Economic Analysis of New Zealand's **Earthquake-Prone Buildings**

Prepared for Ministry of Business, Innovation & Employment

Prepared by Beca Limited

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Contents

Appendices

Revision History

Revision Nº	Prepared By	Description	Date
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Document Acceptance

Action	Name		Date
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Executive Summary

The objective of this project has been to investigate the relationship between cost and benefits to further inform decisions on the earthquake-prone building policy and methodology, primarily in its current state.

The project has considered the costs and benefits of no upgrade, strengthening to 34*%NBS* and also to 67*%NBS* for currently identified earthquake-prone buildings in six population centres: Auckland, Whanganui, Feilding, Wellington, Christchurch, Dunedin, for shaking levels with annual probability of exceedances (APoEs) of 1 in 100, 250, 500, 1000 and 2500. It is expected that the impact on the six centres, which include large and smaller communities, could be extended to other similar communities across New Zealand, but this is beyond the scope of this project.

The methodology employed has considered the following aspects for each centre:

a) Establishing the inventories of current earthquake-prone buildings and the characteristics of the ground on which they sit.

b) Determining the different building structures and categorizing these into 10 generic types (typology).

c) For each generic structural and ground type establishing what physical works are required to structurally upgrade a building to 34*%NBS* and to 67*%NBS*.

d) Establishing the indicative cost for each upgrade option, physical works and disruption costs.

e) Estimating the occupancy for each type of building and number of pedestrians that could be affected by building damage in the evening and during the day.

f) Establishing the expected levels of shaking for each APoE for each ground type using the latest seismic hazard estimates (NSHM2022).

g) Estimating the relationship between shaking levels and building damage and also between damage and repair costs, business downtime, potential lives saved, and injuries prevented, for each structural type.

h) For each APoE, utilise standard risk/loss procedures to estimate the consequences for each earthquake-prone building type in terms of repair, business downtime, potential fatalities and injuries.

i) Accumulate the impacts on all buildings for each APoE for each centre.

j) Ability to "Test" the impact of various input assumptions using an interactive dashboard.

The results of a) to d) represent the assessment of indicative costs and e) to j) represent the assessment of the estimated benefits (avoidance of loss). The ratio of the two provides the APoE benefit-cost-ratios that are the outputs of this project.

It is important to note that the unique APoE approach outlined above does not provide a benefit to cost outcome that is the same that would be obtained from a traditional cost-benefit analysis (CBA), nor can it be directly compared with the impacts from actual earthquakes. . This difference has been reflected in the definition of an APoE benefit-cost-ratio for this project.

The explanation of the difference is as follows:

- **APoE benefit-cost-ratios** do not incorporate discount rates, and probabilities are excluded, resulting in larger ratios that are not comparable to traditional BCRs. However, they offer useful insights into examining different level of severity of the shaking ranging from small to large for each centre. Results of the APoE benefit-cost-ratios are presented in Section 6.0.
- **The traditional BCR** is the sum of the benefits of each APoE are annualised and multiplied with their probability rates and entered for every year but discounted using chosen discount rate. Results of the Traditional BCR are presented in Appendix A.

The limited time available to complete the project has necessitated the use of existing information as far as practicable possible. This has been extended, when necessary and possible, by the application of judgement and comparisons with existing studies and data from earthquakes both within New Zealand and internationally.

In conjunction with this report, a dashboard was developed explicitly for MBIE use only, enabling users to test results based on a range of input assumptions and their various combinations. However, care should also be taken when using the dashboard and users are referred to the warnings provided within this.

It will be apparent that there are many assumptions made in such a methodology and uncertainties and ranges in inputs at every step, some large for critical inputs. Caution is recommended when interpreting the actual costs and benefits that have been determined. It is the relative results and trends observed between different options for increasing severity of the shaking, the characteristics of different centres, and different types of structure that is the prime output from this project.

It is recommended that reference be made back to the project team before any decisions are made based on the results presented in the report to confirm that interpretations being made are appropriate. This is particularly the case when reliance is being made on the results from the dashboard.

The key observations from this project are:

Inventory

1. The relative proportion of building types within a centre has a significant effect on the benefits (losses prevented), i.e. a high proportion of Unreinforced Masonry (URM) buildings leads to higher people related benefits.

Retrofit Costs

2. The scope of work required and therefore cost of retrofitting URM buildings to achieve 34*%NBS* is approximately 30% greater in high seismic zones than for low to medium seismic zones.
3. The relative regional cost variance for similar retrofit in Feilding, Whanganui, Dunedin, Christchurch, Wellington and Auckland was found to be in the ratio of 1.08, 0.94, 0.76, 1.00, 1.18 and 0.87 respectively.
4. It costs approximately twice as much to achieve 67*%NBS* as 34*%NBS*. This was found to be valid for all centres.
5. When there is a step change in structural scope to achieve 34*%NBS* or 67*%NBS*, such as foundation work, this has a much more significant impact on costs.
6. Caution needs to be applied when reviewing the costs as data outliers can significantly skew the results. This applies, in particular, to buildings with large gross floor area (GFA) and those that have a specific use, such as hospitals and education facilities.
7. The spread of costs per building type for our reference buildings was large. For example, the current costs to achieve 34*%NBS* in Wellington was estimated to range for the different types between NZ$700-$3,000/m^2.

Fragility/Damage Vulnerability Modelling

8. The calculation procedure adopted to determine the damage expected from a given level of shaking provided results that compared well with actual available New Zealand and international data.

Occupancy Estimates

9. The loss estimates were to be sensitive to the estimates of the numbers of people within and outside buildings at various times of the day. For instance, overestimating occupancy rates in low-use buildings—such as workshops, suburban corner shops, resulted in inflated loss projections.

Consequence Modelling

10. The loss estimates also proved to be sensitive to the assumed relationship between building damage and the effects on people both inside and outside buildings. For example, parts of brick buildings such as parapets and façade that fail outwards versus multi-storey non-ductile concrete buildings that potentially cause more casualties inside a building.

APoEs

11. Shaking levels for an APoE of 1 in 500 for Wellington are similar to those with an APoE of 1 in 625, 1250, 2500, 5000 and at least 10,000 for Fielding, Whanganui, Christchurch, Dunedin and Auckland respectively.

APoE benefit-to-cost Ratios

12. The APoE benefit-to-cost ratios determined for strengthening in Auckland for an APoE of 1 in 2500 are similar to those calculated for Wellington for an APoE of 1 in 500 but with 2.5 times more buildings.
13. The APoE for Auckland would need to be in the order of 1 in 5000 before the APoE benefit-to-cost ratio is estimated to be higher than 1.
14. The benefit-cost-ratios for Dunedin and Whanganui are high for all APoEs as the people-related benefits are high due to numbers of URM buildings.
15. Dunedin indicates comparatively high levels of benefits due to a large proportion of URM and stone buildings. This, together with the 160% increase in hazard above previous estimates and the relatively low basis for the retrofit schemes, results in higher levels of vulnerability for Dunedin compared with the other centres.
16. Dunedin has elevated risk due to people related losses exceeding Christchurch. At an APoE of 1 in 1000 both indicate a $17bn loss but Dunedin has160 earthquake prone designated buildings whereas Christchurch has 415.
17. 34*%NBS* retrofit reduced people-related losses by 60-80% in relation to the status quo in all centres except Wellington where a 40% reduction was indicated due to Wellington’s higher seismic hazard.
18. For Auckland the benefits increase rapidly (by a factor of 6 or more) for an increase in shaking from an APoE of 1 in 500 to 1 in 2500. The rate of increase could be expected to be higher if the shaking level increases to 1 in 5000, or greater. This could be relevant when considering the potential impact of very rare but potentially high impact/consequence events.

Energy Efficiency Measures

19. Inclusion of energy efficiency measures such as insulation upgrades, lighting efficiency reduces the benefit cost ratios as the required additional cost exceeds the additional benefits (e.g. reduced operational energy cost savings) that are available.

Traditional BCR

20. For retrofit to 34*%NBS* the BCR is calculated to be approximately 5 for URM in all centres, except for Auckland where the BCR is less than 1. The BCR is the highest for Whanganui.
21. The BCR for retrofit to 34*%NBS* is approximately twice that for 67*%NBS* for all centres except for Wellington.

Areas for Further Work

22. There are important wider socio-economic aspects that were unable to be included in this project. For this reason, future decision-making should not solely focus or rely on the BCRs that are presented but should also incorporate socio-economic aspects and recovery potential, which were not explored in this project. Historically, marginalised and vulnerable communities have faced disproportionate impacts from earthquakes and other natural hazards. There is a need to link the results from this project with socio-science research like the work by Sabine Loos (University of Michigan) and NZ socio scientists. Our recommendation is to investigate this socio-science aspect further.

1 Introduction

The project involved four key steps: developing the stock inventory, estimating costs of retrofits, creating fragility and risk models, and analysing benefit streams. The stock inventory of earthquake-prone buildings was created, building typologies were defined, and retrofit concepts for 34*%NBS* and 67*%NBS* were developed and tailored to each location, and cost estimates derived. Fragility functions and consequence models were combined to evaluate damage, people and economic impacts as well as non-financial impacts, while a dashboard was created to support APoE-based cost-benefit analyses with sensitivity checks of uncertainties. Refer Figure 1.3: Outline of process

1.1 Scope of Review

In June 2024, the Ministry of Business, Innovation and Employment (MBIE) commenced a review of the management of seismic risk in existing buildings in New Zealand. The purpose of their review is to ensure seismic risk in existing buildings is being managed effectively and in a workable, equitable and proportionate way. There are two main workstreams of MBIE's review; referred to as the 'current state' and the 'future state'. The current state workstream considers how seismic risk is currently being managed in existing buildings, including through the earthquake-prone building system. The scope of this review is included within a part of the 'current state' workstream and has been requested to be a APoE based economic analysis of the current earthquake-prone building system in New Zealand.

1.2 Regulatory Framework

The New Zealand Building Act 2004 is the primary legislation that governs the building regulatory system in New Zealand. Section 133AA defines the scope of earthquake-prone building (EPB) provisions, specifying which buildings can be identified as potentially earthquake-prone. Section 133AB defines what constitutes an earthquake-prone building.

1.2.1 The Building (Earthquake-prone Buildings) Amendment Act 2016

The Building (Earthquake-prone Buildings) Amendment Act 2016 describes a national system of how earthquake-prone buildings are identified and managed under the Building Act 2004. It uses knowledge learned from past earthquake in New Zealand and overseas. The system is consistent across the country and focuses on the most vulnerable buildings.

The structure of the system for managing earthquake-prone buildings is shown in Figure 1.1.

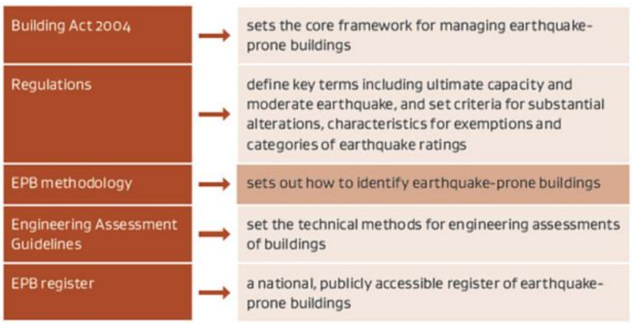


Figure 1.1: The structure of the system for managing earthquake-prone buildings (source: www.building.govt.nz/building-code-compliance)

The system was established to manage seismic risk by aiming for consistency in how earthquake-prone buildings are identified and managed, balancing safety, costs, and the preservation of heritage buildings. As part of this system a methodology was developed for establishing potentially earthquake-prone buildings, and is set out in the MBIE prepared document *EPB Methodology: The Methodology to Identify Earthquake-prone Buildings*.

1.2.2 Earthquake-prone building categories

The Territorial Authority (TA) play a critical role by identifying potentially EPB buildings, requiring owners to address the EPB notice within timeframes that vary according to regional seismic risk, with high-risk areas like Wellington and Hawke's Bay facing stricter schedules. This framework primarily targets three types and are categorised as follows:

- Category A: Unreinforced masonry buildings
- Category B: Pre-1976 buildings that are either three or more storeys, or 12 metres or greater in height above the lowest ground level (other than Category A)
- Category C: Pre-1935 buildings that are one or two storeys in high and medium seismic risk areas (other than Category A).

The TAs must identify potentially earthquake-prone buildings that fall within the categories.

More information on the current system can be found on MBIE's Building Performance website here:

https://www.building.govt.nz/managing-buildings/managing-earthquake-prone-buildings/how-the-earthquake-prone-building-system-works

1.2.3 Earthquake-prone Buildings Register

All of the earthquake-prone buildings are held on a national register, which is publicly available on MBIEs website here. The EPB register provides information about buildings that territorial authorities (TAs) have determined to be earthquake-prone. The register is updated progressively in the timeframes defined in the Building Act 2004.

The register contains the minimum amount of information that is publicly available: Address, building name, notice type, date of notice, earthquake rating, deadline for completing seismic work, priority building status, TA the notice has been issued by and heritage status.

1.2.4 Priority Buildings

Priority buildings are certain types of buildings in high and medium seismic risk areas that are considered to present a higher risk because of their construction, type, use or location. They need to be identified and remediated within half the time allowed for other buildings in the same seismic areas. Some hospital, emergency and education buildings are prioritised in the Building Act because of their function.

1.3 Methodology Overview

The Government has called for an independent economic analysis to assess the current system of remediation for earthquake-prone buildings (EPB) in New Zealand which is described in this report. This economic analysis has employed a APoE-based approach to better evaluate the costs and benefits of seismic strengthening, aiming to improve understanding and regulation in this critical area. The analysis completed acknowledges the substantial immediate and long-term impacts of low-likelihood, high-consequence events of strong earthquakes. The assessment also looked at a broader outcome such as operational energy efficiency to potentially capture the full benefits of seismic retrofits and wider priorities in the area of energy efficiency retrofits.

This document has been prepared to record the methodology and outcomes from the economic analysis from this project. To enable an analysis to be completed within the set timeframe of six months, a level of pragmatism and efficiencies within the methodology have been adopted. This includes utilising existing research for fragility curves, retrofit techniques, established methodologies and developing tools to sort large data sets. Broadly, the methodology has followed the process shown in Figure 1.2:

Step 1: Understand the EPB inventory

Step 2: Identify 10 building typologies

Step 3: Identify cost:
- Retrofit (34% and 67%*NBS*)
- Carbon
- Replacement (structural and contents)
- Energy Efficiency upgrade

Step 4: Quantity benefits of upgrades using consequence models per each scenario APoE and each location:
- Direct and indirect business disruption
- Casualties and injuries
- % fraction of replacement

Step 5: Adjustment moving from single building to cities

Step 6: Monetise impact (0-2% discount rate) over 0 life of project (no time laps)

Step 7: Compare cost and benefits per scenario

Figure 1.2: Outline methodology

In more detail the key steps include:

- **Inventory Creation:** A stock inventory was created based on current earthquake-prone building lists for the six nominated locations. While additional earthquake-prone buildings may exist in these areas, they were deemed beyond the scope of this investigation.
- **Building Details:** Relevant details of the identified buildings—such as size, use, occupation, and foundation soils—were obtained from available sources, including TA records, Google Street View, and enhanced tools such as QuakeCore maps.
- **Building Typologies:** 10 building types were defined across all locations based on vulnerabilities, structural characteristics, occupancy classes, and other factors. Representative (case study) examples of

each building type were selected for detailed analysis. Where applicable, generic structural systems were considered to extend findings across broader inventories.

