Force Status	Total Income	Number of Employed Persons	Average Income
Accommodation and Food Services	Owner manager of enterprise with employees	full-time	6,295	7	900
Agriculture, Forestry and Fishing	Owner manager of enterprise with employees	full-time	70,195	47	1,494
Agriculture, Forestry and Fishing	Owner manager of enterprise without employees	full-time	36,130	39	926
Agriculture, Forestry and Fishing	Owner manager of enterprise with employees	part-time	7,500	3	2,500
Inadequately described	Owner manager of enterprise with employees	full-time	5,500	4	1,375
Inadequately described	Owner manager of enterprise without employees	part-time	1,750	5	350
Other Services	Owner manager of enterprise without employees	full-time	6,500	4	1,625
Professional, Scientific and Technical Services	Owner manager of enterprise without employees	part-time	2,175	3	725
Professional, Scientific and Technical Services	Owner manager of enterprise without employees	full-time	3,375	3	1,125

Industry of Employment	Status of Employment	Labour Force Status	Total Income	Number of Employed Persons	Average Income
Rental, Hiring and Real Estate Services	Owner manager of enterprise with employees	full-time	5,625	3	1,875
Retail Trade	Owner manager of enterprise with employees	full-time	12,670	6	2,110
Wholesale Trade	Owner manager of enterprise with employees	full-time	5,625	3	1,875

These average income values in each category were imported into the GA-BS in order to enable estimation of the business income loss at the resolution of individual buildings.

Likewise, the business interruption periods in the event of an earthquake scenario as a function of damage state and industry classification were estimated using insurance claim data from the 1989 Newcastle Earthquake and mapped to the GA-BS.

In the final step, the conditional probabilities of different damage states for each building and the corresponding business interruption periods were applied to the average Proprietary (owner/managers) and wage/salary income in the Shire of York by Industry, Employment and Labour Force Status and the total income loss in those categories were estimated.

Results

Table 59 and Table 60 present the total proprietary (owner/managers) and wage/salary income losses in the Shire of York for each of the scenario events and the modelled reduction in these losses with each retrofit strategy into the future. For the highest Retrofit Strategy II the losses dropped by 65% to 70%.

TABLE 59 ESTIMATED BUSINESS INCOME LOSS FOR PROPRIETORS BY SCENARIO EVENT (M AUD).

Scenario Event	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
1	0.15	0.12	0.09	0.05	0.12	0.08	0.04
2	0.49	0.39	0.28	0.16	0.38	0.25	0.13
3	1.76	1.52	1.17	0.85	1.47	1.05	0.73

TABLE 60 ESTIMATED BUSINESS INCOME LOSS FOR EMPLOYEES BY SCENARIO EVENT (M AUD).

Scenario Event	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
1	0.26	0.21	0.20	0.14	0.19	0.14	0.09
2	0.84	0.71	0.62	0.44	0.66	0.45	0.27
3	3.44	3.15	2.77	2.19	2.88	2.18	1.59

RENTAL AND LEASE INCOME LOSS

This section presents the methodology, data sources and the estimated values of the rental and lease income losses in the Shire of York for residential and commercial properties.

Estimating Residential Rental Income Loss

Methodology

Each occupied private dwelling is assigned an average weekly rent value and the probabilities for being in different damage states for increasing hazard are assessed. The average weekly rental values for each building are applied to the probabilities of building damage and the rental interruption period associated with the damage states. The estimated rental income loss is aggregated and applied to the proportion of residential buildings rented (0.19) in the Shire of York and the overall residential rental income loss values are estimated for each earthquake scenario. The proportion of residential buildings rented in the Shire of York was estimated using the Census of Population and Housing (ABS, 2017).

Data Sources

In estimating rental income loss in the Shire of York, the first step was to identify a data source that contains information on the properties that are rented as opposed to those that are owner occupied. Additionally, information on the actual rental payments on a weekly/fortnightly/monthly basis was required. The basic information requirements listed below.

1. The proportion of rental or owner occupied properties in the total residential/commercial dwellings in the region.
2. The average weekly/monthly rent paid in each category.
3. The rental interruption period for different damage states by building type.
4. The conditional probabilities of dwelling damage state by building type and earthquake scenario.

Based on input data availability, this report specifically focused on rental or lease income loss from residential and commercially occupied private dwellings only. Data contained in ABS (2017; referred to hereafter as the 'Census') is used. The data was customised for the Shire of York classified by the Dwelling Type, Tenure Type and Weekly Rent in Dollars. The Census contains tenure and rental information on residential properties only. This report uses GA-BS for information on tenure and rental information for dwellings used for commercial purposes in York. The, the scope of this report is limited to estimating rental income loss in those categories only.

Dwelling Type

The Census dwelling type categories include:

1. Separate house;
2. Semi-detached, row or terrace house, townhouse etc with one storey;
3. Semi-detached, row or terrace house, townhouse etc with two or more storeys;
4. Flat, unit or apartment in a one or two storey block;
5. Flat, unit or apartment in a three storey block;
6. Flat, unit or apartment in a four or more storey block;
7. Flat, unit or apartment attached to a house;

8. Caravan, cabin, houseboat;
9. Improvised home, tent, sleepers out;
10. House or flat attached to a shop, office, etc;
11. Not stated; and
12. Not applicable.

The residential buildings in the exposure database were not classified to such as detailed categorisation as used in the Census and presented above. In order to apply the Census rental data to the outcomes from the scenario impact modelling that reported impacts to residential buildings using a coarser categorisation of residential building types the more detailed Census classification was grouped into the following four broad categories. The broad categories combined one or more of the twelve Census categories.

1. Separate House
    a. Separate house
2. Semi-detached, row or terrace house, townhouse etc. with
    a. One storey
    b. Two or more storeys
3. Flat or apartment
    a. In a one or two storey block
    b. In a three storey block
    c. In a four or more storey block
    d. Attached to a house
4. Other dwelling
    a. Caravan
    b. Cabin, houseboat
    c. Improvised home, tent, sleepers out
    d. House or flat attached to a shop, office, etc.

The dwellings in "Not Stated" categories were proportionately distributed among the other categories. There was no positive number of dwellings allocated to the "Not Applicable" category in the Census. Consequently that category has been excluded from the analysis.

Tenure Type

The Census contains information about housing tenure - if the dwelling is

1. owned outright;
2. owned with a mortgage;
3. being purchased under a rent-buy scheme;
4. rented;
5. occupied rent free;
6. occupied under a life tenure scheme; and
7. Other.

For the purpose of residential rental income loss estimation the information requirement is whether a rented, encumbered with a mortgage or subject to any other tenure type. Consequently, the above Census classifications were grouped into the following three broad categories.

1. Pays Rent
    a. rented,
2. Pays Mortgage
    a. owned with a mortgage
    b. being purchased under a rent-buy scheme,
3. Pays Neither
    a. owned outright,
    b. occupied rent free,
    c. occupied under a life tenure scheme

Weekly Rent and Dwelling Structure

The Census also asked how much the household paid in rent or mortgage per week as a continuous variable and in weekly rental/mortgage payment brackets. The rent payment details in the Census for the residential category are presented in Table 61.

TABLE 61 RENT PAYMENT CATEGORIES IN THE SHIRE OF YORK FROM THE CENSUS.

Dwelling Structure	Rent (weekly) Dollar Values	Number of dwellings	Total Rent (AUD)
Separate House	100	4.46	446
	140	4.46	624
	150	5.57	836
	200	22.30	4,460
	220	3.34	736
	225	6.69	1,505
	240	4.46	1,070
	250	18.95	4,740
	260	12.26	3,190
	275	4.46	1,226
	280	5.57	1,560
	290	6.69	1,940
	300	36.79	11,040
	310	5.57	1,730
	320	12.26	3,925
	340	4.46	1,515
	350	6.69	2,340
	360	5.57	2,005

Dwelling Structure	Rent (weekly) Dollar Values	Number of dwellings	Total Rent (AUD)
	380	6.69	2,540
	400	5.57	2,230
Semi-detached, row or terrace house, townhouse etc. with one storey	98	3.05	300
	175	6.10	1,065

The "Not Stated" rental payment categories were proportionately distributed across all other categories and "Not Applicable" values were not considered for the analysis. In all other rent categories actual rent dollar values were considered for estimating the rental income loss.

The average weekly rent values by dwelling structure type are estimated and presented in Table 62.

TABLE 62 THE AVERAGE WEEKLY RENT BY DWELLING TYPE ESTIMATED FROM THE CENSUS.

Dwelling Structure	Number of dwellings	Total Rent paid	Average Rent (AUD)
Separate house	183	49,661	272
Semi-detached, row or terrace house, townhouse etc. with one storey	9.1	1,365	149

Results

The estimated residential rental income loss in the Shire of York for the earthquake scenarios are presented in Table 63.

TABLE 63 ESTIMATED RESIDENTIAL RENTAL AND LEASE INCOME LOSS FOR THE SCENARIO EVENTS 1-3 (M AUD).

Scenario Event	Unretrofitted	Retrofit Scheme II			Retrofit Scheme II		
		10 years later		30 years later	10 years later	20 years later	30 years later
1	0.03	0.03	0.03	0.03	0.03	0.03	0.02
2	0.10	0.10	0.10	0.10	0.10	0.09	0.09
3	0.71	0.70	0.70	0.70	0.70	0.69	0.67

Estimating Commercial Rental Income Loss

The lease values per square metre in the retail and office use categories were estimated based on the information collected in the GA-BS. The rental values in the light industrial use category were source from current York area real-estate lease information on real estate internet sites. The estimated per square metre rental values are presented in Table 64.

TABLE 64 : COMMERCIAL LEASE PER SQUARE METER IN THE SHIRE OF YORK.

Commercial Use	Weekly Lease/Square Meter (AUD)
Retail	2.49
Office Space	1.94
Light Industrial	0.153

The GA-BS was merged with the building exposure database for additional information on building type, the total floor area, number of storeys and the floor usage of the occupied buildings. In this manner each business in GA-BS was assigned with an average weekly lease value. These average weekly lease values for each building were applied to the conditional probabilities of each building damage state for each earthquake scenarios and the business interruption period associated with each damage states applied to estimate the expected lease income loss for each business. The GA-BS contains information on the building occupancy status of the business such as rented, or owner occupied. Based on the businesses that have occupancy status as rented (60% of the business surveyed) the individual rental loss values at the building level were aggregated for the Shire of York. In this manner the overall commercial lease income loss values were estimated for each earthquake scenario. The estimated commercial rental income loss values for each earthquake scenario for the Shire of York are presented in Table 65.

TABLE 65. ESTIMATED COMMERCIAL RENTAL AND LEASE INCOME LOSS FOR THE SCENARIO EVENTS 1 – 3 (M AUD).

		Retrofit Scheme II			Retrofit Scheme II		
Scenario Event	Unretrofitted	10 years later		30 years later	10 years later	20 years later	30 years later
1	0.10	0.08	0.07	0.05	0.08	0.05	0.03
2	0.35	0.27	0.22	0.16	0.27	0.16	0.10
3	1.38	1.16	1.01	0.84	1.12	0.83	0.65

THE COST OF CASUALTIES

Previous research in this project (Mohanty et al, 2018) presents a methodology and work plan for estimating direct health care costs in the immediate aftermath of an earthquake event in Australia. For this project, it was necessary to determine direct costs for the care of earthquake induced casualties. The process relied on the regular Australian patient care costs sourced from the Independent Hospital Pricing Authority (IHPA) that hosts National Hospital Cost Data Collection in Australia (NHCDC). Whilst this data was not sourced from earthquake –specific injuries it does represent the variety of injury severities that may be expected following an earthquake. The categorisation of injury types used by the IHPA does not match with the injury categorisations used in earthquake studies which are typically more concise. Two earthquake injury categorisations are available: a five-point injury severity scale (Spence, 2007) shown in Table 66 and the four-point injury severity scale used by HAZUS shown in Table 28. Thus a mapping was required between the categorisation used by the IHPA and one or both of the earthquake injury classifications. As the software used to estimate casualties following a scenario earthquake output numbers of casualties categorised by the HAZUS injury severity scale the end result of the mapping process had to assign costs per casualty categorised according to Table 28. This section presents the methodology and estimates for direct health care costs for different injury severities that may be encountered following an earthquake event in the Shire of York.

TABLE 66 EARTHQUAKE RELATED EXPECTED INJURY CATEGORIES. AIS DENOTES ABBREVIATED INJURY SCALE (HTTPS://WWW.ACI.HEALTH.NSW.GOV.AU/GET-INVOLVED/INSTITUTE-OF-TRAUMA-AND-INJURY-MANAGEMENT/DATA/INJURY-SCORING/ABBREVIATED_INJURY_SCALE).

Category		Type of Injuries		AIS
1	Uninjured/lightly injured	Head or Face	Bruising/contusions, minor cuts	2
		Abdomen	Bruising, minor cuts	1

Category		Type of Injuries		AIS
		Upper Extremities	Bruising, minor cuts, sprains	1
		Lower Extremities	Bruising, minor cuts, sprains	1
2	Moderately injured	Head or Face	Cuts into soft tissues	2-3
		Abdomen	Cuts into soft tissues	2-3
		Upper Extremities	Dislocation, Cuts into soft tissues	2-3
		Lower Extremities	Dislocation, Cuts into soft tissues	2-3
		Other	Dehydration/exposure; burns 1-2^{o}; unconscious < 1hr	3
3	Seriously	Head or Face	Open head or facial wounds, fractures, brain concussion	3-4
		Abdomen	Pneumothorax and rib fractures, crushing > 3hrs, puncture organs	1-4
		Upper Extremities	Fractures – open, displaced or comminuted (pulverised)	3
		Lower Extremities	Fractures – open, displaced or comminuted (pulverised)	3
		Other	Uncontrolled bleeding; burns 2-3^{o} (% of body?); unconscious > 1 hr	3-5
4	Critical	Head or Face	Internal head trauma, severe crushing, brain damage	5
		Abdomen	Spinal column injuries, internal organ failures due to crushing	5
		Upper Extremities	Traumatic amputations, arms	5
		Lower Extremities	Traumatic amputations, legs	5
		Other	Nerve injuries	5
5	Dead	Asphyxiation, burns and smoke inhalation, intracranial injuries, traumatic complications		6

In Australia, direct health care costs are categorized by Australian Refined Diagnosis Related Groups (AR-DRG) and Urgency Related Groups (URG). In consultation with health care stream experts (IHPA, 2019) the AR-DRG and URG classifications were mapped to the five tier classification shown in Table 66 AR-DRG only cover admitted patients, whereas URG is used to classify and cost emergency department visits.

The injury categories presented in Table 66 reveal it is unlikely that category 1 and 2 injuries need any hospital admission. These injuries are treated in the emergency department. Consequently, category 1 and 2 injuries need to be mapped to URGs. URGs are based on very broad diagnostic categories (known as Major Diagnostic Blocks) and therefore the URGs mapped to the above earthquake related categories (1 and 2) includes emergency department visits that had other injuries other than those listed in the Table 66. Also, URGs included categories for patients with any diagnosis who met the criteria of 'did not wait', 'transferred to another hospital' and 'died in ED'. They are not specific to injury diagnoses, hence they were excluded from this health care cost estimation.

The AR-DRG classification has over 800 groups, so the types of injuries listed in Table 66 may group to any number of DRGs depending on the interventions that occurred during the hospital stay, whether the patient had multiple injuries or required extended hours of mechanical ventilation, there are multiple potential DRGs for each issue. For example, a head injury that required surgical intervention are grouped to a different DRG than a head injury that was managed conservatively.

The AR-DRG classification also has a separate set of DRGs for multi trauma cases. So, if a patient has multiple types of injuries recorded, the episode was assigned to a multi trauma DRG rather than a DRG for the specific type of injury.

The Independent Hospital Pricing Authority (IHPA) provided data containing patient counts and the in scope National Efficiency Price (NEP) that are presented in Table 67 for Western Australia. In Australia, National Efficient Price (NEP) in-scope cost includes a broad range of direct, indirect and overhead hospital costs.

TABLE 67 PATIENT COUNT AND ASSOCIATED COST CATEGORISED BY EARTHQUAKE RELATED INJURY TYPES (IHPA, 2019).

Category	Admitted Acute		Admitted Subacute		Emergency Department	
	Number of patients	NEP in-scope cost (AUD)	Number of patients	NEP in-scope cost (AUD)	Number of patients	NEP in-scope cost (AUD)
Category 1: Head or face	1,435	3,921,616	11	248,969	10,052	6,570,346
Category 1: Abdomen	653	2,415,766	10	250,105	1,429	1,162,946
Category 1: Upper extremities	512	2,250,117	7	96,555	16,153	8,290,196
Category 1: Lower extremities	1,239	8,500,599	63	947,165	18,872	9,943,798
Category 2: Head or face	1,566	5,697,034	10	137,037	10,796	6,218,819
Category 2: Abdomen	200	904,951	*	*	1,063	787,487
Category 2: Upper extremities	2,196	10,019,810	9	172,264	14,457	8,396,043
Category 2: Lower extremities	1,378	8,233,798	22	302,984	7,618	4,590,409
Category 2: Other	1,140	10,203,105	7	260,155	4,818	3,584,557
Category 3: Head or face	1,676	11,248,009	18	417,876	4,359	3,682,224
Category 3: Abdomen	1,115	14,198,998	51	739,309	3,001	3,110,143
Category 3: Upper extremities	5,479	38,646,311	186	3,370,899	17,499	11,828,343
Category 3: Lower extremities	5,135	79,630,577	1,068	22,833,815	11,150	9,453,277
Category 3: Other	214	4,327,809	5	182,854	1,780	1,631,820
Category 4: Head or face	984	23,813,772	276	9,135,257	1,073	1,905,803
Category 4: Abdomen	124	5,231,677	34	4,622,413	171	173,348
Category 4: Upper extremities	262	2,308,238	*	*	15	12,059
Category 4: Lower extremities	21	472,389	*	*	*	*
Category 4: Other	11	117,348	*	*	24	24,901
Category 5: Asphyxiation, burns and smoke inhalation, intracranial injuries, traumatic complications	86	948,991	*	*	148	130,309

Based on Table 67, the average estimated direct health care costs by the care types in 2018 are estimated and presented in Table 68.

TABLE 68 THE AVERAGE ESTIMATED HEALTH CARE COSTS BY THE CARE TYPES IN 2018.

Earthquake Injury Classifications	Patient Counts	Total NEP in Scope Cost	Average NEP in Scope Cost
Category 1	50,436	44,598,177	884
Category 2	45,280	59,508,453	1,314
Category 3	52,736	205,302,262	3,893
Category 4	2,995	47,817,205	15,966
Category 5: Asphyxiation, burns and smoke inhalation, intracranial injuries, traumatic complications	234	1,079,300	4,612

Table 69 shows the resulting direct health care costs adopted for this study. It is derived from those costs shown in Table 68. Category 1 in Table 68 was not used as it was assumed that these injuries would be treated at home outside of the health care system) without recourse to health professionals hence society did not incur a cost. Consequently, the subsequent four injury categories in Table 68 are presented in Table 69 (as Severity 1-4) and they match the HAZUS (FEMA, 2006) injury categories in Table 28. Note that for the purposes of benefit-cost calculations the cost for Category 4 was replaced by $4.3 million (the statistical value of life) as this category represents deceased casualties.

TABLE 69 DIRECT HEALTH CARE COSTS.

Injury Severity Level	Direct Health Care Cost ($ per casualty)
Severity 1	1,314
Severity 2	3,893
Severity 3	15,966
Severity 4	4,612

THE VALUE OF LOST WELFARE FROM FATALITIES

Distinct from direct health care costs, the number of lives disabled and lost due to casualties, presented as severities 1-4 in this report also involve loss of economic welfare to the society that can be estimated using the Value of Lost Welfare (VLW) approach. These costs relate to the loss of total economic welfare (market and non-market) associated with disability and premature mortality (including the loss of utility due to lost leisure time and foregone consumption opportunities) along with less tangible losses such as those due to pain and suffering. This report only estimates the welfare loss from fatalities (Severity 4, Table 69) based on the concept of a Value of a Statistical Life (VSL) to assess the potentially avoidable economic losses. The VSL approach is a robust methodology that was developed for valuing mortality risk reductions in regulatory analysis of environmental health and transport policies in OECD countries (OECD, 2011)and Australia (OBPR, 2019). This is extended in this report to capture the economic value of avoidable earthquake related fatalities. VSL for Australia recommended by the Office of Best Practice Regulation Guidance Note is used (OBPR, 2019). The OBPR (2019) provides a credible estimate of the value of statistical life in Australia as $4.3m and the value of statistical life year is

$182 000 in 2014 dollars. The note primarily intends to provide guidance on the cost-benefit analysis in Regulation Impact Statements assigning values to benefits of regulating change designed to reduce the risk of physical harm. Following the international practice and OBPR (2019), this report applied the VSL estimated by Abelson (2008) for estimating the welfare cost of fatalities.

BENEFIT - COST ANALYSIS OF MITIGATION MEASURES

Benefit from retrofitting URM buildings arises from a variety of savings. This section reports on benefit-cost ratios where the benefit arises from:

- Reduction of repair following earthquake induced damage;
- Reduction in casualties;
- Reduction in losses to fit-out and contents;
- Reduction in rental income for business premises; and
- Reduction in business income and wages.

Reduction of Repair Following Earthquake Induced Damage

Benefit of mitigation measures realized through reduction of building repair following earthquake induced damage was calculated by transforming the vulnerability curves presented in Table 15 to Table 20 to loss-probability curves by applying the replacement costs presented in Table 9 and the hazard curve shown in Figure 2 with adjustment for soil response effects. An example loss-probability curve is shown in Figure 19.

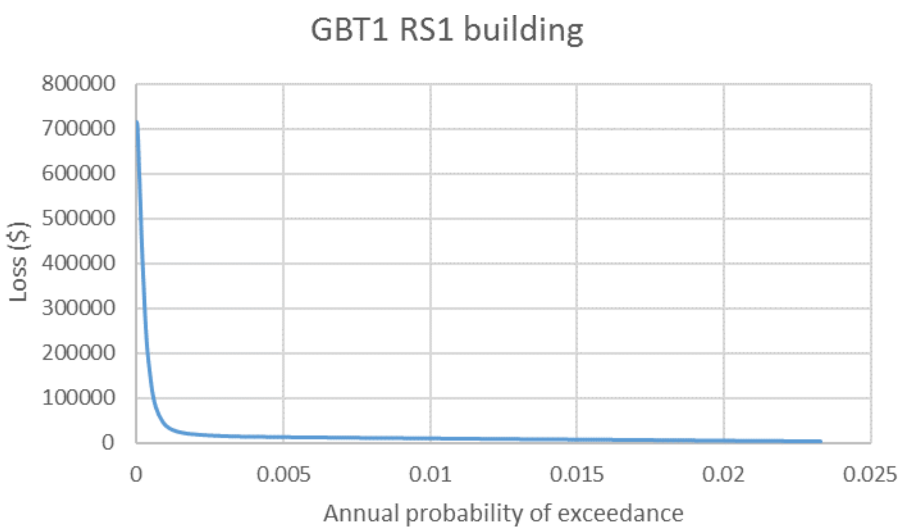


FIGURE 19 LOSS-PROBABILITY CURVE FOR GENERIC BUILDING TYPE 1 WITH RETROFIT SCENARIO 1 APPLIED.

The average annual loss for each unmitigated building type and each retrofit scenario was computed by numerically integrating the area under the relevant loss-probability curve. The benefit was computed by the difference in average annualised loss between the unmitigated building and the retrofitted building as the sum over the remaining lifespan of the building with benefit from future years brought to present value, assuming a discount rate of 4%. The present value of the benefit is compared to the cost of installing retrofit shown in Table 14. Table 70 presents the benefit-cost ratio for each retrofit scenario.

TABLE 70 BENEFIT COST FOR EACH RETROFIT SCENARIO ARISING FROM SAVINGS IN REPAIR OF EARTHQUAKE DAMAGE.

Generic Building Type	Retrofit Scenario	Benefit / Cost Ratio
1	1	0.109
1	2	0.083
1	3	0.058
1	4	0.100
1	5	0.083
1	6	0.075
1	7	0.091
2	8	0.106
2	9	0.125
2	10	0.079
2	11	0.121
2	12	0.095
2	13	0.116
2	14	0.123
3	15	0.156
3	16	0.078
3	17	0.124
4	18	0.093
4	19	0.230
4	20	0.071
4	21	0.223
4	22	0.116
4	23	0.082
4	24	0.122
5	25	0.096
5	26	0.106
5	27	0.114
6	28	0.094
6	29	0.075
6	30	0.075
6	31	0.089
6	32	0.088
6	33	0.092
6	34	0.100

All of the benefit-cost ratios are well below 1.0. Hence, there is no financial benefit to be gained from retrofit when only the benefit accruing from reduced repair of earthquake building damage is considered.

Reduction in casualties

Reductions in casualties was estimated by the change in damage state where the damage state was assigned based on the calculated damage index. The methodology for computing building populations, numbers of casualties and direct costs associated with casualties has been previously described.

Reduction in losses to fit-out and contents

The value of fit-out and contents was evaluated using data collected for the BNHCRC project Launceston Flood Risk Mitigation Assessment Project. This source was chosen as it is one of the few sources of data for value of fit-out and contents and the variety of building stock in Launceston is roughly equivalent to York. The adopted values are set out in Table 71.

TABLE 71 RATES FOR FITOUT AND CONTENTS.

Generic Building Type	Floor Area (m²)	Contents and Fitout Rate ($/m²)
1	134	1400
2	480	2382
3	338	5552
4	414	2382
5	315	3264
6	228	3264

The loss to fit-out and contents was estimated as the damage index based on damage to the building fabric multiplied by the fit-out and contents value established using the data in Table 71.

Reduction in rental income for business premises

The reduction in rental income was estimated as set-out in the Economics section above. The length of time a building was unusable for businesses was determined using the building repair time based on insurance settlement time verse damage index presented in the Building Damage Repair Time section.

Reduction in business income and wages

The reduction in business income and wages was estimated as described in the Economics section.

Benefit Cost

Table 72 shows the benefit components arising from the sources discussed above together with the cost of retrofit and the benefit-cost ratio for each retrofit scenario. For the non-residential building types (types 2 to 6) the majority of the benefit is derived from reductions in outdoor casualties. Many of the benefit-cost ratios do not approach 1.0 due to the comparatively rarity of damaging earthquakes and the cost of retrofit to old URM buildings.

TABLE 72 BENEFIT – COST OF RETROFIT CONSIDERING ALL BENEFITS.

Generic Building Type	Retrofit Scenario	Cost of Retrofit ($)	Benefit from reduced repair (current $)	Benefit from reduced contents losses (current $)	Benefit from reduced casualties (current $)	Benefit from reduced economic losses (current $)	Benefit / Cost ratio of mitigation
1	1	11,787	1280	336	0	0	0.137
1	2	15,911	1324	348	0	0	0.105
1	3	27,203	1579	414	163	72	0.082
1	4	26,059	2602	684	0	124	0.131
1	5	34,072	2826	742	163	72	0.112
1	6	38,940	2906	763	163	72	0.100
1	7	45,809	4173	1096	163	196	0.123
2	8	24,819	2628	1198	0	0	0.154
2	9	47,876	5989	2730	0	0	0.182
2	10	74,709	5938	2706	43723	8855	0.819

Generic Building Type	Retrofit Scenario	Cost of Retrofit ($)	Benefit from reduced repair (current $)	Benefit from reduced contents losses (current $)	Benefit from reduced casualties (current $)	Benefit from reduced economic losses (current $)	Benefit / Cost ratio of mitigation
2	11	69,491	8418	3836	0	10221	0.294
2	12	89,915	8518	3882	43723	8855	0.723
2	13	103,300	11949	5446	44633	19214	0.786
2	14	118,506	14581	6646	44633	19214	0.718
3	15	24,509	3,818	4,716	0	641	0.374
3	16	40,600	3,153	3,894	24,340	3,841	0.868
3	17	58,927	7,322	9,043	28,885	6,829	0.884
4	18	16,326	1,519	816	0	0	0.143
4	19	24,005	5,522	2,964	0	0	0.354
4	20	89,878	6,391	3,431	31,506	8,894	0.559
4	21	30,718	6,835	3,670	0	0	0.342
4	22	104,488	12,083	6,487	31,506	8,894	0.564
4	23	96,591	7,930	4,258	31,506	8,894	0.544
4	24	111,201	13,557	7,278	31,506	8,894	0.551
5	25	12,892	1,241	721	0	0	0.152
5	26	56,883	6,041	3,508	24,697	3,658	0.666
5	27	63,336	7,233	4,200	24,697	3,658	0.628
6	28	21,778	2,057	1,250	9,569	125	0.597
6	29	32,756	2,471	1,501	9,569	125	0.417
6	30	53,000	3,949	2,399	46,706	3,809	1.073
6	31	51,330	4,562	2,772	31,658	3,588	0.83
6	32	72,207	6,335	3,849	58,427	5,647	1.028
6	33	65,165	5,972	3,629	58,427	5,647	1.131
6	34	84,372	8,477	5,150	58,427	5,647	0.921

YORK EARTHQUAKE RISK

AVERAGE ANNUALISED LOSS ASSESSMENT

Average Annualised Loss (AAL) is the common measure of long term financial risk associated with long term exposure to a hazard environment. It is the measure used by the insurance industry to price the component of an insurance premium related to the hazard. In this project it was calculated for building damage as a measure of the current earthquake risk in York. It was also calculated into the future using Retrofit Scheme I and Retrofit Scheme II uptake rates to assess the reduction in risk achieved. The results are presented in Table 73 for the entire York building stock and for the heritage building URM subset alone. The AAL for all the unretrofitted buildings in York was estimated to be 0.022% which is more than double the value of 0.0098% recently assessed for the Perth metropolitan area based on NSHA18 (Edwards et al., 2019c) bedrock hazard, the surface soils and Perth building stock. For the heritage building subset the AAL was estimated to be more than four times greater than for the Perth metropolitan area. The research shows that the earthquake risk in York is quite significant.

TABLE 73 AAL (%) FOR ALL BUILDINGS AND HERITAGE-LISTED BUILDINGS.

Building Group	Unretrofitted	Retrofit Scheme I			Retrofit Scheme II		
		10 years later	20 years later	30 years later	10 years later	20 years later	30 years later
All	0.0222	0.0216	0.0206	0.0198	0.0212	0.0196	0.0185
Heritage-listed	0.0422	0.0403	0.0368	0.0332	0.0390	0.0343	0.0292

As with the scenario impact results, risk reduction by retrofit is clearly observable with a 13% reduction in AAL for the entire town after 30 years and the higher Retrofit Scheme II uptake. For the heritage-listed buildings, which had the greater focus of retrofit, after 30 years under Retrofit Scheme II the long term loss associated with earthquake hazard was modelled to be reduced by 31%.

SCENARIO LOSS LIKELIHOODS

The loss exceedance curves were developed through an event-based probabilistic calculation using the NSHA18 input seismic source and ground motion models to assess the likelihood of the scenario losses. These curves enable the assessment of the likelihood of experiencing a loss as distinct from experiencing a severity of bedrock shaking. The scenarios in Table 31 were selected to match a likelihood of ground shaking intensity in the centre of York at the bedrock surface level (Soil Class Be). The loss experience in each scenario is the result of the surface shaking as modified by the overlying soils and the distribution of the building stock across the town. The likelihood of loss as a measure of impact does not necessarily correspond with the likelihood of ground shaking.

The scenario losses have been plotted on the loss exceedance curve for the present day town of York in Figure 20. Scenario 1 to Scenario 3 ground shaking has return periods of 500, 1,000 and 2,500 years. It can be seen that the losses are indicated to be approximately twice as likely as the ground motion. This is due, in part, to the incorporation of aleatory ground motion uncertainty in the event-based probabilistic calculation, whereas the scenario-based approach did not include this uncertainty. It is also influenced by the spatial distribution of surface soils and building stock across York. What is evident is that the scenario impacts are more likely than indicated by the ground motion shaking likelihood.

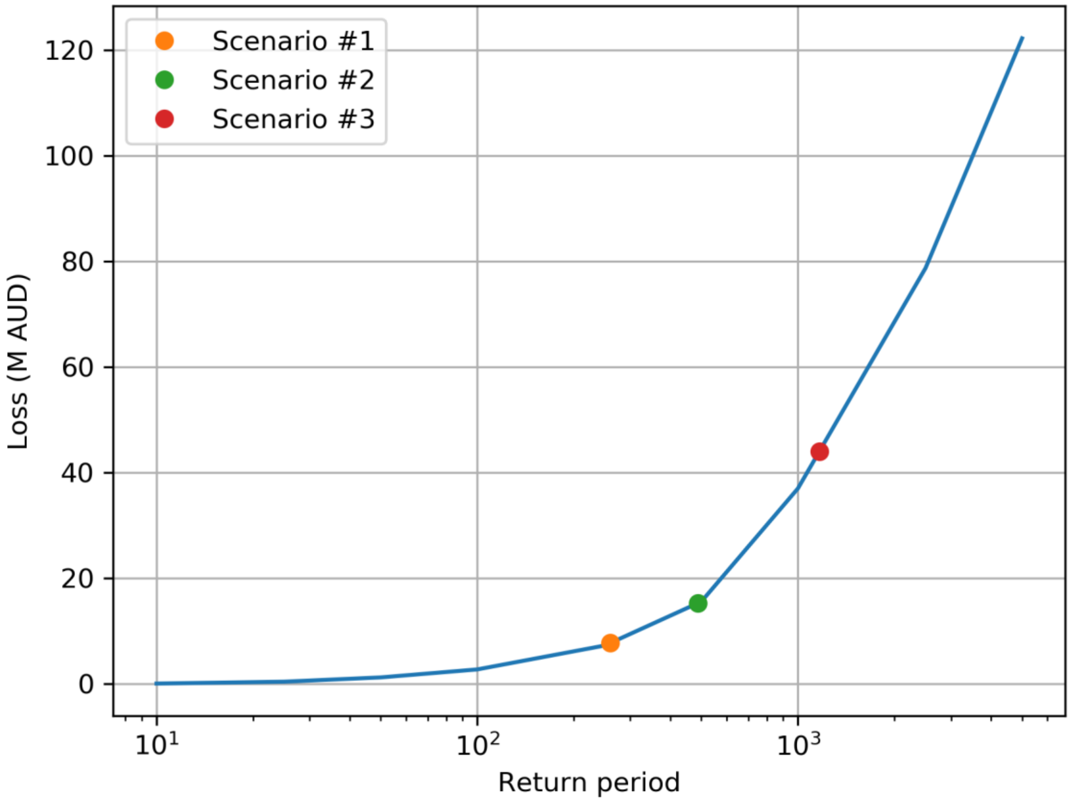


FIGURE 20 LOSS EXCEEDANCE CURVE FOR THE PRESENT DAY YORK BUILDNG STOCK WITH AGGREGATE LOSS FROM THE SCENARIO EVENTS PLOTTED.

The effect of retrofit on the entire York building stock can be seen in the loss exceedance curves in Figure 21. The horizontal shift of the curves indicates a reduced likelihood of loss achieved through retrofit after 30 years under Retrofit Scheme II. The horizontal shift in more evident for the heritage building subset and plotted in Figure 22.

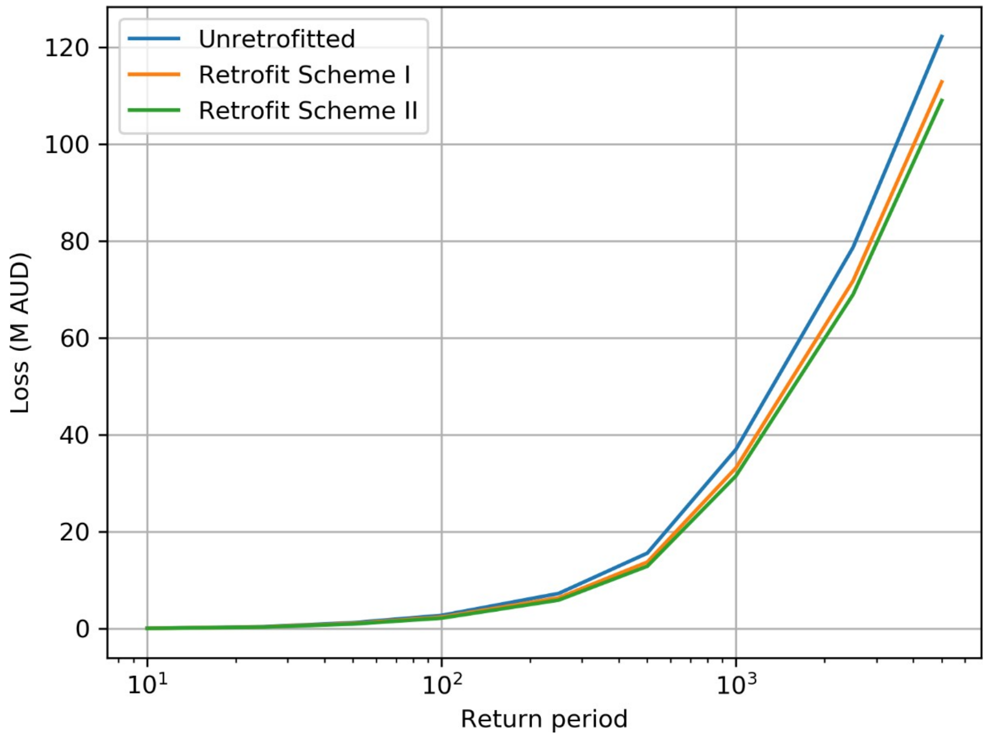


FIGURE 21 LOSS EXCEEDANCE CURVES FOR THE TWO RETROFIT SCHEMES COMPARED WITH THE CURRENT STATE FOR ALL BUILDINGS.

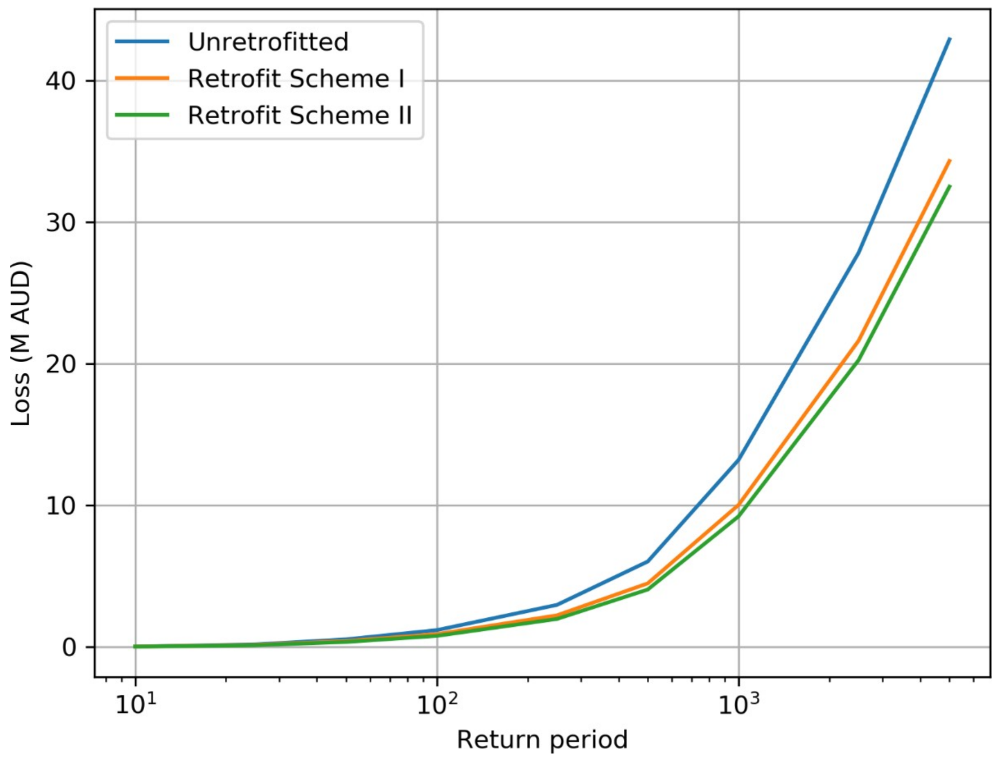


FIGURE 22 LOSS EXCEEDANCE CURVES FOR THE TWO RETROFIT SCHEMES COMPARED WITH THE CURRENT STATE FOR HERITAGE-LISTED BUILDINGS.

DISCUSSION

UNCERTAINTIES AND LIMITATIONS

The study has several limitations as to inputs, modelling and scope. For the bedrock earthquake hazard in York, the study has drawn upon the latest Australian assessment, NSHA18 (Allen et al, 2018a). It is the most comprehensive assessment of Western Australian bedrock hazard available but does have uncertainty associated with it. The targeted levels of bedrock hazard used for the three scenario events are the expected values but have uncertainty about them and the actual ground shaking could be greater than expected, as also is the application of the earthquake hazard in the assessment of risk. Furthermore, greater uncertainty is associated with the filtering effect of overlying soils in attenuating and amplifying the bedrock shaking frequency components. Not only do the attenuation models used to predict the effects of soils on surface ground motion have uncertainty, in addition the surface geology mapping has been limited by available surface geology maps. The soil classes also step abruptly whereas natural soil deposits typically smoothly transition from one class to another. With the very nonlinear nature of earthquake damage with increased shaking, actual damage and disruption outcomes in the scenario earthquakes could be higher than predicted.

The development of an understanding of York buildings, businesses and human exposure has been a central part of this project. For buildings the exposure definition is very specific but is limited in the understanding of the nature of construction that is concealed by linings etc. Essentially every business was surveyed giving a good understanding of the nature of business activity, but few business owners were prepared to provide all the information sought. These information gaps were bridged through resort to higher level statistical data. Further, the valuation of rental and lease costs were assessed using statistical and real estate data that may or may not be representative. Finally, the human exposure of York presented special challenges in that the tourism nature of the town leads to great variations in human activity from very quiet Mondays through to typically very busy weekends. The town also hosts several large events in which Avon Terrace is closed and crowded with thousands of people. Collectively, all of these exposure related factors contribute to uncertainty.

The vulnerability functions developed and used in this study also have uncertainty associated with them. Through the BNHCRC research, they represent the best publically available models for the Australian building types considered, particularly in quantifying the beneficial effects of retrofit. However, despite the efforts to calibrate these against historical damage data, they have uncertainty. They also represent the vulnerability of the building selected to represent this type, but the building stock shows many variations which will subtly influence vulnerability.

The casualties and USAR logistics associated with falling masonry on pedestrians were significant and greatly influenced the overall economics of investment benefits. There is a paucity of models for these and several assumptions were made with comparison to another study to assess these. This represents an uncertainty to the outcomes reported.

Finally, there have been limitations in the scope of the study, particularly in the economic cost assessment. While a significant range of direct costs have been captured, others have not which include clean-up costs and the cost of emergency services response. Demand surge that can increase repair costs in more remote locations following large scale disasters has not been included. The mitigating behaviour (and cost) of relocating a business out of damaged premises to a temporary location after an earthquake has not been included. Further, the disruption period has been linked to insurance claim data that represented the industry at the time of the 1989 Newcastle Earthquake, but may be less representative of the industry today. Finally, the study has not considered the higher level macro-economic behavior of the local, regional and state economy where other businesses beyond the impact zone benefit from the inability of York businesses to operate.

EARTHQUAKE HAZARD OF YORK

Arguably the state of Western Australia has the highest overall seismicity of any jurisdiction. This can be seen from Figure 23 which is the NSHA 18 bedrock hazard map in terms of PGA with a 500 year exceedance return period. Western Australia has more extensive areas of higher hazard. This can also be noted from the summary of damaging earthquake in Australia from 1897 to the present presented in Table 74. Of the 18 events (some multiple earthquake events) seven occurred in WA, the largest number for any state. The table includes the Meckering Earthquake of 1968 that had an epicentre approximately 37km from York and caused significant damage in the town.

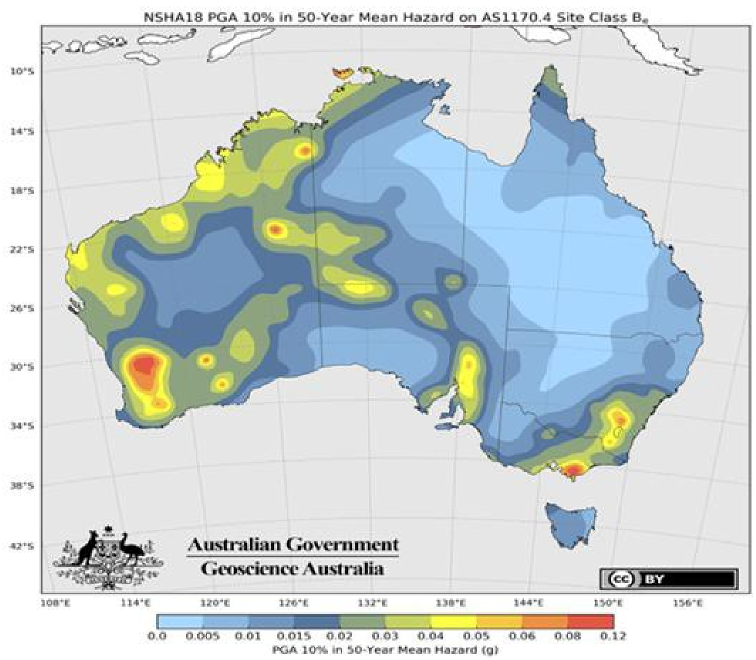


FIGURE 23 BEDROCK HAZARD ACROSS AUSTRALIA AS ASSESSED IN NSHA 18 AND PRESENTED AS PEAK GORUND ACCELERATION HAVING A 500 YEAR EXCEEDANCE RETURN PERIOD.

TABLE 74. SUMMARY OF DAMAGING EARTHQUAKES IN AUSTRALIA FROM 1897 TO THE PRESENT.

Date	Location	Magnitude	Comments
2019	Offshore Broome, WA	6.6	minor damage
2018	Lake Muir, WA	5.7, 4.6, 5.4	minor damage

Date	Location	Magnitude	Comments
2012	Moe, Vic	5.4	minor damage
2010	Kalgoorlie, WA	5.0	moderate damage
1997	Collier Bay, WA	6.3	minor damage
1994	Ellalong, NSW	5.4	major damage
1989	Newcastle, NSW	5.6	13 fatalities
1988	Tennant Creek, NT	6.2, 6.3, 6.5	gas pipeline cut
1979	Cadoux, WA	6.0	buildings damaged
1973	Picton, NSW	5.5	buildings damaged
1970	Calingiri, WA	5.2	minor damage
1968	Meckering, WA	6.5	major damage
1961	Robertson, NSW	5.6	buildings damaged
1954	Adelaide, SA	5.4	major damage
1941	Meeberrie, WA	6.3	largest onshore
1902	Warooka, SA	6.0	2 deaths
1897	Beachport, SA	6.5	major damage

The bedrock hazard of NSHA 2018 (Allen et al, 2018b) shows the greatest bedrock hazard in the WA to be close to Cadoux, North of York, with a 500 year average recurrence interval peak ground acceleration of 0.2g. This corresponds with moderate seismic hazard on a global scale. The corresponding bedrock hazard beneath the Perth central business district is 0.04g, and would be considered low by global standards. York has a bedrock hazard of 0.08g which is between the two. This is at the higher end of low by global standards and closer to moderate if a 2,500yr average recurrence interval is considered, as used for the third scenario event. Finally, this hazard increases by a factor close to 1.6 where buildings sit on Avon River sediments through the centre of York. This is the case for all the Avon Terrace business district and for much of the heritage building stock in York.

BUILDING VULNERABILITY AND MITIGATON

The research has considered six URM building types and assessed their present vulnerability and how this is mitigated by a range of mitigation measures used in isolation or in combination. The assessed present vulnerability of the building types are presented together in Figure 24. The relative vulnerabilities can be noted. The most vulnerable type was the two story commercial building (Type 4) whereas the single storey residential structure (Type 1) was the least. The relatively is intuitively correct with the Type 4 considered to be at greatest risk to earthquake shaking.

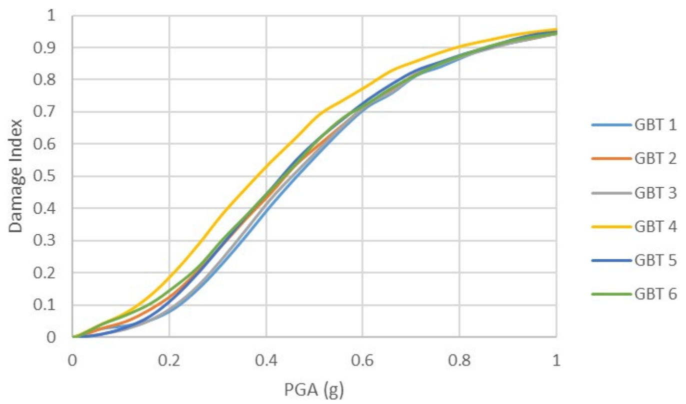


FIGURE 24 UNMITIGATED VULNERABILITIES OF THE SIX BUILDNG TYPES THAT WERE THE FOCUS OF THE YORK STUDY.

The reduction in vulnerability of these buildings that is afforded by retrofit can be seen in Figure 25, which is for the two storey commercial building Type 4. The significant reduction in vulnerability is evident, though the strengthening measures do not render the building earthquake proof, nor as resilient as a modern URM building built to current building standards. The corresponding reduction in the likelihood that the Type 4 building damage will exceed the range of damage state severities in shown in Figure 26. Again, the reduction in expected damage is evident. The strategies address the more likely damaging earthquake events and reduce the significant portion of the risk they contribute.

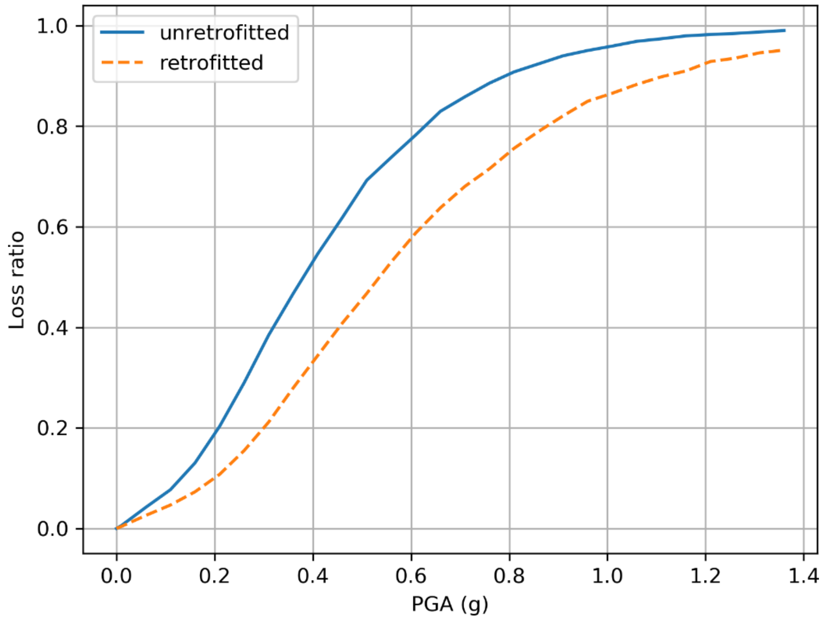


FIGURE 25 UNRETROFITTED AND RETROFITTED TYPE 4 TWO STOREY COMMERCIAL BUILDING EARTHQUAKE VULNERABILITY.

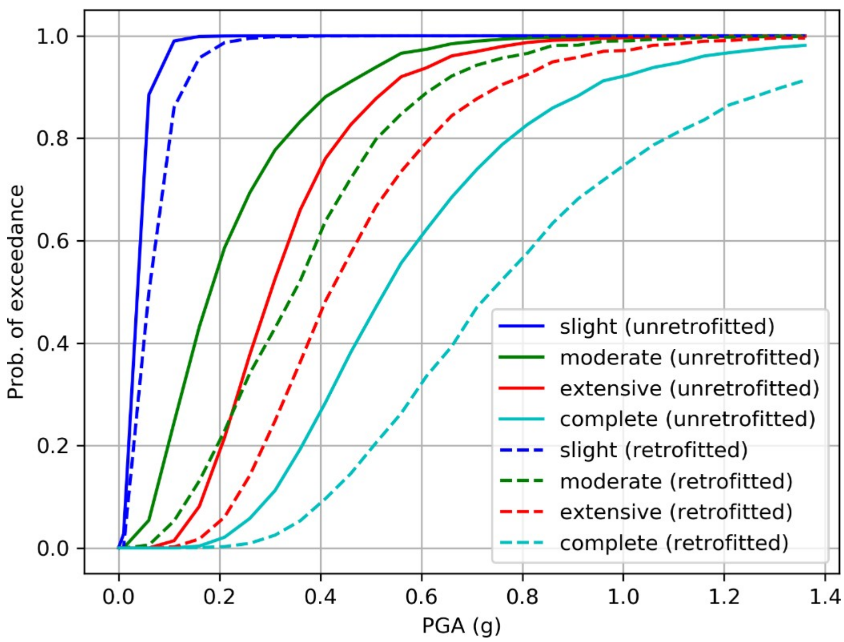


FIGURE 26 UNRETROFITTED AND RETROFITTED TYPE 4 TWO STOREY COMMERCIAL BUILDING EARTHQUAKE FRAGILITY.

The cost effectiveness of mitigation measures has been summarised in Table 75. The study has assessed some six economic measures of avoided impact. The most immediate being avoided damage and repair cost to the building itself, and then to progressively include the avoided contents damage, rental losses, commercial lease losses, wage losses, lost proprietary income, cost for medical care, and the loss to society more broadly through deaths using the value placed on a human life. These progressively accumulating benefits can be seen in Table 75.

What is clear is that the economic benefit to an individual property owner is small. It can also be seen that deeper retrofit is more expensive and typically yields smaller incremental benefits. The avoided injury and loss of life was found to be very significant for building Types 2 to 6 in the pedestrian precinct which can have components fall on pedestrians. Particularly for buildings in pedestrian precincts, the increase in B/C ratio with the benefits of avoided injury and deaths was about 2.5 times. Heritage preservation objectives aside, this could be a justification for external incentives for retrofit initiatives.

TABLE 75 SUMMARY OF THE RETROFIT COSTS AND THE BENEFITS TO A RANGE OF NOTIONAL DECISION MAKERS.

Generic Building Type	Retrofitted Components	Cost of Retrofit [$]	Notional Decision Maker							
			Building Owner		Building Owner/Occupier		York Shire		State Government	
			Benefit from reduced building repair [$]	B/C reduced building repair	Benefit from reduced contents losses [$]	B/C reduced building repair and contents loss	Benefit from reduced economic losses [$]	B/C reduced building repair, contents and economic loss [$]	Benefit from reduced casualties [$]	B/C ratio of mitigation for all reductions
Type 1 - Single Storey House	Chimneys - C	11,800	1,280	0.11	340	0.14	0	0.14	0	0.14
	Gables - G	15,900	1,320	0.08	350	0.11	0	0.11	0	0.11
	Building Box - B	27,200	1,580	0.06	410	0.07	72	0.08	163	0.08
	C + G	26,100	2,600	0.10	680	0.13	124	0.13	0	0.13
	C + B	34,100	2,830	0.08	740	0.10	72	0.11	163	0.11
	G + B	38,900	2,910	0.07	760	0.09	72	0.10	163	0.10
	All Measures	45,800	4,170	0.09	1,090	0.12	196	0.12	163	0.12
Type 2 – Hotel	Chimneys - C	24,800	2,630	0.11	1,200	0.15	0	0.15	7,310	0.45
	Parapets - P	47,900	5,990	0.13	2,730	0.18	0	0.18	16,070	0.52
	Building Box - B	74,700	5,940	0.08	2,710	0.12	8,860	0.23	43,720	0.82
	C + P	69,500	8,420	0.12	3,840	0.18	10,220	0.32	17490	0.58
	C + B	89,900	8,520	0.09	3,880	0.14	8,860	0.24	43,720	0.72
	P + B	103,300	11,950	0.12	5,450	0.17	19,210	0.35	44,630	0.79
	All Measures	118,500	14,580	0.12	6,650	0.18	19,210	0.34	44,630	0.72
Type 3 – Single Storey Commercial	Parapets - P	24,500	3,820	0.16	4,720	0.35	641	0.37	9,130	0.75
	Building Box - B	40,600	3,150	0.08	3,890	0.17	3,840	0.27	24,340	0.87
	All Measures	58,900	7,320	0.12	9,040	0.28	6,830	0.39	28,890	0.88
Type 4 – Two Storey Commercial	Chimneys - C	16,300	1,520	0.09	820	0.14	0	0.14	0	0.14
	Parapets - P	24,000	5,520	0.23	2,960	0.35	0	0.35	9,450	0.75
	Building Box - B	89,900	6,390	0.07	3,430	0.11	8,890	0.21	31,510	0.56
	C + P	30,700	6,840	0.22	3,670	0.34	0	0.34	11,030	0.70
	P + B	104,500	12,080	0.12	6,490	0.18	8,890	0.26	31,510	0.56
	C + B	96,600	7,930	0.08	4,260	0.13	8,890	0.22	31,510	0.54
	All Measures	111,200	13,560	0.12	7,280	0.19	8,890	0.27	31,510	0.55
Type 5 – Two Storey Institutional	Chimneys - C	12,900	1,240	0.10	720	0.15	0	0.15	4,050	0.47
	Building Box - B	56,900	6,040	0.11	3,510	0.17	3,660	0.23	24,700	0.67
	C + B	63,300	7,230	0.11	4,200	0.18	3,660	0.24	24,700	0.63
Type 6 –	Chimneys - C	21,800	2,060	0.09	1,250	0.15	125	0.16	9,570	0.60

Generic Building Type	Retrofitted Components	Cost of Retrofit [$]	Notional Decision Maker							
			Building Owner		Building Owner/Occupier		York Shire		State Government	
			Benefit from reduced building repair [$]	B/C reduced building repair	Benefit from reduced contents losses [$]	B/C reduced building repair and contents loss	Benefit from reduced economic losses [$]	B/C reduced building repair, contents and economic loss [$]	Benefit from reduced casualties [$]	B/C ratio of mitigation for all reductions
Two Storey Bank	Parapets - P	32,800	2,470	0.08	1,500	0.12	125	0.13	9,570	0.42
	Building Box - B	53,000	3,950	0.07	2,400	0.12	3,810	0.19	46,710	1.07
	C + P	51,300	4,560	0.09	2,770	0.14	3,590	0.21	31,660	0.83
	P + B	72,200	6,340	0.09	3,850	0.14	5,650	0.22	58,430	1.03
	C + B	65,200	5,970	0.09	3,630	0.15	5,650	0.23	58,430	1.13
	All Measures	84,400	8,490	0.10	5,150	0.16	5,650	0.23	58,430	0.92

EMERGENCY MANAGEMENT NEEDS

The emergency management needs assessed in terms of building damage and USAR for the most severe Scenario Event 3 (approaching a Meckering Earthquake event) for the current town and for York in 30 years are summarized in Table 76.

TABLE 76 SUMMARY OF EMERGENCY MANAGEMENT LOGISTICS FROM SCENARIO EVENT 3 AND ON A BUSY WEEKEND IN TERMS OF BUILDING DAMAGE SEVERITY AND URBAN SEARCH A RESCUE FOR PRESENT YORK AND AFTER THIRTY YEARS UNDER RETROFIT STRATEGY II.

Emergency Management Measure	Severity	Un-retrofitted	After 30 years of retrofit	Percentage reduction
All Buildings	Moderate damage	153	142	7
	Extensive Damage	20	15	25
	Complete Damage	6	5	17
Heritage Buildings	Moderate damage	31	24	23
	Extensive Damage	10	6	40
	Complete Damage	3	2	33
Urban Search and Rescue	Number Lightly Entrapped	23	9	61
	Number Deeply Entrapped	6	2	67

It should be noted in Table 76 that, while the severity of damage reduced is not very evident when expressed in terms of damage state and across the entire town, they become more evident with a focus in the heritage precinct where retrofit efforts are concentrated and for USAR logistics that are largely associated with this precinct.

The casualties figure show an even greater beneficial change through retrofit. The estimated numbers for each of the three levels of injury that require hospital care are summarised in Table 77 for each scenario event. The logistics are for York today and after thirty years under Retrofit Scheme II. The injuries represent the outcome soon after the event and will be exacerbated where poor USAR response impacts the survival of seriously injuries and entrapped individuals.

TABLE 77 SUMMARY OF EXPECTED CASUALTIES IN SCENARIO EVENTS FOR UNRETROFITTED AND RETROFITTED YORK UNDER RETROFIT SCHEME II,

Scenario Event	Scenario Timing	Injury Severity Category	Status of Retrofit		Percentage Reduction after 30yrs
			Un-retrofitted)	After 30 years	
1 500 year Return Period	Night-time	2 Moderate	0	0	NA
		3 Serious	0	0	NA
		4 Deaths	0	0	NA
	Busy Weekend	2 Moderate	0	0	NA
		3 Serious	0	0	NA
		4 Deaths	1	0	100
	Festival Event	2 Moderate	2	0	100
		3 Serious	3	0	100
		4 Deaths	18	2	89
2 1,000 year Return Period	Night-time	2 Moderate	0	0	NA
		3 Serious	0	0	NA
		4 Deaths	2	0	100
	Busy Weekend	2 Moderate	0	0	NA
		3 Serious	1	0	100
		4 Deaths	5	1	80

Scenario Event	Scenario Timing	Injury Severity Category	Status of Retrofit		Percentage Reduction after 30yrs
			Un-retrofitted)	After 30 years	
3 2,500year Return Period	Festival Event	2 Moderate	7	1	86
		3 Serious	15	3	80
		4 Deaths	89	16	82
	Night-time	2 Moderate	1	0	100
		3 Serious	2	1	50
		4 Deaths	9	3	67
	Busy Weekend	2 Moderate	2	1	50
		3 Serious	5	2	60
		4 Deaths	30	11	63
	Festival Event	2 Moderate	38	14	63
		3 Serious	83	29	65
		4 Deaths	496	176	65

The injuries are biased towards severe due to the nature of the cause. Falling masonry was the primary mechanism which tends to cause serious injury or death. It was also found that there were no injuries for the 500 year RP Scenario Event 1 and an un-retrofitted York for a nighttime exposure and with a single death for a busy weekend. The logistics start to emerge for Scenario 1 during a busy festival event with large crowds. For Scenario Events 2 and 3 the injuries climb and are very significant for Scenario Event 2 during a festival event. The mortality associated with the rarest scenario occurring during a crowded festival having 5,000 people in the street approached 500. What is also evident is that retrofit is very effective in eliminating or reducing these logistics. For Scenario Event 1 injuries are essentially eliminated and for Scenario Event 2 the logistics are reduced by over 80%. For Scenario Event 3 the logistics are reduced by about 67%.

Overall, retrofit has a very beneficial effect on both USAR and casualty numbers. The reduction in building damage was less evident in the damage state numbers, but the reduced damage loss showed clear evidence of improvement, particularly for the heritage building stock, which had greater focus of the retrofit efforts. Finally, the assessment of the scenario losses in the context of the spectrum of scenario losses consider to assess risk, show that the likelihood of impact for EM is higher than suggested by the ground motion likelihood.

YORK RISK

The financial earthquake risk for York was assessed in terms of long term damage to all building types and contents. The long term risk for an older URM building is 0.042% which translates into an annual cost of $210 for a building plus contents having a total value of $500,000. The equivalent financial cost of earthquake hazard for a corresponding older URM building in Perth is 0.01% or $50 pa and for a light framed structure 0.001%. These figures are consistent with the insurance industry pricing of risk. What is clear is that older URM buildings contribute the most to community risk. Secondly, this risk is higher in York than Perth due to the greater earthquake hazard beneath York. Finally, if location specific pricing of earthquake insurance were adopted, premiums for building and contents cover would be significantly affected with potential affordability issues for the York community.

COMMUNITY RECOVERY NEEDS

The top down ANDRI sub-indices for coping and adaptive capacity, along with and overall ANDRI index for the York-Beverley SA2, are presented in Table 78. The commentary in the table should be viewed as generic to this community profile and needs to be tempered by local information which is available in the case of this study. The indices and commentary have been used for comparative purposes in conjunction with the community survey information directly accessed for this project. Overall the communities of York and Beverly are in the lowest 25% of SA2 areas for ANDRI in Australia with an assessed low coping capacity and moderate adaptive capacity. This level of resilience is typical of more remote rural communities.