- **Retrofit Concepts:** A retrofit concept was developed for each of the 10 building types for both the 34*%NBS* and 67*%NBS* level for all six centres by structural engineers for each building example across the different locations, accounting for the varying seismic hazard. These designs included sufficient detail to support costing and the development of collapse and damage models.
- **Cost Estimation:** Cost data was provided for reference replacement costs and retrofit implementation costs for each of the 10 building types. When variations were significant, cost estimates were tailored to individual locations. Fit-out replacement costs were also assessed to evaluate non-structural losses and repair expenses against losses calculated as a percentage of replacement costs.
- **Fragility Curves:** 30 fragility functions were developed to estimate the probability of damage (three states) and collapse for each building type for "no upgrade", 34*%NBS*, and 67*%NBS* retrofit options. The process utilised a displacement-based approach to define fragility curves for each structural type using principals of the Engineering Assessment Guidelines(1) and NZ-specific data research, referencing New Zealand's fragility references. Comparisons were made with the HAZUS Technical Manual version 6.1, and fragility research papers summarising findings from the Christchurch earthquake CEBA database. A pragmatic approach was adopted to balance project constraints while ensuring robust outputs, with input from specialists and peer reviewers.
- **Intensity Measures:** Various Annual Probability of Exceedance shakings ranging from 25 to 2500 years were selected for each location based on the latest New Zealand's National Seismic Hazard Model 2022 (NSHM2022).
- **Consequence Models and Loss Estimation:** Fragility curves were combined with consequence models to estimate damage associated with each APoE state, including casualties, injuries, repair costs (as a fraction of replacement), and other impacts.
- **Scaling from individual to totals for each location**: Adjustment moving from individual building to total of one building type to total EPB stock for each centre.
- **Economic Study (total Benefit and Cost):** Economic analyses were conducted using techniques similar to those suggested in NIBS 2019, Noy & Uher paper (2022), and The Treasury's CBAx tool. The economic analysis has used no discount rate for the APoE levels. A 2% discount rate is only applied for the consideration of energy efficiency. This is because the use of the APoE approach essentially abstracts from time, so the analysis of economic costs and benefits are not very sensitive to the discount rate chosen. This is considering sustainability impacts, community effects during and after seismic events, as well as implications for owners, occupiers, local communities, regional stakeholders, and national interests. The integration of retrofit measures with upgrades such as energy efficiency improvements was also considered.
  - APoE benefit-to-cost: no discount rate used (abstract from time)
  - Energy Efficiency: 8% discount rate also tested at 0%, 2% and 5%
  - Traditional CBA: 2% base plus sensitivity using 8% discount rate
- **Data Integration and Dashboard Development**: All the data and processes were combined in a Python script. The results were then embedded into a dashboard which was developed to support APoE-based cost-benefit analyses and simplified presentation. This dashboard facilitated sensitivity checks on key variables such as discount rates, economic life assumptions, cost escalation factors, and probabilities of damage or collapse. The dashboard has been designed for MBIE internal use only and should always be used with care and a full appreciation of the underlying methodology and assumptions.

The general pross adopted for this project is outlined in Figure 1.3

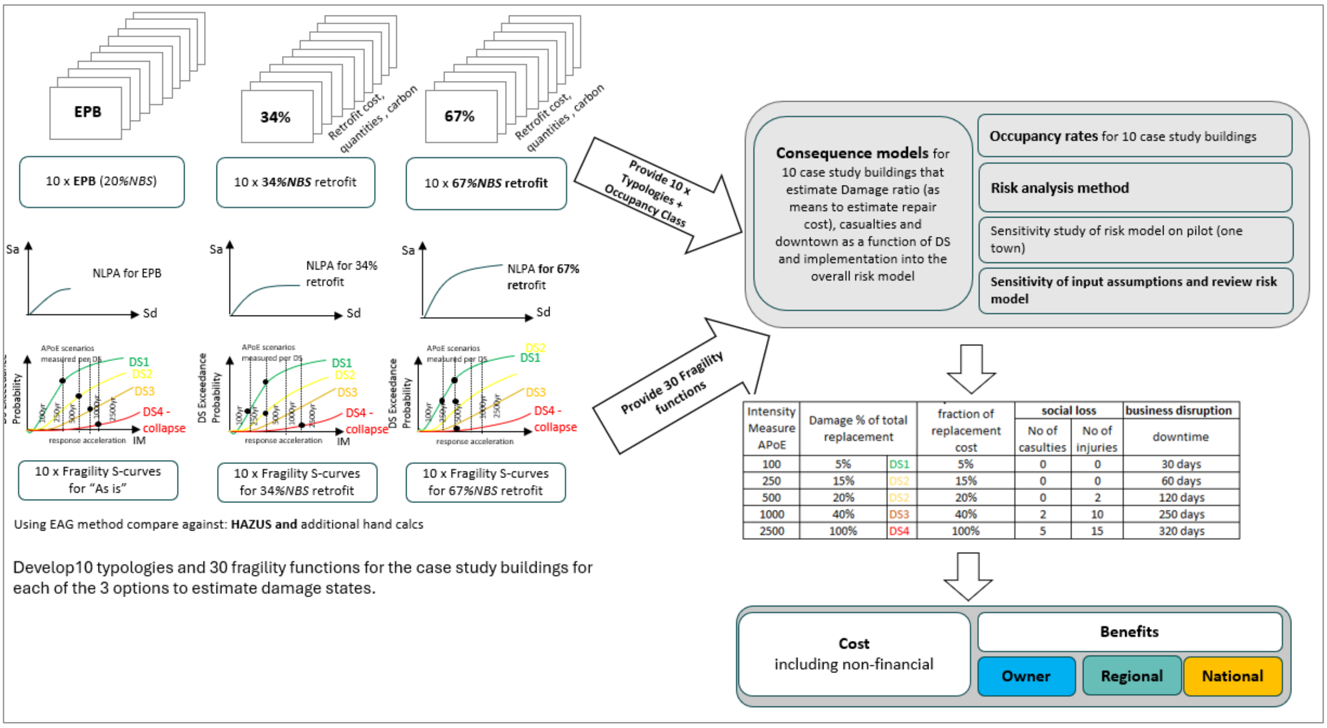


Figure 1.3: Outline of process adopted for the project

1.3.1 Why this is not a traditional CBA

This project is based on a novel methodology; looking at total benefits versus total costs at a city level based on the APoE of the shaking and the assumption that all buildings are similarly affected. It assumes that any retrofit and the shaking associated with the APoE occurs in the same year. It is therefore not equivalent to a traditional CBA which accounts for the time value of the costs and benefits and is annualised using the probability rates.

This project provides insights into the impacts of different APoE shaking levels, including for low probability, high consequence events. It is estimating the "average" impacts on the inventory over a long period of time.

1.3.2 What is the difference between the APoE and a Seismic scenario approach

The ApoE approach is not the same as considering the losses during a true scenario event where an event is targeted at a given probability of exceedance and epicentre, and the shaking varied to represent the different levels of shaking that might be estimated at different building locations.

The scenario approach might allow direct comparisons with the results from actual earthquakes but is very dependent on the choice of scenario to understand the implications of decision making. It might be considered that the results from combining multiple scenarios will be represented by the results for the APoE approach that has been undertaken here.

It is felt that the APoE approach might better represent the benefit to cost ratios that should be considered for decision making around rare but high consequence shaking. It is also better aligned to the decision process that underlies the standards that are required for new buildings.

1.4 Definitions and Acronyms

(New Zealand) Building Code	Section B1 of the New Zealand Building Code Schedule 1 to the
APoE	likelihood of earthquake shaking of a certain level occurring within • 1:100 earthquake shaking has an annual probability of • 1:2500 earthquake shaking has an annual probability of It is a statistical average based on historical data and modelling.
BCR	Total benefits to total cost. Cost includes upgrade cost to related loss, property related repair works and downtime / business
APoE benefit to cost ratios	A study special term 'APoE benefit-to-cost ratios' was introduced to refer to the total benefit-to total cost ratios for this APoE approach. probabilities are excluded from consideration. Their value is expected to be much larger compared to a traditional BCR and cannot be directly compared. This ratio abstract from time means future costs or benefits are treated at face value, as if they have the same weight
Building Element	Any structural or non-structural component and assembly incorporated into or associated with a building. Included are fixtures,
Damage Ratio (DR)	
Detailed Seismic Assessment (DSA)	A quantitative seismic assessment carried out in accordance with Part A and Part C of the *Engineering Assessment Guidelines*.
Downtime	Measure of average time that the building will not be at 100% of its intended functionality. Based of HAZUS and NZ based data. Includes time for engineering assessments, claims assessment, claims negotiation, repairs/demolition, rebuilds. Estimate is average time in days.
Earthquake prone Building (EPB)	Has the scope defined in section 133AA and the meaning defined in section 133AB of the New Zealand Building Act 2004, and explained in Section A5.1.1 of the *Engineering Assessment Guidelines*.

Earthquake rating	The rating given to a building as a whole to indicate the seismic standard achieved in regard to human life safety compared with the minimum seismic standard required by the NZ Building Code of a similar new building on the same site. Expressed in terms of XXX*%NBS* (percentage of the minimum standard required. The earthquake rating for a building as a whole takes account of, and may be governed by, the earthquake scores for individual building elements. For earthquake-prone buildings the earthquake rating has
EPB register	A national, publicly accessible register of earthquake-prone buildings. The earthquake-prone building system is a national system Act 2016 that regulates how seismic risk is identified and remediated in the most vulnerable existing buildings. territorial authorities identify
The Engineering Assessment Guidelines (EAG)	*Engineering Assessment Guidelines*, specifically *The Seismic* *Engineering Assessments*, dated July 2017. These set the technical methods for engineering assessments of buildings , also known as
GFA	Gross Floor Area (m^2)
Importance Level (IL)	Categorisation defined in the New Zealand Loadings Standard, AS/NZS 1170.0:2002 used to define the Ultimate Limit State (ULS) shaking for a new building based on the consequences of failure. A critical aspect in determining the earthquake rating. Normal buildings like offices are Importance level IL2. Importance level IL3 are governed by crowds (>300 people) like larger halls, cinema or swimming pools. Importance level IL4 are buildings with post-disaster functions such as hospitals or substations.
Initial Seismic Assessment (ISA) and **Initial Evaluation Procedure (IEP)**	The ISA using the IEP method is a qualitative assessment. A seismic assessment carried out in accordance with Part A and Part B of the EAG. An ISA is a recommended first qualitative step in the overall assessment process.
Internal Rate of Return (IRR)	The Internal rate of return (IRR) is a method of calculating an investment's rate of return. More specifically it is the breakeven discount rate where the net present value (NPV) of the discounted costs and benefits are equal. This is similar to the social return on investment discussed on p18 of the New Zealand Treasury's CABx guidance https://www.treasury.govt.nz/publications/guide/cbax-tool-user-guidance
Inherent Capacity Factor (ICF)	A study specific term, is the 'overstrength' of the existing structure allowing to relate scaling from ultimate limit state to collapse margin
Moderate earthquake (shaking demand)	Has the meaning defined in the Building (Specified Systems, Change the Use, and Earthquake-prone Buildings) Regulations 2005 (as amended).
Net Present Value (NPV)	Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. NPV, or net present value, is how much an investment is worth throughout its lifetime, discounted to today's value.

Occupancy Models	Peak: Expected maximum of people at any time under normal use. Average: Average occupancy rate when averaged over time (hourly time slices). Please note for this study two events were considered. One occurring at night and one occurring during daytime.
Territorial authority (TA)	Territorial authorities, NZ's local councils have a key role as part of the EPB system to identify potentially earthquake-prone buildings. TA's determine whether buildings are earthquake-prone, assign ratings, issue notices, and publish information about the buildings in a public register owners display notices on their building regarding its status as earthquake-prone and remediate the building within specified timeframes
Ultimate limit state (ULS)	A limit state defined in the New Zealand loadings standard NZS 1170.5:2004 for the design of new buildings
(XXX)%*NBS*	
URM	Unreinforced masonry or brick
Hazus	Loss estimate methodology as defined in *Hazus Inventory Technical Manual*, version 6.1 November 2022.
QuakeCore	Opensource for soil shear wave velocity data of V_{s30}

2 Building Inventory

2.1 Overview

This project only considers the earthquake-prone buildings that have already been designated within the six nominated towns (population centres).

2.2 Source for Building Inventory

This project uses building inventory data sourced from the earthquake-prone building (EPB) register (https://epbr.building.govt.nz/) as of 25 November 2024, focusing on addresses with current EPB status. After confirmation with territorial authorities (TAs), and resolution of discrepancies due to demolitions, remediations, and duplicate entries, the final inventory includes 2,570 buildings across the six locations.

The distribution is shown in Table 2.1

Table 2.1: Summary of inventory per location

Location		Nº of buildings
Auckland	AKL	1,351
Wellington	WEL	540
Christchurch	CHC	415
Dunedin	DUN	160
Feilding	FEI	77
Whanganui	WHA	27
		2570

Not all TAs have completed their Earthquake-Prone Buildings (EPBs) identification, particularly for the lower seismic zones where the deadlines for this activity have not yet been reached.

The earthquake-prone buildings are the most vulnerable ones, which only represent a small portion of the stock of a typical New Zealand city, refer Figure 2.1.

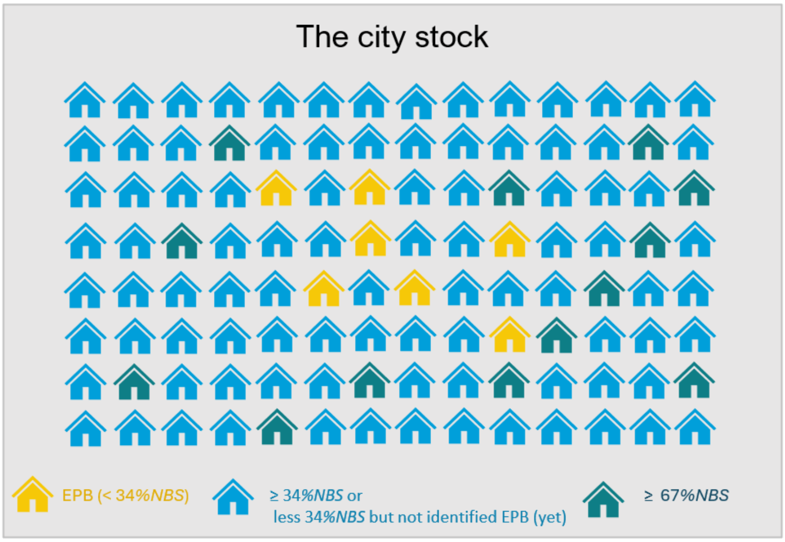


Figure 2.1: Indicative distribution of earthquake-prone buildings over entire city stock

For example, 540 earthquake-prone Wellington buildings are considered as part of this study, which is only approximately 6% of the city's total building stock of approximately 8,440 buildings.

This study presents results specifically related to the six locations and focuses solely on the small portion of earthquake-prone buildings. It does not encompass all of New Zealand or include every building within the nominated centres.

2.2.1 Building Inventory Exclusions and Clarifications

The following exclusions and clarifications apply to the building inventory.

- Wellington includes the catchment covered by the Wellington City Council. It excludes the greater Wellington regional areas, such as Porirua, Lower Hutt, Upper Hutt, Kapiti Coast and Wairarapa.
- Only those buildings with EPB status and on the EPB register are included. If there are other buildings that may be potentially EPB, but not on the register, then they are excluded from this study.
- There are some locations that have not yet exceeded the mandatory timeframe for TAs to identify potentially EPB based on the underlying seismic risk and building type (priority or other) as specified in section 133AG(4) of the Building Act. Therefore, the study only includes those buildings that have currently been identified.
- It excludes buildings that have at some time been removed from the EPB register either through demolition, strengthening or further engineering justification.

2.3 Information Extracted from Building Inventory Database

The minimum amount of information available from the EPB register is:

- Building address
- EPB status
- Construction type. Typically to align with the three categories identified within the EPB methodology
- Priority status
- Heritage status.

In some instances, additional information was made available by the TAs, including; age of construction, lateral load resisting system, number of storeys, Gross Floor Area (GFA), age of building and heritage status.

The following steps were taken when reviewing each building address:

- Identification of the predominant lateral load resisting system. Governed by the most vulnerable direction. This identification process adopted the hierarchy outlined below but was dependent on the information available.
  - Information provided within the TA inventory list
  - An aerial satellite and street view from GoogleTM Maps and Layers (Streetview)
  - Contact of a senior Beca engineer familiar within the region to see if they have knowledge of the specific building
  - Undertook eight site visits in Wellington and Christchurch to confirm estimated building's type
  - If neither of the above steps clearly identify the lateral load resisting system, an assumption will be made. Should more time have been allocated to this study, sourcing the original ISA or DSA held on the TA records could have been undertaken to confirm the lateral load resisting system. Alternatively, identified via a site visit.
- Identification of the typology category (refer also Building Types section for definition).
- Identification of the number of storeys, design date and Gross Floor Area (GFA) from either building inventory supplied data or Google TM. In instances where there is a discrepancy between the Google TM review or the TA list, the TA list will take precedence
- Identification the Occupancy Class as defined by Hazus. (Identification process included TA list and if no information available check against information available GoogleTM Maps and Layers (Streetview) and local knowledge. TA list governs.). Hazus is a risk assessment tool which contains generic data associated with assessing seismic related risks.

The detailed inventory list includes details such as:

- Building location (address, latitude, and longitude)
- Gross floor area
- Number of storeys
- Occupancy classification
- Type 1-10 allocation
- Year of construction
- Soil shear wave velocity V_{s30}
- *%NBS* if available, otherwise set as 20%
- Importance level IL2/IL3/IL4 if available
- Heritage Category if available.

The availability of building inventory data is summarised in Table 2.2.