TABLE 78 DISASTER RESILIENCE, COPING CAPACITY AND ADAPTIVE CAPACITY RESULTS FOR THE YORK-BEVERLEY SA2 ASSESSED AS PRIMARY COMPONENTS OF THE AUSTRALIAN NATURAL DISASTER RESILIENCE INDEX.

Index	Index value	Class	Class description
Disaster resilience (ANDRI)	0.3951	Low <25th percentile	Communities in areas of low disaster resilience may be constrained in their capacity to use available resources to cope with adverse events, and are constrained in their capacity to adjust to change through learning, adaptation and transformation. Limitations to disaster resilience may be contributed by entrenched social and economic disadvantage, less access to or provision of resources and services, lower community cohesion and systems that do not encourage adaptive learning and problem solving.
Coping capacity	0.2658	Low	Communities in areas of low coping capacity may be constrained in their capacity to use available resources to cope with adverse events and to prepare for, absorb and recover from a natural hazard event.
Adaptive capacity	0.5122	Moderate	Communities in areas of moderate adaptive capacity have some capacity to adjust to change through learning, adaptation and transformation.

The communities are also classified as *Typology Group 3* and approximately 3.2 million Australians live in communities of this type. With reference to the eight sub-index rating in Appendix B, the typical strengths of these communities are in their *Social Character* (moderate) with mid-level ranges of education, employment and English language proficiency. The *Community Capital* (moderate) is also a strength with the community well connected. The *Social and Community Engagement* (moderate) is an added strength which could be stronger for York due to a more stable population. Barriers are associated with *Economic Capital* (low) which is, to a degree, true for York with many in the community just getting by, both as households and businesses. *Planning and the Built Environment* (low) is not seen to reflect York along with *Government and Leadership* (low). The York Shire Council has demonstrated the very opposite to this in advancing strategies to mitigate risk and is benefitting from the latest science and construction approaches to address natural hazard risk. *Emergency Services* (low) and *Information Access* (low), are other typical barriers for Typology Group 3, but are not considered representative of York.

The ANDRI index uses measures that are more associated with households than businesses. On balance, for the specific case of the York community, the community does have lower resilience that will impact its ability to cope with and recover form a major earthquake. Surveyed businesses were generally small, local and appeared to have a low resilience. The importance of the visitors to the town's economy will exacerbate this in the context of an earthquake that could destroy the heritage value of the town and long term visitor numbers. However, with the benefit of bottom up local knowledge, this research has concluded that the ANDRI metrics may under-state the community's resilience to natural disasters.

PHYSICAL MITIGATION NEEDS AND OPPORTUNITIES

The benefits of mitigation have been explored at two scales and for several stakeholders. The finest scale was at individual property owner and building user levels and the results were earlier summarized in Table 75 and discussed. What is clear is that retrofit by the owners based on the benefits back to them is not justified on economic grounds.

The avoidance of severe casualties and deaths does bring the benefit/cost of mitigation close to 1.0 or marginally above where high pedestrian exposure is the case. This has clear benefits to DFES and the state government more generally in avoided EM logistics, the cost of health care and the lost value to Society (in the case of a fatality). Individual owners, however, do not realize these benefits. The cost of mitigation to tie back elements that could potentially fall in the Avon Terrace precinct was found to be between 21% and 60% of full retrofit, with an average cost of 42%. There is a clear opportunity to focus retrofit on these elements on Type 2 to 6 buildings in the high exposure pedestrian precincts.

At the full community scale, the benefits of reduced local losses have been summarized in Table 79. In total, six loss sources were considered and for the three scenario events the reduction of loss to York after 30 years of applying Retrofit Scheme II were between 23 and 24%. The rarest Scenario Event 3 would cause $73m in assessed loss, which would reduce to $56m with 90 buildings retrofitted. This does not include all losses including the greater economic losses due to heritage and future tourism losses over future years.

TABLE 79 SUMMARY OF REDUCED LOSSES TO THE COMMUNITY OF YOUK THROUGH MTIGATION.

Scenario Loss Measures	Earthquake Scenario Event Losses [$m]					
	Scenario Event 1 500yr RP		Scenario Event 2 1,000yr RP		Scenario Event 3 2,500yr RP	
	Un-retrofitted York	After 30yrs of Retrofit	Un-retrofitted York	After 30yrs of Retrofit	Un-retrofitted York	After 30yrs of Retrofit
Building Damage	7.69	6.20	15.25	12.61	43.95	36.09
Contents Loss	3.75	2.70	7.57	5.67	21.48	16.28
Proprietor Income Loss	0.15	0.04	0.49	0.13	1.76	0.73
Wage Loss	0.26	0.09	0.84	0.27	3.44	1.59
Rental Income Loss	0.03	0.02	0.1	0.09	0.71	0.67
Lease Income Loss	0.10	0.03	0.35	0.10	1.38	0.65
Total	11.98	9.08	24.6	18.87	72.72	56.01
%age reduction	24.2		23.3		23.0	

AUSTRALIAN LESSONS FROM NZ MITIGATION INITIATIVES

In this study the progress being made in New Zealand to retrofit similar building types has been reviewed. Unlike Australia, NZ has legislation in place that requires the identification and address of earthquake prone buildings with a constraint on the time to reduce the risk. It does not stipulate the level of retrofit above 33% of current code and typically the extent of retrofit action is less than that needed to achieve full code compliance. New Zealand has made considerable progress in addressing its risk which was reviewed in the context of two local governments. The NZ experience is informative to the Australian setting in the following areas:

- While enforceable retrospective legislation is very helpful, this is not available in Australia for any natural hazard. Other approaches to motivate retrofit behaviour are needed.
- Risk awareness is a challenge due to the limited experience in Australia of damaging earthquake. Scenario modelling of expected impacts can be useful in communicating this risk to raise awareness and may raise the expectations of tenants of their landlords to have safe premises and residences.
- Increased NZ insurance costs based on more informed pricing is adding a further incentive. As learned from the insurance industry at the 9th August 2018 workshop in York, currently the earthquake risk of York buildings is priced on a larger region with lower overall risk. If it were to change to location based risk pricing such as is done in Australia for severe wind, flood and bushfire, York property owners would likely will face increased premiums and affordability issues.
- Incentives may be needed to motivate retrofit behaviour. The review (Falcon Consulting 2019) of the 18 month UMBP in Wellington City stated that the incentive provided were essential for its success. This may be particularly the case in York where many building owners lack the resources to fully fund retrofit intervention measures.
- The NZ process of giving higher retrofit priority to areas of high hazard and consequences of damage may assist in targeting activity. In particular, the focus on avoided major loss of life and injury through falling masonry could focus efforts on securing these elements at lower cost that would potentially cause this, thereby providing a minimum retrofit scope.

SUMMARY OF OUTCOMES

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 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 oncommunity 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.

RECOMMENDATIONS FOR FUTURE MITIGATION STRATEGIES

The following recommendations are made:

- That there is a need to communicate risk in a clearly understandable way that will clearly convey the need for action to undertake mitigation activity. The need for this is particularly due to the intermittent nature of earthquakes when compared to other weather related natural hazards that leads to complacency.
- That in the absence of legislation requiring retrospective address of high risk buildings, there are benefits in providing incentivisation in the form of grants and subsidies. This would be increasingly so in York where many building owners lack the resources to fully fund retrofit measures.
- That prioritization of retrofit should consider the criteria in the NZ approach where the avoidance of major injury and loss of life in a rare event is minimised. This would point to the retrofit of elements that pose a risk to people in pedestrian precincts. While there may not be a purely financial basis for the investment associated with avoided costs, the avoidance of major loss of life and injury in high exposure precincts may be an over-riding imperative for action.
- There is a need to preserve Australia's heritage. Older heritage buildings of URM construction are inherently vulnerable based on the materials used and subsequent deterioration with age. Preservation efforts for such buildings should go beyond the cosmetic to address their underlying vulnerabilities with a possible prioritisation in the high hazard regions of WA. Further, it could be extended to a multi-hazard approach where vulnerabilities to other hazards (wind, bushfire, flood) are also addressed in a single process.
- That mitigation measures need to be tested, refined, broadened in scope and made accessible. Alternative and more cost effective approaches can also be added and developed through industry. The information should also include best estimates of the benefits. This would include the translation of the information to other earthquake hazard settings within Australia.
- There is a need to support the development of skills with the design professionals and the construction industry to promote competency in each. This will promote the implementation of effective retrofit measures and affordability.

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APPENDIX A - YORK 9TH AUGUST 2018 WORKSHOP MINUTES

Reporting on Workshop: Earthquake Mitigation Case Study for Regional Town of York, WA
9th August 2018, YRCC York, York, WA

This document reports on the proceedings and outcomes of an earthquake mitigation workshop held at the York Recreation and Convention Centre in York, Western Australia on the 9th August, 2018. The workshop was convened as part of a research utilisation project under the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC) project entitled "Cost-Effective Mitigation Strategy Development for Building Related Earthquake Risk".

The research utilisation project entails working with a variety of stakeholders with the aim of translating earthquake mitigation research to a form that can inform mitigation.

The workshop structure featured presentations and discussion that covered progress with field survey work to date, the categorization of building types for detailed study, mitigation options and uptake rates for consideration, EM scenario selections, information on intangible value assessment and a proposed study in York by UWA on heritage values. The key workshop aims were achieved and a series of 'next steps' were identified and documented in this report.

Attendees

The workshop had 14 attendees representing a broad spectrum of stakeholders:

Paul Martin	Shire of York
Carol Littlefair	Shire of York
Stephen Gray	Department of Fire and Emergency Services (DFES)
Yvette Grigg	Department of Fire and Emergency Services (DFES)
Harriet Wyatt	Office of Heritage, WA
Janine Symons	Office of Heritage, WA
Peter Baxendale	Engineering Heritage, WA
Martin Silk	Engineering Heritage, WA
Bruce Buckley	IAG
Karl Robson	IAG
Abbie Rogers	University of Western Australia
Martin Wehner	Geoscience Australia
Mark Edwards	Geoscience Australia
Jerry Vaculik	University of Adelaide

Agenda and Workshop Aims

The workshop agenda is appended. The structure of presentations and discussion followed a logical flow from context setting, scope refinement/consensus through to governance and next steps. The workshop aims are presented below:

- To brief stakeholders on project aims, approach and progress;
- To present outcomes of recent York survey activity;

- To review and achieve consensus on proposed building types for detailed study;
- To understand of heritage building earthquake retrofit constraints in WA;
- To select range of mitigation retrofit roll-out strategies for investigation;
- To select earthquake scenarios for EM planning purposes;
- To discuss how project aims may support a wider group of stakeholders;
- To identify the next steps.

Workshop Presentations

The workshop included the following specific presentations:

Overview of Workshop Aims (Stephen Gray)

In the presentation the aims of the utilisation project were outlined.

Project Aims and Approach (Mark Edwards)

The motivations for retrofitted URM was presented with reference to the Christchurch Earthquake of 2011 and the similarities in the badly damaged building stock in Christchurch to that in York. The overarching BNHCRC project was also described along with its applicability to York. The nature of the York building stock, its value and its earthquake hazard were reviewed in being an excellent community to undertake an Australian mitigation study. Finally, the activities and timelines for the utilisation project were reviewed.

Earthquake Mitigation of WA Regional Towns – York Case Study: Survey (Martin Wehner)

The methods used and the outcomes of the survey of buildings, businesses and people in York was presented. Methods comprised Streetview camera capture, foot survey, camera capture of people and vehicle movement in the main street, and analysis of aerial photography. The predominance of older URM was presented along how they are presently used and their location in the town.

Earthquake Mitigation of WA Regional Towns – York Case Study: Building Types (Martin Wehner)

The nature of the older URM buildings was described with a focus on their vulnerability features and their expected lateral load resistance. The six building types proposed representing distinct vulnerability classes were also presented for review along with the basis for the selection of each.

Earthquake Mitigation Options (Jerry Vaculik)

In the presentation a broad overview was presented on the methods for retrofitting URM buildings. The nature of the vulnerable features were highlighted and the restraint needed described. The physical features of the works were also described along with the access needs and visibility of the strengthening once completed.

Scenario and Risk Modelling Methodology (Mark Edwards)

In the presentation an overview of risk modelling and the associated elements within the risk modelling framework was described. The economic metrics for inclusions was presented and how these translate into an economic evaluation of retrofit investment. The approach for assessing USAR logistics was also presented. Finally a presentation was made of the changed scenario damage outcomes of central Sydney with the application of retrofit to vulnerable building. The presentation illustrates the value chain of information that would be developed for the End Users.

Community Implementation Strategies for Consideration in York : A Tale of Three Cities (Mark Edwards)

The learnings from the retrofit of buildings in New Zealand were reviewed. In particular the activity of Wellington City Council, Masterton City Council and Napier City Council were reviewed. The impediments and enablers of retrofit in each of the three LGA areas were identified and lessons learned that could inform retrofit activity in York were identified.

Earthquake Scenario Selection (Mark Edwards)

The rarity of ground shaking considered for building design was reviewed with its implications for the performance of code compliant and non-compliant buildings. The likelihood of ground shaking being exceeded during the life of a structure was also presented. With this background, the workshop group was asked which three target likelihoods of ground shaking would be of interest for the scenarios? The severity of shaking would be generated by the scenario events to be developed for EM planning by the End Users.

Intangible Impacts of Earthquakes: Quantifying Non-market Values for use in Economic Decision Frameworks (Abbie Rogers)

In the presentation the challenge of assigning economic values to non-market impacts was discussed. The concept of willingness to pay to avoid what are considered intangible impacts was described. The "Value Tool for Natural Hazards" was described as a resource of the York project. Further, the proposed survey of the York community to assess the value people place on their heritage buildings was described.

Workshop Discussions

The following key points from the workshop discussion were noted:

- The building vulnerability types nominated were discussed. In the review of the Type 1 single storey house the need for an additional two storey house type was raised. This type would capture bed and breakfast establishments. Architectural features may differ such as having an absence of parapets but with the presence of verandas. Similarities with the Type 6 and similar small internal rooms as a house structure were discussed. Project team is to assess the similarity of vulnerability with Type 6, the predominance of two storey houses in York and the need to include a further type.
- GA explained the utility and applicability of the representative structure types. They will not provide specific information but will highlight indicative options that may be the best investment which can

subsequently be reviewed with a heritage architect and engineer for a property owner seeking to reduce earthquake risk.

- York Shire expressed an interest in identifying the buildings that should have the highest priority based on risk. These could be targeted first for retrofit.
- GA assured the End Users that the total earthquake impact on the town would be assessed but using vulnerability models from other sources for types not specifically studied in the project.
- The heritage engineers described the use of Helifix (UK) products in heritage building strengthening. They highlighted that retrofit for earthquake also results in improved structural behaviour for other issues such as settlement cracking. Hence, retrofit often provides added benefits.
- The uncertainties of undertaking retrofit work were discussed. The requirements for tying back parapets was discussed as an example and how these can vary greatly depending on what is discovered in the roof once the roof sheeting is removed. GA highlighted the value of understanding the range in costs for a given retrofit strategy as this can be sampled in the risk assessment process.
- IAG highlighted the importance of getting businesses running again after a major event as a key factor that promotes community recovery.
- Heritage Services explained that this initiative in York comes at an opportune time where their forward strategy is to be addressing resilience to natural hazards.
- Office of Heritage could run a priority program to support York retrofit. This would be similar to the priority given a heritage precinct in Albany, WA.
- York Shire has an "Avon Terrace" grants program to fund 50% of the cost of repainting the main street façades along Avon Terrace. It is presently a modest $20k pa. It was noted that the activity spurred on other building owners who had not received the grant to improve their property also. The question of whether to commit the funds to a number of smaller projects or one big project was noted. The Avon Terrace grants program could be a mechanism that could be augmented to direct funds to earthquake retrofit.
- IAG is the second largest purchaser of reinsurance in the world. Typically 85% of building cover is associated with natural perils, not theft or structural fire. IAG advised that York URM building owners are not charged the true cost of their earthquake risk. The York premium is Premium is based on whole SW WA regions of similar scale the Cresta zones.
- IAG has introduced address level pricing for flood and wind. It is moving towards doing so for earthquake. When it occurs many York businesses and residents will not be able to afford to insure buildings. IAG pointed out that the decision to move to address level pricing was implemented for other hazards swiftly without any transition period. It was noted that enabling mitigation ahead of this will head off the unaffordability of

insurance, lost risk transfer and reduced resilience due to lost financial support within the community after a disaster.

- An incentive program trialed on York for several years could lead to a national program.
- IAG raised the consideration of demand surge, particularly due to the size and remoteness of the community. Project team to consider this effect in avoided losses with IAG to assist with parameters.
- Discussion had on the partial retrofit on heritage buildings undertaken using a Heritage Service grants and whether this would be acceptable. It was noted that full code upgrade prohibitive and typically not achieved in other countries like New Zealand.
- After review of the broad effectiveness of earthquake mitigation programs in three NZ LGA's and subsequent discussion, two roll-out strategies of retrofit for research were developed:-
    - One Alignment of York Shire "Avon Terrace" and the Heritage Services grants program to support a 50% cost sharing of retrofit targeting the most vulnerable/high risk to human life buildings. It is assumed initially that a single property could be retrofitted each year, with half the rate for non-heritage buildings. Rates to be checked against uptake rates realised in the Albany restoration and York Avon Terrace repainting programs.
    - Two Augmented program with IAG "Safer Communities" participation whereby the focus is on all pre 1945 high risk URM and the uptake rate is assumed to be some multiple of strategy One above.
- The Shire of York highlighted the benefit of education by the Heritage Council in addressing local fears by York building owners that any initiative by owners to retrofit will trigger constraints from the Heritage office that will impact costs.
- Proposed scenario events discussed and selection to be finalised post workshop. Communication was discussed and the avoidance of return periods was recommended as people will not grasp the concept of likelihood. Propose the assessment of depth/magnitude to match range of ARIs with comparison with historical events. ARI's to extend out to 2,500yrs. Adopting actual earthquake events in the region will address credibility issues with the community.
- IAG could assess which above-Perth-hazard communities in WA are likely to be affected the most. This could lead to a state level targeting of communities.

Workshop Outcomes

The following workshop outcomes were noted:-

- Project team to assess the need to include an additional vulnerability type. As a variation to Type 6 to better cover large two storey houses.
- Project tram to identify which of the building types have the highest vulnerability for potential retrofit prioritisation based on risk.
- Project team to consider this effect of demand surge in avoided losses with IAG to assist with parameters.

- Two retrofit uptake rates agreed for a virtual retrofit of the town of York decadally out to 30years agreed.
- The three scenario events are to have the three likelihoods proposed of 500yr, 1,000yr, 2,500yr Return Period. However, communication to avoid reference to likelihoods but, rather, to be communicated in terms of historical WA earthquakes relocated to generate the target ground motions.
- Heritage Services will explore the opportunity to gain some insights on uptake rates from the Albany program they recently ran.
- There may be opportunity for IAG to assess which above-Perth-hazard communities in WA are likely to be affected the most. This could lead to a state level targeting of communities

WORKSHOP AGENDA

EARTHQUAKE MITIGATION CASE STUDY FOR REGIONAL TOWN OF YORK, WA

BNHCRC Project Title: – "Cost-Effective Mitigation Strategy Development for Building Related Earthquake Risk"

WORKSHOP

THURSDAY 9TH AUGUST 2018 : YORK RECREATION AND CONVENTION CENTRE

BARKER ST (VIA FORREST ST), YORK, WA

Workshop Aims

- To brief stakeholders on project aims, approach and progress.
- To present outcomes of recent York survey activity.
- To review and achieve consensus on proposed building types for detailed study.
- To understand of heritage building earthquake retrofit constraints in WA.
- To select range of mitigation retrofit roll-out strategies for investigation.
- To select earthquake scenarios for EM planning purposes.
- To discuss how project aims may support a wider group of stakeholders.
- To identify the next steps

Agenda

9:30 to 10:00am	Morning tea on arrival	
10:00am to 12:15pm		
Welcome and Logistics (Paul Martin)		5mins
Introductions (Steve Gray - Chair)		20mins

Overview of Workshop Aims (Chair)	5mins
Project Aims and Approach (Mark Edwards)	7mins
Questions	3mins
York Survey Outcomes (Martin Wehner) • Buildings • Businesses • Human Mobility • Outcomes	10mins
Discussion	5mins
Selected Building Types for Detailed Study (Martin Wehner, Jerry Vaculik)	10mins
Facilitated Discussion	10mins
Earthquake Mitigation Options (Jerry Vaculik)	20mins
Facilitated Discussion	10mins
Heritage Perspectives on Earthquake Mitigation (Peter Baxendale)	15mins
Facilitated Discussion	20mins
12:20 to 1:00pm Lunch	45mins
1:00pm to 3:00pm	
Modelling Approach (Mark Edwards) • Economic investment metrics • Intangible impact metrics • Scenario modelling approach and metrics • Risk assessment (current and future)	15mins
Questions	5mins
Community Level Mitigation Roll-Out Strategies (Facilitated Discussion)	
Discussion	30mins
Selection of Earthquake Scenarios for Emergency Management (Facilitated Discussion)	
Discussion	20mins
Options for Project Outcomes Communication (Facilitated Discussion)	
Discussion	25mins
Value Tool for Natural Hazards – Proposed York Heritage Value Survey (Abbie Rogers)	
Discussion	10mins
Next Steps (Chair)	
Facilitated Discussion	10mins
Closing Comments (Paul Martin) • Thanks to all for participation	5mins
3:00pm Workshop Close	

APPENDIX B - UNE COMMUNITY RESILIENCE REPORT

The Australian Natural Disaster Resilience Index: York-Beverley overview

Dr Melissa Parsons
Bushfire and Natural Hazards CRC
University of New England Armidale NSW 2351 Australia

Email: melissa.parsons@une.edu.au
Phone: 02 6773 3527

Final version

Report prepared for Geoscience Australia

Revised April 2019

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BACKGROUND

1.1 The Australian Natural Disaster Resilience Index

The Australian Natural Disaster Resilience Index assesses the resilience of communities to natural hazards at a national scale (Parsons et al. 2016). The Australian Natural Disaster Resilience Index assesses resilience based on two sets of capacities – coping capacity and adaptive capacity:

- Coping capacity is the means by which people or organisations can use available resources and abilities to face adverse consequences that could lead to a disaster (sensu UNISDR 2009). In a practical sense, coping capacity relates to the factors influencing the ability of a community to prepare for, absorb and recover from a natural hazard event.
- Adaptive capacity is the arrangements and processes that enable adjustment through learning, adaptation and transformation. Adaptation is the ability of a system to modify or change its characteristics or behaviour to cope with actual or anticipated stresses (Folke et al. 2002). Adaptive capacity entails the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups (Folke et al. 2002).

A hierarchical structure was used in the Australian Natural Disaster Resilience Index (Figure 1). The top level is the overall assessment of disaster resilience (Figure 1). The second level is made up of adaptive capacity and coping capacity. The third level is made up of themes that convey the latent dimensions of disaster resilience within adaptive capacity and coping capacity. The fourth level is comprised of indicator sets that measure the status of a theme. A composite index is computed for the first, second and third levels. Full details of the indicators and index computation methods are provided in Parsons et al. (in press).

Themes are the latent dimensions – related to coping capacity or adaptive capacity – that contribute to community resilience to natural hazards (Table 1). Themes have a basis in the literature: some with empirical evidence of the relationship between the theme and resilience, and others that conceptualise this relationship but with developing evidence. Coping capacity is comprised of six themes that encapsulate the factors influencing the resources and abilities that communities have to prepare for, absorb and recover from natural hazard events (Table 1). Adaptive capacity is comprised of two themes that encapsulate the factors that enable institutional and social learning, flexibility and complex problem solving (Table 1). Indicators provide the data for a theme – together the indicators measure the status of the theme.

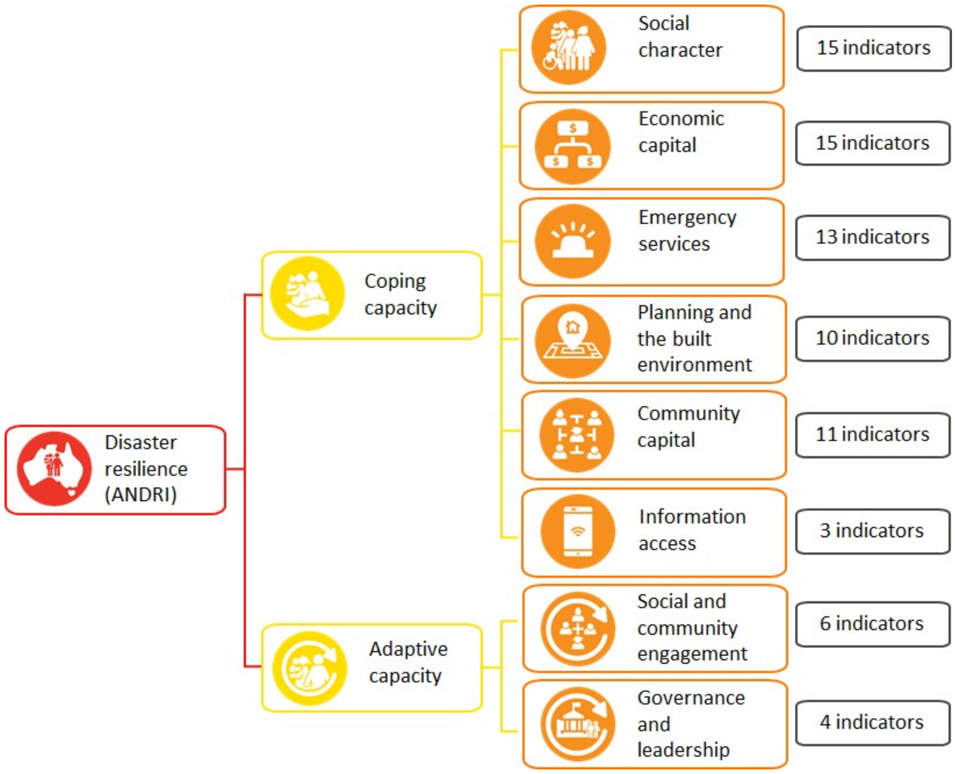


Figure 1: The hierarchical structure of the Australian Natural Disaster Resilience Index.

1.2 Spatial resolution

The grain of the Australian Natural Disaster Resilience Index (ANDRI) is Statistical Area Level 2 (SA2), defined in the 2011 Australian Statistical Geography Standard (ABS 2011). SA2s are delineated by the Australian Bureau of Statistics (ABS) using criteria of population, functional areas, growth, gazetted suburbs or localities, local government area boundaries and rural or city locations (ABS 2011). SA2s generally have a population range of 3,000 to 25,000 persons, with an average population of about 10,000 persons (ABS 2011).

1.3 This report

This report will examine the state of disaster resilience in the regional town of York as part of the Earthquake Impact and Risk Assessment for Perth and Supporting Infrastructure (EIRAPSI). It uses one SA2 (509021245 York-Beverley, ASGS 2011 boundary) from the Australian Natural Disaster Resilience Index to report:

1) The current Australian Natural Disaster Resilience Index results for the York-Beverley SA2, at the three levels of the index: overall disaster resilience; coping and adaptive capacity; and themes;
2) Use a typology to describe the strengths and opportunities for disaster resilience in communities of the York-Beverley SA2; and,
3) Comment on the capacity of the communities in the York-Beverley SA2 to cope with, recover from and adapt to earthquake impact and risk.

Table 1: Explanation of disaster resilience themes within the Australian Natural Disaster Resilience Index.

Theme	Description	Relationship to disaster resilience
Coping capacity		
Social character	The social characteristics of the community. Represents the social and demographic factors that influence the ability to prepare for and recover from a natural hazard event.	Social and demographic factors have well known influences on capacity to prepare for, respond to and recover from a natural hazard events. These include household and family composition, age, sex, education, employment, disability, language, and length of residence.
Economic capital	The economic characteristics of the community. Represents the economic factors that influence the ability to prepare for and recover from a natural hazard event.	Economic capital can facilitate disaster resilience by reducing the losses from natural hazard events. Economic resilience can contribute to the reduction of losses from natural hazard events through improved mitigation and risk management, individual flexibility and adaptation, enhanced recovery, market continuity and business continuity. Losses from natural hazards may increase with greater wealth, but increased potential for loss can also be a motivation for mitigation. High level of economic capital often goes hand in hand with high levels of social capital.
Emergency services	The presence, capability and resourcing of emergency services. Represents the potential to respond to a natural hazard event.	Emergency management is a core function of government. The capacity for emergency response is integral to community disaster resilience. Emergency management is also a key inclusion in policy guiding disaster resilience and disaster risk reduction. Remoteness influences the provision of and access to services.
Planning and the built environment	The presence of legislation, plans, structures or codes to protect communities and their built environment. Represents preparation for natural hazard events using strategies of mitigation, planning or risk management.	Considered land use planning is a core hazard mitigation strategy in built environments. Good planning policy is essential to reduce risk and enhance resilience. Good planning policy can also reduce future risk. Building codes set construction standards to reduce damage from natural hazards.
Community capital	The cohesion and connectedness of the community. Represents the features of a community that facilitate coordination and cooperation for mutual benefit.	Participation in social networks can enhance solutions to collective action problems. Disaster resilience is enhanced by the ways the sense of community fosters participation, community competency, pro-social behaviour and preparedness through working with others to solve shared local problems. Social capital facilitates disaster resilience before, during and after disasters. Social capital is often highlighted in times of disaster because it is a resource that facilitates collective action for mutual benefit.

Table 1 (cont.)

Theme	Description	Relationship to disaster resilience
	Coping capacity	
Information access 	The potential for communities to engage with natural hazard information. Represents the relationship between communities and natural hazard information and the uptake of knowledge required for preparation and self-reliance.	Telecommunication and internet access is vital to information sharing through all phases of a disaster. As digital communication has become the default medium for everyday exchanges, information sharing, and access to essential services, the disadvantages of being offline increase. Community engagement activities enable disaster resilience through public participation in decision making about natural hazards. Community engagement has been shown to have direct benefit for community resilience through capacity building, social connectedness and empowerment, self-reliance, education and training, awareness of risk and psycho-social preparation.
	Adaptive capacity	
Social and community engagement 	The capacity within communities to adaptively learn and transform in the face of complex change. Represents the resources and support available within communities for engagement and renewal for mutual benefit.	Adaptive communities are able to manage complex change. Characteristics of adaptive communities include social engagement, trust, cooperation, learning and well-being.
Governance and leadership 	The capacity within organisations to adaptively learn, review and adjust policies and procedures, or to transform organisational practices. Represents the flexibility within organisations to learn from experience and adjust accordingly.	Adaptive institutions have conditions suited to the development of the skills, knowledge and culture for managing complex change. Enabling conditions include social learning, research, innovation, collaboration and leadership. Effective response to natural hazard events can be facilitated by long term design efforts in public leadership.

THE YORK-BEVERLEY SA2

This assessment applies to the York-Beverley SA2 (509021245 – Figure 2). This SA2 has an area of 5,502 km^2 and an estimated resident population (2015) of 5,331 people.

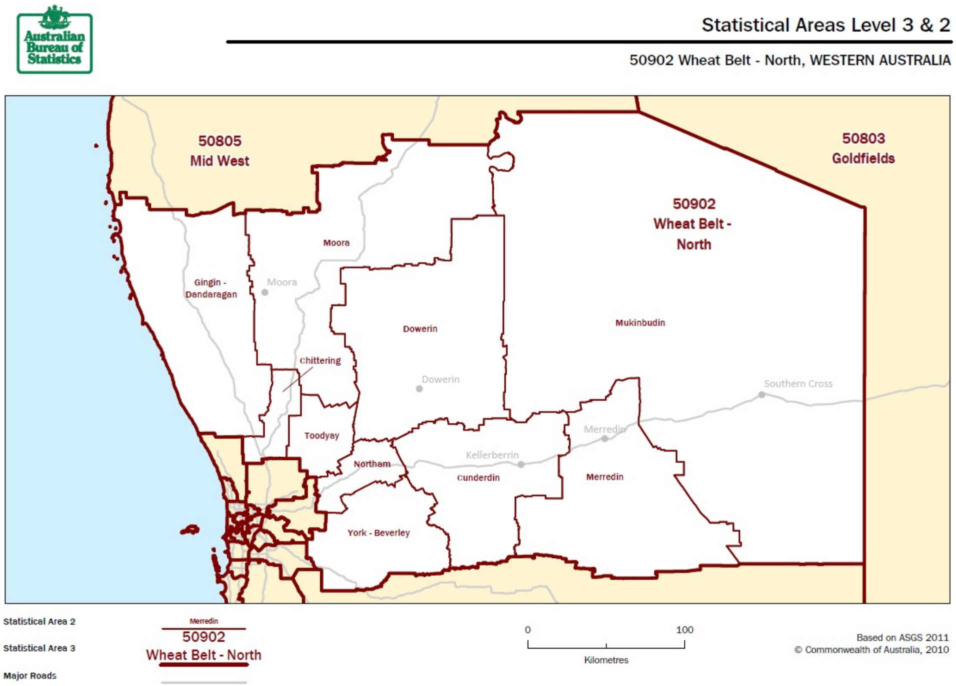


Figure 2: Location of the York-Beverley SA2 (509021245) within the Wheat Belt North SA3.