Table 2.2: Attributes available from TA's registers versus data supplemented as part of this project

Attributes	Auckland	Wellington	Christchurch	Dunedin	Feilding	Whanganui
Street number	A	A	A	A	A	A
Street name	A	A	A	A	A	A
Suburb	A	A	A	A	A	A
Town/city	A	A	A	A	A	A
Notice types	A	A	A	A	A	A
Earthquake-prone status	A	A	A	A	A	A
%NBS rating*	P	P	P	P	P	P
Latitude/Longitude	A	A	A	A	A	A
Design date	A	A	A	A	A	A
Importance level IL2/IL3/IL4	S	S	S	S	S	S
Priority building	A	A	A	A	A	A
Priority routes	A	A	A	A	A	A
Heritage status	A	A	A	A	A	A
Foot traffic count	-	P	-	-	-	-
Typology	S	S	S	S	S	S
Primary lateral load resisting system	P	P	S	S	S	S
Number of storeys	S	S	S	S	S	S
Vs30 shear wave	S	S	S	S	S	S
Occupancy class (use)	S	S	S	S	S	S
Gross Floor Area (GFA)	S	S	S	S	S	S
Ground floor storey height	S	S	S	S	S	S
Building height	S	S	S	S	S	S
Building period (unstrengthened)	S	S	S	S	S	S
Ductility μ (unstrengthened)	S	S	S	S	S	S

A – available

P – partial info available. For some addresses a note whether "20% to less than 34%" or "0% to less than 20%".

S – supplemented

2.4 Building Types

2.4.1 Outline

The purpose of sorting the building inventory into various types is to categorise them by their structural features so that the required structural and economic analyses could be more practically completed. The building types have been split into 10 groups and represent a reasonable distribution of the various attributes governed by their primary lateral load resisting system. Each building type represents between 5-20% of the overall buildings by number.

Establishing the list of the ten types was based on a review of the building inventory list to establish trends in the data, a review of relevant research papers for typical structural vulnerabilities and engineering experience with these buildings

2.4.2 Establishing URM sub-categories

Unreinforced masonry (URM) buildings make up approximately 50% of the buildings on the EPB list across the six centres. Splitting the URM building types into further sub-categories warranted a focused review.

The (URM) category comprises predominantly low-rise (1-2 storeys) and are typically of modest floor area (approx. 500m^2 on average for low-rise buildings). However, there are some significant outliers with large gross floor area (GFA) and multiple storeys (up to six storeys) as demonstrated in Figures 2.2 and 2.3.

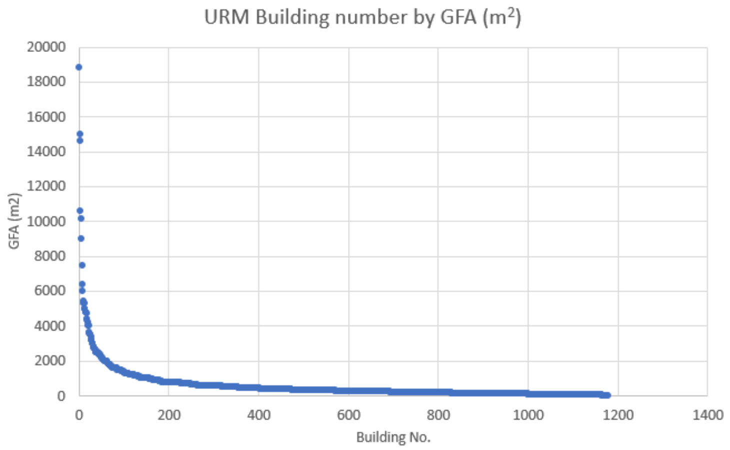


Figure 2.2: Distribution of URM Buildings by GFA across all centres

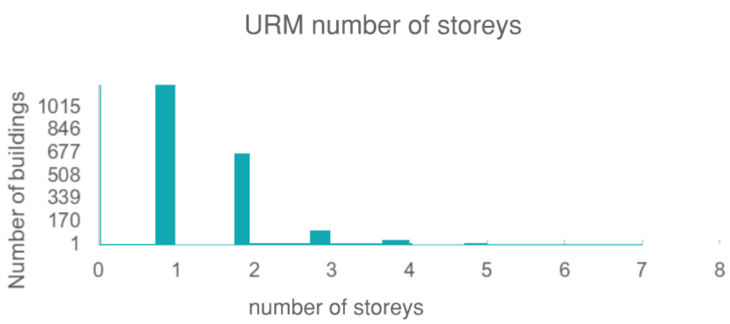


Figure 2.3: Distribution of URM Buildings by number of storeys. Across all centres

Figure 2.3 shows the distribution of buildings by number of storeys for each of the centres. This is in line with other published information about geometric characteristics of unreinforced buildings in Auckland and Dunedin that has been reviewed as part of this investigation [20].

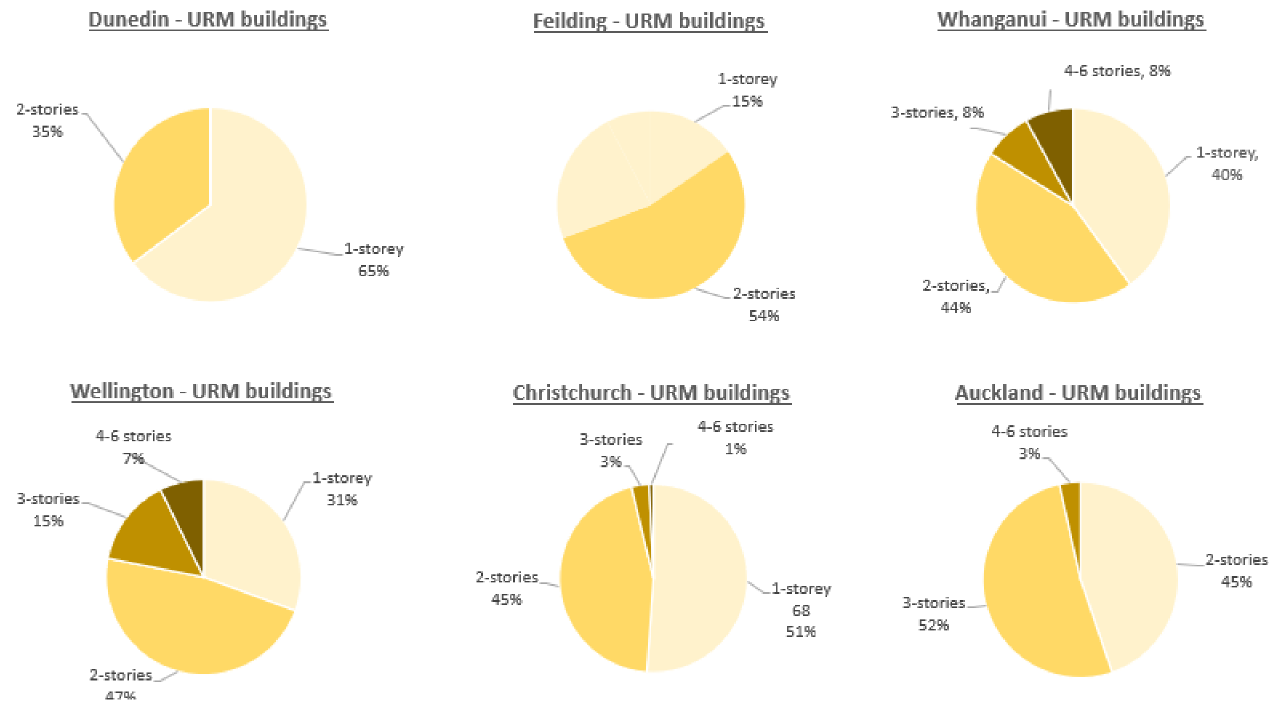


Figure 2.4: Distribution of URM buildings by number of storeys across the six centres

To better split the URM buildings into sub-categories, a review was undertaken on the building inventory data for the number of storeys and also by gross floor area GFA.

A review of the data, targeting approximately one third of each sub-category, provided the numbers shown in Table 2.3 (represented graphically in Figure 2.5) which gives the resulting representative split by number and gross floor area for each of the URM sub-categories.

Table 2.3: URM sub-categories targeting approximately one third by % GFA

Typology number	Description	Nº of buildings	% by number of buildings	Total GFA (m^2)	% by GFA
2	1 storey, GFA<2,000m^2	500	42%	134,000	19%
3	2+ storeys, GFA<2,000m^2	634	53%	311,000	45%
4	GFA >2,000m^2	58	5%	251,000	36%
	Total	1,192	100%	696,000	100%

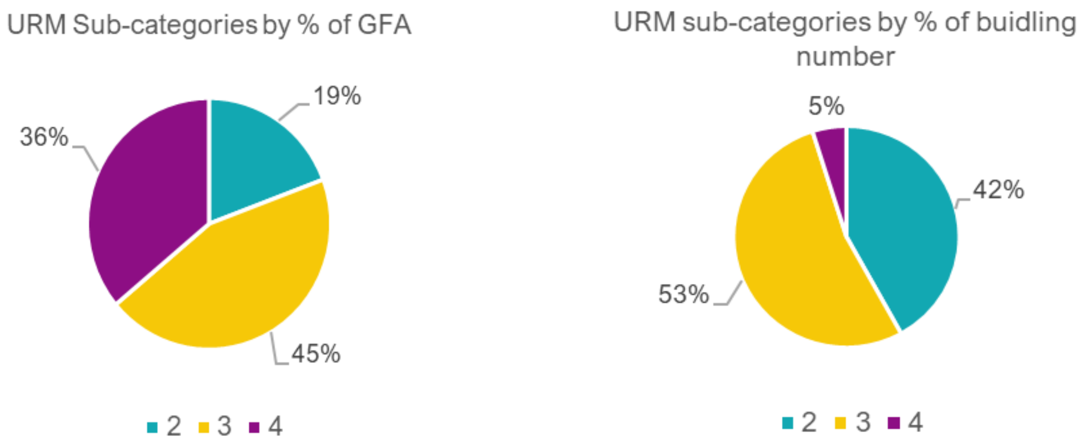


Figure 2.5: Graphical representation of the split of the three URM sub-categories GFA and number of buildings.

These findings are consistent with other surveys conducted on unreinforced masonry (URM) buildings in New Zealand. Refer Table 2.4, summarised from the 2014 research paper by Walsh, Dizhur, and Ingham [10].

Table 2.4 shows some of the statistical properties of the sub-category datasets. What is apparent is that splitting the smaller buildings (less than 2,000m^2) into two types has aided in grouping the datasets to have a tighter spread of GFA, but has revealed a wide data spread in Type 4, for the larger URM buildings (>2,000m^2).

Table 2.4: URM sub-categories by GFA with mean, standard deviation and 95% confidence interval

Type number	Description	Mean	95% confidence interval range	
			Lower bound	Upper bound
All URM	Combines 2, 3 and 4	590	520	660
2	1 storey, GFA<2,000m^2	270	240	300
3	2+ storeys, GFA<2,000m^2	490	460	520
4	GFA >2,000m^2	4,400	3,500	5,300

2.4.3 Uncertainties associated with the Building Typology Dataset

Where possible, we have attempted to remove uncertainties in the data set. However, the following uncertainties in establishing the building inventory dataset are noted:

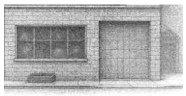
- Accuracy of the EPB list provided by the TA.
- Limitations with the accuracy of the gross floor area (GFA) measurements. There may be some error associated with digital measuring off the Google^{TM} aerial view. Data obtained using this method is only approximate.
- Uncertainties relating to establishing the lateral load resisting system. There may be instances where the lateral load resisting system will be approximated, due to it not being available from any other methods outlined in Section 3.3. This uncertainty is likely to predominately relate to reinforced concrete frame and reinforced concrete shear wall buildings. This is due to URM being obvious from external views and steel frame buildings being less likely, as they are not one of the Profile Categories in the EPB methodology.

For the purposes of inputting into the methodology, only the uncertainty in the URM datasets has been provided in this report.

2.4.4 Adopted Building Typology

Following the interrogation of the building inventory dataset the adopted building typology for this study is shown in Table . These types have been used across the analyses for all centres.

Table 2.5: The project typology represented as ten building types

	Structural System	Remarks	EPB Cat	Example	% of total	Occupancy Class
1	Light timber frames + URM elements	Pre-1935, 1-3 storey with URM elements such as brick party walls, chimneys	N/A		18%	30%RES+ 60%COM+ 5%EDU
2	Unreinforced Masonry (URM)	1 storey, GFA < 2000m^2	Cat A		19%	10%RES+ 70%COM (COM13 common)
3	Unreinforced Masonry (URM)	(3A) 2 storey, GFA < 2000m^2	Cat A		22%	70%RES+ 25%COM
		(3B) 3 - 7 storey, GFA < 2000m^2	Cat A		3%	
4	Unreinforced Masonry (URM)	(4A) 1 - 2-storey, GFA > 2000m^2	Cat A		1%	40%RES+ 35%COM+ 15%IND
		(4B) 3 - 7 storey, GFA > 2000m^2	Cat A		1%	
5	RC shear walls (low-rise)	1-2 storey, RC masonry block or walls	N/A		13%	20%RES+ 65%COM
6	RC shear walls (mid-rise)	≥ 3-storey high, RC shear walls, pre-1976, most 1960s	Cat B		2%	40%RES+ 45%COM+ 10%IND
7	RC frame with masonry infill	1-2 storey high, pre-1976	N/A		6%	25%RES+ 50%COM+ 15%IND
		3-6 storey high, pre-1976	Cat B		1%	
8	Pre-1976 RC frame	Mid-rise, 3-14 storeys high, non-ductile frame building with cast-in situ floors	Cat B		6%	20%RES+ 60%COM+ 15%IND
9	Post-1976 RC frame + precast flooring	2-14 storeys high, hollow core slab, precast cladding panels, ductile frames.	N/A		1%	10%RES+ 85%COM
10	Steel MRF + parts	Moment resisting frames, mostly industrial sheds with heavy cladding	N/A		7%	50%COM+ 40%IND

2.4.5 Overlaps of the 10 building types with EPB methodology categories

The comparison of the project building types with the EPB methodology categories and the resulting overlaps are shown in Figure 2.6.

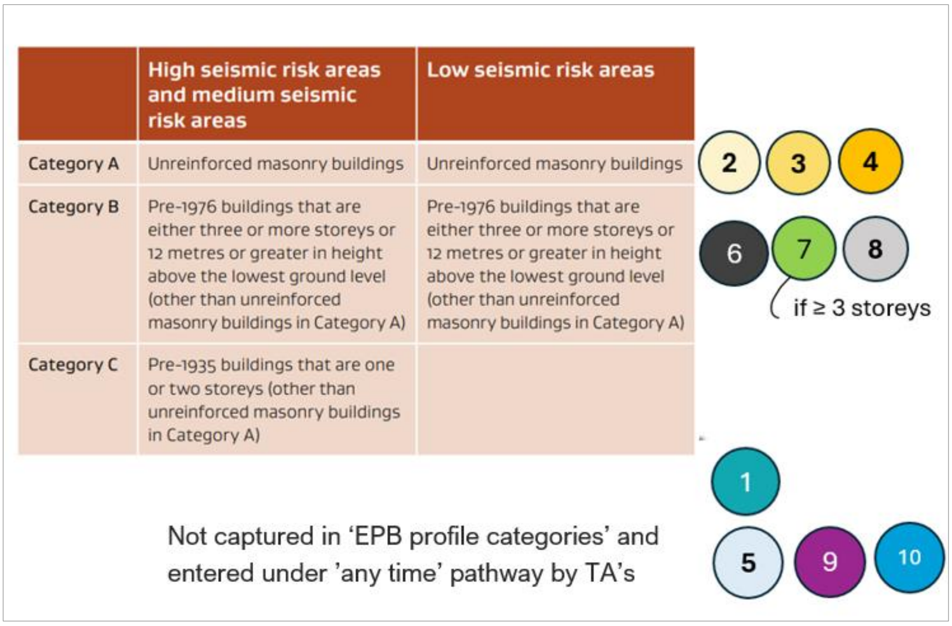


Figure 2.6: Overlaps of 10 types with three EPB profile categories

Certain building types (1, 5, 9, 10) do not fully align with the EPB profile categories and appear to have been classified under the 'any time' pathway. Territorial authorities use the EPB methodology to identify potentially earthquake-prone buildings through two pathways: either within set time frames based on 'profile categories' for specific building types or via the 'any time' pathway, which requires owners to provide engineering assessments.

Most of the buildings are low rise structures, and have 1 or 2-storeys, refer Figure 2.7.

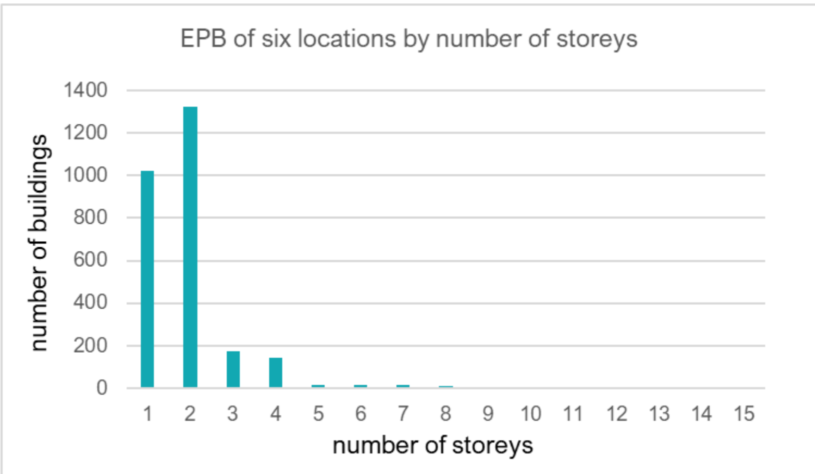
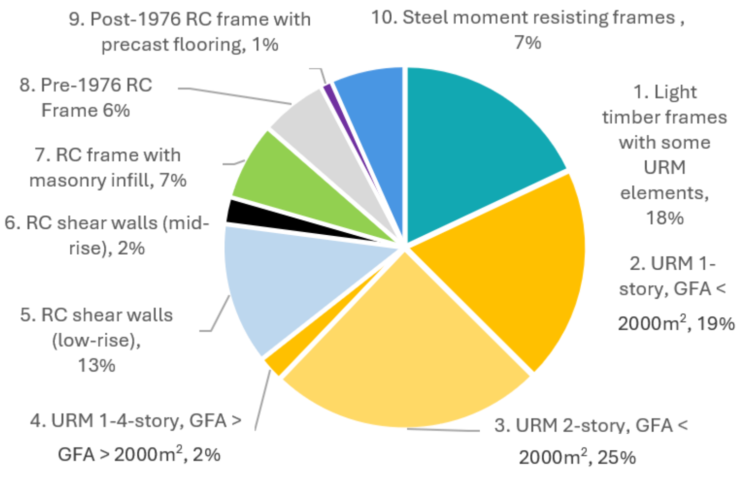


Figure 2.7: Number of storeys for all EPBs across the six centres

2.4.6 Distributions of building types

Figure 2.8 shows the final distribution of building numbers per type over all six centres.



1	Light timber frames + URM elements
2	URM 1-storey, GFA < 2000m^2
3	URM 2-4-storeys, GFA < 2000m^2
4	URM 1-4-storeys, GFA > 2000m^2
5	RC block walls (low-rise)
6	RC walls (mid-rise)
7	RC frame with masonry infills
8	Pre-1976 RC frame
9	Post-1976 RC frame + precast floor
10	Steel MRF + heavy cladding

Figure 2.8: Distribution of building types over all six Centres

Table 2.6 provides the distribution of building types for each of the centres which is shown pictorially in Figure 2.9.

Table 2.6: Distribution of Building Types for each centre

Typology		Auckland	Wellington	Christchurch	Dunedin	Feilding	Whanganui	total	% of total
1	Timber frames + URM elements	265	124	61	3	7	3	463	18%
2	URM 1-storey, GFA < 2000m^2	338	75	33	22	32	0	500	19%
3a	URM 2-storey, GFA < 2000m^2	382	66	16	74	8	17	563	22%
3b	URM ≥ 3 storey, GFA < 2000m^2	31	21	2	14	0	3	71	3%
4a	URM 1-2 storey, GFA > 2000m^2	12	4	3	7	0	1	27	1%
4b	URM ≥ 3 - 7 storey, GFA > 2000m^2	6	12	5	7	0	1	31	1%
5	RC walls (low-rise), 1-2 storeys	127	70	99	18	12	0	326	13%
6a	RC walls (mid-rise), 3 storeys	20	6	0	2	0	0	28	1%
6b	RC walls (mid-rise), ≥ 4 storeys	8	23	1	1	0	0	33	1%
7a	RC frame with masonry infills, 1-2 storey	52	38	34	3	4	0	131	5%
7b	RC frame with masonry infills, ≥ 3 storeys	15	23	5	5	0	0	48	2%
8a	Pre-1976 RC Frame, 1- 2 storey	43	13	32	0	5	0	93	4%
8b	Pre-1976 RC Frame, ≥ 3 storey	27	24	7	0	0	1	59	2%
9	Post-1976 RC frame w precast	4	8	14	0	0	0	26	1%
10	Steel MRF + heavy cladding	21	33	103	4	9	1	171	7%
	Total	1351	540	415	160	77	27	**2,570**	

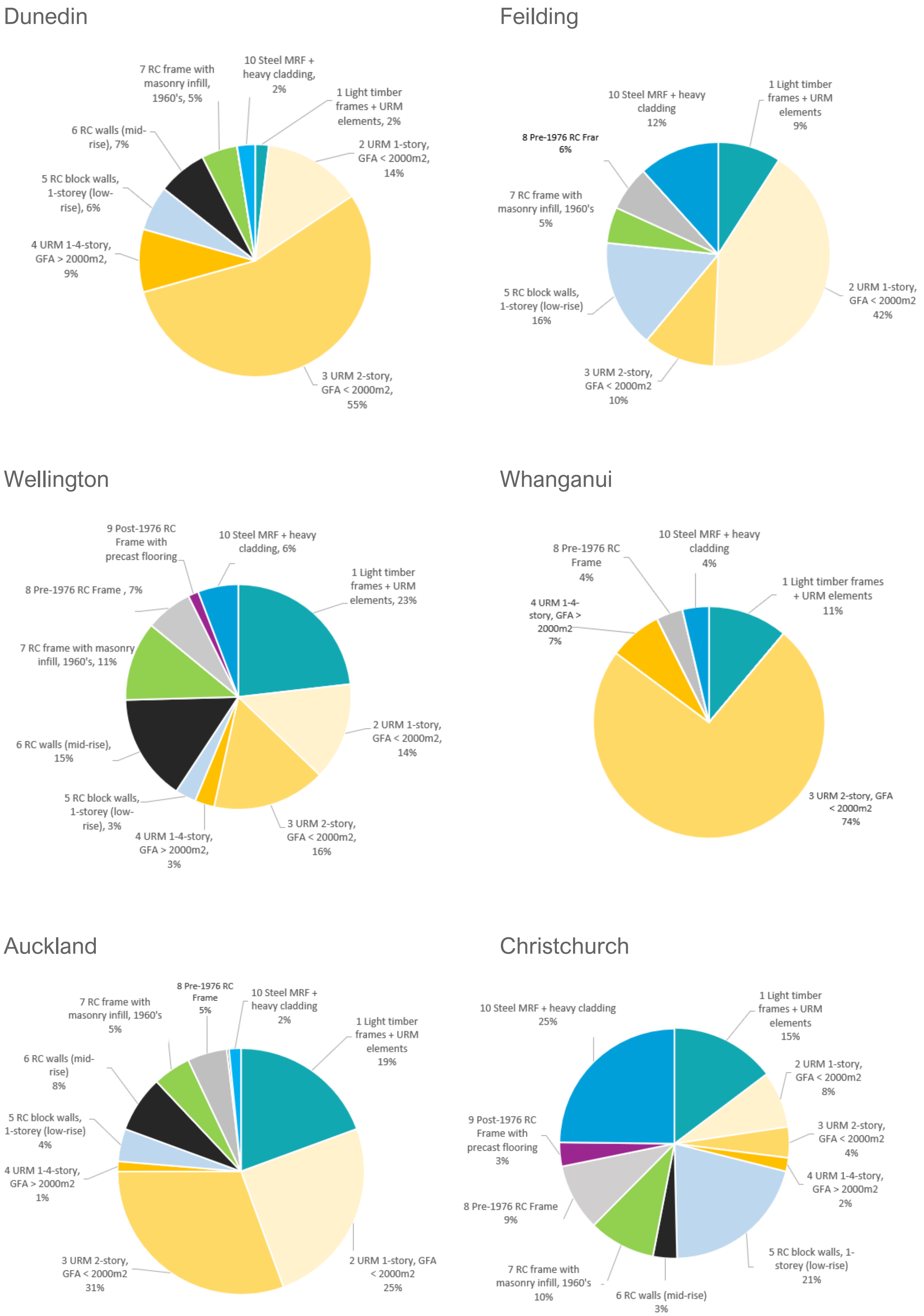


Figure 2.9: Pictorial distribution of building types for each centre

2.5 URM Features and Discussions

The building type 2,3 and 4 are discussed in Table 2.7.

Table 2.7 Building type characteristics

Type 2, 3 and 4: Unreinforced Masonry Buildings		
		**Type 2: One-storey isolated building** • Single storey isolated buildings often small GFA area and retail use type. This is the most common typology of buildings in the EPB stock of this study.
 	 	**Type 3: Two storey isolated buildings** • Multi-use primary level retail or restaurant, top floors residential use • URM walls and wooden floor construction • Often with URM parapet at street frontage • Commercial URM buildings in this class often with an open ground floor with a steel frame GFA area of 300-700m^2. • Residential URM, typically 1-2 storeys. • URM wall construction with flexible or rigid diaphragm, sometimes URM walls mixed with wooden wall construction.
		**Type 3 (cont'd): Two-storey row buildings** • Several URM buildings joint along the street • Often with a steel frame at ground floor along open shop frontage.
		**URM churches (Type 3 typical)** • URM churches often with towers and tall gable end walls and single storey, light or heavy roofs. • Only small portion of churches in the EPB inventory of this study.
		**Type 4: Multi-storey or Large GFA URM buildings** • A small portion of URM buildings of this EPB inventory of this study have a large gross floor area and are multi-storey construction. [Note: Images shown are generic, for illustration only; they are not real buildings.]

2.5.1 Vulnerability of URM Buildings

Cousins suggests that URM buildings are 5.4 times more vulnerable than post-1980 reinforced concrete (RC) buildings, based on the empirically based mean ratio of repair cost to replacement cost [10]. In comparison, pre-1980 RC buildings are the second-most vulnerable, with a vulnerability 2.3 times that of post-1980 RC buildings. As was evident by the building performance observed during the Canterbury earthquakes, URM buildings are very vulnerable. Past earthquakes in New Zealand have shown that damage typically first occurs to the appendages and ornaments of URM buildings within a community, particularly chimneys and parapets. For example, widespread chimney and parapet damage was observed during the 2007 Gisborne earthquake and the 2010 Darfield earthquake. At higher shaking intensities, significant out-of-plane response can occur. Refer Figures 2.10 and 2.11.

Figure 2.10: Post-22 February 2011 - collapse of outer leaf of cavity wall

Figure 2.11: Post-13th June 2011 – collapse of inner leave of cavity wall

2.5.2 Characteristics of URM Buildings in New Zealand

Russell and Ingham [10] have detailed the characteristics of unreinforced masonry (URM) buildings in New Zealand, grouping them into several categories They suggest that the nation's stock of URM buildings is relatively homogeneous, with most structures sharing a narrow range of material and geometric features.

- URM Type A – one-storey isolated building
- URM Type B – one-storey row building
- URM Type C – two-storey isolated building
- URM Type D – two-storey row building

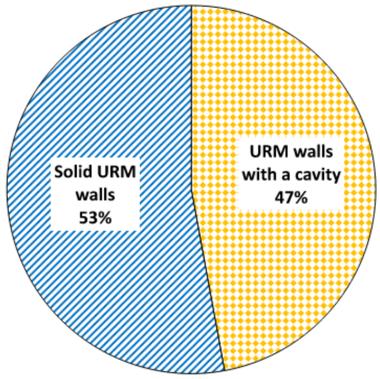
This aligns closely with the observations from the review of building inventory carried out for this investigation.

The sub-sections below have informed the scope of seismic retrofit required to address these elements.

2.5.2.1 Solid versus cavity perimeter wall construction

Most URM buildings in New Zealand were originally constructed before 1940, although a few were constructed in Auckland as late as the 1950s. Rapid field investigations have been undertaken in New Zealand and findings summarised in several papers.

Approximately 50% of the buildings surveyed in the Auckland Council Civil Defence and Emergency Management (CDEM) study, as summarised by Russell and Ingham [10], feature cavities, (refer Figure 2.12) indicating an air gap between the brick wythes (horizontal layers in a wall's cross-section). Although these brick cavity walls were typically tied together during their original construction, the ties have often corroded to such an extent that they will no longer function effectively. As a result, the individual wall wythes are likely to respond independently to lateral loads, without acting compositely.



(b) Proportions of URBM buildings documented for the CDEM study by presence of a cavity within the load-bearing wall.

Figure 2.12: Source Russell & Ingham [10]

The rapid field CDEM survey wall thickness measurements at the ground storey of the buildings indicated:

- Cavity walls at GF typically between 230 mm and 470mm, with the vast majority of solid walls documented as being 350mm thick (i.e., three wythes thick).
- Upper floor levels include an inset ledge (hence, reduced thickness)

2.5.2.2 Parapets

Parapets are appendages attached to the building extending above roof level, typically on the street frontage to enhance the buildings aesthetics and on boundaries for fire protection. Parapets can be a critical element in seismic assessments due to the risk they pose to people external to the building. Nearly all (92%) of the buildings examined in the CDEM study were found to have parapets on at least one side typically 1400mm in height. The findings of the parapet wall heights are shown in Figure 2.13. This indicates a typical parapet height of 1000-1400mm.

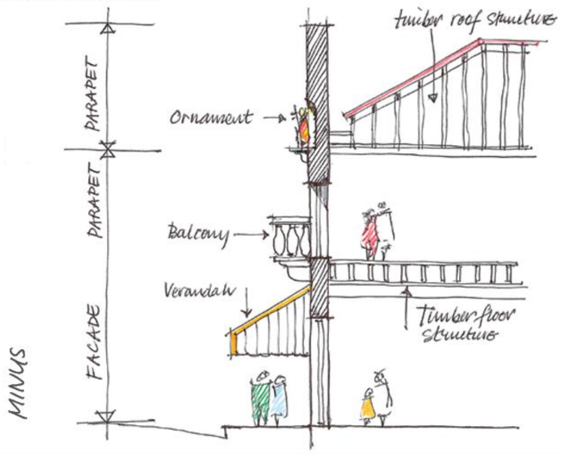


Figure 1: *A typical example of the parapet and facade of a small URM building is illustrated below. A parapet is the section of front wall that is elevated above the roof eaves line.*

Figure 2.13: From MBIE Guideline Securing Parapets and Facades on URM buildings

2.6 Vulnerability of Non-ductile Concrete Buildings

Reinforced concrete (RC) buildings in New Zealand, pre-1976 exhibited significant structural deficiencies during the Canterbury earthquake sequence of 2010–2011. Pre-1976 buildings were particularly vulnerable due to inadequate seismic detailing. Key issues included insufficient transverse reinforcement in columns, poor confinement leading to buckling and failure at lap splices, displacement incompatibilities between lateral load-resisting systems and floor systems, and irregularities in plan and elevation causing torsional responses. Although modern design philosophies began to emerge in the late 1960s, widespread adoption of robust seismic provisions was not fully realised until after the introduction of NZS 3101:1995 standards.

- According to the EPB methodology (2017), buildings classified under Categories B and C are addressed in this sub-group.
- The pre-1976 non-ductile concrete buildings are listed under type 6, 7 and 8.
- Buildings in type 5 are single storey concrete buildings which do not fit neither category B nor C of the EPB methodology. These buildings of type 5 might have been registered before the EPB methodology was introduced in 2017.

The *Engineering Assessment Guidelines* provide guidance for engineers, how to identify deficiencies like non-ductile columns and shear walls as shown in Figure 2.14.

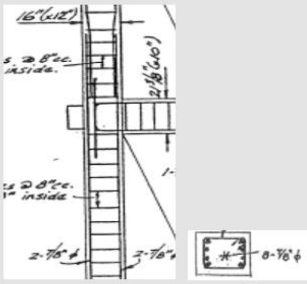
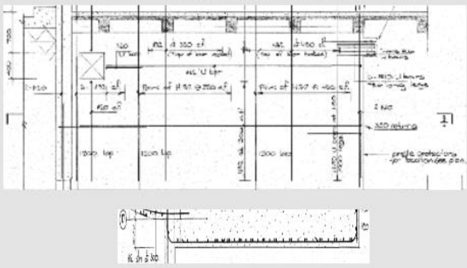
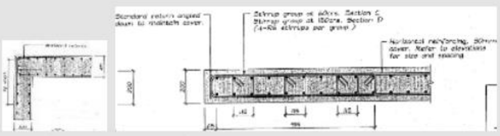
Component or global structure	Typical deficiency	Observed damage
Columns	Inadequate confinement detailing in the plastic hinge region: • not all of the bars of the longitudinal reinforcement are confined with stirrups • inadequate spacing for anti-buckling.  Figure: Structural drawings of column confinement details	Shear failure of the column at the plastic hinge Buckling of the longitudinal reinforcement at the plastic hinge  Photo: Example of shear failure and bucking of column in plastic hinge region
Walls	Inadequate confinement in boundary elements as well as core area  Figure: Structural drawings of wall reinforcement and confinement details  Figure:Structural drawings of confinement details at wall corner and boundary element	Crushing, spalling of concrete; bar buckling; out-of-plane failure  Photos: Spalling of concrete at wall end, and buckling failure  Photos: Shear failure at ground floor wall

Figure 2.14: Table C5.1 EAG Section C5 Concrete Buildings (source: EAG 2017)

2.7 Occupancy Classes

The occupancy class for each building is required to inform the quantity surveyor determined cost of reinstatement and replacement, and for the loss analysis (casualties and time of occupancy). An occupancy class has been assigned to each building as shown in Table 2.8 in accordance with the definition for occupancy class as defined by the FEMA Hazus Inventory Technical Manual version 6.1 Table 4-1, November 2022 [5] (refer Figure 2.15), with minor modifications to suit the properties of this dataset.