INDEX RESULTS: DISASTER RESILIENCE, COPING CAPACITY AND ADAPTIVE CAPACITY

In the overall Australian assessment of disaster resilience, the York-Beverley SA2 was assessed as having low capacity for disaster resilience, low coping capacity and moderate adaptive capacity (Table 2).

Figure 3 shows the York-Beverly SA2 in comparison to the Australian Natural Disaster Resilience Index values for Western Australia.

Table 2: Disaster resilience, coping capacity and adaptive capacity results for the York-Beverley SA2, assessed as part of the Australian Natural Disaster Resilience Index.

Index	Index value	Class	Class description
Disaster resilience (ANDRI)	0.3951	Low <25th percentile	Communities in areas of low disaster resilience may be constrained in their capacity to use available resources to cope with adverse events, and are constrained in their capacity to adjust to change through learning, adaptation and transformation. Limitations to disaster resilience may be contributed by entrenched social and economic disadvantage, less access to or provision of resources and services, lower community cohesion and systems that do not encourage adaptive learning and problem solving.
Coping capacity	0.2658	Low	Communities in areas of low coping capacity may be constrained in their capacity to use available resources to cope with adverse events and to prepare for, absorb and recover from a natural hazard event.
Adaptive capacity	0.5122	Moderate	Communities in areas of moderate adaptive capacity have some capacity to adjust to change through learning, adaptation and transformation.

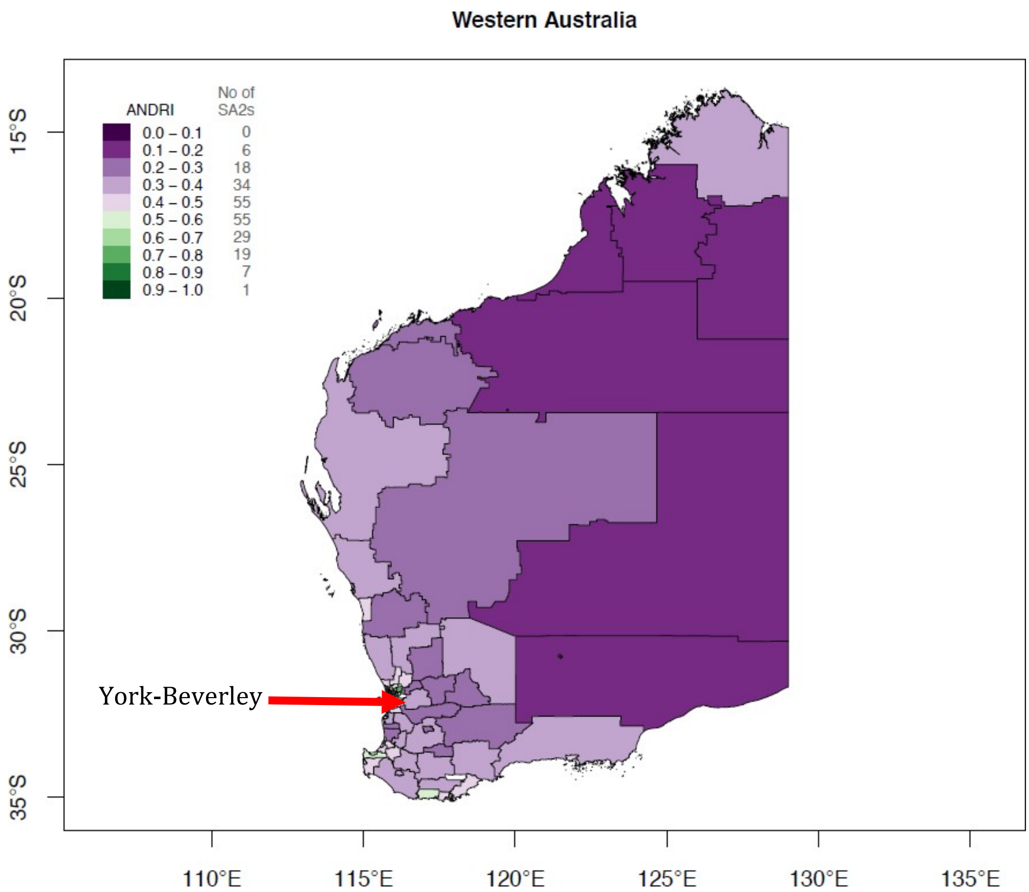


Figure 3: Australian Natural Disaster Resilience Index results, Western Australia.

INDEX RESULTS: THEMES

The latent dimensions – or themes – that influence disaster resilience in different locations are summarised using a typology. A typology identifies groups of SA2s with similar disaster resilience profiles. The profile associated with each group can then be used to understand disaster resilience in local communities and the strengths and opportunities for enhancing or improving disaster resilience.

The York-Beverley SA2 falls into typology group 3. The strengths of SA2s with this disaster resilience profile are shown in Table 3.

The disaster resilience strengths associated with communities with the group 3 disaster resilience profile are social character, community capital and social and community engagement (Table 3). Thus, the disaster resilience of these communities is contributed by a strong pro-social setting characterised by community coherence, community capital and capacity for communities to adapt to complex change. Although these factors were classed as moderate (Table 3) they suggest the potential for community as a resource and asset to prepare for, respond to and recover from disasters, and to adapt to complex change.

Communities with the group 3 disaster resilience profile face the greatest structural constraints to disaster resilience, in comparison to the other profiles. Constraints to disaster resilience arise from economic capital, planning and the built environment, emergency services, information access and governance and leadership (Table 3). Thus there are many factors that could be addressed to improve disaster resilience in these communities, usually sitting outside community control. These include improving economic prosperity, systems of planning for hazards, access to telecommunications and access to and provisioning of emergency services.

Figure 4 shows the distribution of the theme indexes for the York-Beverley SA2 in more detail. While any individual SA2 must be considered in relation to others of the same type (Group 3), York-Beverley has particular disaster resilience constraints arising from telecommunications access (Figure 4). However, in comparison to the other WA SA2s belonging to typology group 3, York-Beverley has a higher index value for social character, governance and leadership and community capital (Figure 4). These aspects of disaster resilience enhance the capacity for disaster resilience, within the broader constraints on disaster resilience associated with typology group 3.

Table 3: Overview of the disaster resilience profile of the York-Beverley SA2, belonging to typology Group 3.

Typology group	Group 3
Number of SA2s	447 (Australia)
Mean ANDRI value	0.3717 (Australia)
Approximate population	3.2 million (Australia)
Land area	7,211,800 km^2 (Australia)
Disaster resilience strengths	Social character (Moderate) These communities have some social and demographic characteristics that support the capacity to prepare for, respond to and recover from natural hazard events, but may also have some social and demographic characteristics that constrain this capacity. The combination of supporting and constraining social and demographic characteristics will vary across SA2s within the group, but it is likely that communities will have mid-range levels of education, employment and English language proficiency.
	Community capital (Moderate) The cohesion and connectedness of these communities supports the capacity to coordinate and cooperate for mutual benefit, including preparing for, responding to and recovering from natural hazard events. However, there may be some community capital characteristics that constrain this capacity. The combination of supporting and constraining circumstances will vary across SA2s in the group, but capacity may be constrained by mid-range crime rates, slightly less supportive and well-off neighbourhoods and lower levels of volunteering.
	Social and community engagement (Moderate) These communities have some capacity to adaptively learn and transform in response to complex change, including that associated with natural hazards, but may also face some constraints on this capacity. While the characteristics supporting and constraining capacity will vary across SA2s in the group, but these communities can be expected to have mid-range levels of in and out migration, suggesting a slightly less stable population.
Barriers to disaster resilience	Economic capital (Low) These communities have economic characteristics that may constrain their capacity to prepare for, respond to and recover from natural hazard events. The circumstances limiting this capacity will vary, but it is likely that these communities will have relatively high proportions of rental households and low income households, resulting in a limited capacity to buffer external financial shocks. In many cases this will be exacerbated by an economy dominated by a single industry sector.
	Planning and the built environment (Low) Planning systems and the character of the built environment may constrain the capacity of these communities to prepare for natural hazard events using strategies of mitigation, planning or risk management. While the characteristics constraining this capacity will vary across SA2s in the group, most communities are likely to have a predominance of older building stock and relatively more people residing in caravans or improvised dwellings.

Table 3 (cont.)

Barriers to disaster resilience (cont.)	Emergency services (Low) These communities have emergency services characteristics that may constrain their capacity to respond to natural hazard events. Constraint largely arises because of remoteness, which limits the availability of emergency and other services. Due to other sources of disadvantage, these communities may have a greater presence of welfare support workers and police, but these positive aspects of response capacity are offset by their very limited access to medical services. Information access (Low) These communities have constrained capacity to engage with natural hazard information and to access knowledge associated with natural hazard preparation, self-reliance and response. The main characteristic contributing to reduced capacity is limited telecommunications access. Governance and leadership (Low) These communities are associated with a governance environment that may be limited by the capacity of organisations to adaptively learn, transform and adjust to complex change, including that related to natural hazards. The characteristics constraining capacity will vary across SA2s in the group, but it is likely that these communities do not have the benefit of research organisation presence and innovative commercial firms. Levels of local economic development support may also be limited.

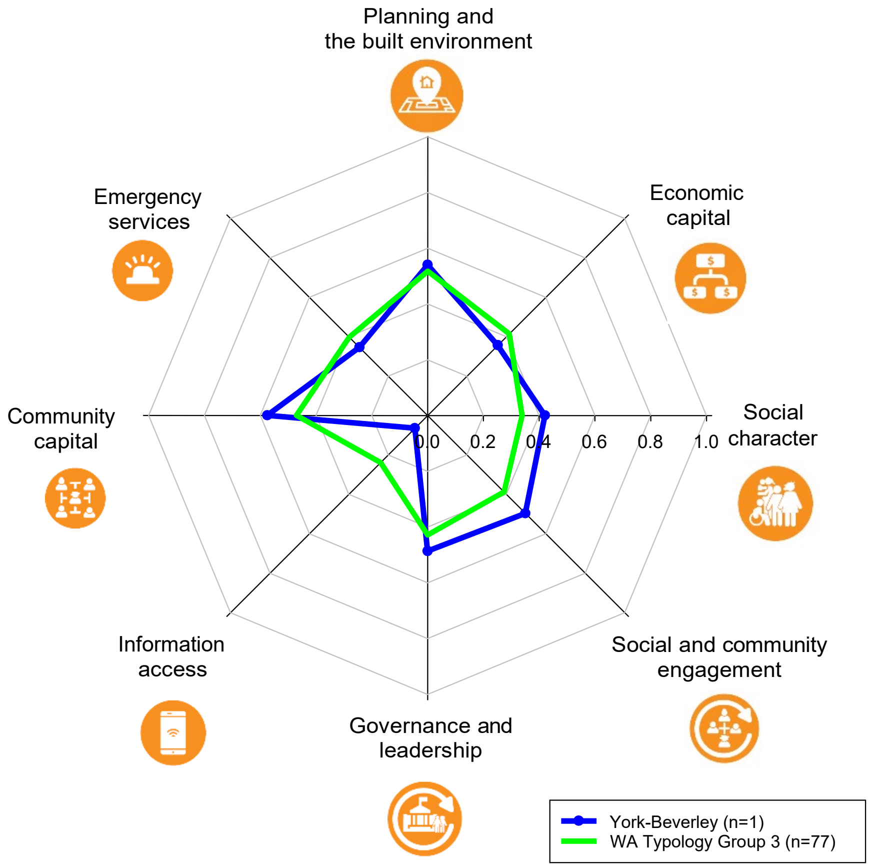


Figure 4: Overview of the disaster resilience theme index results for the York-Beverley SA2, belonging to typology Group 3.

4.1 Earthquake impact and disaster resilience in the York Beverley SA2

Earthquakes are rapid-onset geological natural hazard events. Unlike meteorological natural hazards, earthquakes cannot be accurately predicted and at best, warnings occur only minutes to seconds before an event. However, risk mapping can identify areas of likely seismic activity and model the potential for damage and impact, thus providing capacity to prepare and plan for earthquake events in the York Beverley SA2.

The Australian Natural Disaster Resilience Index adds to physical earthquake damage and impact modelling by providing a social lens to the estimation of earthquake damage and impact. How might the disaster resilience profile of an area affect earthquake mitigation, preparation, response and recovery in the York Beverley SA2? This section explores the implications of the Australian Natural Disaster Resilience Index results for understanding earthquake damage and impact in the York Beverley SA2.

As evidenced in recent major events such as the 2011 Christchurch earthquake in Aotearoa New Zealand, the broad outcomes of an earthquake in the York Beverley SA2 are likely to include:

- Widespread and severe damage to housing, public infrastructure and utilities
- Long (months to years) repair times for public infrastructure
- Long (months to years) periods of service disruption (e.g. transport, communications)
- Opportunities for transformative township and regional renewal
- Self-emergence of social capital, or entrenchment of underlying social divisions and power imbalances
- Opportunities for transformative learning and adaptation requiring complex problem solving and reformation of principles, beliefs and governance processes.

This section explores how disaster resilience – as assessed using the Australian Natural Disaster Resilience Index – might interact with or influence these earthquake outcomes. Interpretations draw from the overall disaster resilience index, the coping and adaptive capacity sub-indexes and the typology groups. Note that psycho-social impacts to individuals, such as trauma, grief, and financial stress are not considered here because the Australian Natural Disaster Resilience Index is focused on communities, not individuals.

The York-Beverley SA2 falls within typology Group 3. Only this group will be discussed.

<u>Widespread and severe damage to housing, public infrastructure and utilities</u>

Group 3	SA2s in this group face substantial barriers to disaster resilience from lower economic capital, and government services such as planning and emergency services. Communities with lower economic capital may be more likely to live in rental housing,

making post-event accommodation needs complex. Damage to infrastructure may also have flow-on effects and exacerbate already unstable employment situations.

Long infrastructure repair times and periods of service disruption

Group 3 SA2s in this group face substantial barriers to disaster resilience because of long infrastructure repair times. Communities with lower economic capital may be more likely to live in rental housing, and delays to repairs may make post-event accommodation needs complex. Long repair times and disruption to transport, business and government systems are likely to be most disruptive to these communities. Delays in infrastructure repair may also have flow-on effects and exacerbate already unstable employment situations. This group may also not have resources to navigate complex post-event administrative systems.

Opportunities for transformative township and regional renewal

Group 3 Planning and the built environment and governance and leadership are low in these SA2s and may represent barriers in the capacity to plan for and manage pre- or post-event township and regional renewal. High levels of community capital may engender a strong sense of place, although this can also present a barrier to transformative renewal, either before or after an earthquake event.

Self-emergence of social capital

Group 3 The characteristics of SA2s in group 3 support the emergence of social capital. SA2s in this group have moderate community capital and are somewhat cohesive and connected. Community capital is also paired with moderate social character and enhanced disaster resilience capacity arising from moderate levels of education, employment and needs for assistance. Social and community engagement is also moderate, suggesting skills are present in these SA2s for adaptive learning. However, economic capital is low in these SA2s and may present a barrier to the realisation of underlying social capital potential.

Opportunities for transformative learning and adaptation

Group 3 Community capital and social and community engagement are moderate in these areas. Thus, the receptiveness to and skills for adaptation and learning are likely to be mixed. Low economic capital and information access may present a barrier to participation.

REFERENCES

Australian Bureau of Statistics (ABS), (2011). Australian Statistical Geography Standard (ASGS): Volume 1 – Main Structure and Greater Capital City Statistical Areas. Australian Bureau of Statistics, July 2011 (1270.0.55.001).

APPENDIX C - SURVEY FORMS

RICS SURVEY FORM

The RICS survey images, accompanying aerial imagery and images available through the internet such as real estate advertisements were interrogated to record the building attributes shown in Appendix Table 1.

APPENDIX TABLE 1 RICS SURVEY FORM.

No.	Attribute	Values	Comments
1	Address	Text	
2	Latitude	Decimal degrees	
3	Longitude	Decimal degrees	
4	Building type	Drop down list • House – normal • House – cottage • House – mansion • House – outbuilding • Religious Hall • Institutional Hall • Generic Hall • Industrial / warehouse • Other building type	
5	GA building code	Drop down list • SH • SD • F0 • F3 • F4 • 13_LBM_T • 13_LBM_C • 13_LBM_S • 13_C_O • 13_S_URM • 13_S_O • 47_LBM_T • ISS_URM_S • ISS_URM_PS • ISS_RM_S • ISS_SS_S • ISS_SSURM_S • ISS_SSPC_S • ISS_SPC_S • ISS_PC_S • IDS_CSURM_S	

No.	Attribute	Values	Comments
		• IDS_CSPC_S • IDS_CURM_S • ISSB_CSPC_S • ISSB_SSS_S • Unknown	
6	Vintage	Drop down list • Old • Modern	Buildings noted as 'Old' will be targeted for follow-up foot survey.
7	Number of storeys above ground	Drop down list • 1 • 2 • 3 • 4 • >4	
8	Attic floor present	Drop down list • Yes • No	
9	Building on stumps	Drop down list • Yes • No	
10	Roof material	Drop down list • Sheet metal • Tiles • Slate • Fibro • Other	
11	Roof shape	Drop down list • Hip • Gable • Mixed hip and gable • Other	
12	Roof pitch	Drop down list • Shallow • Moderate • Steep	
13	Number of chimneys	Integer	
14	Chimney aspect ratio	Drop down list • NA • Squat • Medium • Slender	
15	Percentage of perimeter with awnings	Integer	
16	Percentage of veranda	Integer	

No.	Attribute	Values	Comments
	perimeter (first floor)		
17	Front wall masonry parapet	Drop down list • None • Yes – low plain • Yes – medium plain • Yes – tall plain • Yes – low ornate • Yes – medium ornate • Yes – tall ornate	
18	Percentage of front wall with masonry parapet	Integer	
19	Front wall parapet material	Drop down list • NA • Brick • Stone • Rendered masonry • Other	
20	Existing retrofit - props to front wall parapet	Drop down list • Yes • No	
21	Existing retrofit - front wall restraints	Drop down list • Yes • No	
22	Number of steps (floor height above external ground)	Integer	
23	Lower floor usage	Drop down list • Retail • Office • Residential – private • Residential – commercial • Petrol station • Garage • Light industrial • Warehouse • Education • Religion • Aged care • Health • Pub • Entertainment and recreation • Other	
24	Upper floor usage	Drop down list • NA • Retail	

No.	Attribute	Values	Comments
		• Office • Residential – private • Residential – commercial • Petrol station • Garage • Light industrial • Warehouse • Education • Religion • Aged care • Health • Pub • Entertainment and recreation • Other	
25	Front wall material – lower storey	Drop-down list • Brick – stretcher bond • Brick – header bond • Painted brick • Stone – course ashlar • Stone – broken ashlar • Stone – coursed rubble • Stone – random rubble • Painted stone • Rendered (assume brick) • Rendered (assume stone) • Rendered (unknown) • Shopfront • Block • Weatherboard • Metal • Fibro • Rammed earth • Other	
26	Front wall material – upper storey	Drop-down list • NA • Brick – stretcher bond • Brick – header bond • Painted brick • Stone – course ashlar • Stone – broken ashlar • Stone – coursed rubble • Stone – random rubble • Painted stone	

No.	Attribute	Values	Comments
		• Rendered (assume brick) • Rendered (assume stone) • Rendered (unknown) • Shopfront • Block • Weatherboard • Metal • Fibro • Rammed earth • Other	
27	Building separation	Drop down list • Isolated • Row – internal • Row – end • Row - corner	
28	Neighbour falling hazard	Drop down list • No • Yes- chimneys • Yes – parapets • Yes- gable walls • Yes – gable walls and parapets • Yes – gable walls and chimneys	
29	Perimeter	Decimal in metres	From foot printing
30	Plan area – lower floor	Decimal in square metres	From foot printing
31	Upper floor % living area	Percentage	
32	Comments (FiDAT & 2nd Survey)	Text field	

FOOT SURVEY FORM

The building foot survey aimed to capture remaining attributes that the RICS survey was unable to capture. It used the survey form in Appendix Figure 1 where the green shaded cells represent attributes captured during the RICS survey. The aim for the foot survey was to fill all the unshaded cells.

Survey date:	Surveyor:	Sequence Number:	Lat:	Long:
Address:				

Building type	Number of storeys	Grnd flr hgt above ext grnd	Lower floor usage	Upper floor usage
House – normal	Original	Lower sty hght	Retail	Retail
House – cottage	Added	Upper sty hght	Office	Office
House – Mansion	Age		Residential	Residential
House – outbuilding			Wholesale	Wholesale
Warehouse – normal hgt			Carparking	Carparking
Special – religious			Transport	Transport
Special – Institutional			Petrol station	Petrol station
Special – Industrial			Garage	Garage
Special – generic hall			Factory	Factory
Other building			Warehouse	Warehouse
			Agriculture	Agriculture
			Education	Education
			Religion	Religion
			Aged care	Aged care
			Health	Health
			Hotel	Hotel
			Entertainment	Entertainment
			Other	Other

Roof material	Roof pitch	Wall corners
Metal	Steep	Interlocked
Tiles	Medium	Vertical joint
Slate	Low	Unknown

Number of chimneys	Building separation
Chimney height	Isolated
Chimney material	Row, internal
Brick	Row, end
Stone	Row, corner
Rendered masonry	Connected (but not row)
Other	Unknown
Unknown	

Sides with awnings	Fire Protection
Sides with upper floor veranda	Sprinklers
	Detectors and extinguishers
	Other

Ground flr construction	A/C system
Slab on grade	Central ducted
Raised timber flor	Domestic split systems
Other	Evaporative
Unknown	None
	Unknown

Upper floor construction	HWS
Timber floor	Solar
Concrete	Electric
Unknown	Gas – storage
	Gas – instant
	Unknown

Internal wall finish
Face masonry
Painted masonry
Rendered masonry
Plasterboard
Unknown

Wall material

Front - bottom	Front - upper	Side	Rear
Brick – stretcher bond	Brick – stretcher bond	Brick – stretcher bond	Brick – stretcher bond
Brick – header bond	Brick – header bond	Brick – header bond	Brick – header bond
Painted brick	Painted brick	Painted brick	Painted brick
Stone – coursed ashlar	Stone – coursed ashlar	Stone – coursed ashlar	Stone – coursed ashlar
Stone – broken ashlar	Stone – broken ashlar	Stone – broken ashlar	Stone – broken ashlar
Stone – coursed rubble	Stone – coursed rubble	Stone – coursed rubble	Stone – coursed rubble
Stone – random rubble	Stone – random rubble	Stone – random rubble	Stone – random rubble
Painted stone	Painted stone	Painted stone	Painted stone
Rendered (assume brick)	Rendered (assume brick)	Rendered (assume brick)	Rendered (assume brick)
Rendered (assume stone)	Rendered (assume stone)	Rendered (assume stone)	Rendered (assume stone)
Rendered (unknown)	Rendered (unknown)	Rendered (unknown)	Rendered (unknown)
Shopfront	Shopfront	Shopfront	Shopfront
Block	Block	Block	Block
Weatherboard	Weatherboard	Weatherboard	Weatherboard
Metal	Metal	Metal	Metal
Fibro	Fibro	Fibro	Fibro
Rammed earth	Rammed earth	Rammed earth	Rammed earth
Other	Other	Other	Other
Unknown	Unknown	Unknown	Unknown

Wall Retrofit

Front	Side	Rear
Yes	Yes	Yes
No	No	No
Unassessable	Unassessable	Unassessable

Masonry Parapets - material

Front	Side	Rear
NA	NA	NA
Brick	Brick	Brick
Stone	Stone	Stone
Rendered masonry	Rendered masonry	Rendered masonry
Other	Other	Other

Masonry Parapets - form

Front	Side	Rear
None	None	None
Yes – low plain	Yes – low plain	Yes – low plain
Yes – medium plain	Yes – medium plain	Yes – medium plain
Yes – tall plain	Yes – tall plain	Yes – tall plain
Yes – low ornate	Yes – low ornate	Yes – low ornate
Yes – medium ornate	Yes – medium ornate	Yes – medium ornate
Yes – tall ornate	Yes – tall ornate	Yes – tall ornate

Masonry Parapets Retrofit

Front	Side	Rear
No	No	No
Yes	Yes	Yes

Comments

APPENDIX FIGURE 1 FOOT SURVEY FORM.

BUSINESS SURVEY FORM

The business survey aimed to capture information about businesses that would enable estimates of economic activity loss in the event of an earthquake. This survey used the form in Appendix Table 2.

APPENDIX TABLE 2 BUSINESS SURVEY FORM.

York Business Survey					
Survey ID:	**Date:**	**Time:**	**Surveyor:**	**Photo ID(s):**	
General Information and Business Type			**Business Organisation**		
Business name			Business Structure	o Sole Trader	
Business type/nature				o Partnership	
Street Address				o Trust	
Contact person's name				o Company	
Contact person's position			If it is a company?	o Corporation	
Contact person's phone/email				o Government	
				o Non-Profit	
Is the business operationally active?	o YES			o Households	
	o NO		What is the total number of employees in your business?	o Full Time	
Does the business operate throughout the year or seasonally?	o Over the year			o Part Time	
	o Seasonal (Pls specify the months)		What is the number of employees that come to work in a regular day? Please exclude the number on leave.	o Part time	
Does the business operate Full time/ Part time	o Full time			o Fulltime	
	o Few days a week (specify no. of days)		Ownership of the premises (Please report the weekly /fortnightly AUD$ value of Rent or Mortgage where appropriate)	o Own outright	
	o Few hours in a day (specify no. of hours)			o Paying Mortgage	
Since when has the business been operating?				o Paying Rent	
				o Other (Specify Please)	
Business Income [(1)=(2) + (3)]			**Business Expenditure [(5) = (6) + (7) + (8)]**		
(1) Total Revenue/Turnover (in the last financial year, 30/06/2017)			(5) Total Expenditure (in the last financial year, 30/06/2017)		
(2) Income from Sales of Goods and Services (in the last financial year, 30/06/2017)			(6) Labour Cost ((in the last financial year, 30/06/2017)		
(3) Income from any other secondary activities e.g. bank interest/any other			(7) Raw material Cost (in the last financial year, 30/06/2017)		

financial gains (in the last financial year, 30/06/2017)			(8) Other Operational Cost (other indirect cost not directly linked to the production of goods and services) in the last financial year, 30/06/2017		
(4) How much the total revenue has risen of fallen since the previous financial year, 30/06/2016?			(9) How much the total expenditure has risen of fallen since the previous financial year, 30/06/2016?		
Value of the Fixed Assets	Building		Value of the Short-term liabilities	Overdrafts/Overdraft charges	
	Fit-out			Short-term loans	
	Contents			Creditors, including trade creditors	
	Plant/Mechinery				
	Motor Vehicle/Other				
Value of the Current Assests	Cash at Bank		Value of the Long-term liabilities	Long-term loans	
	Short-term investments			Secured bills	
	Stocks/Products			Director's loans (to the business)	
	trade debtors (people who owe the business money)			residual value on leases due in more than 12 months	
	Petty cash				
Goodwill Value	The amount the owner would charge for the reputation/performance, if s/he decides to sell the business?				

Business Interruption Information	
(1) Are you covered for BI / when would it trigger / covered for how long?	
(2) If an earthquake damages your premises rendering them unusable, what will you do in the interim period to keep your business operating?	

(3) How long would it take to resume business external to your premises?		(4) How long do you estimate your business will take to come back to normal operations once the building is repaired/replaced?	

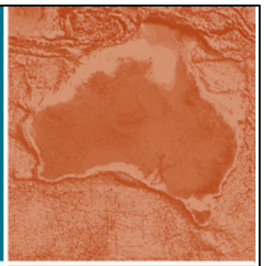
Flood Related Information	
If your business was forecast to flood, what would be your strategy for protecting contents, plant and fit-outs?	

Ground floor dimensions (L & B)			Fit-out value vertical distribution, List key items:	○ Level 1: _______ %	_______m	_______m
Bathroom on ground floor	○ Number (0,1,2...)			○ Level 2: _______ %	_______ m	_______m
	○ Don't know			○ Level 3: _______%	m	_______m
Kitchen / Kitchentte on ground floor	○ Number (0,1,2...)			○ Level 4: _______%	_______ m	_______m
	○ Don't know					
Floor finish (%)	○ Timber		Machinery value vertical distribution, List key items:	○ Level 1: _______ %		
	○ Lino			○ Level 2: _______ %		
	○ Carpet			○ Level 3: _______%		
	○ Tiles			○ Level 4: _______%		
	○ Stone					
	○ Bare		Products value vertical distribution, List key items:	○ Level 1: _______ %		
Fit-out quality (circle)	Low / Standard / Prestigious			○ Level 2: _______ %		
				○ Level 3: _______%		
				○ Level 4: _______%		

Ground Floor Plan

APPENDIX D – PROJECT FLYER

Australian Government
Geoscience Australia



Earthquake Mitigation of WA Regional Towns

Case Study of York

The Shire of York is partnering with the WA Department of Fire and Emergency Services (DFES), the University of Adelaide and Geoscience Australia in a collaborative project that will examine the opportunities for reducing the vulnerability of the township of York to a major earthquake. The project forms part of the Bushfire and Natural Hazards Collaborative Research Centre project "Cost-effective Mitigation Strategy Development for Building related Earthquake Risk".

Western Australia's oldest inland town is located in one of Australia's most active earthquake regions and has a number of valuable historical buildings that are vulnerable to damage by a large earthquake. This project will examine practical approaches for retrofitting the older building stock in York. It will use technology to virtually apply various retrofits to York historical buildings to understand what modifications are most effective in reducing the damage from a large earthquake.

The project involves: a field survey of the older masonry buildings in the town of York; a survey of the nature of community businesses to enable the assessment of the disruption to economic activity that would occur due to an earthquake event; assessment of the reduced economic losses and benefit versus cost for a staged implementation of mitigation; and the development of scenarios to assist DFES and the Shire of York with emergency management planning.

Images top-bottom: York Town Hall; Earthquake damage to Boulder heritage building from 2010 Kalgoorlie earthquake; Earthquake damage to Boulder Hotel from 2010 Kalgoorlie earthquake.

What will residents of York notice?

During February and March 2018, small teams from Geoscience Australia and the University of Adelaide will gather information about the older masonry buildings in York. Information such as construction type, building materials, building height and the presence of features such as chimneys and parapets will be recorded. The teams will be using hand-held computers, digital cameras and a vehicle-mounted camera system called the Rapid Inventory Collection System to collect this information. Typically the teams will view buildings from the street. They may also ask permission to briefly view the interior of some buildings.

Why is this research important?

Many Australian buildings are quite vulnerable to low to moderate earthquake ground motion. Earthquake hazard was only fully recognised for Australian building design in the early 1990's following the Newcastle Earthquake in 1989. This has resulted in a significant legacy of buildings that are inherently more vulnerable. Knowledge of the most effective retrofit measures for older masonry buildings will enable and encourage the strengthening of buildings resulting in more resilient communities. The research will not only benefit the Shire of York but also other small Australian towns with similar structures.

For Further Information:

Paul Martin
CEO of the Shire of York
Ph: +61 8 9641 0503

Steve Gray
Department of Fire and Emergency Services
Ph: +61 8 9395 9438

Professor Michael Griffith
University of Adelaide
Ph: +61 8 8313 4316

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Geoscience Australia
GPO Box 378
Canberra ACT 2601
www.ga.gov.au

APPENDIX E - EXAMPLE REPAIR WORK SPECIFICATION FOR GENERIC BUILDING TYPE 1

APPENDIX TABLE 3 REPAIR WORK TO GENERIC BUILDING TYPE 1 FOR EACH DAMAGE STATE (DAMAGE STATES 3 AND 4 HAVE THE SAME REPAIR WORK).

Generic Building Type 1: Single storey residential				Required repair			
				Damage State 1	Damage State 2	Damage State 3, 4	Damage State 5
				Narrow cracking in masonry at some window and door corners. Fine cracks along cornice - wall joins.	Wide cracking in masonry requiring local demolition and reconstruction of masonry. Some windows require replacing. Heavy fittings dislodged requiring refixing and repair.	Partial failure of external masonry. Severe cracking of internal masonry. Heavy fittings dislodged requiring refixing and repair. Damage to water supply pipework.	Collapse of most of building. Remaining portions to be demolished and all debris removed and building reconstructed.
Component ID	**Component name**	**Units**	**Quantity**				
1	Roofing - metal sheeting	m2	179	Nil	Replace 5m of eaves linings	Replace 100% eaves linings, gutters and downpipes	Replace all
2	Roofing - clay tile	m2	0				
3	Roofing - conc tile	m2	0				
4	Roofing slates	m2	0				
5	Roof framing - bolted timber trusses	m2	0				
6	Roof framing - timber rafters	m2	179	Nil	Nil	Nil	Replace all
7	Roof framing - church timbers	m2	0				
8	Roof framing - wrought iron trusses	m2	0				
9	Roof insulation	m2	153.1	Nil	Nil	Nil	Replace all
10	Ceiling - plasterboard	m2	0				
11	Ceiling - plaster on laths	m2	133.56	Nil	Nil	Replace 40%. Repaint remainder	Replace all
12	Ceiling - pressed metal	m2	0				
13	Ceiling - suspended acoustic tile	m2	0				
14	Ceiling - timber boarding	m2	0				
15	Cornices - preformed plasterboard	m	0				
16	Cornices - set ornate plaster	m	136.73	Fill cracks and repaint 40% of total length	Replace 20m, fill cracks and repaint remainder	Replace all	Replace all
17	Cornices - moulded timber	m	0				
18	Chimneys - Brick - short	No	0				
19	Chimneys - Brick - tall	No	3	Nil	Nil	Nil	Replace all
20	Chimneys - Stone - short	No	0				

Generic Building Type 1: Single storey residential				Required repair			
				Damage State 1	Damage State 2	Damage State 3, 4	Damage State 5
Component ID	Component name	Units	Quantity	Narrow cracking in masonry at some window and door corners. Fine cracks along cornice - wall joins.	Wide cracking in masonry requiring local demolition and reconstruction of masonry. Some windows require replacing. Heavy fittings dislodged requiring refixing and repair.	Partial failure of external masonry. Severe cracking of internal masonry. Heavy fittings dislodged requiring refixing and repair. Damage to water supply pipework.	Collapse of most of building. Remaining portions to be demolished and all debris removed and building reconstructed.
21	Chimneys - Stone - tall	No	0				
22	Parapets - low brick plain	m	0				
23	Parapets - low stone plain	m	0				
24	Parapets - low stone decorative	m	0				
25	Parapets - medium brick plain	m	0				
26	Parapets - medium stone plain	m	0				
27	Parapets - medium stone decorative	m	0				
28	Parapets - high brick simple	m	0				
29	Parapets - high brick decorative	m	0				
30	Parapet finish - paint	m2	0				
31	Parapet finish - render	m2	0				
32	Verandah roof 3m wide	m	35.34	Nil	Nil	Replace 30%	Replace all
33	Balcony floor	m	35.34	Nil	Nil	Replace 30%	Replace all
34	Cantilever awning	m	0				
35	Stayed awning	m	0				
36	Stairs - external steel	No	0				
37	Stairs - timber 1200 wide	No	0				
38	Stairs - timber 2400 wide	No	0				
39	Substructure - strip footing	m	96.14	Nil	Nil	Nil	Replace all
40	Columns - CI	No	0				
41	Suspended timber floor	m2	133.56	Nil	Nil	Nil	Replace all
42	Ground floor Slab on Ground	m2	0				
43	External walls - Brick cavity 110/110	m2	253.1	Epoxy inject cracks (30m)	Demolish 16.5m2 of bwk walls over 5 locations and reconstruct. Epoxy injection grout 8m of cracks.	Remove debris from 67m2 of fallen walls and reconstruct. Demolish 16 m2 total of bwk walls at 5 locations and reconstruct. Epoxy injection grout 27m of cracks.	Replace all
44	External walls - Brick cavity 110/230	m2	0				

Generic Building Type 1: Single storey residential				Required repair			
				Damage State 1	Damage State 2	Damage State 3, 4	Damage State 5
Component ID	Component name	Units	Quantity	Narrow cracking in masonry at some window and door corners. Fine cracks along cornice - wall joins.	Wide cracking in masonry requiring local demolition and reconstruction of masonry. Some windows require replacing. Heavy fittings dislodged requiring refixing and repair.	Partial failure of external masonry. Severe cracking of internal masonry. Heavy fittings dislodged requiring refixing and repair. Damage to water supply pipework.	Collapse of most of building. Remaining portions to be demolished and all debris removed and building reconstructed.
45	External walls - Brick solid 230	m2	0				
46	External walls - Brick solid 350	m2	0				
47	External walls - Dressed stone cavity	m2	0				
48	External walls - Dressed stone solid	m2	0				
49	External walls - Partly dressed stone cavity	m2	0				
50	External walls - Partly dressed stone solid	m2	0				
51	Internal walls - 110 brick	m2	192.44	Nil	Demolish 6m2 of bwk walls over 4 locations and reconstruct. Epoxy injection grout 10m of cracks.	Demolish 26 m2 of bwk walls at 3 locations and reconstruct. Epoxy injection grout 10m of cracks	Replace all
52	Internal walls - 230 brick	m2	0				
53	Internal walls - 300 dressed stone	m2	0				
54	Internal walls - plaster on timber	m2	0				
55	Skirting boards - moulded timber	m	117.98	Nil	Nil	Replace 25%	Replace all
56	Internal doors - solid timber	No	10	Nil	Remove and rehang 4	Remove and rehang 5, replace 1	Replace all
57	External doors - double leaf solid timber with fanlight	No	0				
58	External doors - single leaf solid timber with fanlight	No	1	Nil	Remove and refix	Remove and refix	Replace all
59	External doors - single leaf solid timber with side & fanlights	No	1	Nil	Remove and refix	Remove and refix	Replace all
60	External doors - Commercial aluminium framed shop front	m2	0				
61	External wall finishes - paint	m2	0				
62	External wall finishes - render	m2	0				
63	External wall finishes - cement bagged	m2	0				

Generic Building Type 1: Single storey residential				Required repair			
				Damage State 1	Damage State 2	Damage State 3, 4	Damage State 5
Component ID	Component name	Units	Quantity	Narrow cracking in masonry at some window and door corners. Fine cracks along cornice - wall joins.	Wide cracking in masonry requiring local demolition and reconstruction of masonry. Some windows require replacing. Heavy fittings dislodged requiring refixing and repair.	Partial failure of external masonry. Severe cracking of internal masonry. Heavy fittings dislodged requiring refixing and repair. Damage to water supply pipework.	Collapse of most of building. Remaining portions to be demolished and all debris removed and building reconstructed.
64	Internal wall finishes - paint on plaster	m2	0				
65	Internal wall finishes - paint on masonry or render	m2	445.9	Repaint 40%	Repaint 80%	Repaint all	Repaint all
66	Internal wall finishes - render	m2	445.9	Nil	Remove damaged render and repair (5 % of total area)	Remove damaged render and repair (40 % of total area)	Replace all
67	Windows - single glazed timber casement	No	0				
68	Windows - single glazed timber sash	No	13	Nil	Replace 7 No	Replace 10 No	Replace all
69	Windows - single glazed textured fixed	No	2	Nil	Nil	Replace all	Replace all
70	Floor finishes - polyurethane floorboards	m2	107.56	Nil	Nil	Nil	Replace all
71	Floor finishes - lino	m2	14.16	Nil	Nil	Nil	Replace all
72	Floor finishes - Ceramic tiles	m2	11.84	Nil	Nil	Replace all	Replace all
73	Floor finishes - Carpet	m2	0				
74	Bathrooms cabinetry and fittings	No	1	Nil	Nil	Remove and refix to allow wall repairs	Replace all
75	Domestic kitchen cabinetry and fittings	No	1	Nil	Nil	Replace all	Replace all
76	Commercial kitchen cabinetry and fittings	No	0				
77	No. of Spire Type 1	No	0				
78	No. of Spire Type 2	No	0				
79	No. of Spire Type 3	No	0				
80	Internal wall finishes - tiles	m2	37.4	Nil	Replace 50%	Replace 100%	Replace all
81	Hydraulic services	m2 of floor area	133.56	Nil	Nil	Replace 50% of supply piping	Replace all

Generic Building Type 1: Single storey residential				Required repair			
				Damage State 1	Damage State 2	Damage State 3, 4	Damage State 5
				Narrow cracking in masonry at some window and door corners. Fine cracks along cornice - wall joins.	Wide cracking in masonry requiring local demolition and reconstruction of masonry. Some windows require replacing. Heavy fittings dislodged requiring refixing and repair.	Partial failure of external masonry. Severe cracking of internal masonry. Heavy fittings dislodged requiring refixing and repair. Damage to water supply pipework.	Collapse of most of building. Remaining portions to be demolished and all debris removed and building reconstructed.
Component ID	**Component name**	**Units**	**Quantity**				
82	Electrical services	m2 of floor area	133.56	Nil	Nil	Replace 15% of lights and GPOs	Replace all
83	Fire services	m2 of floor area	133.56	Nil	Nil	Nil	Replace all
84	Mechanical services	m2 of floor area	133.56	Nil	Replace roof mounted evaporative cooler	Replace roof mounted evaporative cooler	Replace all

APPENDIX F - FRAGILITY CURVES FOR OUT-OF-PLANE FAILURE OF MASONRY PARTS AND COMPONENTS

Jerry Vaculik, University of Adelaide

INTRODUCTION

The objective of this report is to provide fragility curves for the out-of-plane (OOP) failure of a range of unreinforced masonry parts and components. These include parapets, simply-spanning out-of-plane walls, chimneys, and gable end walls.

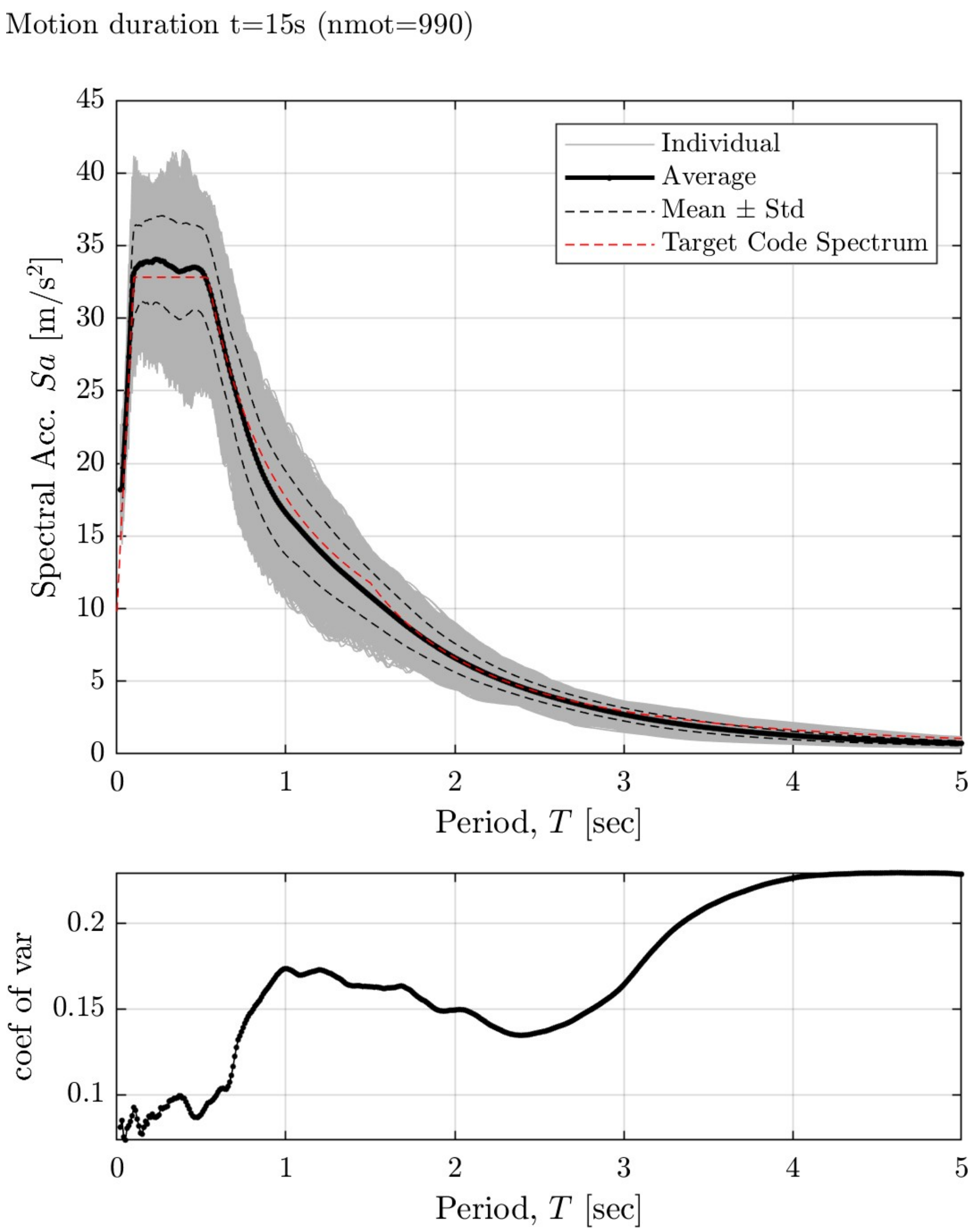
GROUND MOTIONS

The ground motions used throughout these analyses are code-compatible motions generated in Seismoartif:

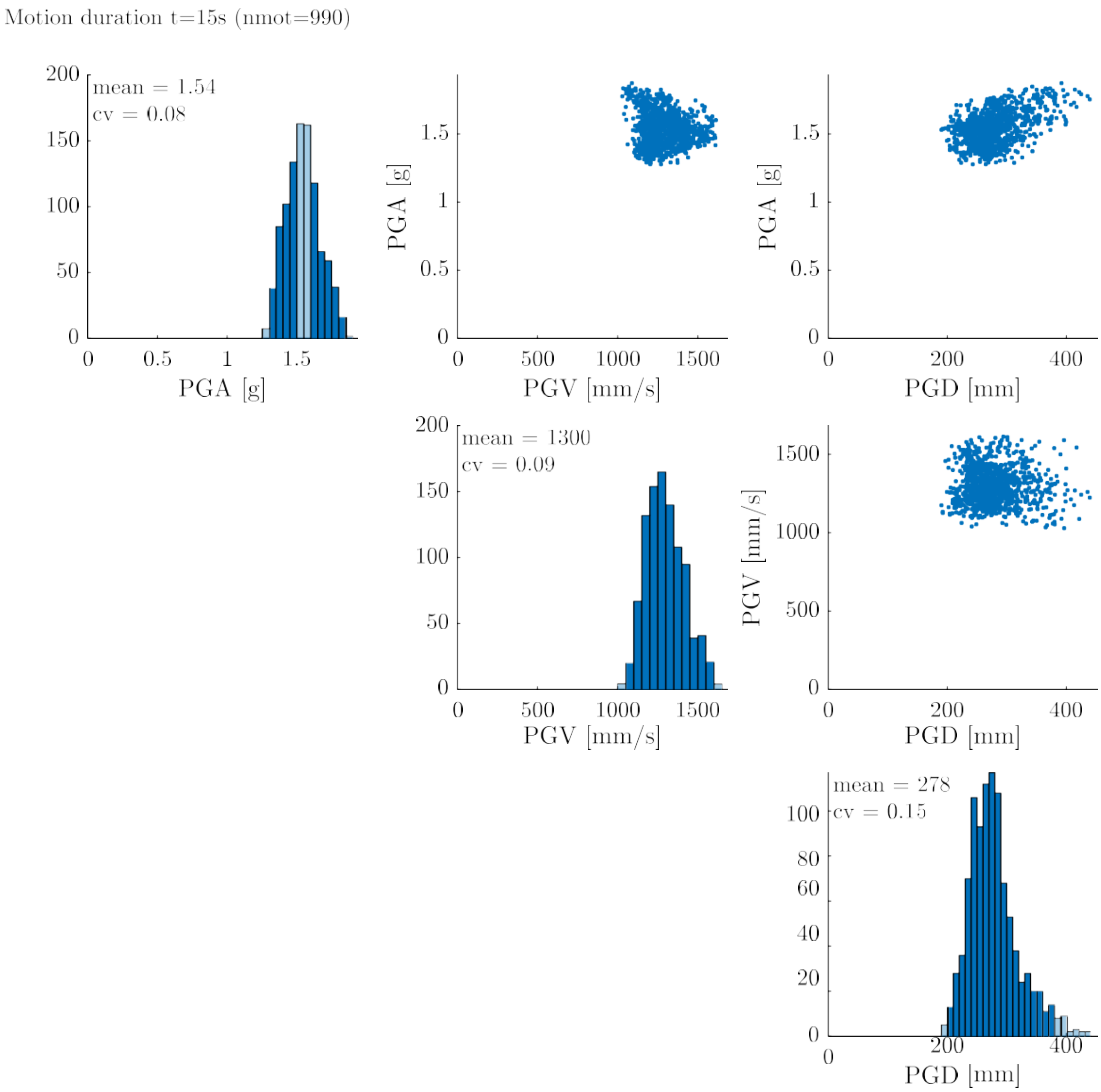
- All motions are compatible with the subsoil De spectrum in AS 1170.4.
- Four series of motions were generated, distinct in their duration as either 10, 15, 20 and 30 seconds.
- For 10 sec duration there are just under 2000 unique motions. For the remaining durations there are just under 1000 unique motions.

In the preliminary stage, a sensitivity analysis was undertaken which established that the results of the time-history analyses in terms of maximum response displacement were not sensitive to the motion duration. Therefore, for the remainder of analyses, including the ones reported here, only the 15 second duration motion was used.

A comparison of the synthetic motions to the target acceleration spectrum is shown in APPENDIX FIGURE 2. APPENDIX FIGURE 3 shows the relationship between the actual-PGA (peak ground acceleration), PGV (peak ground velocity) and PGD (peak ground displacement) of the generated motions.



APPENDIX FIGURE 2 Comparison of the acceleration spectra of the 15 second duration synthetic ground motions and AS1170.4 subsoil class De spectrum that was used to generate the motions. The deviation between the two in terms of a coefficient of variation is shown by the bottom graph.



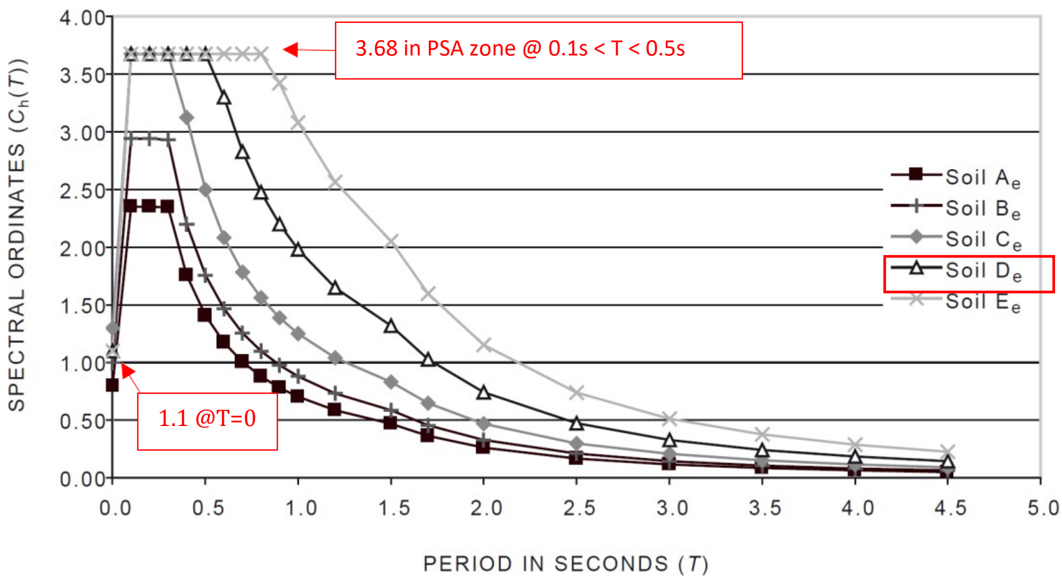
APPENDIX FIGURE 3 Distribution of actual-PGA, PGV and PGD in the 15 second duration synthetic ground motions. All motions are scaled such that nominal PGA = 1 g.

Nominal PGA as the motion intensity measure

The PGA in the target acceleration spectrum used to generate the synthetic acceleration records in Seismoartif is referred to here as the “nominal PGA”.

It was found that whilst the generated synthetic ground motions gave good match to the target spectrum period T > 0.1 sec, the actual PGA always exceeded the nominal PGA. However, the implications of this in relation to the analyses undertaken are considered to be negligible, because both the building and the component walls have periods exceeding 0.1 s, and are thus not sensitive to the PGA.

The nominal PGA will be used as the ground motion intensity measure for constructing fragility curves.



APPENDIX FIGURE 4 AS 1170.4 normalised ground motion spectrum for soil De.

As shown by APPENDIX FIGURE 4, in the AS 1170.4 soil De spectrum, the normalised PGA is equal to 1.1, and the spectral acceleration in the peak spectral acceleration (PSA) zone is 3.68.

Therefore, the nominal PGA can be interpreted such that nominal PGA = 0.1 g corresponds to an intensity that causes the PSA to be equal to 0.1g x 3.68/1.1 = 0.335 g.

METHODOLOGY

Fragility curves were analytically constructed by the method of incremental dynamic analysis (IDA) using nonlinear time-history analysis (THA) applied to individual URM wall components.

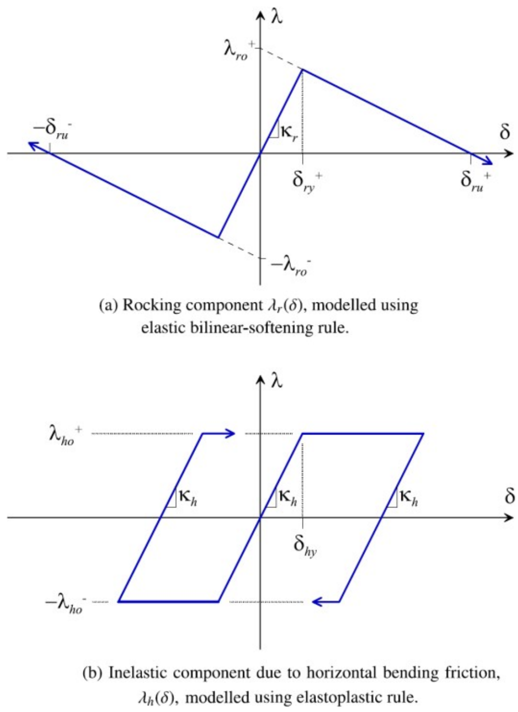
Nonlinear THA

Capacity Curves

The elastic rocking and inelastic friction force and displacement capacities of the wall component were computed using the method described in Vaculik and Griffith (2017) as a function of the wall's geometry and support conditions. This approach ignores the contribution of any bond strength and assumes the wall to be pre-cracked.

As per this approach, the wall's force-displacement capacity curve was modelled by superimposing an elastic rocking component and inelastic friction component, see Appendix Figure 5. Both of these were modelled as bilinear. Note that inelastic friction component is active only in walls with two-way bending.

The yield displacement in both components (δ_{ry} in the rocking component) was taken equal to 10% of the wall's thickness.



APPENDIX FIGURE 5 Hysteresis model for out-of-plane walls (from Vaculik & Griffith, 2017).

Algorithm

Nonlinear THA was undertaken using the conventional step-by-step algorithm, which is based around solving the incremental equation of motion.

Viscous damping

The following values of the viscous damping ratio (ξ) were used.

- 3% damping for cantilevering mechanisms – unrestrained parapets, chimneys, and gable walls;
- 5% damping for simply-spanning mechanisms including unstrengthened vertically spanning out-of-plane walls;
- 5% damping was used for strengthened components.

The damping model implemented within the THA kept the damping ratio ξ constant, and continually updated the damping coefficient, c, by calculating the wall's period using the instantaneous secant stiffness.

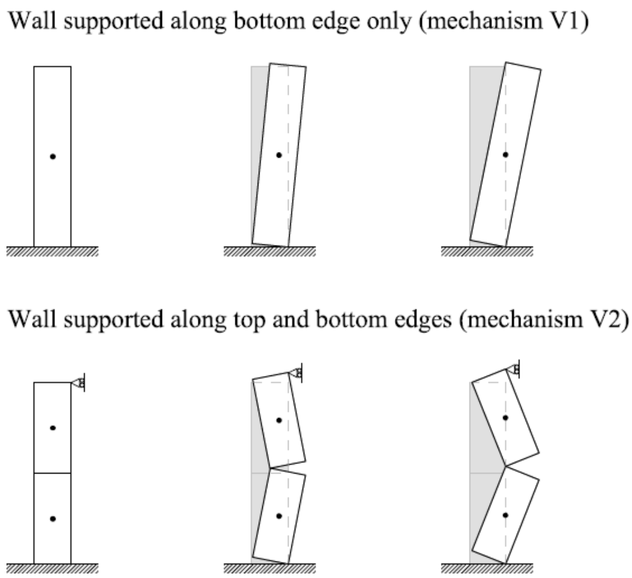
Performance limits and damage states

Five damage states were defined in terms of displacement limits as summarised in Appendix Table 4. Note that D1–D3 are defined in terms of the displacement at peak load in the rocking component (δ_{ry}), and D4–D4 in terms of the rocking instability displacement (δ_{ru}). Both are illustrated in APPENDIX FIGURE 6.

Appendix Table 4 Definition of damage states.

Performance limit	**Damage state**	**Displacement limit**	**Displacement Δ * in a 110mm thick wall**
D1	Slight/minor cracking	50% of δ_{ry}	6 mm
D2	Moderate cracking, attainment of peak load capacity	100% of δ_{ry}	11 mm
D3	Fully formed out-of-plane collapse mechanism, widening of cracks	25% of δ_{ru}	28 mm
D4	Near collapse, major spalling and/or sliding along cracks	50% of δ_{ru}	55 mm
D5	Total collapse	100% of δ_{ru}	110 mm

* i.e. the top displacement in mechanism V1 and mid-height displacement in mechanism V2, see APPENDIX FIGURE 6.



APPENDIX FIGURE 6 Vertically spanning mechanisms V1 and V2 (from Vaculik and Griffith, 2017).

Dynamic filtering by the building

The overall sequence of analysis involved first subjecting an idealised 1 or 2 storey building to the ground motion by means of a linear time-history analysis. This process was used to generate the floor acceleration histories that were then used as input for the components.

This process made the following assumptions:

- The first mode period of the building was computed using the AS 1170.4 formula
  $T_1 = 1.25 k_t h_n^{0.75}$
  where $k_t = 0.05$, and h_n is the height of the building. The height of the building was calculated as the number of storeys times an assumed storey height of 4.0 metres. Thus for a 1 storey building T1 = 0.18s, and for 2 storey building T1 = 0.30s.

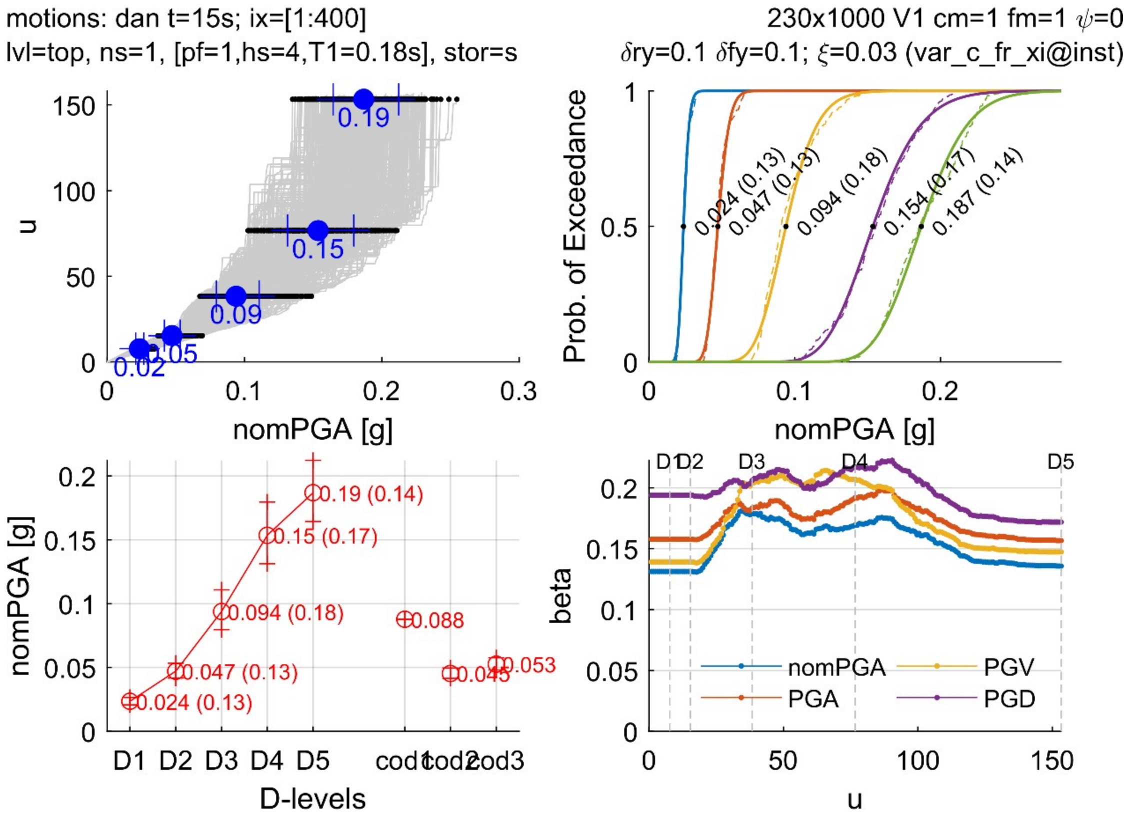
- The building was modelled as having n-degrees-of-freedom where n is the number of storeys. Both the interstorey stiffness (k) and floor mass (m) was taken as constant at each storey. Based on these assumptions, the k/m ratio was tuned to produce the target first mode period.

Incremental dynamic analysis

The ground motion intensity to achieve the various performance limits (D1-D5) was obtained using incremental dynamic analysis (IDA). This process involves subjecting the component to a THA using a floor excitation corresponding to a step-wise increase to the ground motion intensity.

A single IDA curve, i.e. a plot of displacement response versus IM, is produced by analysing the component with respect to an individual ground motion record. From such a curve, the IM required to achieve each of the performance limits is obtained. Despite being generated for the same target spectrum, each synthetic ground motion produces a slightly different IDA curve, so this process needs to be repeated using a large number of motions for confidence in the reliability of results. A total of 400 records were used to generate each set of fragility curves.

Typical results of the IDA are shown in APPENDIX FIGURE 7 below. It is worth noting that the fragility curves obtained from the analyses can be reasonably approximated by fitting the lognormal distribution.



APPENDIX FIGURE 7 Typical example of THA on a single type of component subjected a large number of synthetic motions: (a) IDA curves for 400 separate ground motion records; (b) resulting fragility curves (dashed line shows actual IDA results, solid line shows lognormal fit); (c) plot of IM vs performance levels (brackets indicate log-space standard deviation ≡ β); (d) plot of β versus alternative intensity measures.

RESULTS OF IDA AND FRAGILITY CURVES

This section presents the results of incremental dynamic analysis (IDA) and the recommended fragility curves for the out-of-plane failure mechanisms of a range of different types of masonry elements, as follows.