Table 4-1 Hazus General and Specific Occupancy Classes

Hazus General Occupancy Class	Hazus Specific Occupancy Class	Class Description
Residential	RES1	Single-family Dwelling
Residential	RES2	Mobile Home
Residential	RES3A	Multi-Family Dwelling – Duplex
Residential	RES3B	Multi-Family Dwelling – 3-4 Units
Residential	RES3C	Multi-Family Dwelling – 5-9 Units
Residential	RES3D	Multi-Family Dwelling – 10-19 Units
Residential	RES3E	Multi-Family Dwelling – 20-49 Units
Residential	RES3F	Multi-Family Dwelling – 50+ Units
Residential	RES4	Temporary Lodging
Residential	RES5	Institutional Dormitory
Residential	RES6	Nursing Home
Commercial	COM1	Retail Trade
Commercial	COM2	Wholesale Trade
Commercial	COM3	Personal and Repair Services
Commercial	COM4	Business/Professional/Technical Services
Commercial	COM5	Depository Institutions (Banks)
Commercial	COM6	Hospital
Commercial	COM7	Medical Office/Clinic
Commercial	COM8	Entertainment & Recreation
Commercial	COM9	Theaters
Commercial	COM10	Parking
Industrial	IND1	Heavy
Industrial	IND2	Light
Industrial	IND3	Food/Drugs/Chemicals
Industrial	IND4	Metals/Minerals Processing
Industrial	IND5	High Technology
Industrial	IND6	Construction
Agriculture	AGR1	Agriculture
Religion	REL1	Church/Non-Profit
Government	GOV1	General Services
Government	GOV2	Emergency Response
Education	EDU1	Schools/Libraries
Education	EDU2	Colleges/Universities

Figure 2.15: Digital Hazus, Technical manual 6.1, Occupancy classes Tab 4-1

The methodology for identifying the occupancy class was determined by the following in order of hierarchy:

- If available, as defined within the building inventory register provided by the TA.
- From review of Google StreetView™ to determine identifiable features to enable categorisation.

Table 2.8: Summary of occupancy classes for the building inventory

Specific Occupancy Class	Class Description	Source for Scheme	% of total building inventory
RES1	Single-family dwelling	HAZUS[4][1]	2.6%
RES2	Mobile homes	Removed	0%
RES3A	Apartment/multi-family dwelling: duplex	HAZUS	1.7%

[1] Reference [4] Hazus Inventory Technical Manual, Hazus 6.1, November 2022

Specific Occupancy Class	Class Description	Source for Scheme	% of total building inventory
RES3B	Apartment/multi-family dwelling: triplex/quad	HAZUS	3.3%
RES3C	Apartment/multi-family dwelling: 5-9 units	HAZUS	1.6%
RES3D	Apartment/multi-family dwelling: 10-19 units	HAZUS	1.9%
RES3E	Apartment/multi-family dwelling: 20-49 units	HAZUS	0.7%
RES3F	Apartment/multi-family dwelling: 50+ units	HAZUS	0.4%
MULTI-RES	Multi-use primary level: Retail + upper residential	Added	23.4%
COM1	Department store, shopping mall	HAZUS	0.6%
COM3	Garage, repair	HAZUS	3.6%
COM4	Office	HAZUS	19.5%
COM6	Hospital	HAZUS	0.6%
COM7	Medical Office/clinic	HAZUS	0.1%
COM8	Restaurants	HAZUS	0.9%
COM9	Movie theatre *(Opera house, galleries, exhibitions)*	HAZUS	0.1%
COM10	Parking garage	HAZUS	0.1%
COM11	Swimming pools, sport centres, community halls	Added	5.0%
COM12	Grandstands, racecourse	Added	0.2%
COM13	Small retail areas, NZ “corner shops”	Added	16.4%
MULTI-COM	Multi-use primary level: Retail + upper commercial	Added	3.4%
UTI1	Suburb substations	Added	1.2%
IND1	Factory	HAZUS	6.5%
IND2	Industrial Warehouse, heavy	HAZUS	1.3%
IND3	Lab, food/drugs/chem	HAZUS	0.1%
IND4		Removed	0%
IND5		Removed	0%
IND6		Removed	0%
REL1	Churches	HAZUS	3.4%
GOV1	Town halls	HAZUS	0.4%
GOV2	Police stations, fire stations	HAZUS	0.7%
EDU1	Schools	HAZUS	0.7%
EDU1a	Early Childhood centres	Added	
EDU2	University classrooms	HAZUS	0.2%

2.7.1 Summary of Occupancy Classes across building inventory

Figures 2.16 and 2.17 show the type of use (residential, commercial or industrial) across all the six centres. However, the identification has some uncertainties, hence it is worth stating that there is ‘some residential’ given the nature of classification.

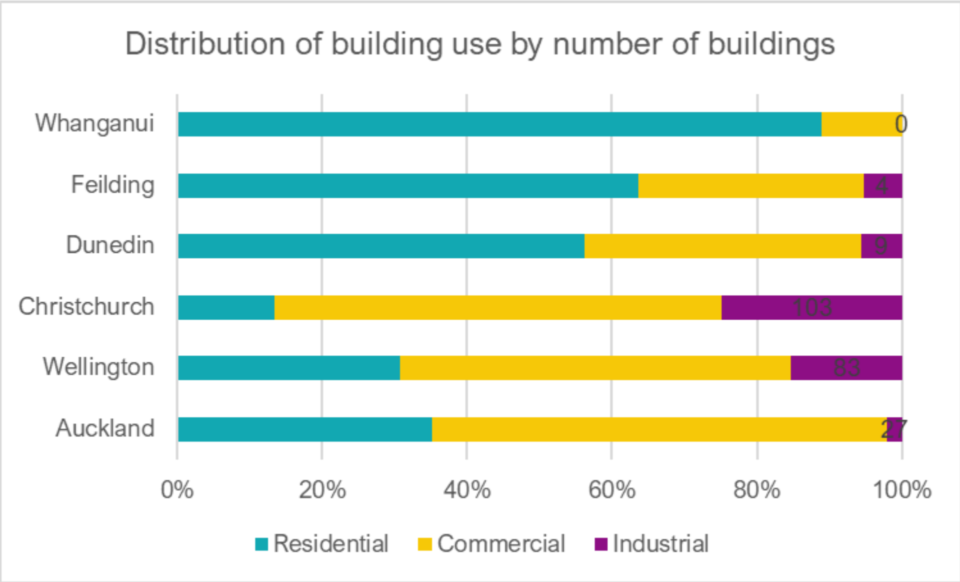


Figure 2.16: Distribution of building use by number of buildings for six locations

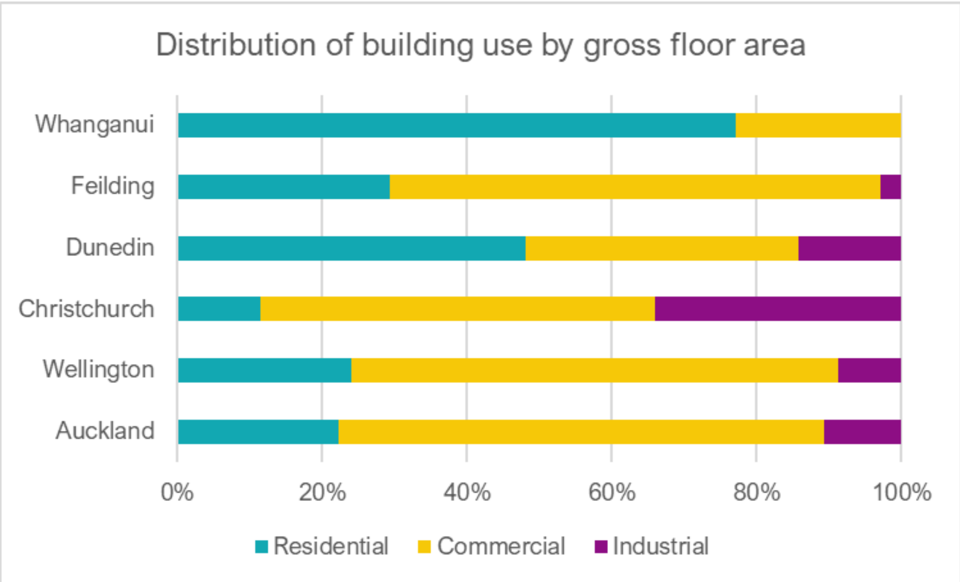


Figure 2.17: Distribution of building use by gross floor area (GFA) for six locations

2.8 Shear Wave Velocity, V_{s30}

The average shear wave velocity (Vs) for the upper 30m in soil depth, denoted as Vs30 has been used to inform the earthquake hazard for each site using QuakeCore maps.

As a reference QuakeCore maps https://quakecoresoft.canterbury.ac.nz/vs30/ and "Combined Geology/Terrain" value have been used for each site.

The QuakeCore database provides a regional map with V_{s30} values for each site, though these values come with some uncertainties. At the time of writing this report, it was considered the best available source for V_{s30} data for this study, alongside the New Zealand Geotechnical Database. The considerations for this study are as follows: Within a city, certain V_{s30} values may be overestimated by +50 m/s, while others may be underestimated by -50 m/s. However, across various sites within a city, these discrepancies are expected to balance out. Initially, a variance of ±50 m/s was tested and found not to significantly impact the final outcome.

We are aware that QuakeCore is updating this information with more detailed data related to the new hazard model; however, it was not readily available at the time of writing this report.

2.9 Shear Wave Graphical Map of EPB sites

A graphical map was created of the EPB building inventory for each of the six locations with filters for location, building typology, occupancy class and number of storeys. The digital display tool uses the QuakeCore map overlayed with the EPB register map for each site. An example of this is shown in Figure 2.18 for Wellington.

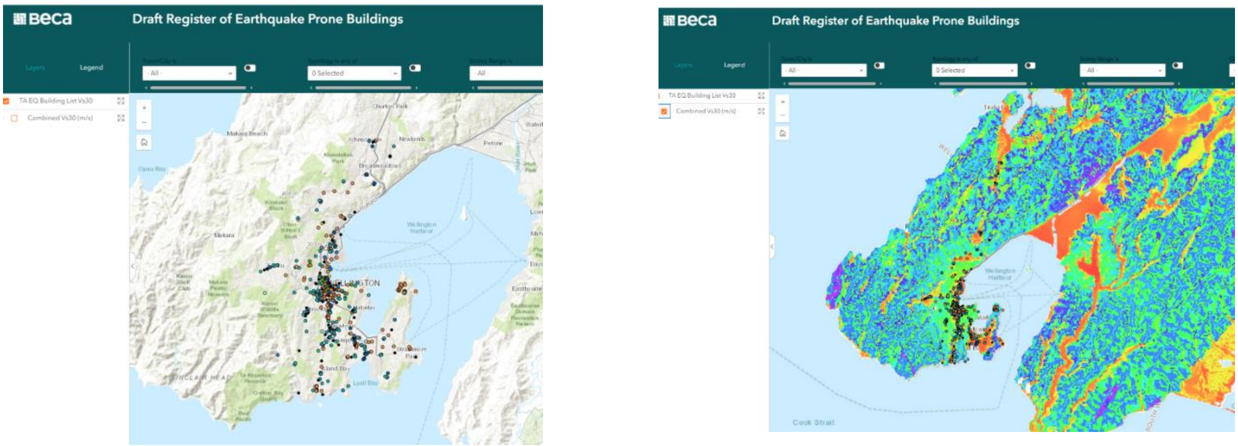


Figure 2.18: Digital maps of EPB buildings, typologies and V_{s30} filter

2.10 Selection of 10 Reference Building Types for this Project

Figure 2.19 illustrates the 10 building types, identified through a review of the EPB inventory across the six centres. Following this review, 10 case study buildings were chosen to represent the common geometry and typical features of the building stock. These reference buildings served as the basis for developing retrofit concepts and fragility curves for this project.

		
1. Light-timber frame building with URM party wall and chimney, 2-storeys, mainly residential.		
		
2. URM wall building with parapet, 1-storey, mainly commercial use	3. URM wall building with parapet, 2-storeys, mainly mixed-use.	4. URM wall building with parapet, 4-storeys, mainly public building.
		
5. Concrete block wall building, 1-storey, mainly workshops or utilities rooms	6. Pre-1935 RC shear wall building, 4-storeys, mainly commercial or offices	7. Pre-1976 RC frame with masonry infill, 4-storeys, mainly commercial use
		
8. Pre-1976 RC frame building, 5-storeys, mainly commercial or offices	9. Post-1976 RC frame with precast flooring, mainly commercial offices	10. Steel portal frame building with heavy cladding, single storey tall, mainly industrial use

Figure 2.191: The 10 selected reference building types

2.10.1 Establishing a representative building for each building type

A representative building for each building type was established from the building inventory list following a review of GFA, number of storeys and typical vulnerabilities to establish the scope of seismic retrofit.

The time and data limitations in establishing representative buildings for this investigation are noted. To address the time constraint, previously established studies for similar building types were utilised to inform the choice of reference buildings, as noted below.

The building inventory data for the building typology was analysed for trends and outliers in the data. Similar to what has been undertaken for the establishment of the URM sub-categories defined above, this included a review of the average values.

The distribution of the individual building type data sets based on GFA varies. Where there appeared to be reasonable correlation between the median (central number of the data set) and mean (the individual data values divided by the total number), the reference building is closer to the mean. Where there are outliers in the dataset which skew the mean significantly from the median, then the reference building is closer to the median. When the median is approximately less than 70% of the average, representing a skewed dataset, the median value has been adopted.

The GFA parameter adopted for each building type is shown in Table 2.9.

Table 2.9: Summary of GFA from inventory dataset for each building type

Building Type	Average GFA (m^2)	Median GFA (m^2)	Average Nº of storeys	Adopted reference building GFA (m^2)
1	300	230	1.4	200
2	300	180	1	200
3	500	360	2.2	500
4	4500	3200	3	4400
5	600	340	1.5	300
6	2200	1070	4.8	1150
7	1100	730	2.5	830
8	4000	1000	3	1500
9	9100	4000	4	5200
10	1700	900	1.3	900

2.11 Seismic Retrofit Concept Designs

The seismic retrofit concept designs were developed for each building type across the different locations for 34%*NBS* and 67%*NBS* in sufficient detail for a high-level cost estimate to be completed. The following steps were undertaken.

- Assume existing EPB buildings are 20%*NBS* (“as-is” status).
- Establish a “representative” building for each of the building types. The process of this is described further below.
- Develop seismic retrofit concept designs for 34%*NBS* and 67%*NBS* for Christchurch for each building prototype.

The Christchurch region has been adopted as the base for retrofit due its seismic hazard being in the mid-range of the six locations. This has been documented with 1-3 pages of pdf mark-up sketches with an accompanying schedule. An example of the sketch and schedule is shown in Figure 2.20. The sketches prepared for the other building types are provided in Appendix D. Where there is a change in scope other than by volume of materials, this is noted directly on the sketches.