Parapets:

- 230 x 1000, top of 1 storey building
- 230 x 1000, top of 2 storey building

Simply-spanning (SS) OOP walls:

- 230 x 3500, top storey of 1 storey building
- 230 x 3500, top storey of 2 storey building

Combined failure of parapet and wall below

- 230 x 3500, 1 storey building
- 230 x 3500, 2 storey building

Chimneys:

- Squat: 460 x 1400, located top of 1 storey building
- Medium: 460 x 2100 "
- Slender: 460 x 2800 "
- Squat: 460 x 1400, located top of 2 storey building
- Medium: 460 x 2100 "
- Slender: 460 x 2800 "

n.b. The base of all chimneys has been kept constant. Modification of the fragility curves for base thickness different to the reference value can be made in post-processing using the process described below.

Gable walls:

- 110 thick x 2500 tall gable, located top of 1 storey building

Each of the above elements (with the exception of the gable) was considered at the top level of either a 1- or 2-storey building. This amounts to 11 different fragility curve sets.

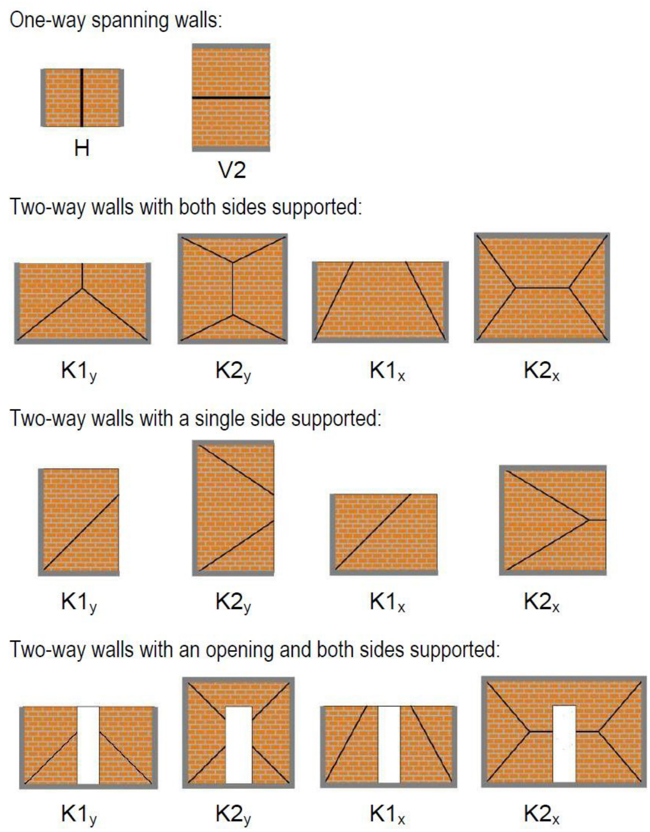
Adjusting IDA results / fragility curves for different wall thickness

For conciseness, the curves provided for parapets and OOP walls consider only the single wall thickness of 230 mm, which corresponds to double-leaf clay brickwork.

When dealing with wall thickness different to that assumed in the presented fragility curves, a transformation can be applied by scaling the median IMs for each damage state by the ratio of the two thicknesses. For example, to transform the curves from a 230mm thick wall to 110mm thick is made by scaling the median IMs using the factor 110/230 = 0.48 ≈ 0.5. For example if the median IM (at a particular damage level) is 0.2g for a 230 thick wall, then the median IM would be 0.1g for a 110 thick wall.

<u>This transformation is essential when dealing with either single-leaf walls or cavity walls, both of which are effectively 110 thick</u>.

This general scaling principle applies for converting between different wall thickness, as long as the wall height remains constant.

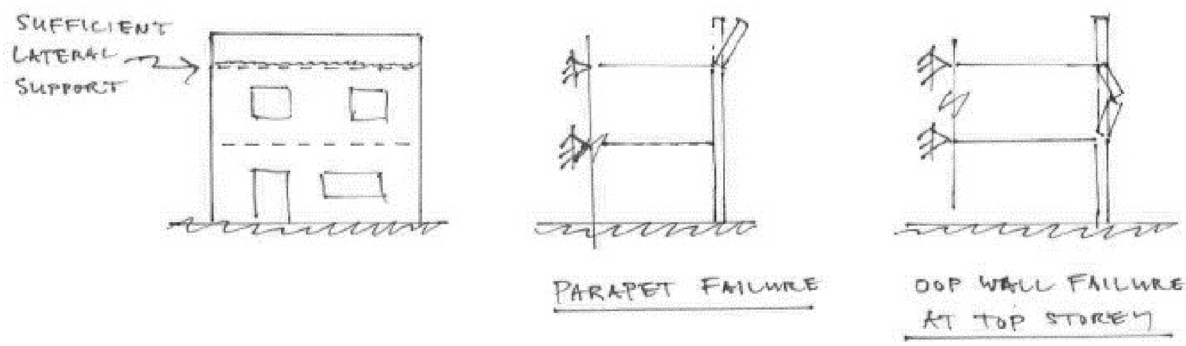


APPENDIX FIGURE 8 Collapse mechanisms which are dependent on support arrangements. Vertical cantilever mechanism V1 not shown. From Vaculik (2012), originally from Lawrence and Page (1999).

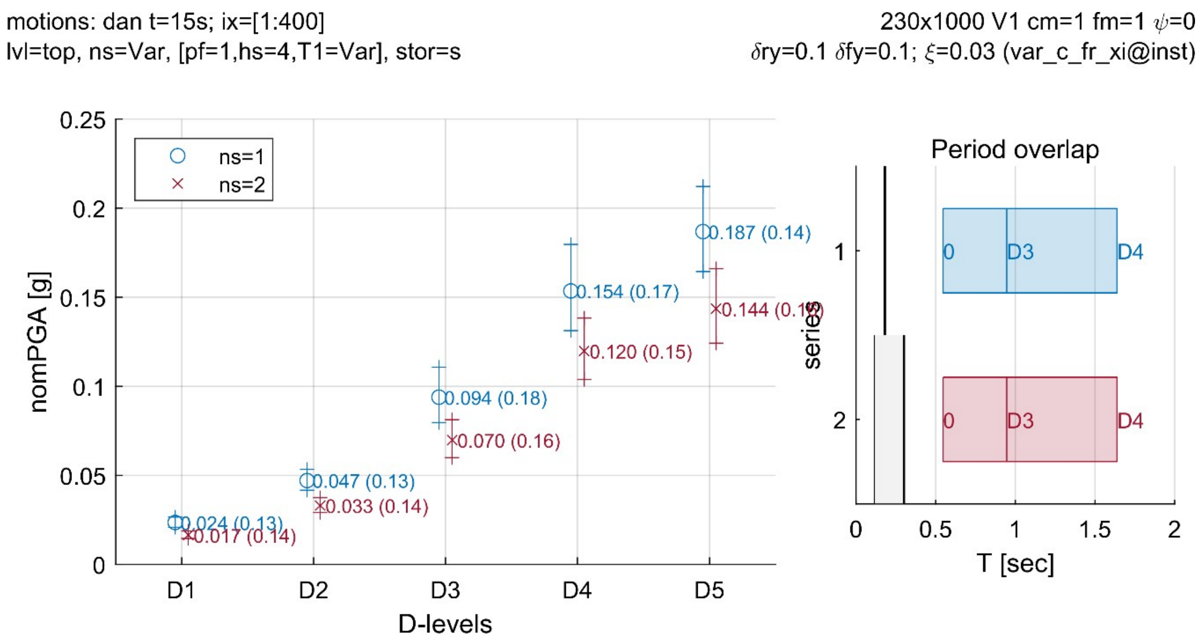
Parapets

As-built condition

Unstrengthened parapets were analysed as vertically cantilevering elements (mechanism V1). The thickness of the parapet was taken as 230 mm and its height as 1000 mm. This mode of failure assumes that the façade wall (parapet + OOP wall below) is sufficiently tied to the roof diaphragm so that the base of the parapet can be considered at the roof line, as shown in APPENDIX FIGURE 9. The results of the IDA are shown in APPENDIX FIGURE 10.



APPENDIX FIGURE 9 Failure modes when the façade wall is sufficiently tied at the roof line.



APPENDIX FIGURE 10 IDA results for unstrengthened parapets.

*Note: The Left-hand-side of the plots (*APPENDIX FIGURE 10*) shows the results of the IDA including: the median value, shown by the marker, and the ± standard deviation in the logarithmic space (i.e. = β) indicated in parentheses. The right-hand-side plot compares the period of the wall to the modal period(s) of the building for each series analysed. The period of* *the wall at different secant stiffness are indicated by coloured bars (same colour as the corresponding IM vs D-level plot) at the initial rising branch (indicated as "0") and damage states D3 and D4. The modal periods of the building are shown by black lines with thickest line indicating the first mode.*

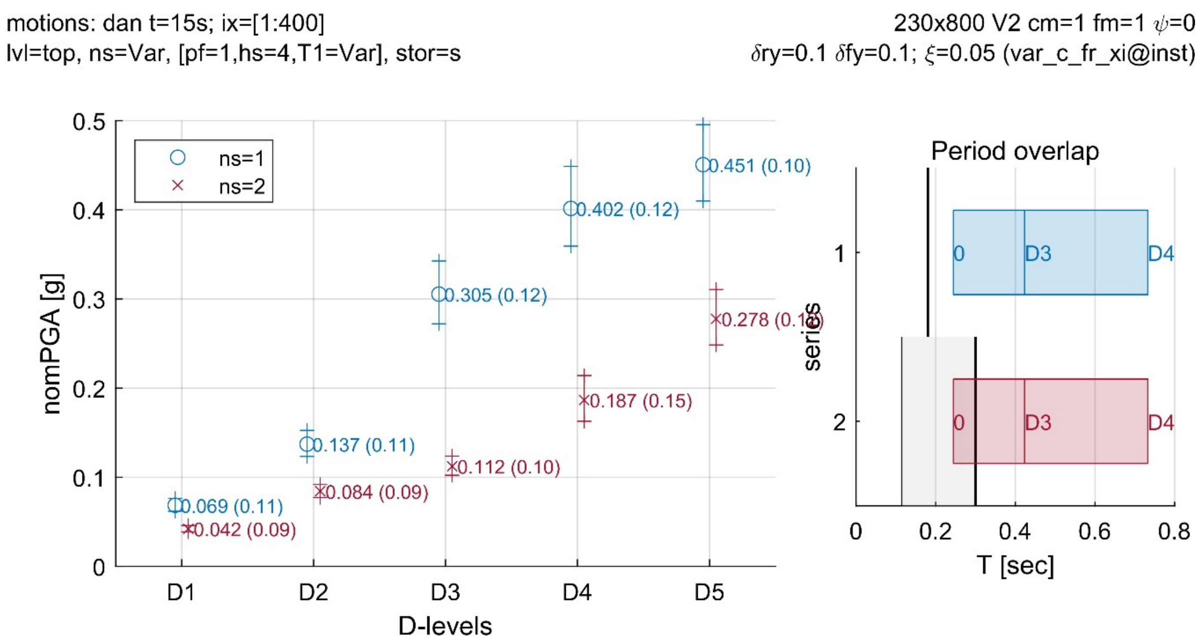
With Strengthening

It is assumed that:

- Retrofit will be in the form of lateral bracing which renders the wall from a cantilevering mechanism (V1) to a simply-supported mechanism (V2), see APPENDIX FIGURE 6.
- The new height span of the mechanism becomes 800 mm, based on the assumption that the top support is 200 mm below the top of the parapet.

N.B. As a reference, if the span was to remain the same (i.e. the new lateral support is applied at the top of the parapet) then the force capacity of the wall would increase by a factor of 4.

The results of the IDA are shown in APPENDIX FIGURE 11.

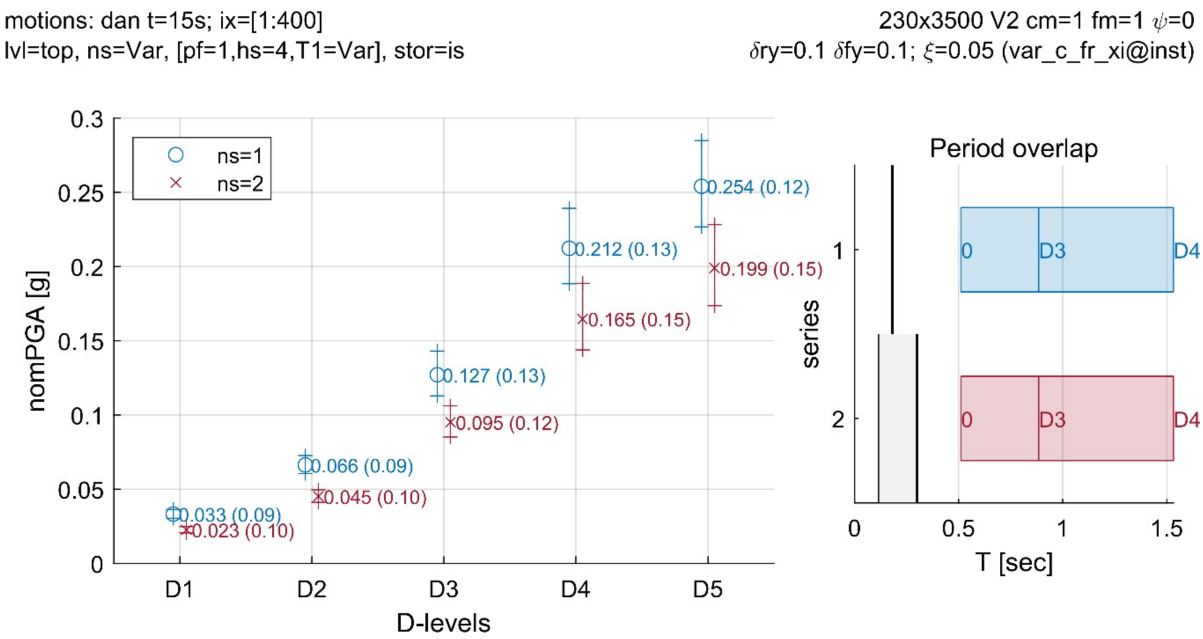


APPENDIX FIGURE 11 IDA results for strengthened parapets.

Simply-supported OOP walls

As-built condition

Unstrengthened walls were treated as simply-spanning between their top and bottom supports (mechanism V2, see earlier Figure). The thickness of the wall was taken as 230 mm and its height as 3500 mm. This mode of failure assumes that the façade wall (parapet + OOP wall below) is sufficiently tied to the roof diaphragm, so that the base of the parapet can be considered at the roof line (APPENDIX FIGURE 9). The results of the IDA are shown in APPENDIX FIGURE 12.



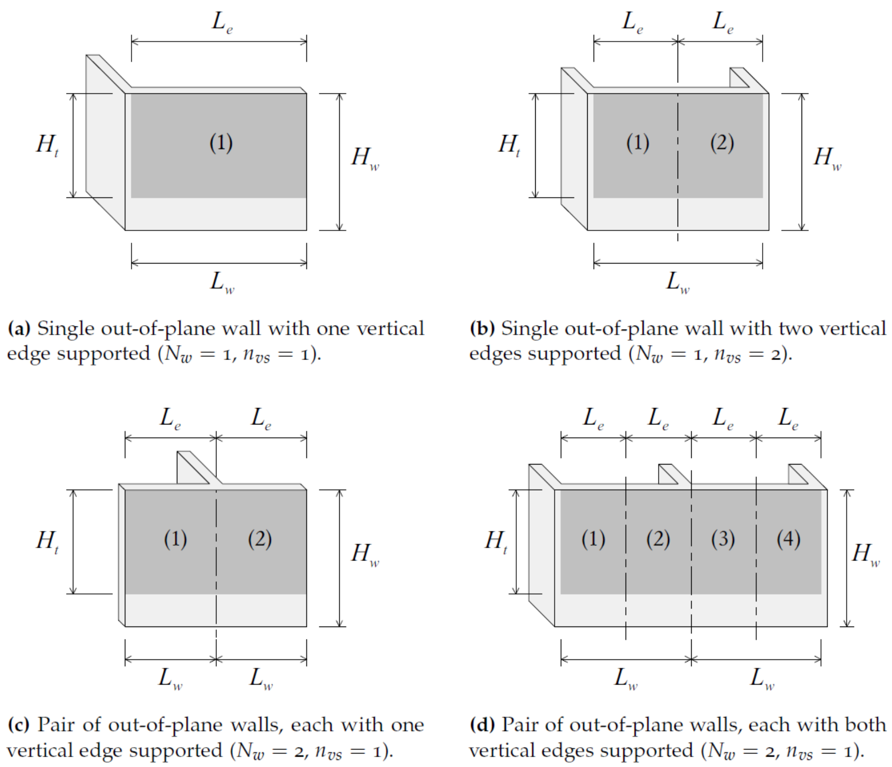
APPENDIX FIGURE 12 IDA results for unstrengthened simply-spanning OOP walls.

With Strengthening

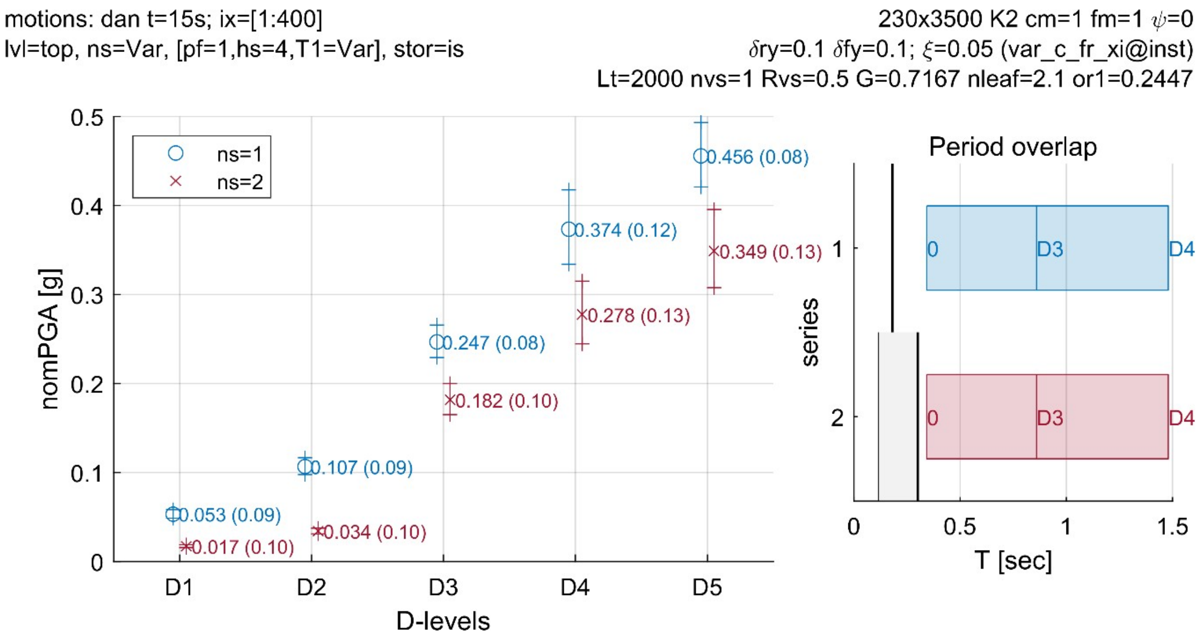
It is assumed that:

- Retrofit will be in the form of vertical lateral restraints that will induce two-way bending. These lateral restraints must be spaced at maximum 4000 mm horizontal centres.
- For the purposes of the analysis, it is assumed that the mechanism switches from V2 to K2 (see APPENDIX FIGURE 8), where the effective length of the mechanism, L_e, is 2000 mm. In walls with only 1 vertical support L_e is defined as the horizontal span from new vertical support to a free edge; or in walls with two vertical supports L_e is defined as half of the distance between the vertical supports (see APPENDIX FIGURE 13).
- Rotational support factor at the new vertical support = 0.5.
- Horizontal bending friction assumed to contribute 50% of its full capacity, to account for the fact that mode of failure will be mixed between stepped and line failure.

The results of the IDA are shown in APPENDIX FIGURE 14.



APPENDIX FIGURE 13 Definition of the effective length, Le. From Vaculik (2012).

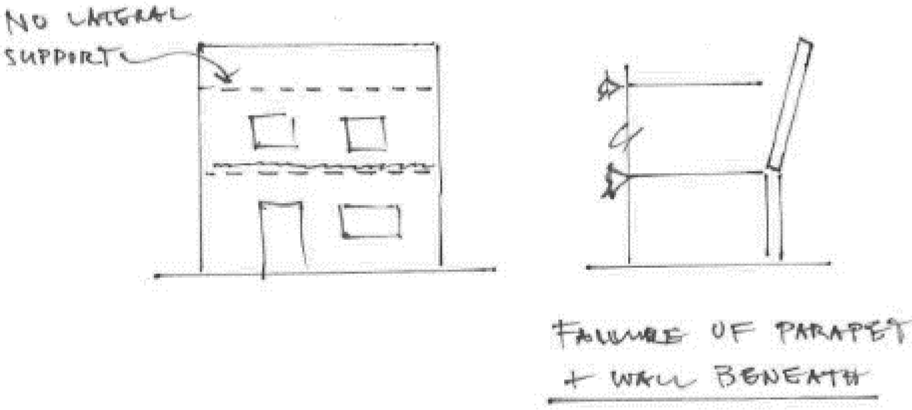


APPENDIX FIGURE 14 IDA results for strengthened simply-supported OOP walls.

Combined parapet + OOP wall failure in the case of insufficient ties at roof level

As-built condition

If the façade wall is insufficiently tied into the roof diaphragm, then the roof diaphragm will not provide lateral restraint. Thus, treating the parapet above as a standalone cantilevering element and the OOP wall below as a standalone simply-spanning element becomes inaccurate (i.e. the treatments in Section 0 and 0). Instead, both the parapet and wall below will fail as a single component, as shown in APPENDIX FIGURE 15.



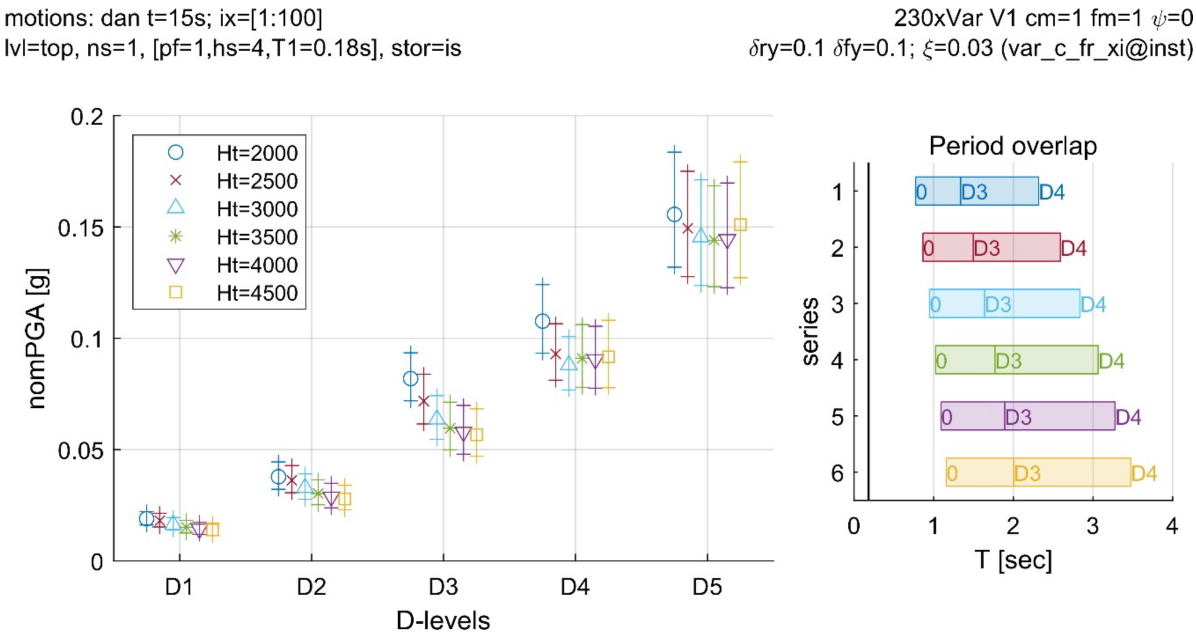
APPENDIX FIGURE 15 Combined failure mode of the parapet and wall below if the façade wall is insufficiently tied at the roof line.

We can treat this case as a tall cantilevering 'super-component' wall whose total height can be up to 1000 mm (parapet) + 3500 mm (wall below) = 4500 mm.

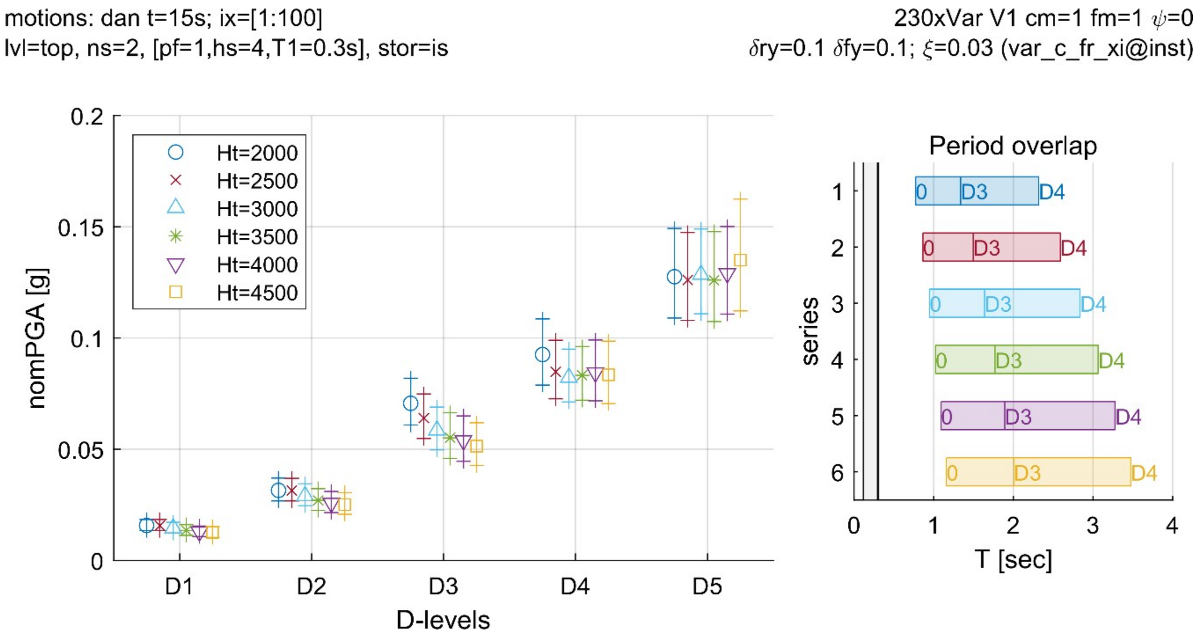
However, because of component/building resonance interaction, the critical mechanism height (H_t) may not necessarily utilise the full 4500 mm wall height. To determine the critical mechanism height, we'll use the lowest energy principle (as per virtual work method), where the critical height corresponds to minimisation of the collapse load.

As motion input, use the average motion at the roof and floor below. Use 3% damping.

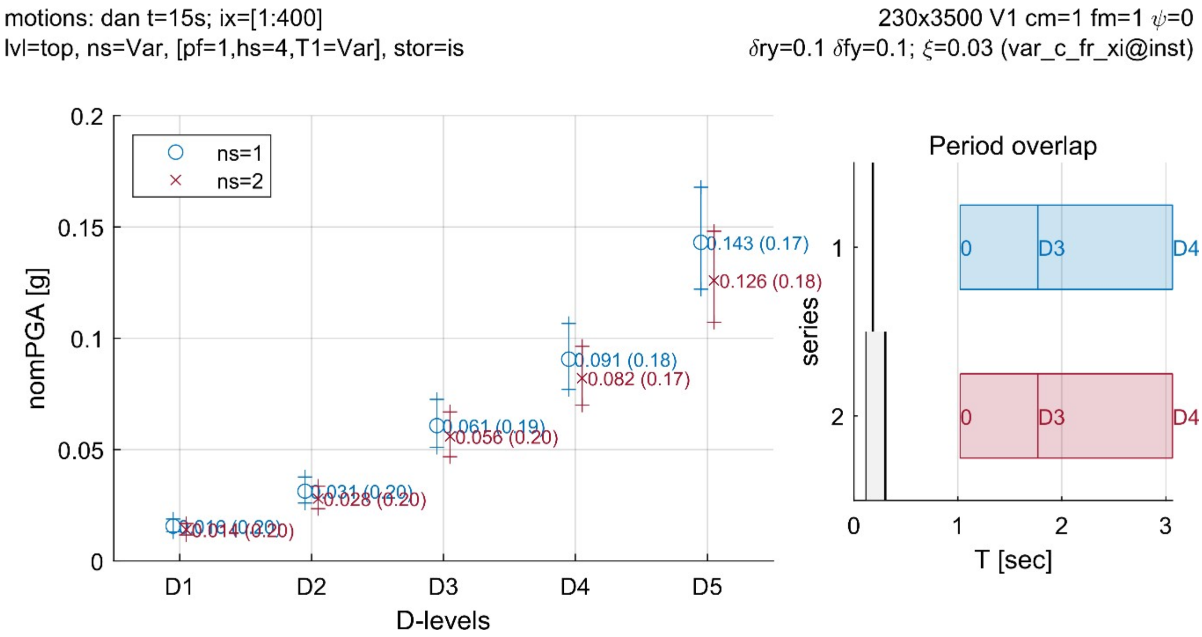
Therefore, first undertake IDA a range of possible heights. These results are shown in Appendix Figure 16 and Appendix Figure 17, where it is seen that based on the collapse limit state D5, 3500 mm could be treated as the critical height in both the 1- and 2- storey building. Thus take H_t = 3500 mm to construct the fragility curves (IDA results in APPENDIX FIGURE 18).



APPENDIX FIGURE 16 IDA results for parapet + OOP wall 'super-component' for varied mechanism height Ht. Considered for a 1-storey building.



APPENDIX FIGURE 17 IDA results for parapet + OOP wall 'super-component' for varied mechanism height Ht. Considered for a 2-storey building.



APPENDIX FIGURE 18 IDA results for parapet + OOP wall ‘super-component’.

With Strengthening

Strengthening is not considered in this instance, as the first course of strengthening would be to install ties at roof level which would simply create the separate scenarios considered previously (i.e. free-standing parapet and simply-supported wall below).

Chimneys

As-built condition

The chimney was treated as cantilevering element with base thickness of 460 mm and three alternate heights: 1400 mm (H/t slenderness = 3), 2100 mm (slenderness = 4.5), and 2800 mm (slenderness = 6).

This assumes that:

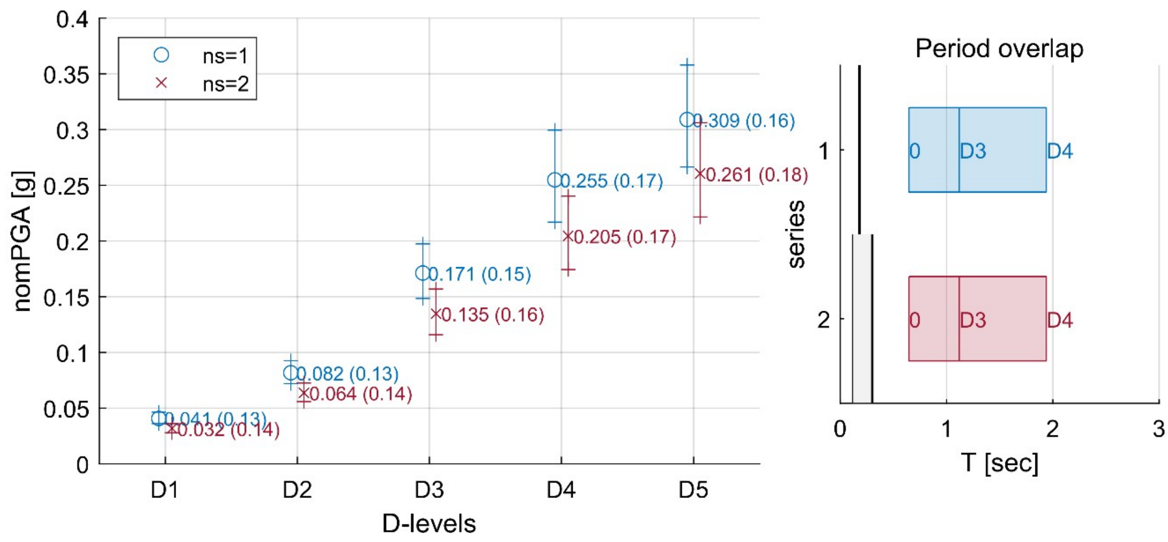
- The chimney has sufficient lateral restraint at the roof-line; and
- The base of the chimney it is not subjected to rotation due to building drift.

The results of the IDA are shown in APPENDIX FIGURE 19.

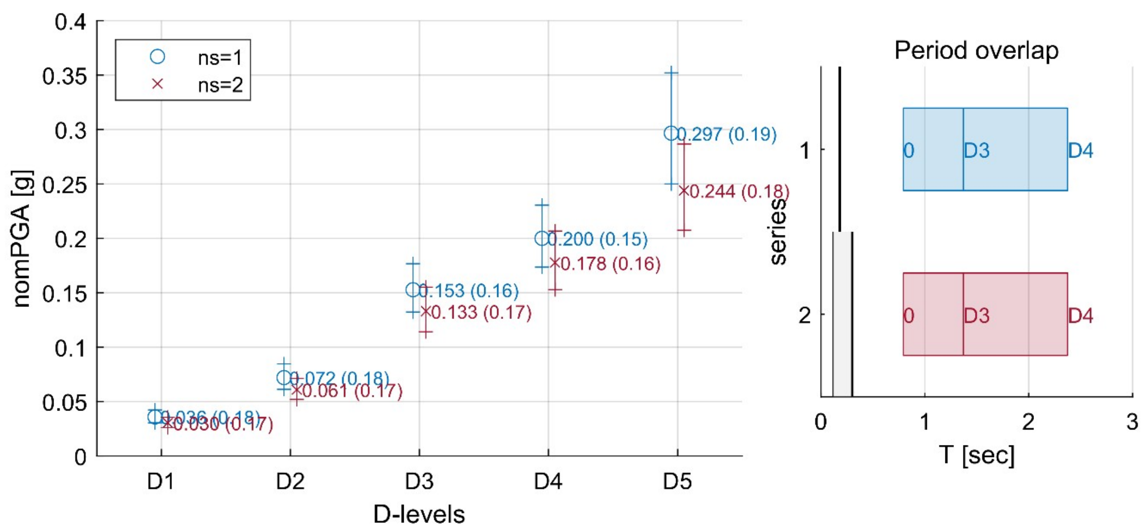
Note that for the selected chimney heights, the secant period of the chimney is sufficiently far removed from the period of the building. However, if the chimney was to be located in a taller building or one responding at a longer period due to in-plane damage, component-building resonance effects could become significant. In such instances the chimneys could become more vulnerable than these analyses suggest.

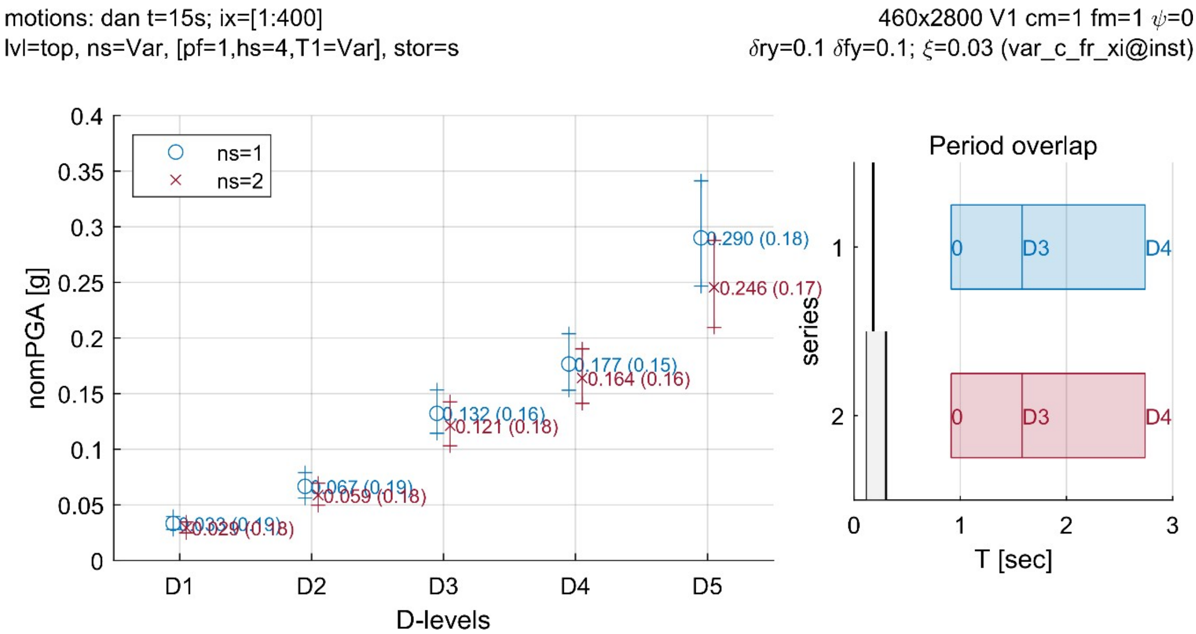
APPENDIX FIGURE 20 plots the same data but groups the different H_t values for direct comparison. It is seen that although the vulnerability increases with height, the sensitivity is not particularly strong. This is largely because for each height the component's period is sufficiently removed from resonance with the building.

motions: dan t=15s; ix=[1:400] 460x1400 V1 cm=1 fm=1 ψ=0
lvl=top, ns=Var, [pf=1,hs=4,T1=Var], stor=s δry=0.1 δfy=0.1; ξ=0.03 (var_c_fr_xi@inst)

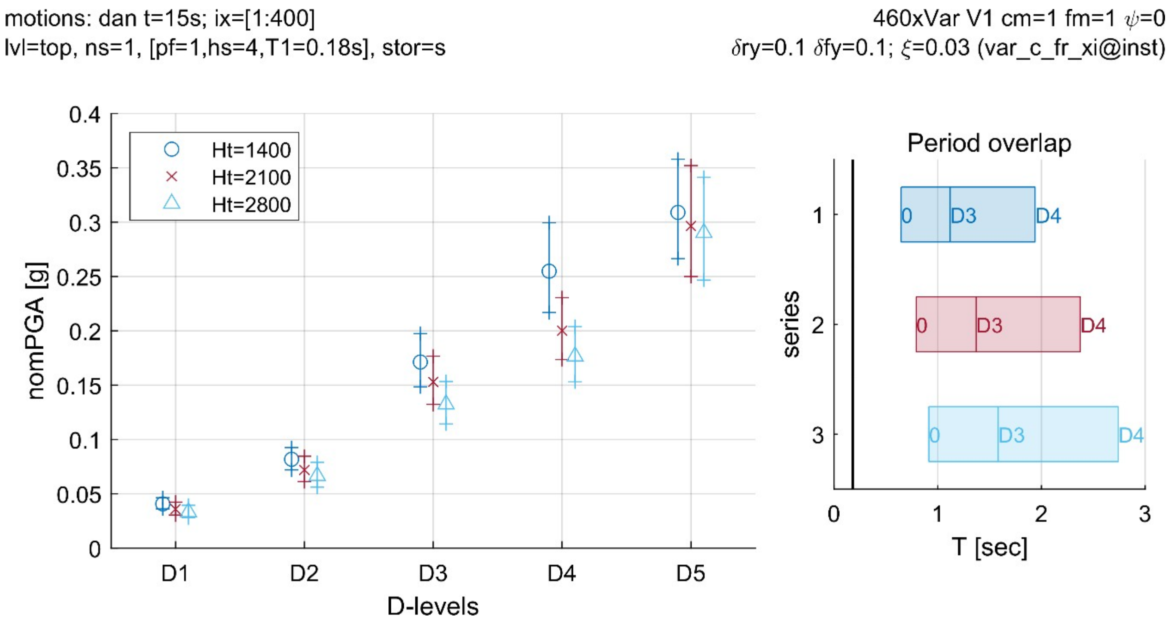


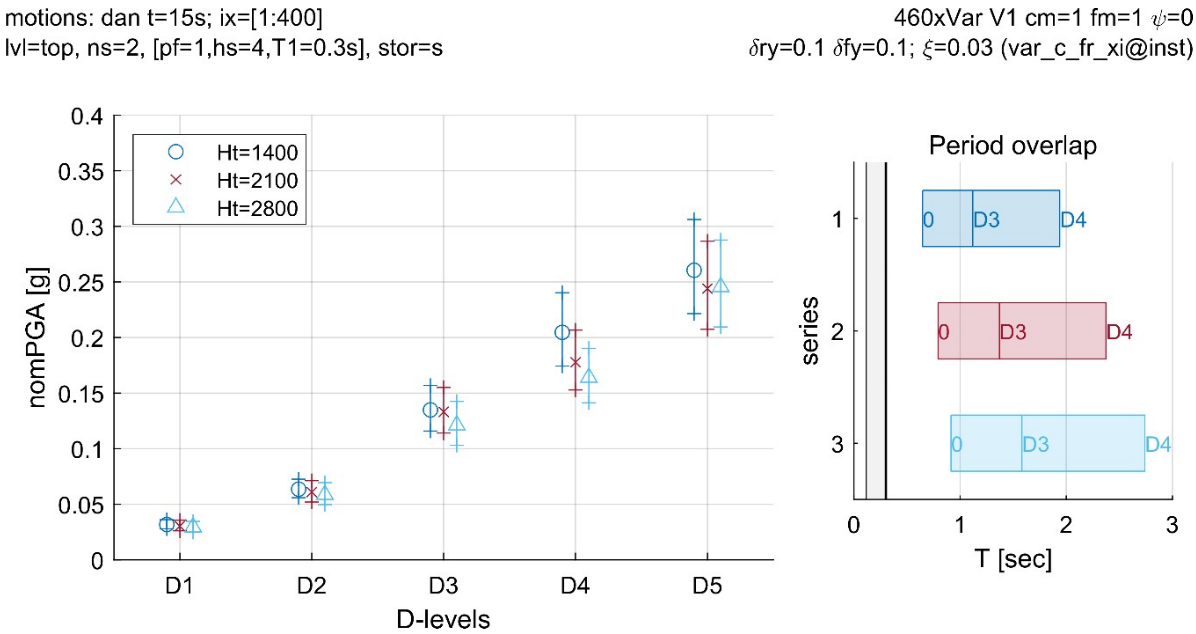
motions: dan t=15s; ix=[1:400] 460x2100 V1 cm=1 fm=1 ψ=0
lvl=top, ns=Var, [pf=1,hs=4,T1=Var], stor=s δry=0.1 δfy=0.1; ξ=0.03 (var_c_fr_xi@inst)





APPENDIX FIGURE 19 IDA results for unstrengthened chimneys.





APPENDIX FIGURE 20 IDA results for unstrengthened chimneys; comparison of different chimney heights.

With Strengthening

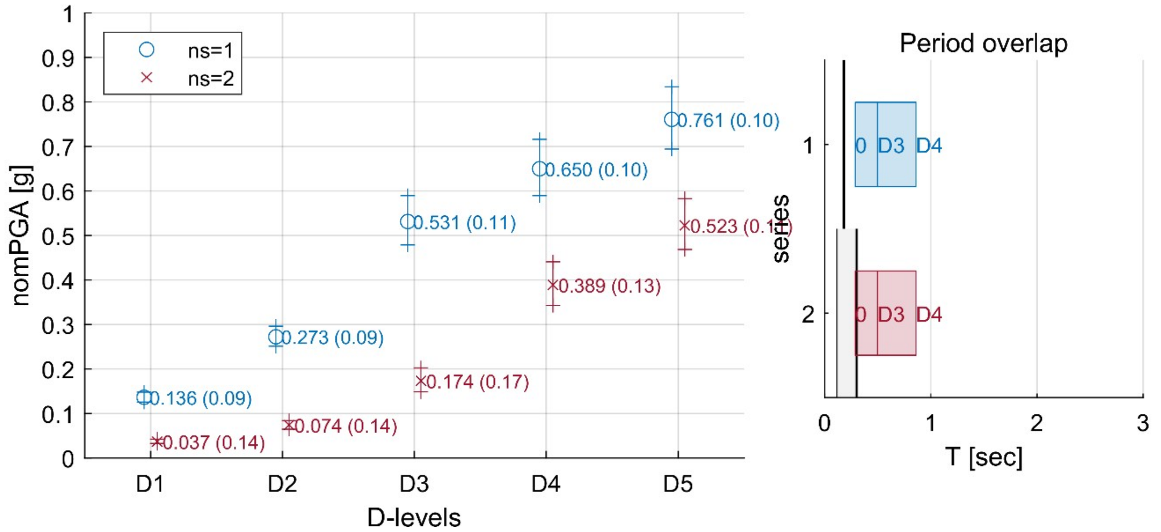
It is assumed that:

- Chimneys will be laterally braced at a location 80% of the original cantilever height measured from the roof line restraint.
- The resulting chimney undergoes a V2 type mechanism.

The results of the IDA are shown in APPENDIX FIGURE 21.

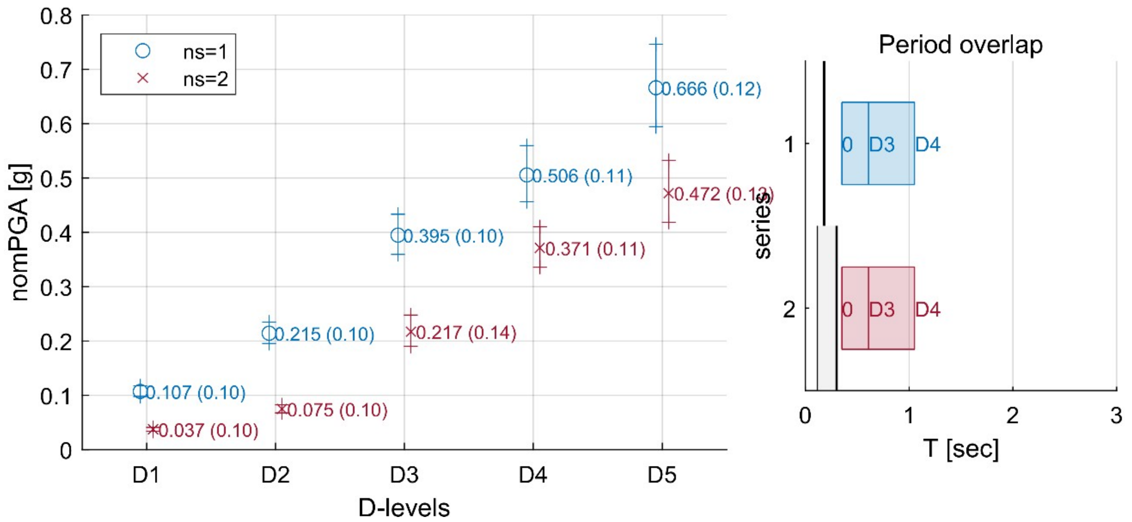
motions: dan t=15s; ix=[1:400]
lvl=top, ns=Var, [pf=1,hs=4,T1=Var], stor=s

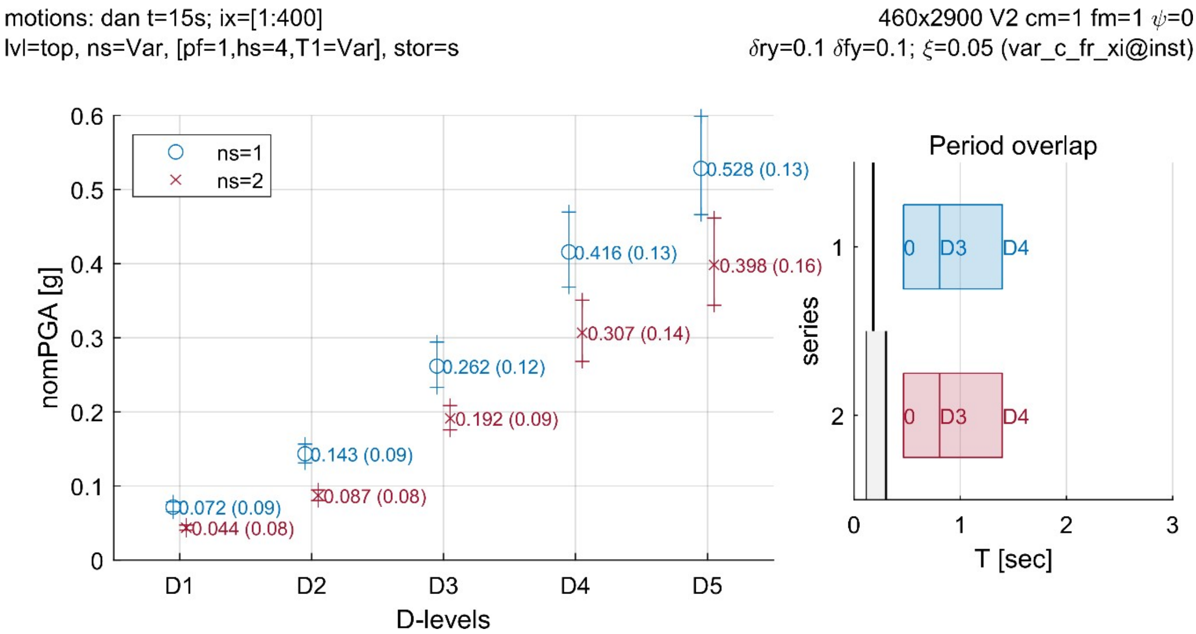
460x1100 V2 cm=1 fm=1 ψ=0
δry=0.1 δfy=0.1; ξ=0.05 (var_c_fr_xi@inst)



motions: dan t=15s; ix=[1:400]
lvl=top, ns=Var, [pf=1,hs=4,T1=Var], stor=s

460x1650 V2 cm=1 fm=1 ψ=0
δry=0.1 δfy=0.1; ξ=0.05 (var_c_fr_xi@inst)





APPENDIX FIGURE 21 IDA results for strengthened chimneys.

Gable wall

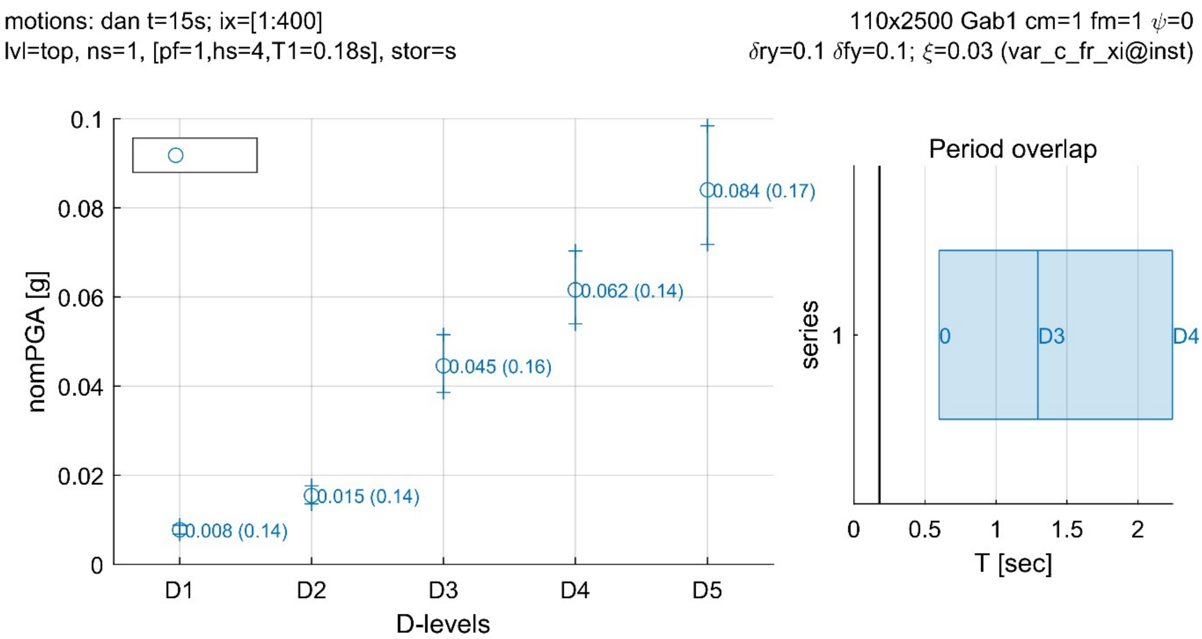
As-built condition

The gable wall (triangular in shape) was taken as 110 mm thick and 2500 mm tall. Note that the length of the base of the triangle does not influence the results of the analysis. The wall was treated as a vertical cantilever mechanism with suitable adjustment made to the effective wall displacement to account for the triangular shape of the wall.

This assumes:

- The gable wall is sufficiently supported at the base of the triangle.
- The wall is not connected to the roof at the sloped edges, so that it undergoes a simple V1 rocking type mechanism about its base.

The results of the IDA are shown in APPENDIX FIGURE 22.



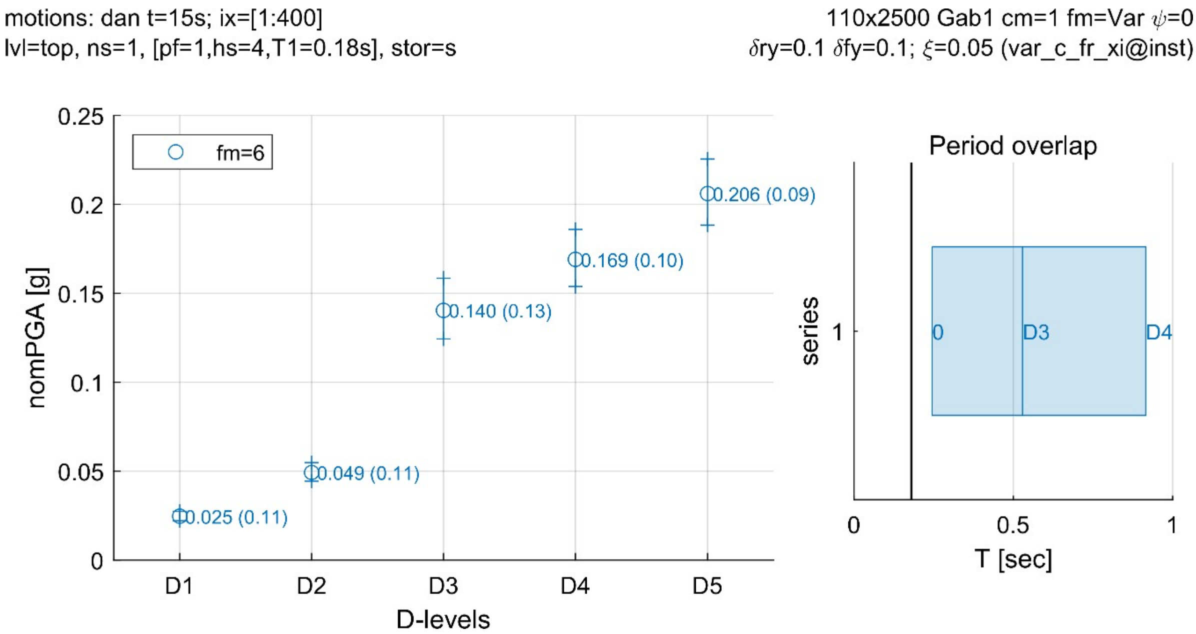
APPENDIX FIGURE 22 IDA results for unstrengthened gable.

With Strengthening

It is assumed that:

- Strengthening will involve stitching the sloped sides of the gable to the roof, and that the roof is capable of providing lateral support.
- The capacity after implementing this strengthening would depend on the length of the gable, as the altered boundary conditions would generate two-way bending. However the new collapse mechanism is not readily analysable with existing tools. Based on judgement, it is assumed that this would amount to a 6-fold increase in force capacity, and whilst the displacement capacity would also increase, assume that it remains unaffected.

The results of the IDA are shown in APPENDIX FIGURE 23.



APPENDIX FIGURE 23 IDA results for strengthened gable.

Final fragility curves

Fragility curves for each damage state are defined in terms of the lognormal cumulative distribution function (CDF) given by the formula:

$$P = \Phi\left(\frac{\log x - \log x_{\mathrm{med}}}{\beta}\right)$$

Where Φ(..) is the CDF of the standard normal distribution, x = intensity measure; x_{med} = median intensity measure for the damage state given in the tables below; β = uncertainty parameter which more formally represents the standard deviation of the IM after log transformation.

It is recommended that β is taken as 0.57 (refer to Vaculik and Griffith, 2018). This value is intended to account for modelling uncertainty only, and not ground motion uncertainty. Note that the recommended value is irrespective of the variability observed in the IDA, which generally ranged between 0.12 and 0.17 but which exhibited variation only due to differences in the synthetic ground motions.

Appendix Table 5 - Appendix Table 11 summarise the median values of the intensity measure for the unstrengthened condition. These do not consider any effect of the motion directivity. The benefit of strengthening is embodied within the IM enhancement factor given in the rightmost column of the tables, which is used to shift the unstrengthened curves to the right. These factors were obtained by considering the results of the IDA at damage states D4 and D5.

Further assumptions

1. In the IDAs, the walls were modelled using their full thickness. This assumes "knife edge" bearing of rocking elements. To allow for combined effects of: 1) the non-zero bearing width required due to finite compressive strength, and 2) geometry imperfections at the mortar joints, the median IMs from these analyses are reduced by multiplying by 0.95.

Appendix Table 5 Fragility curve IMs for 230 x 1000 parapet.

No. storeys in building	UNSTRENGTHENED CONDITION Median IM where IM=nominal PGA [g]					STRENGTHENED Median IM enhancement factor
	D1	D2	D3	D4	D5	
ns = 1	0.023	0.045	0.089	0.146	0.178	2.5
ns = 2	0.016	0.031	0.067	0.114	0.137	1.7

Appendix Table 6 Fragility curve IMs for simply-spanning OOP wall, 230 thick x 3500 tall.

No. storeys in building	UNSTRENGTHENED CONDITION Median IM where IM=nominal PGA [g]					STRENGTHENED Median IM enhancement factor
	D1	D2	D3	D4	D5	
ns = 1	0.031	0.063	0.121	0.201	0.241	1.8
ns = 2	0.022	0.043	0.090	0.157	0.189	1.7

Appendix Table 7 Fragility curve IMs for parapet + wall below failing together due to insufficient lateral restraint at roof level, 230 thick.

No. storeys in building	UNSTRENGTHENED CONDITION Median IM where IM=nominal PGA [g]					STRENGTHENED Median IM enhancement factor
	D1	D2	D3	D4	D5	
ns = 1	0.015	0.029	0.058	0.086	0.136	n/a
ns = 2	0.013	0.027	0.053	0.078	0.120	n/a

Appendix Table 8 Fragility curve IMs for squat chimney, 460 wide x 1400 tall.

No. storeys in building	UNSTRENGTHENED CONDITION Median IM where IM=nominal PGA [g]					STRENGTHENED Median IM enhancement factor
	D1	D2	D3	D4	D5	
ns = 1	0.039	0.078	0.162	0.242	0.294	2.5
ns = 2	0.030	0.061	0.128	0.195	0.248	2.0

Appendix Table 9 Fragility curve IMs for medium chimney, 460 wide x 2100 tall.

No. storeys in building	UNSTRENGTHENED CONDITION Median IM where IM=nominal PGA [g]					STRENGTHENED Median IM enhancement factor
	D1	D2	D3	D4	D5	
ns = 1	0.034	0.068	0.145	0.190	0.282	2.4
ns = 2	0.029	0.058	0.126	0.169	0.232	2.0

Appendix Table 10 Fragility curve IMs for slender chimney, 460 wide x 2800 tall.

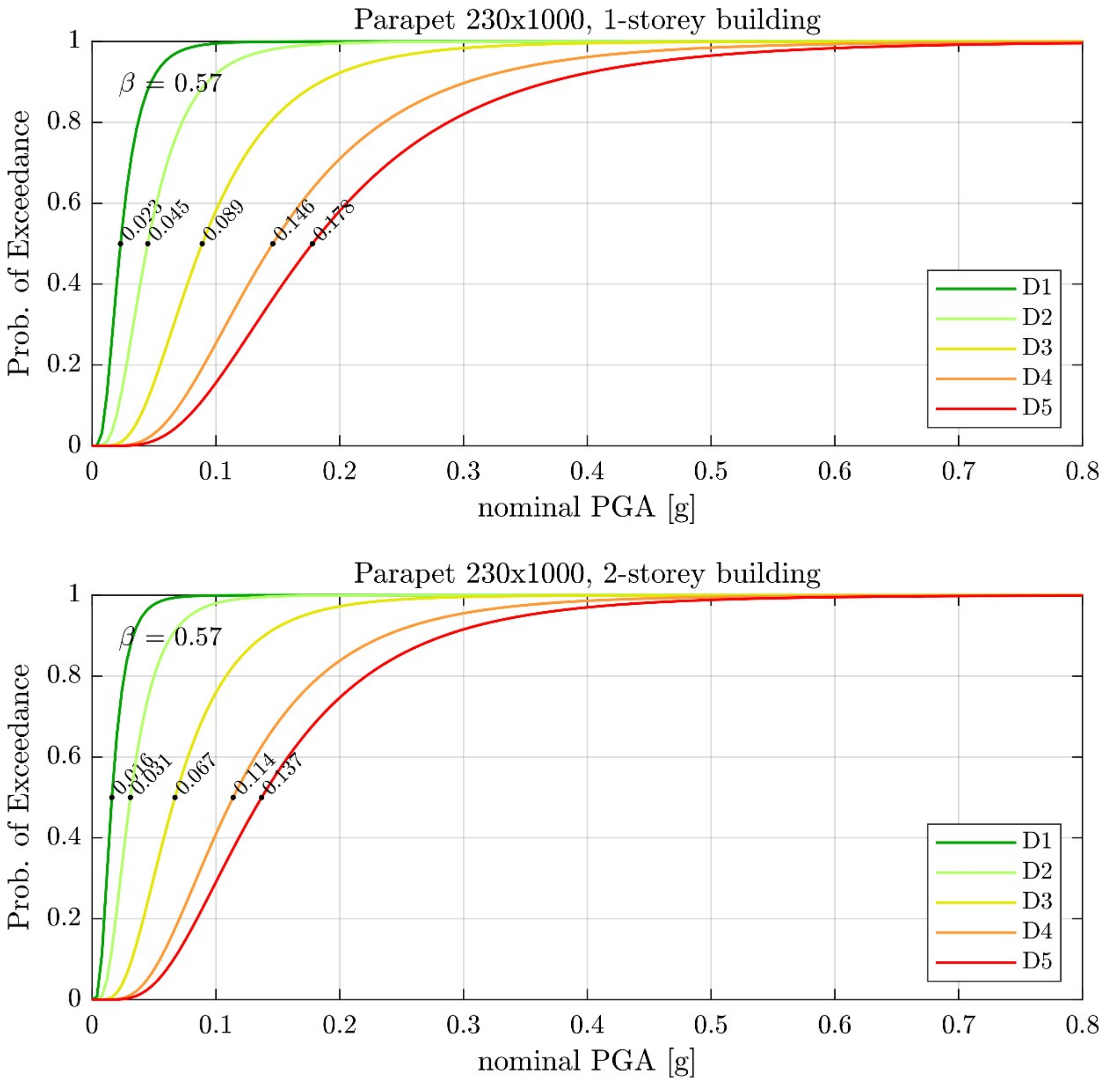
No. storeys in building	UNSTRENGTHENED CONDITION Median IM where IM=nominal PGA [g]					STRENGTHENED Median IM enhancement factor
	D1	D2	D3	D4	D5	
ns = 1	0.031	0.064	0.125	0.168	0.276	2.3
ns = 2	0.028	0.056	0.115	0.156	0.234	1.9

Appendix Table 11 Fragility curve IMs for gable wall, 110 thick x 2500 tall.