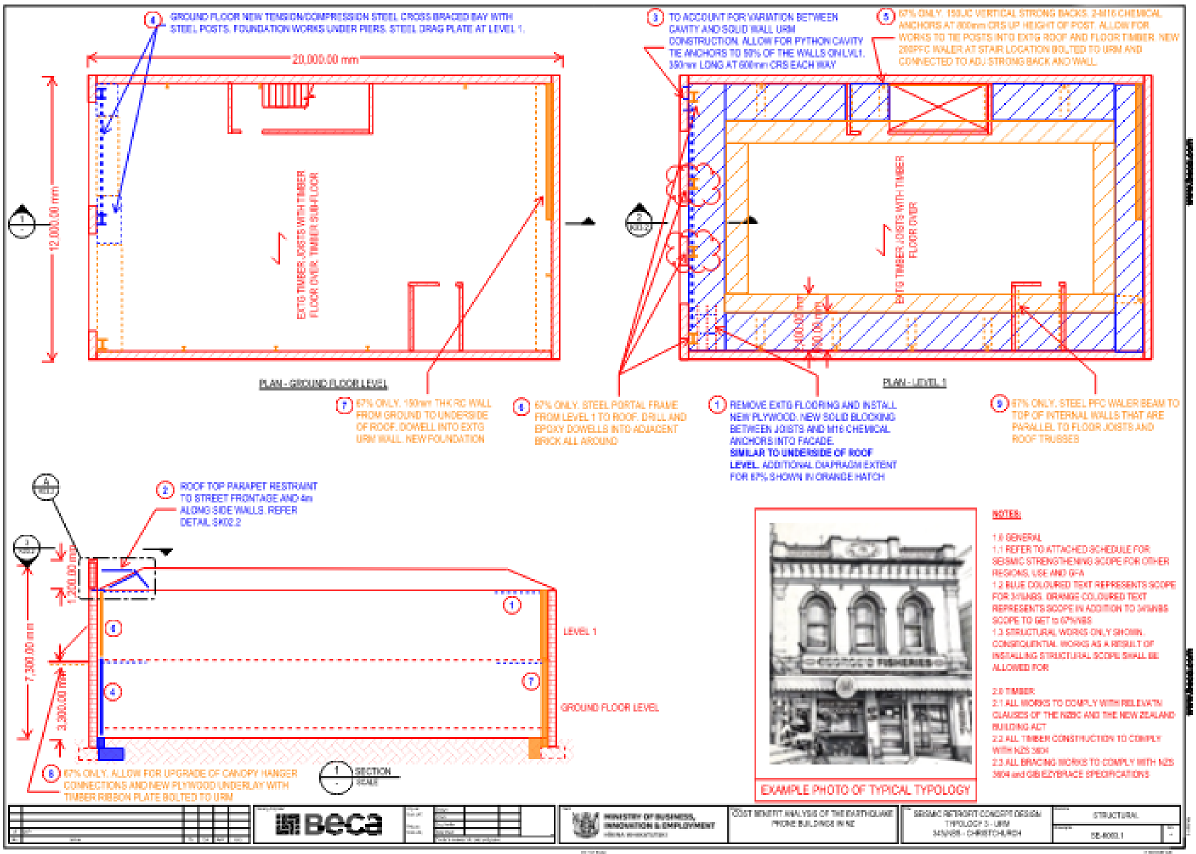


Figure 2.20: Retrofit Concept (Building Type 3 shown). for 34%*NBS* (red) and 67%*NBS* (blue)

A schedule has then been prepared to communicate the relative scaling (%) for each of the scope items from the concept design each of the centres. The scaling factors adopted are shown in Figure 2.11. For example, the extent of structural scope to install a new bracing system will be higher in Wellington compared to Auckland. Whereas some mitigation measures may be applicable to all centres e.g. chimney removal. The percent modifiers represent the change in structural volume of materials (e.g. the increase in steel tonnage), rather than an increase or decrease in overall scope of works (i.e. variation to total number of braced bays).

Scope item (refer sketch for definition)

Location	Z-values	34 %NBS 1	2	Scope item 1 to 4 (3)	(4)
Auckland	0.13	43%	43%	43%	43%
Dunedin	0.13	43%	43%	43%	43%
Whanganui	0.25	83%	83%	83%	83%
Christchurch	0.3	100%	100%	100%	100%
Fielding	0.37	123%	123%	123%	123%
Wellington	0.4	133%	133%	133%	133%

Location	Z-values	67 %NBS 1	2	3	4	Scope items 1 to 9 (5)	(6)	7	8	9
Auckland	0.13	85%	54%	85%	85%	0%	43%	43%	0%	0%
Dunedin	0.13	85%	54%	85%	85%	0%	43%	43%	0%	0%
Whanganui	0.25	164%	104%	164%	164%	100%	83%	83%	42%	100%
Christchurch	0.3	200%	125%	200%	200%	100%	100%	100%	100%	100%
Fielding	0.37	243%	154%	243%	243%	123%	123%	123%	123%	123%
Wellington	0.4	263%	200%	263%	263%	133%	133%	133%	133%	133%

Scope item 5 has been downgraded for Whanganui and Dunedin to acknolwedge the larger proportion of 'row' type buildings and therefore half as much scope to restraint the party wall

Figure 2.11: Relative retrofit scope scale factors for various scope items based on the reference building for 34*%NBS* and 67*%NBS*. The 'scope item' numbers on the top line of the tables relate to scope items identified on the Concept Design sketches. The 'z-values' indicate the magnitude of the seismic hazard in each of the locations.

2.11.1 Methodology to establish seismic strengthening scope

A range of sources have been used to establish retrofit solutions for each reference building. These include:

- Referring to the EAG [3] and the section 'Improving the Seismic Performance' for each building type. This is applicable to concrete, structural steel, moment resisting frames with infill panels, URM and timber buildings.
- Industry established retrofit publications, such as, Structural Engineers Society New Zealand (SESOC) guidance, MBIE guidance for retrofit of URM street frontage buildings [9], research paper publications for reinforced concrete retrofit solutions. A full list of references is captured in the Section 9 References.

A level of engineering judgement has been applied by engineers experienced in seismic retrofit solutions. A number of senior engineers within Beca have reviewed the concepts and have conferred so that an approximately representative scope has been developed for each building type and location.

A review of available existing strengthening drawings for each building type. This background review has ensured that the engineer developing the concepts aligns the scope with 'typical' scope completed on similar projects nationwide by different engineers.

A summary of typical building seismic vulnerabilities for each building type and how this has been addressed for each of the 34*%NBS* and 67*%NBS* strengthening levels has been prepared and can be found in Appendix B Structural Retrofit Concept Design Assumptions.

2.12 Culturally Significant and Heritage Buildings

Culturally significant sites and heritage buildings, including te ao Māori, have value and significance in many ways, such as: providing continuity (in the midst of change); a source of community identity and wellbeing; enabling a sense of where we are in time and contributing to the economy (Figure 2.22 and 2.23).

Figure 2.22: Heritage building - Auckland

Culturally significant sites and heritage status buildings:

- Help to define a unique sense of identity for individuals, communities and the city.
- Help to create communities by connecting individuals to neighbourhoods, social groups and the city as a whole through its physical, cultural, emotional, intellectual and spiritual aspects.
- Provide continuity in a constantly changing society and environment, affirming where our communities have come from and enabling an understanding of the present in order to plan for the future.
- Have value to the whole community and serves beyond individual interests to contribute to the greater public good and community prosperity.

Figure 2.23: Image showing a New Zealand ‘Wharenui’ building of cultural significance

One third (849) of all the EPB buildings (2565) across the six centres are categorised as heritage. There are 58 buildings with Historic Place Category 1, 51 buildings listed as Historic Place 2, and others with a note on the register by the TA with reference to heritage. Figure 2.24 indicates the distribution of buildings noted as being heritage on the EPB register for the inventory used in this project.

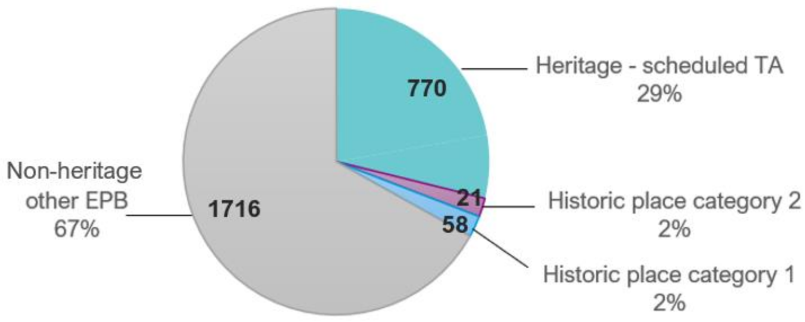


Figure 2.24: Distribution of buildings noted as heritage compared with the total buildings on the EPB registers for all six centres

Evaluating the particular value of protecting heritage assets in a wider sense is complex because of the different models of ownership. The ownership of heritage assets is by groups of individuals, but the benefits accrue to different individuals. Heritage assets are typically designated as such for public good creating a sense of place and identity for communities. Although many assets which have heritage value are in private ownership, the context within which heritage values are realised is very much part of a larger public context.

It has been argued that heritage is a resource, but is an example of an intangible asset, and as such its value can be difficult to determine, as per Murray & Fairgray 2015 [34]. When heritage is embodied in physical assets, then those assets typically have other values which are not part of the heritage value. Consequently, valuing heritage or determining the benefits accruing from limiting the damage to these assets can pose methodological challenges.

As part of this project, we reviewed the heritage category, importance level and sites with cultural significance as allocated by the TA for each asset on the EPB register.

The Hazus Occupancy Classes has designations including community centres, churches, town halls and railway stations which may include culturally significant sites. These occupancy classes may also include sites that are not considered culturally significant and therefore analysing these data sets in isolation will have uncertainty. More time would be required to analyse this aspect in full which is outside of the time allocation for this project.

2.13 Intangibles

This project quantifies many of the significant benefits of seismic retrofitting but does not capture all of them Therefore actual savings are expected to extend beyond the estimates presented here.

As the NIBS study indicated "*Earthquake disaster disconnects people from friends, schools, work and familiar places. In cases of larger disasters, they can inflict lasting damage on culture and ways of life, disproportionately affecting those who are socially or financially marginalised "*.

The long-term impacts on health and collective well-being for those affected can be profound. Additionally, such events may harm or kill pets, devastate communities, and displace populations in ways that are challenging to describe—let alone quantify in monetary terms.

This project has not considered these important socio-economic aspects. For this reason, future decision-making should not solely focus on BCRs but also incorporate socio-economic aspects and recovery potential, which were not explored in this project. Historically, marginalised and vulnerable communities have faced disproportionate impacts from earthquakes and other natural hazards. There is a need to link this study with socio-science research like the work by Sabine Loos (University of Michigan) and NZ socio scientists. Our recommendation is to investigate this socio-science aspect further.

3 Costs

3.1 Cost Estimates for Seismic Retrofit

Cost estimates for seismic retrofit for each representative building for each building type have been prepared to inform the input cost for three cost input variables: no seismic retrofit, seismic retrofit to 34*%NBS* and seismic retrofit to 67*%NBS*.

Full building replacement costs have also been estimated to inform the consequential costs for a given earthquake event and resulting Damage State.

Providing high-level cost estimates for seismic strengthening projects comes with inherent limitations due to the complex and variable nature of such undertakings. Factors like the unique structural characteristics of each building, varying site conditions, and evolving regulatory requirements can significantly impact on cost.

The methodology for retrofit cost estimation is outlined in 3.1.1.

The cost estimates prepared by Beca's Quantity Survey team have been subjected to independent peer review by Rawlinsons, a specialist New Zealand based cost estimating company.

3.1.1 Methodology for Cost Estimation of Seismic Retrofit Designs

Cost estimates for the structural seismic retrofits for all concept designs have been undertaken by a qualified quantity surveyor (QS) adopting the following process:

The cost estimates have been split into the four categories of scope:

- Enabling works. Soft strip out and removal of finishes to access the areas of work.
- Structural works. As identified on the structural concept designs.
- Fit out works. Reinstatement of the wall, floor and/or ceiling finishes and joinery.
- Building services works. Reinstatement of removed building services and components.

The fitout works scope considers the designated building occupancy of each typology, recognising the variation in costs to remediate areas in a commercial building compared to say an industrial building.

Prices are based on Christchurch initially, to align with the structural concept methodology. The costs are then scaled proportionally to consider regional cost differences and structural scope variations.

Undertake a regional cost adjustment study to inform the step above. This is discussed in more detail in the section below. Regional cost adjustments include regional material, labour, Preliminary and General (P&G) and margin variations across the six locations.

Once the regional cost adjustment and structural scope variations have been factored in, the on-costs are then applied to obtain an expected project cost. The on-costs include risk, contingency, fees, owner costs and building consent.

The output is expressed as a dollar per square meter ($/m^2) for each typology, location and *%NBS* strengthening level.

3.1.2 Regional Factors for Cost Estimates

Accounting for regional variation in cost estimates has been undertaken to allow for differences in labour rates, material costs, availability of resources, and local construction practices as these can significantly affect project costs.

Regional factors considered are:

- Regional pricing variable
- On-site overheads (Preliminary and General provisions)
- Off-site overheads (margin)
- Structural retrofit scope. Larger extent of scope for the higher seismic regions, and vice versa for lower seismicity. This variation in scope is provided by the structural engineer.

The impact of regional cost differences that have been determined for each retrofit level are indicated in Figures 3.1 and Figure 3.2 which compares the total cost of retrofitting the whole inventory in each centre to that determined for Christchurch for 34% and 67%*NBS* respectively.

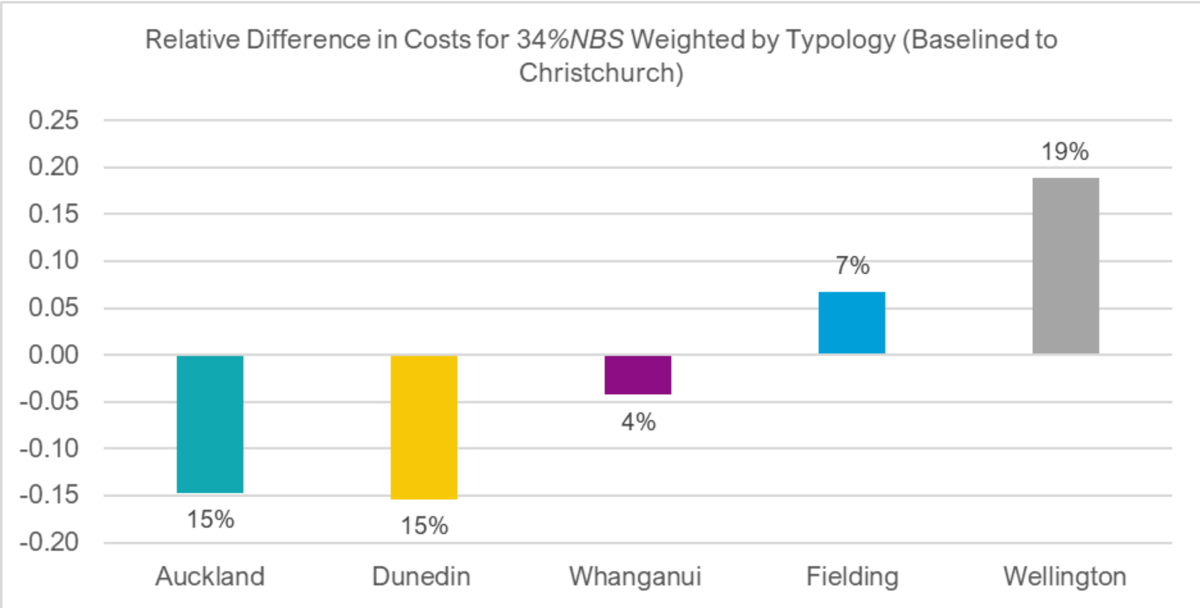


Figure 3.1: Relative difference in total costs for 34%*NBS* baselined to Christchurch

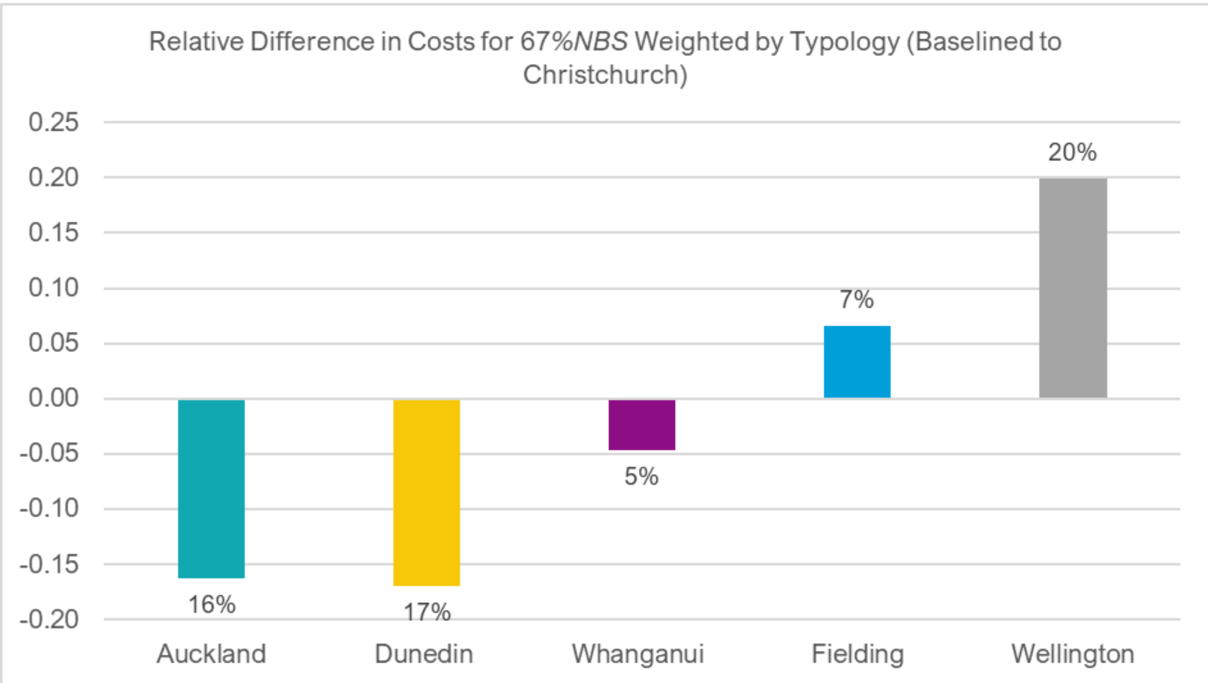


Figure 3.2: Relative difference in total costs for 67%*NBS* baselined to Christchurch

3.1.3 Summary Results of Seismic Retrofit Costs

A summary of retrofit costs that have been determined for each retrofit level for each centre are shown in Figures 3.3 and 3.4.