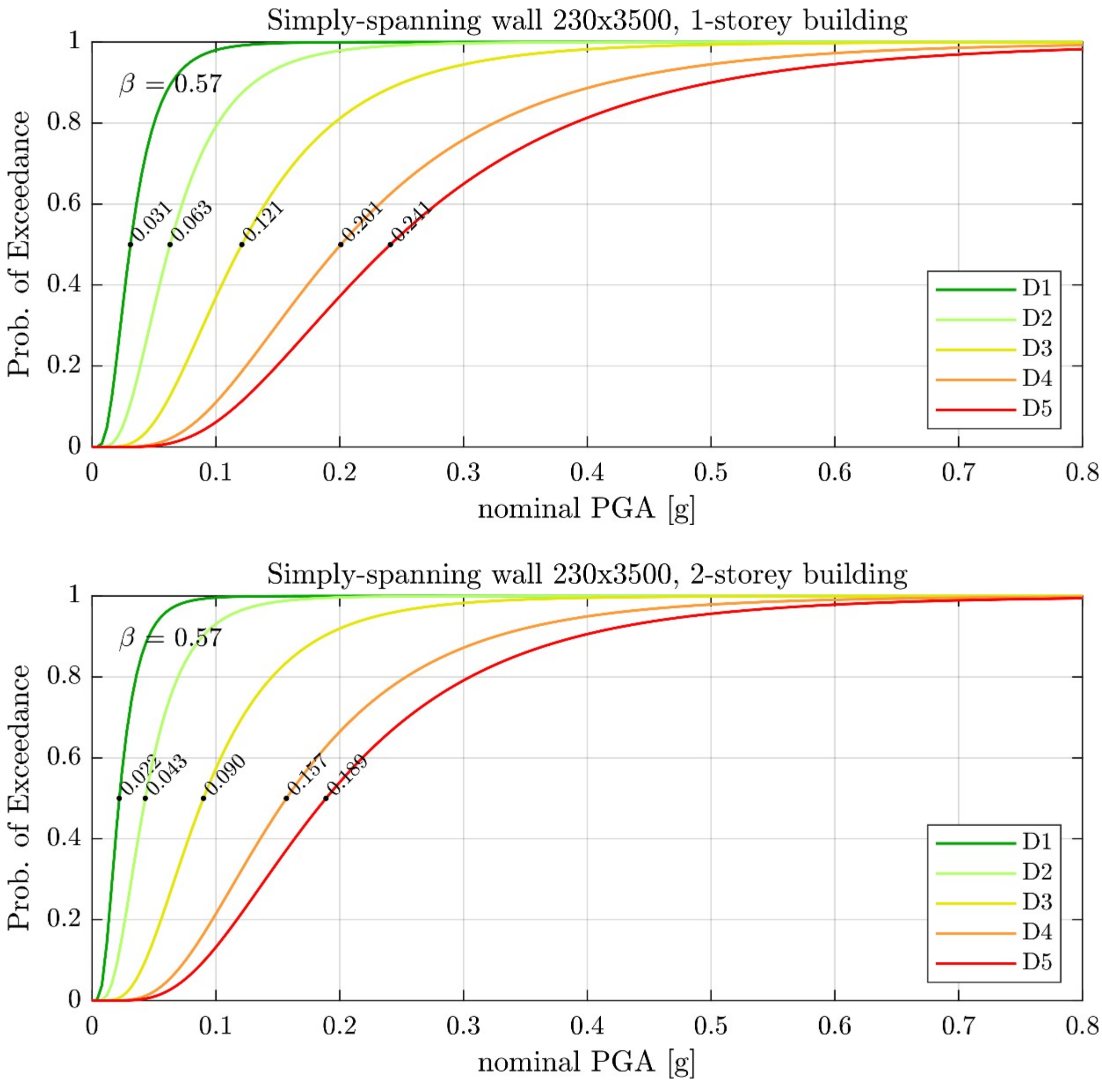
No. storeys in building	UNSTRENGTHENED CONDITION Median IM where IM=nominal PGA [g]					STRENGTHENED Median IM enhancement factor
	D1	D2	D3	D4	D5	
ns = 1	0.008	0.014	0.043	0.059	0.080	2.6

Fragility curves for unstrengthened elements

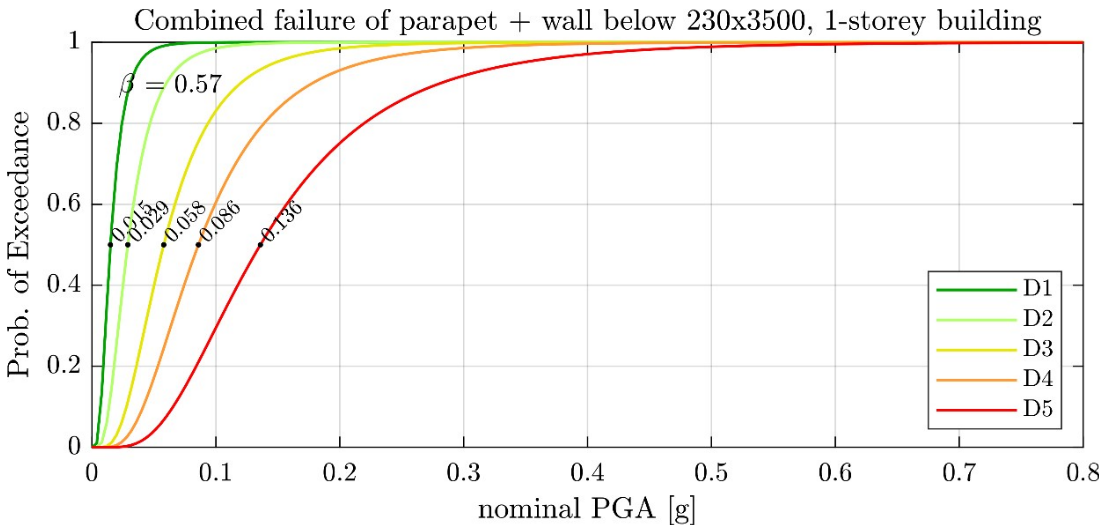
These are presented in APPENDIX FIGURE 24 to APPENDIX FIGURE 30.

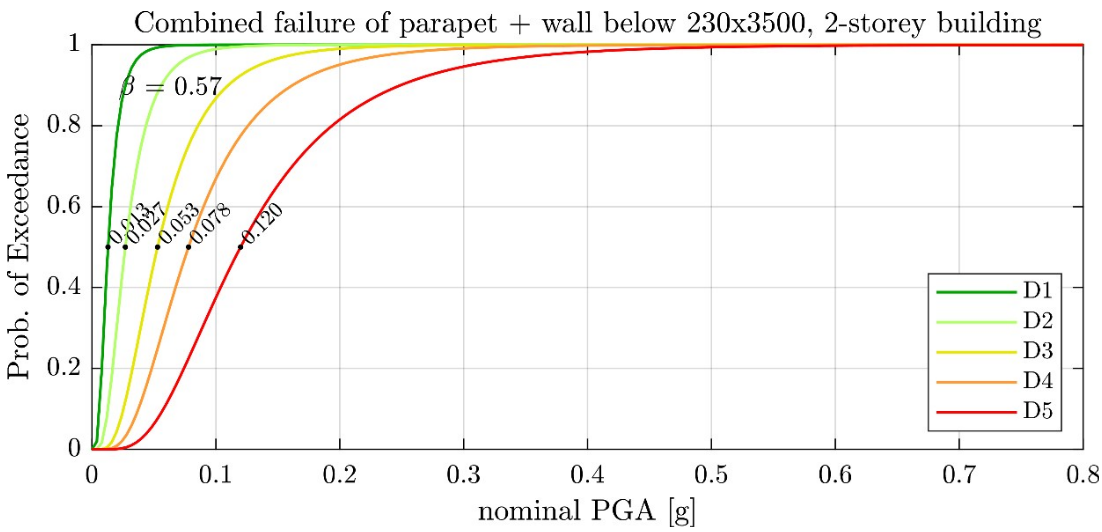


APPENDIX FIGURE 24 Fragility curves for 230 x 1000 parapet.

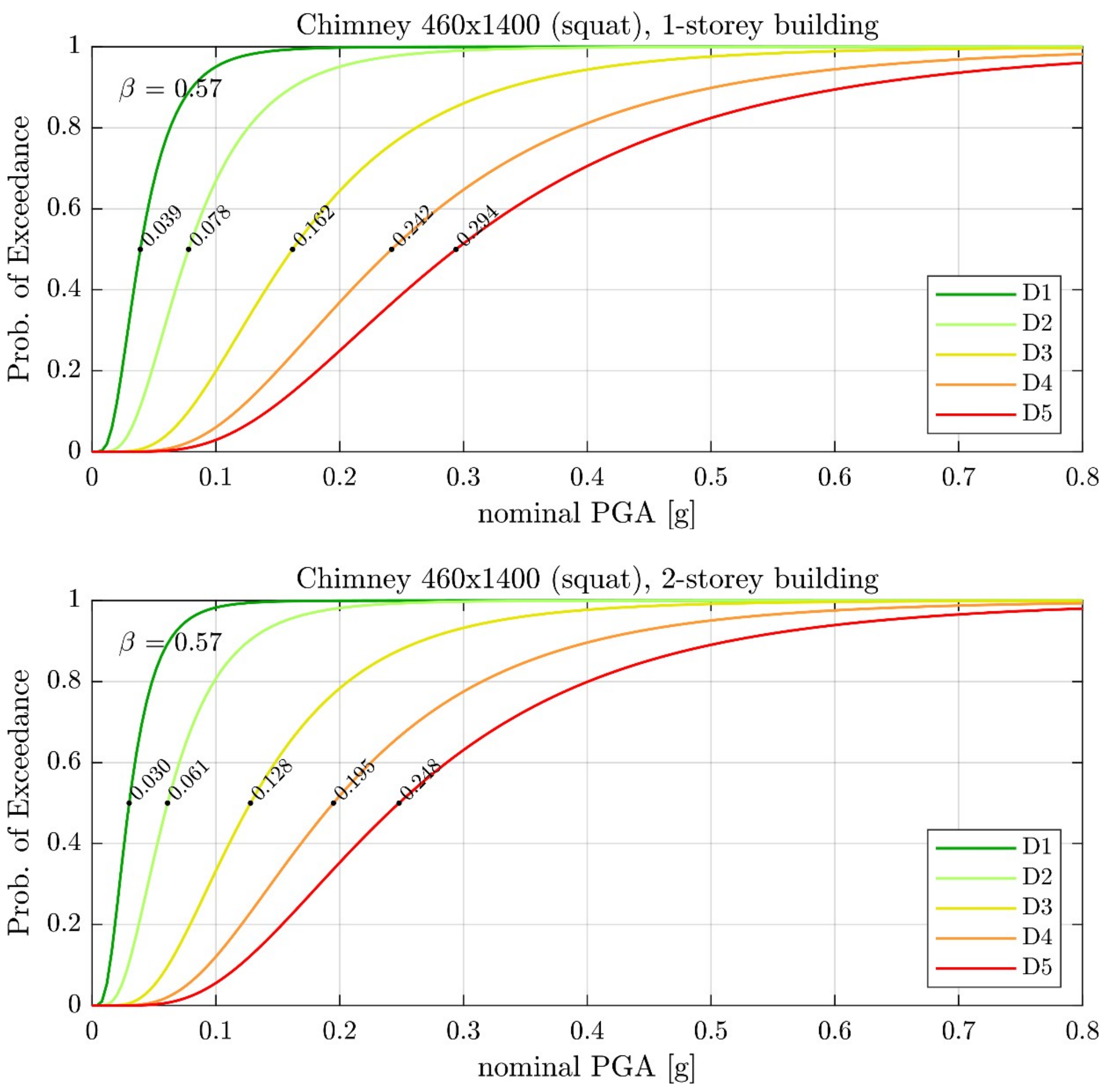


APPENDIX FIGURE 25 Fragility curves for simply-spanning OOP wall, 230 thick x 3500 tall.

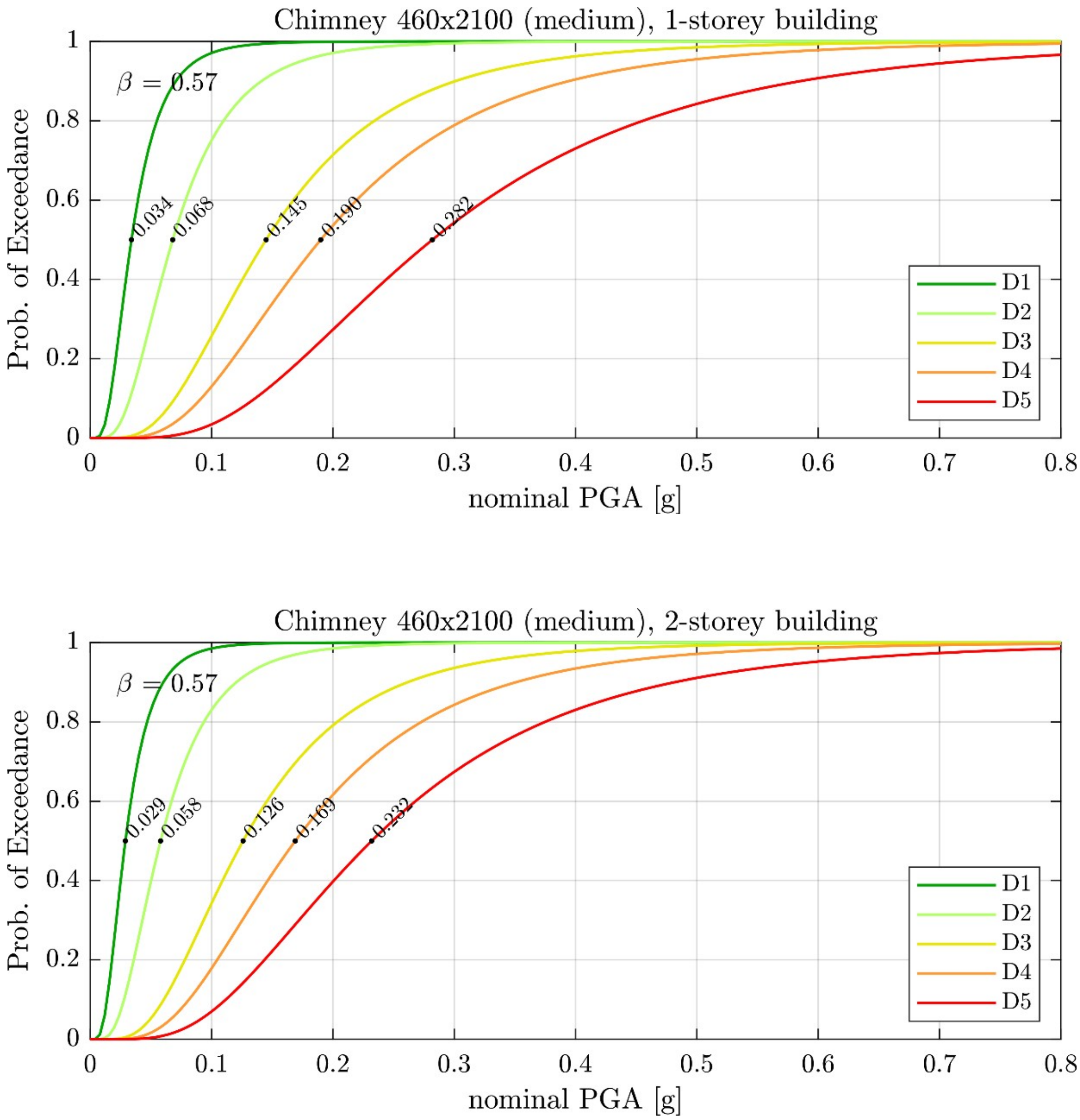




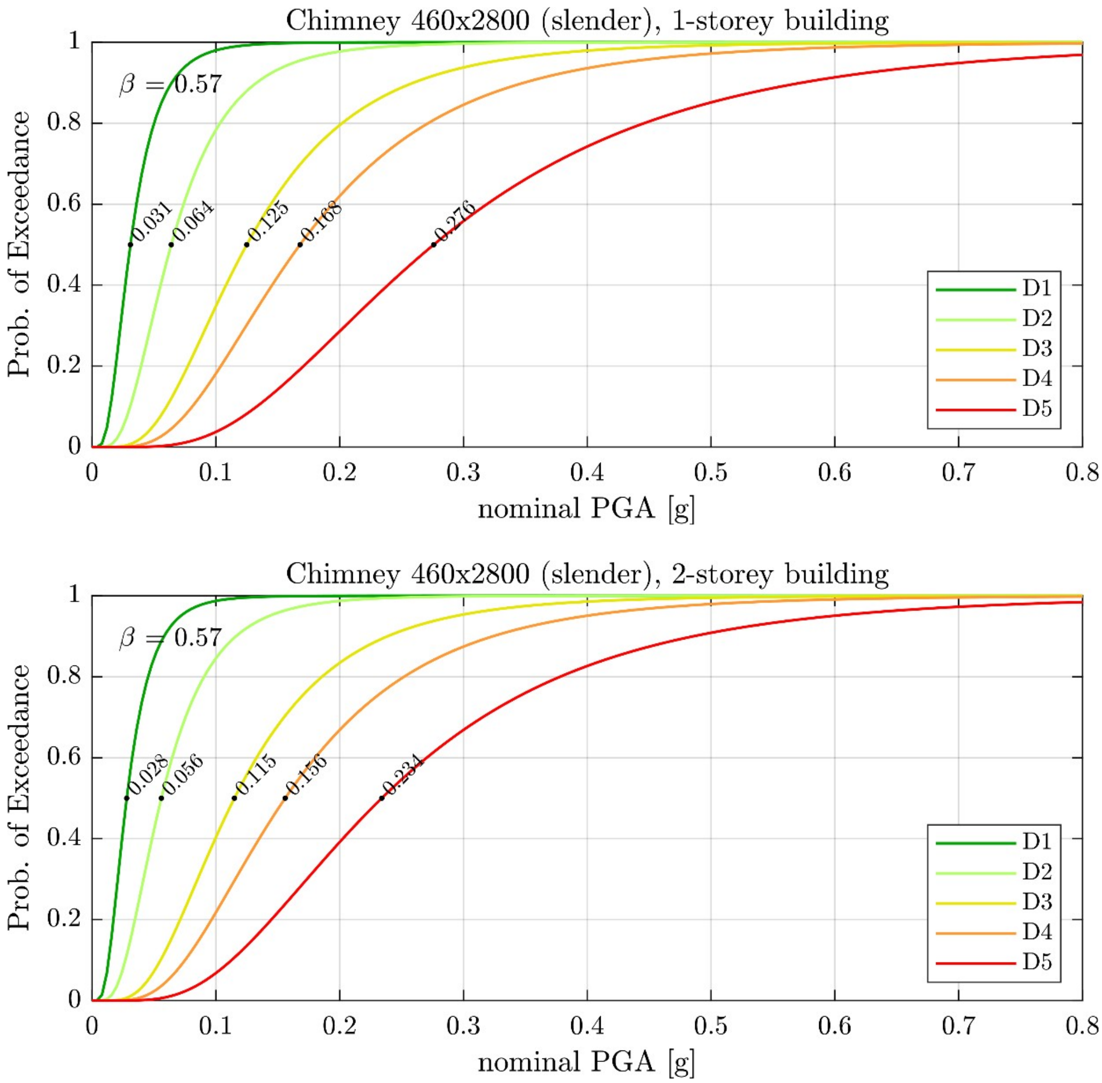
APPENDIX FIGURE 26 Fragility curves for parapet + wall below failing together due to insufficient lateral restraint at roof level, 230 thick.



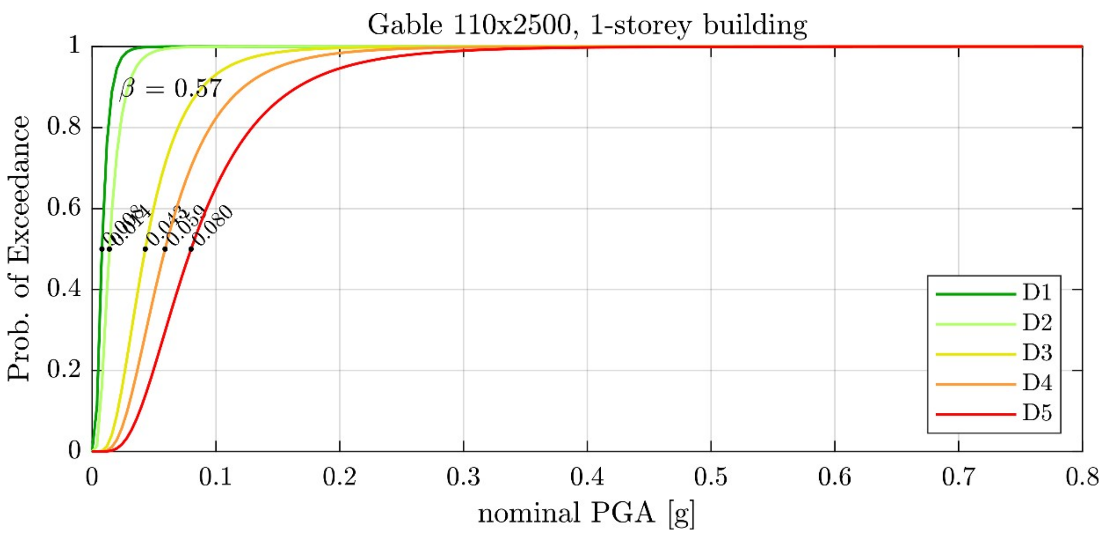
APPENDIX FIGURE 27 Fragility curves for squat chimney, 460 wide x 1400 tall.



APPENDIX FIGURE 28 Fragility curves for medium chimney, 460 wide x 2100 tall.



APPENDIX FIGURE 29 Fragility curves for slender chimney, 460 wide x 2800 tall.



APPENDIX FIGURE 30 Fragility curves for gable wall, 110 thick x 2500 tall.

Allowance for random motion directivity

The fragility curves in the preceding sections were based on the assumption that the ground motion acts perpendicularly to the wall element (i.e. the parapet, simply-supported wall, or gable).

In actuality, the principal direction of the earthquake will act along a random orientation, which is unlikely to be exactly at 90 degrees to the wall. Therefore, the 'true' capacity of the wall to withstand a particular ground motion intensity will be greater than implied by these curves.

To account for these effects, the following method is proposed:

1. Assume that the intensity envelope of the earthquake along the horizontal plane is defined by an ellipse whose major axis = 1 and minor axis = a. Take a = 0.3 on the basis of the 100%-30% rule required by AS 1170.4 to account for bi-directional effects.

2. Since this ellipse can be oriented along any random direction, the motion intensity that acts perpendicular to the plane of the wall is equivalent to the furthest extent of the rotated ellipse. Using the notation $R_x = 1$ and $R_y = 0.3$, the furthest extent in the x-direction after rotation θ is given by

   $$e_x = \sqrt{R_x^2 \cos^2\theta + R_y^2 \sin^2\theta}$$

   For example if the ellipse is rotated by 30 degrees, then $e_x = 0.879$, as shown by APPENDIX FIGURE 31. A plot of e_x versus θ is shown in APPENDIX FIGURE 32.

3. Since the component of shaking intensity acting perpendicular to the plane of the wall after rotation θ > 0 is lower than when the motion acts perpendicular to the wall (θ = 0), an increase to the ground motion intensity is required to reach the same effect on the wall. This increase is given by the multiplier, m, which is

   $$m = 1/e_x$$

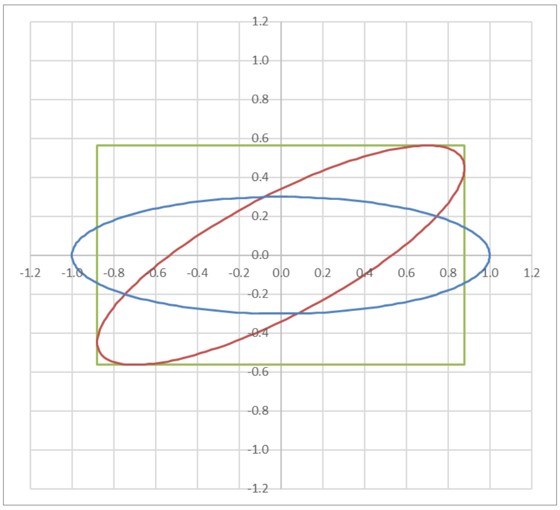
   This assumes that the wall has infinite strength in-plane and can fail only out-of-plane. A plot of m versus θ, where θ can range between 0 and 90 degrees, is shown in APPENDIX FIGURE 32.

4. Multiplier m can't be applied simply to the median IM of a fragility curve. Instead, the full range of m within 0 ≤ θ ≤ 90 deg must be applied to the full population of randomly sampled IMs that define a fragility curve, and from this, the new probability distribution can be determined.

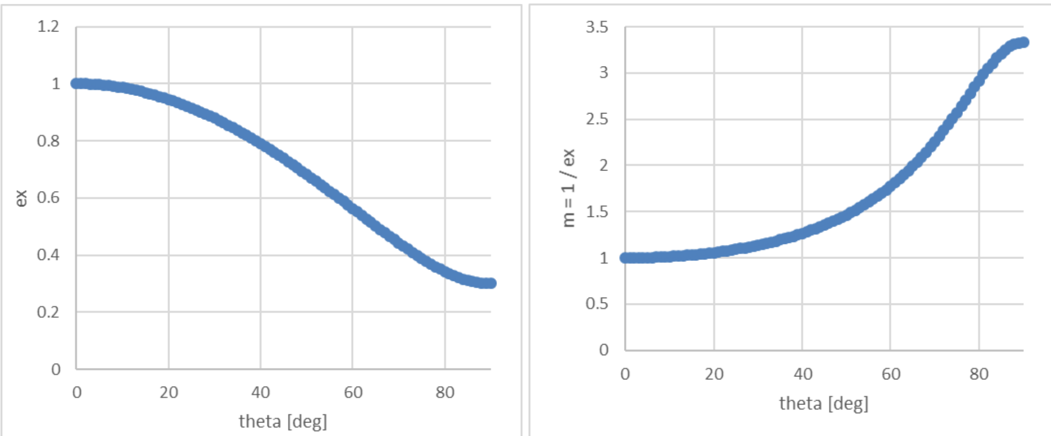
The above process was undertaken numerically by assuming that the original (orthogonal directivity) distribution follows the lognormal distribution with a median X = 1. The results are shown in APPENDIX FIGURE 33 for several different values of σ (≡ β) in the original distribution, taking a = 0.3.

It is seen that the resulting transformed curve does not generally follow a simple distribution, especially at small σ. However, within certain ranges of parameters σ and a, the transformed curve can be reasonably approximated by the lognormal distribution. For instance, if β = 0.57 is used for the original un-transformed distribution, the corresponding fragility curve for random earthquake directivity is closely approximated as lognormal with median X = 1.51 times the median in original distribution and β = 0.70.

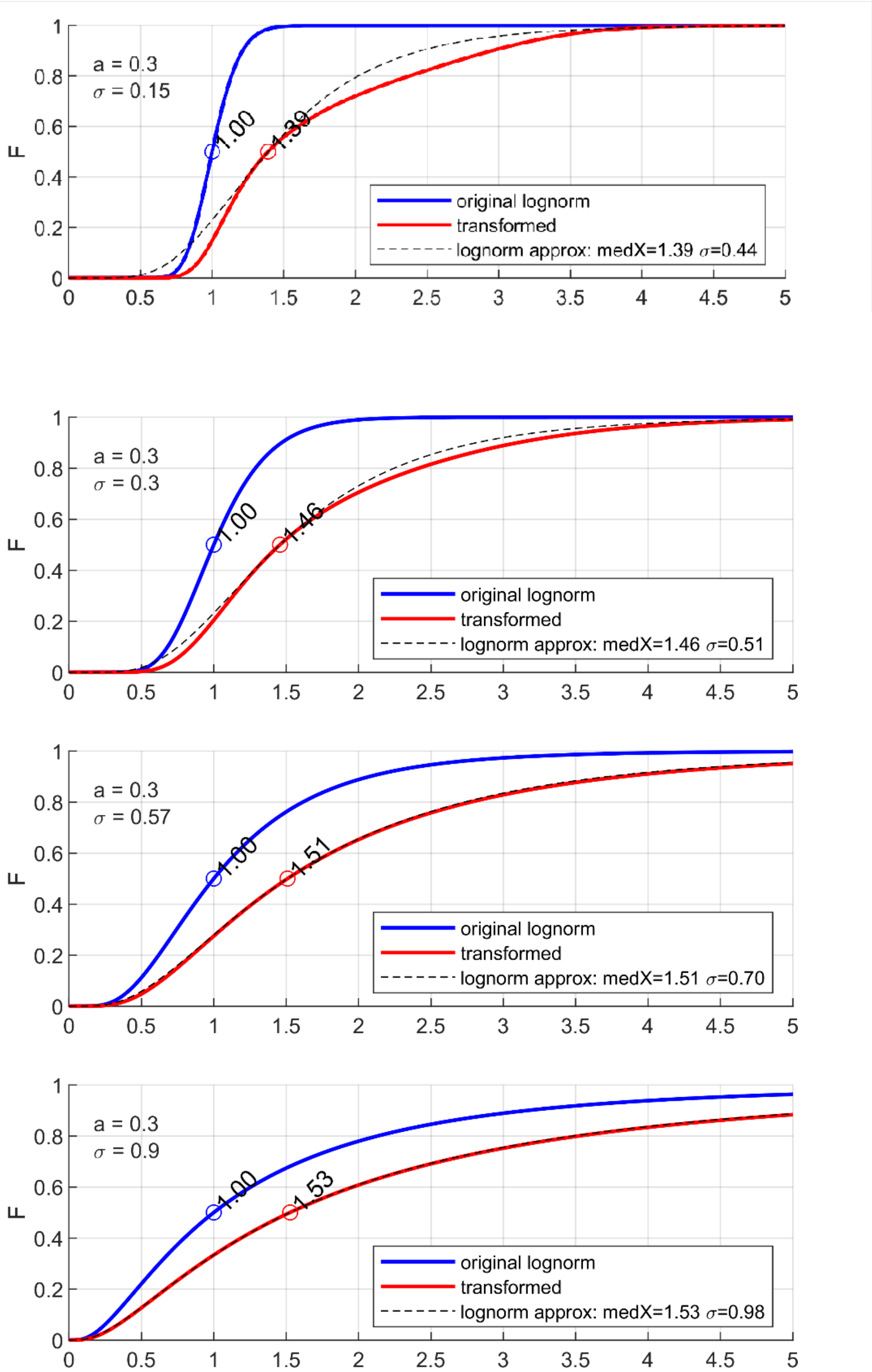
For example, for 230x1000 parapet in a 1-storey building, allowing for random directivity produces the curves shown in APPENDIX FIGURE 34.



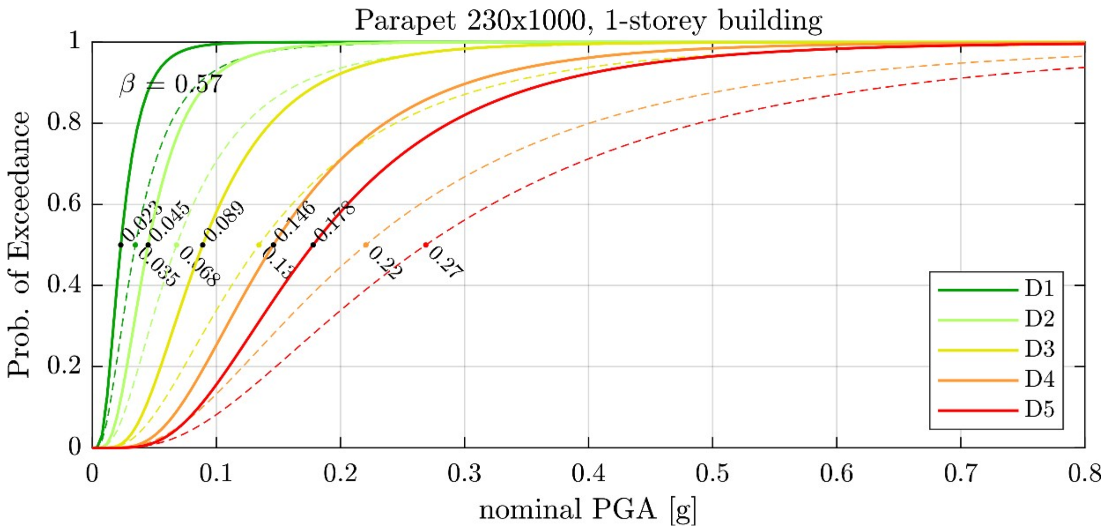
APPENDIX FIGURE 31 Rotation of ellipse by θ = 30 deg.



APPENDIX FIGURE 32 Plots of ex vs rotation (left) and multiplier (m) vs rotation (right).



APPENDIX FIGURE 33 Transformation of probability distribution to allow for random ground motion directivity on the out-of-plane wall. Shown for different σ (≡ β).



APPENDIX FIGURE 34 Example showing transformed curves allowing for random motion directivity plotted by dashed lines. Original curves shown as thick solid lines.

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