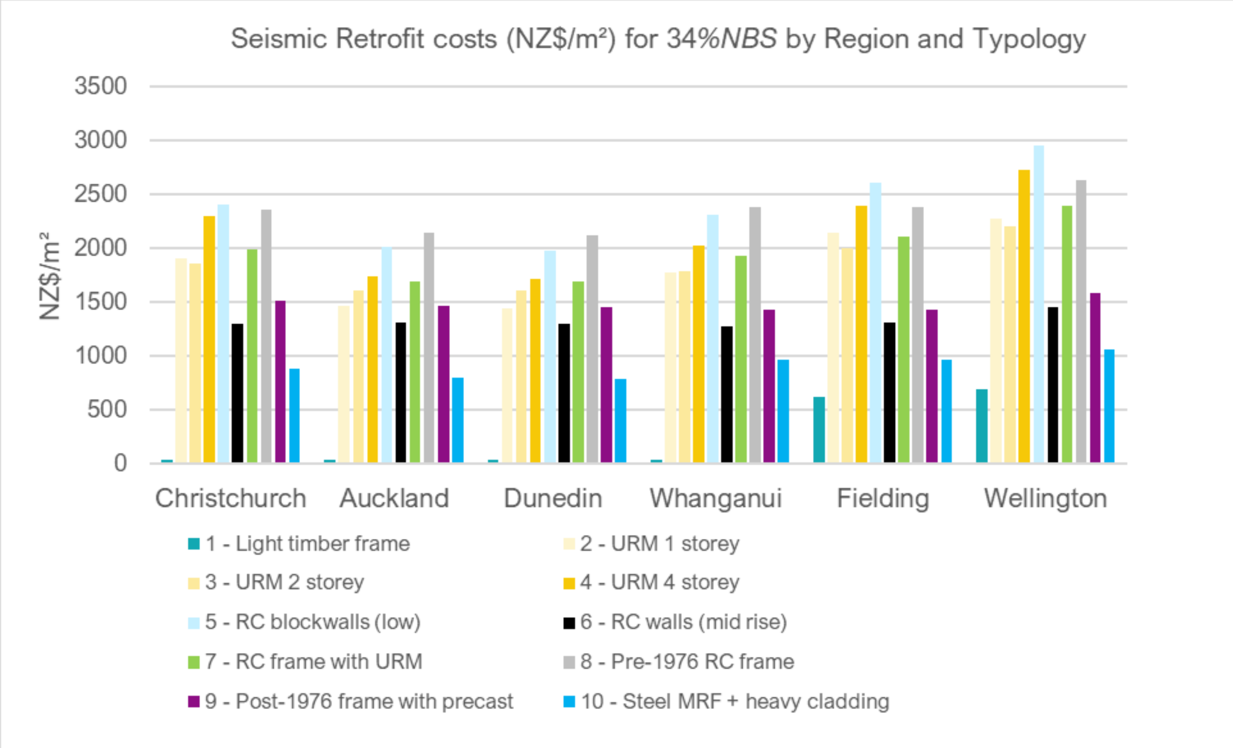


Figure 3.3: Seismics retrofit costs for 34%*NBS* by region and building type

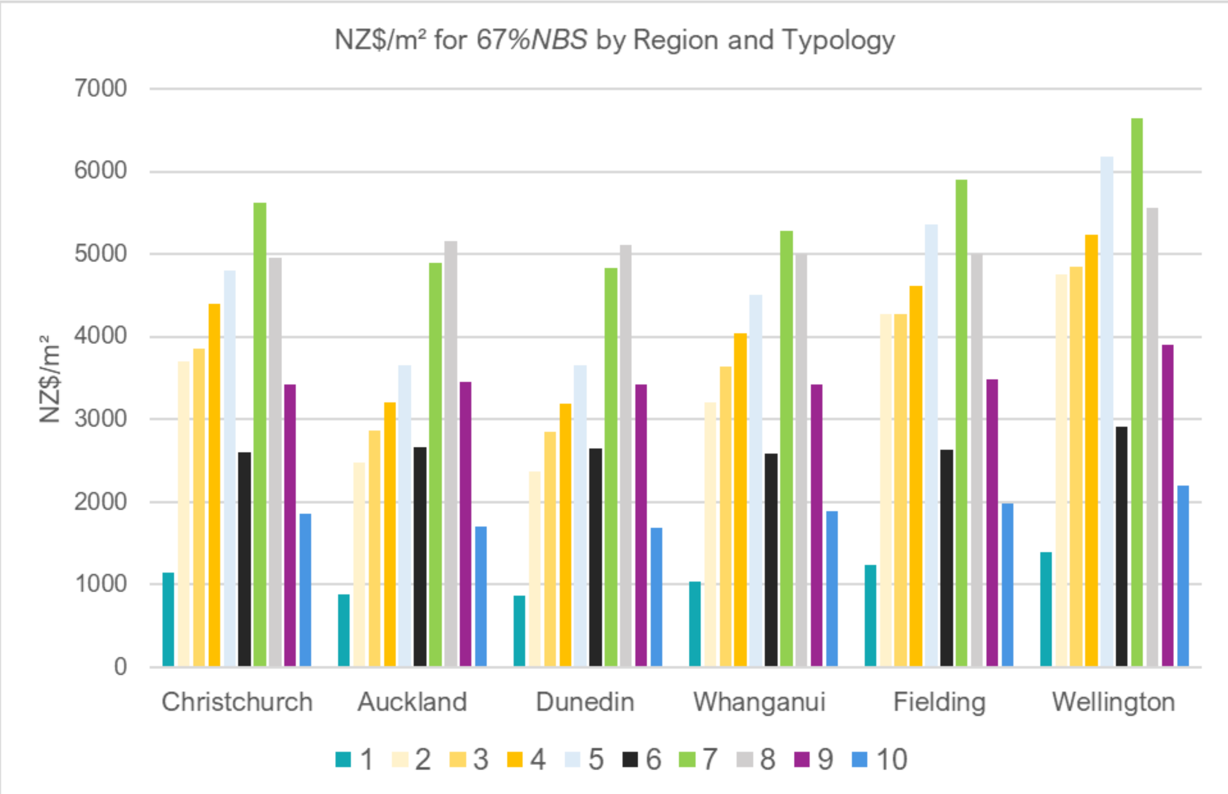


Figure 3.4: Seismic retrofit costs for 67%*NBS* by region and building type

3.1.4 Cost Estimate Assumptions

As a consequence of timing limitations for this project, it has been necessary to make several assumptions when deriving the cost estimates.

Refer to Appendix C for a summary of these assumptions.

3.2 Energy Efficiency Cost when Integrated with Seismic Work

The energy efficiency upgrades have been included as an additional option in the final dashboard production. The capital works represents an upgrade of insulation, glazing and central plant. The recent review of the thermal performance cost benefit analysis commissioned by MBIE was referred to for developing the energy efficiency scope for this project.

The energy efficiency opportunities which are included in the energy efficiency upgrade option are:

- Wall and roof insulation upgrade to current building code
- Window performance upgrade to low e solar control double glazing
- Lighting upgrade to high efficiency LED.

These upgrade costs and benefits are only developed for the 67*%NBS* refurbishment options as the scope of work for the 34*%NBS* upgrade did not provide sufficient alignment with the energy efficiency upgrade scope (i.e. it could not be considered a “connected” upgrade). It is assumed that no energy efficiency upgrade to the building fabric has been undertaken prior to the seismic retrofit works. It is assumed that lighting within older buildings had been upgraded to compact fluorescents/fluorescent battens prior to the seismic retrofit works but is due for replacement.

Upgrade costs have developed by the Beca QS, based on the following scope of upgrades when applied to building areas subject to earthquake strengthening.

Insulation and Glazing

- Remove existing insulation (if any)
- Add insulation to current NZBC levels
- Replace existing glazing with new low-e double glazing units
- Costs include supply and install but assume that no builders work is required in addition to earthquake strengthening.

Lighting

- Replacement of existing light fittings with LED fittings and lamps.

Costs include supply and install but assume that no builders work of additional costs associated with ceiling removal/reinstatement are required.

Figure 3.5 shows the spread of costs for these items across the different building types for a residential upgrade and a commercial building upgrade. These were considered sufficiently granular for the purposes of assessing the financial performance of the energy efficiency initiatives.

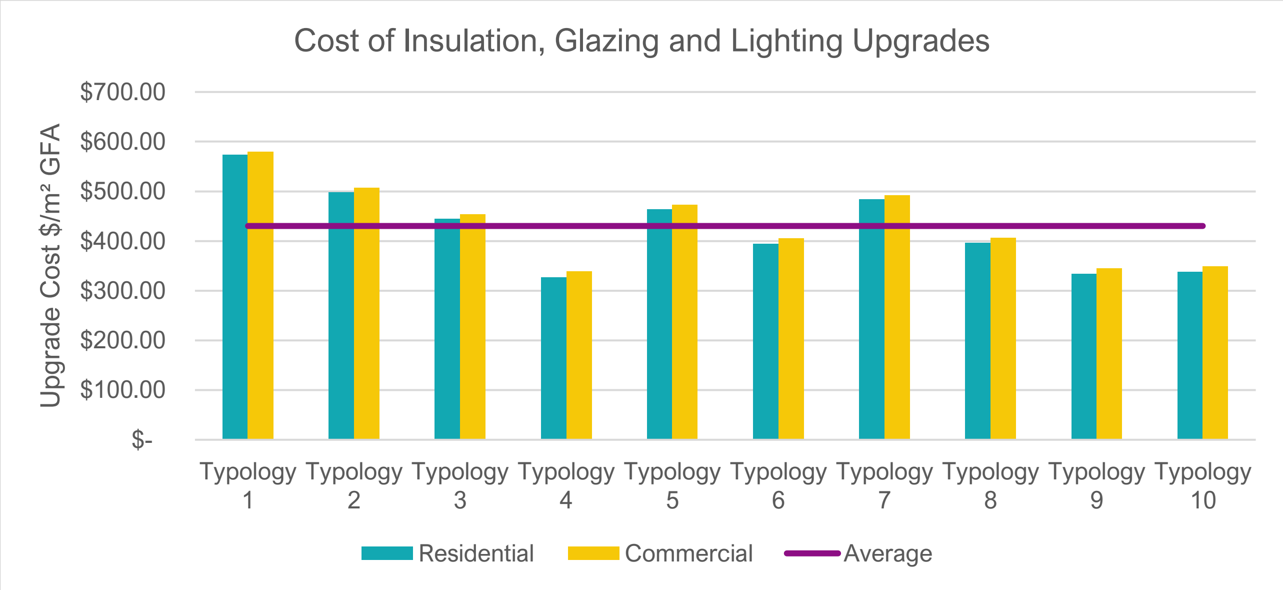


Figure 3.5: Cost of insulation, glazing and lighting upgrades

4 Hazard (APoE)

In New Zealand, a recent large-scale study by GNS Science was completed to create a National Seismic Hazard Model hereby referred to as the NSHM 2022. The study characterizes the variation of seismic hazard throughout New Zealand based on updated ground motion models and seismic source models beyond those used for design codes such as NZS 1170.5:2004 that are used for assessing earthquake-prone buildings.

For this study, an estimate of spectral acceleration was required for a variety of earthquake APoE levels. GNS Science provides this data based on their NSHM 2022 study dependent on input building and soil characteristics. The data can be extracted in the form of hazard curves or uniform hazard spectra. Because discrete hazard scenarios are sought, the uniform hazard data has been used in this study.

For the fragility model, the latest publicly available NSHM2022 hazard model from GNS was adopted. This gave the short period acceleration response values given in Table 4.1.

Table 4.1: An example of Uniform hazard spectrum for short period buildings
[Source: *https://nshm.gns.cri.nz/Hazardcurves*]

Probability of Exceedance	APoE	Wellington	Feilding	Christchurch	Whanganui	Dunedin	Auckland
50% in 50 years	1:100	0.68	0.59	0.39	0.45	0.22	0.11
20% in 50 years	1:250	1.30	1.10	0.69	0.79	0.41	0.21
10% in 50 years	1:500	1.80	1.50	0.95	1.10	0.59	0.31
5% in 50 years	1:1000	2.30	2.00	1.30	1.40	0.82	0.44
2% in 50 years	1:2500	3.20	2.70	1.60	1.90	1.20	0.67

Please note in regards to the table above that statistically 10% in 50 years is 0.0021 or 1 in 476 and not exactly 1 in 500.

5 Benefits

5.1 Average Loss Avoided

The outputs of this workstream include the evaluation of *average loss avoided* (e.g. structural damage, injuries, fatalities, economic downtime, and recovery) alongside benefits including non-financial such as emissions reductions when energy efficiency retrofits are bundled with seismic retrofit costs, to allow the relationships between costs and benefits from various perspectives to be determined. The results are broken down by building type, location, and size/scale of seismic shaking.

The following key inputs and outputs form part of the economic analysis:

Costs

- Building seismic upgrade costs for two upgrade options
- Building energy efficiency upgrade costs

Benefits - Avoidance of

- Building repair or replacement costs
- Content replacement costs
- Deaths, injuries and post-traumatic stress disorder (PTSD)
- Time-element losses (residential displacement and direct and indirect business interruption)
- Search and rescue costs
- Carbon emissions

Benefits do not include

- The cultural impacts on heritage sites
- Wider social costs beyond direct and indirect displacement such as the impact on the city/town as a whole due to fewer fatalities or lower levels of damage
- Financial and commercial impacts such as any rent increases following strengthening (the benefit for the tenant is already accounted for as part of less damage and life safety and this would be double counting this aspect).

Costs, including both financial and non-financial factors, were identified at various stakeholder levels—individual building/owner level, regional level, and national level. This ensured a comprehensive understanding of impacts across different scales. It provided critical insights into the cost-effectiveness of interventions at varying risk levels. Cost-benefit analysis (CBA) results were presented in two formats.

Integrated across all future events, as per traditional CBA methodologies. Disaggregated by APoE, building type, and location to offer detailed insights tailored to specific APoE levels and stakeholder needs.

5.2 Loss Analysis - How it was Done

For the seismic loss estimation of this study a displacement-based method (DBM) was used to establish fragility functions and relate them to ground motion shaking intensity.

The DBM considers ground motion demands in terms of spectral displacement.it considers every building typology represented by a case study building which is modelled as an equivalent single degree of freedom (SDOF) oscillator.

These functions quantified damage probabilities for unstrengthened buildings and retrofitted options (34*%NBS* and 67*%NBS*), using methods like Hazus, structural backbone analysis, and capacity calculations. The results included fragility curves for various types across regions, enabling comparisons of seismic risks and retrofit benefits.

The procedure used to undertake the loss analysis including deriving at loss fragility functions for each of the retrofit options (including no retrofit) consisted of the five Steps A to F shown in Figure 5.1 and Table 5.1.

A	B	C	D	E	F
Capacity curves *%NBS* for options →	Building performance - Structural fragilities →	Shaking hazard using latest NSHM2022 →	Concequence model at individual building level →	Scaling from ULS to collapse and iteration over many buildings →	Testing of Risk model and final settings and results

Figure 5.1: Loss analysis steps

Table 5.1: Fragility methodology outlined

Step	Methodology step	What we did	Based on / source
A	Capacity curves (*%NBS)*	Capacity pushover curves for three options: nil (20%), 34% and 67*%NBS* for each typology	Assessment Guidelines for EPB dated 2017 based on current code (hazard 2004)
B	Building performance	Fragility curves for four damage states of each of the 10 typologies for each of the three retrofit options	C.1 Displacement-Based Method (Beca), compared against C.2: HAZUS [5] C.3: CEBA[2] (Christchurch data) literature research [20] to [28]
C	Shaking hazard	Shaking intensity APoE levels: 1:100, 1:250, 1:500, 1:1000, 1:2500	National Seismic Hazard Model 2022 by GNS
D	Consequence model of a single building	Probability of collapse at single building level for each typology and occupancy rates	[17] Horspool et al (2020), [18] Horspool (2022) [19] Scheel et al (2023)
E	E1 - Scaling form ULS to Collapse. E2 - Iteration over many buildings of a city	Applying the ICF factor for the scaling from ULS to collapse margin. Iteration over many buildings to produce a full risk distribution at a city level	FEMA P695
F	Risk model and loss analysis	Final risk model using probability of consequences for each consequence (damage, downtime, injury / deaths) per APoE level	

The steps are described in greater detail below in Figure 5.2, 5.3 and 5.4.

5.3 Step A – Capacity Curves %*NBS*

Capacity curves for three options: Nil, 34%*NBS* and 67%*NBS* retrofit

1. Capacity curve of 20%*NBS* (nil retrofit)

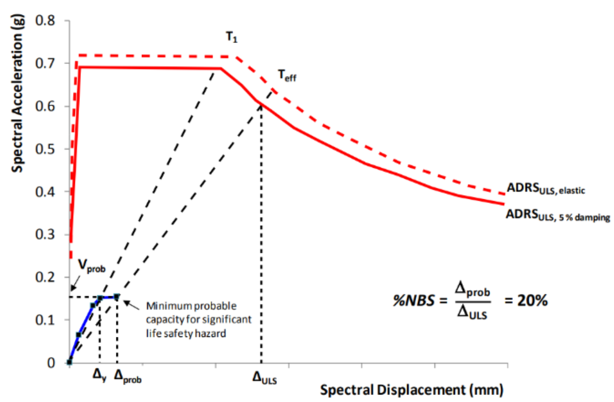


Figure 5.2: Nonlinear static pushover 20%*NBS* using ADRS plot

The capacity curve for the earthquake-prone building without retrofit is determined using the current 2004 hazard, as specified in NZS1170.5:2004, with system damping e.g. $\zeta_{sys} = 5\%$.

2. Capacity curve of 34%*NBS* retrofit

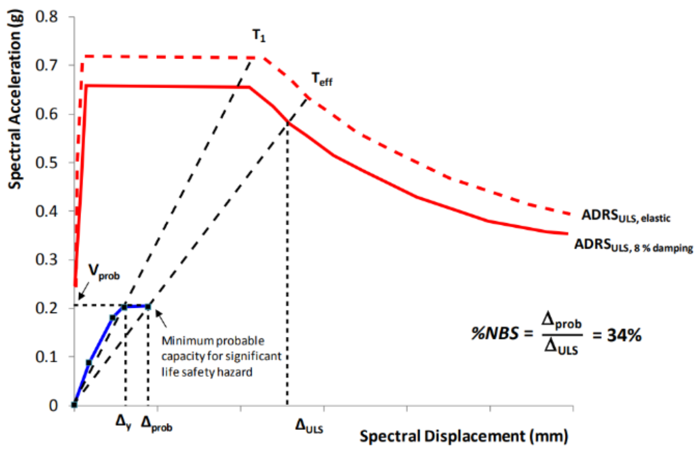


Figure 5.3: Nonlinear static pushover 34%*NBS* using ADRS plot

The second step involves determining the 34%*NBS* capacity curve with enhanced ductility and/or strength. This curve is plotted against the ADRS hazard spectrum, incorporating enhanced system damping e.g.. $\zeta_{sys} = 8\%$.

3. Capacity curve of 67%*NBS* retrofit

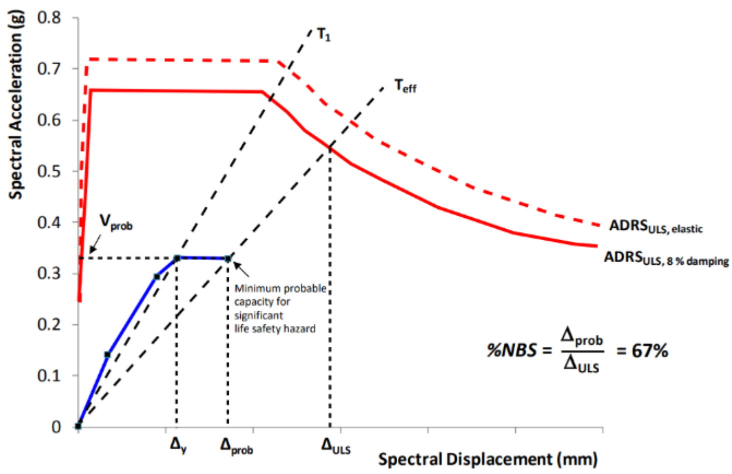


Figure 5.4: Nonlinear static pushover 67%*NBS* using ADRS plot

For the third option, the 67%*NBS* curve was plotted, taking into account the improved displacement (ductility) and increased strength provided by the strengthening methodology. Below is the matrix adopted for enhanced ductility based on various strengthening options and building types.

5.3.1 Strengthening based on vulnerability and determination of fragility data

As explained in section 2, common retrofit strategies have been based on the vulnerabilities of the reference structures and involve selective intervention such as targeting strength-only, ductility-only, stiffness-only, as well as selective weakening, or securing works - or a combination of these approaches. This project currently excludes advanced retrofit methods like energy dissipating technologies (base isolation or fluid viscous dampers) and only focuses on conventional methods.

Each reference building has certain weaknesses and tailored retrofit strategies which may vary for 34% and 67%*NBS*. Depending on the specific strategy applied for each case, there will be a shift in the unstrengthened fragility curve to the right by the increased structural capacity e.g. by strength increase, period shift, ductility increase (refer Figure 5.5).

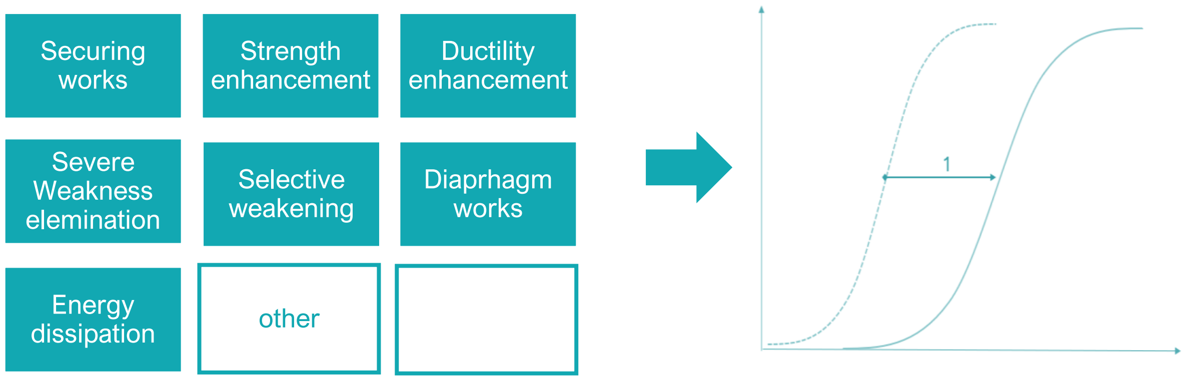


Figure 5.5: Common retrofit strategy and fragility adjustment

Table 5.2: Matrix of assumptions for strength/ductility enhancement as per retrofit methodology

Building Type	Period	ductility μ			Strength improvement		Displacement improvement	
	seconds	20%*NBS*	34%*NBS*	67%*NBS*	34%*NBS*	67%*NBS*	34%*NBS*	67%*NBS*
1	0.4	1.25	1.25	1.25	1.0	1	0	0
2	0.4	1.0	1.0	1.0	1.0	1	0	0
3	0.4	1.00	1.00	1.00	1.0	1	0	0
4	0.5	1.00	1.25	2.00	1.0	0.5	0	0.5
5	0.4	1.25	1.25	1.25	1.0	1	0	0
6	0.5	1.25	1.25	2.0	1.0	0	0	1.0
7	0.5	1.25	1.25	2.0	1.0	0.5	0	0.5
8	0.6	1.25	2.0	3.0	0.0	0	1.0	1.0
9	0.7	1.25	1.25	3.0	1.0	0	0	1.0
10	0.54	1.25	1.25	2.0	1.0	0	0	1

5.4 Step B – Building Performance determined by Structural Fragility Curves

The 'displacement-based fragility' method that has been selected for the determination of fragility relies on the estimated capacity curves created for each structure in the inventory. Fragility functions are drawn as a two-parameter log-normal function with the median value as the damage state threshold limit and the logarithmic standard deviation as the dispersion factor to account for various sources of uncertainty.

5.4.1 Defining Damage State limits

For the determination of defining the damage state limits DS1 to DS4 for each building typology we used the pre-code spectral acceleration limits as defined in HAZUS[2] (Table 5-22) as shown below in Table 5.3. This method uses a displacement-based approach to determining the fragility curves.

Table 5-22 Structural Fragility Curve Parameters - Pre-Code Seismic Design Level

Building Properties			Inter-Story Drift at Threshold of Damage State				Spectral Displacement (Inches)							
Type	Height (Inches)						Slight		Moderate		Extensive		Complete	
	Roof	Modal	Slight	Moderate	Extensive	Complete	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	168	126	0.0032	0.0079	0.0245	0.0600	0.40	1.01	1.00	1.05	3.09	1.07	7.56	1.05
W2	288	216	0.0032	0.0079	0.0245	0.0600	0.69	1.04	1.71	0.96	5.29	0.90	12.96	1.00
S1L	288	216	0.0048	0.0076	0.0162	0.0400	1.04	0.85	1.65	0.83	3.50	0.79	8.64	0.95
S1M	720	540	0.0032	0.0051	0.0108	0.0267	1.73	0.71	2.76	0.76	5.84	0.82	14.40	0.97
S1H	1,872	1,123	0.0024	0.0038	0.0081	0.0200	2.70	0.68	4.30	0.71	9.11	0.85	22.46	0.93
S2L	288	216	0.0040	0.0064	0.0160	0.0400	0.86	1.01	1.38	0.96	3.46	0.88	8.64	0.98
S2M	720	540	0.0027	0.0043	0.0107	0.0267	1.44	0.73	2.30	0.75	5.76	0.79	14.40	0.97
S2H	1,872	1,123	0.0020	0.0032	0.0080	0.0200	2.25	0.71	3.59	0.70	8.99	0.84	22.46	0.91
S3	180	135	0.0032	0.0051	0.0128	0.0350	0.43	1.06	0.69	1.03	1.73	1.07	4.73	0.88
S4L	288	216	0.0032	0.0051	0.0128	0.0350	0.69	1.11	1.11	1.03	2.77	0.99	7.56	0.98

Figure 5.6: HAZUS *'Pre-Code' Table 5-22 as basis of Damage State limits*

Table 5.3: Final input assumption for the four Damage States

	< 33%*NBS* Hazus: Pre-Code *Hazus v6.1 Tab 5-15 & 5.22*		Height		Inter-Story Drift Ratio				Spectral Displacement - Fragility -FINAL							
			Roof	Modal	Slight	Moderate	Extensive	Complete	Slight		Moderate		Extensive		Complete	
			[m]	[m]	%	%	%	%	Median	Beta	Median	Beta	Median	Beta	Median	Beta
W1	1	Light timber frames with URM elements	4.3	3.2	0.003	0.008	0.025	0.060	10	0.64	25	0.64	78	0.64	192	0.64
URML	2	URM 1- storey	4.6	3.4	0.002	0.005	0.012	0.028	8	0.64	17	0.64	41	0.64	96	0.64
URML	3	URM 2-4-storeys < 2000m^2	4.6	3.4	0.002	0.005	0.012	0.028	8	0.64	17	0.64	41	0.64	96	0.64
URMM	4	URM 1-4-storeys > 2000m^2	10.7	8.0	0.002	0.003	0.008	0.019	13	0.64	26	0.64	64	0.64	149	0.64
C2L	5	RC walls (lowrise)	6.1	4.6	0.003	0.006	0.016	0.040	15	0.64	28	0.64	72	0.64	183	0.64
C2M	6	RC walls (midrise)	15.2	11.4	0.002	0.004	0.011	0.027	24	0.64	46	0.64	120	0.64	305	0.64
C3M	7	RC frame and masonry infill (midrise)	15.2	11.4	0.002	0.003	0.008	0.019	18	0.64	37	0.64	91	0.64	213	0.64
C1M	8	Pre-1976 RC frame	15.2	11.4	0.003	0.004	0.011	0.027	30	0.64	49	0.64	122	0.64	305	0.64
C1H	9	Post-1976 RC frame with precast	36.6	21.9	0.002	0.003	0.008	0.020	44	0.64	70	0.64	176	0.64	439	0.64
S1L	10	Steel MRF and heavy cladding	7.3	5.5	0.005	0.008	0.016	0.040	26	0.64	42	0.64	89	0.64	219	0.64

5.4.2 Why was HAZUS used for the spectral acceleration limits of the fragility curves?

The HAZUS method was utilised as the basis because it is a robust, internationally peer-reviewed platform that establishes detailed relationships between structural behaviour, damage states, and fragility curves tailored to different code levels. The relationship between the damage state and the displacement is difficult to establish from scratch. It requires a large amount of damage data and sound engineering judgement. HAZUS has been extensively tested against numerous data points and a wide range of real earthquake scenarios, far exceeding the scope of any New Zealand research papers or alternative platforms.

5.4.3 Why were 'Pre-code' HAZUS thresholds used for this study?

"Pre-code HAZUS" refers to buildings constructed before modern seismic design codes, lacking significant seismic provisions. In New Zealand, earthquake-prone buildings are particularly vulnerable as they often lack both seismic design provisions and the application of capacity design principles. HAZUS uses this classification to tailor fragility curves and damage probabilities accordingly.

It is not straightforward to relate the US code assumptions of "Pre-code" to New Zealand's earthquake-prone definitions, such as buildings with less than 33%*NBS* under moderate ground shaking. However, HAZUS "Pre-code" serves as a measure of performance relative to the ASCE7-22 code. Based on seismic demand quantities and coefficients, Pre-code performance corresponds to approximately 25% of current ASCE7-22

[2] HAZUS Earthquake Model Technical Manual, Version 6.1 (Federal Emergency Management Agency, 2024)

code requirements, which—with some rounding—aligns with about 25–33%ULS under NZS 1170.5:2004, and close to the earthquake-prone status.

As part of our study, other levels, such as "Low Code" and "Moderate Code," were tested and compared with New Zealand research papers utilising real earthquake data from the 2011 Christchurch event. It was found that the closest fragility assumptions aligned with "Pre-code."

5.4.4 How was the ‘Pre-code’ threshold applied for 34% and 67%NBS options?

After thorough review and testing, the damage state threshold of 'Pre-code' was applied to all three options 20% (no upgrade), 34% and 67*%NBS*. We have considered whether the fragility curves for structures of different *%NBS* values should be associated with different modifiers for HAZUS damage-state-to-spectral-displacement relationships and decided that those relationships should be consistent regardless of the *%NBS* rating of the building. Our testing using an adjustment factor revealed that it would result in unrealistic outcomes, too conservative. For the adjustment factors we tested two scenarios. First testing setting was looking at applying adjustment factors for 34% and 67*%NBS* options of 1.1 and 1.4 to the pre-code thresholds respectively as outlined in the Vaculik & Griffith research paper [28]. In the second testing setting we looked at applying a ratio of 1.7 (34% to 20%) and 3.35 (67% to 20%) respectively. In the end, the threshold of pre-code was applied for all three options 20, 34 and 67%, because increasing both the force and displacement capacity led to a disproportionate improvement of the 34 and 67 fragility curves. What does change when the *%NBS* of the building is improved is its force and displacement capacity reflected through improvements to the backbone. This has been reflected by only using improvements to the structural backbone (maintaining elastic stiffness) to improve the equivalent elastic spectral acceleration capacity of the structure.

5.4.5 How were HAZUS building type mapped to New Zealand’s building typologies?

Its applicability to New Zealand typologies is complemented by comparisons with observed damage from Christchurch and insights from local literature on building stock and materials.

Table 5.4: Types of this study and allocated Hazus similar types

#	Types of this study	Case Study	Hazus 6.1 Section 5.3 and Label as per Table 5 1	Hazus Description
1	Light timber frames with URM elements	2 storeys	Wood, Light Frame (W1) (≤ 5,000 sq.ft)	1-2 storeys, typical 1 storey, 14 feet
2	URM 1- storey	1 storey	Unreinforced Masonry Bearing Walls (URML) Low-Rise	1-2 storeys, typical 1 storey, 15 feet
3	URM 1-4 storeys GFA < 2000m2	2 storeys	Unreinforced Masonry Bearing Walls (URML) Low-Rise	1-2 storeys, typical 1 storey, 15 feet
4	URM 1-4-storeys GFA > 2000m2	3 storeys	Unreinforced Masonry Bearing Walls (URMM) Mid- Rise	3+ storeys, typical 3 storeys, 35 feet
5	RC walls (low-rise)	1 storey	Concrete Shear Walls (C2L) Low-Rise	1-3 storeys, 2 storeys, 20 feet
6	RC walls (mid-rise)	3 storeys	Concrete Shear Walls (C2M) Mid-Rise	4-7 storeys typical 5 storeys, 50 feet.
7	RC frame and masonry infill (mid-rise)	4 storeys	Concrete Frame with Unreinforced Masonry Infill Walls (C3M) Mid-Rise	4-7 storeys, typical 5 storeys, 50 feet

#	Types of this study	Case Study	Hazus 6.1 Section 5.3 and Label as per Table 5 1	Hazus Description
8	Pre-1976 RC frame	4 storeys	Concrete Moment Frame (C1M) Mid-Rise	4-7 storeys, typical 5 storeys and 50 feet
9	Post-1976 RC frame with precast	9 storeys	Concrete Moment Frame (C1H) High-Rise	8+ storeys, typical 12 storeys, 120 feet
10	Steel MRF and heavy cladding	1 storey	Steel Moment Frame (S1L) Low-Rise	1-3 storeys, typical 2 storeys 24 feet

5.4.6 Why did we adopt a Beta of 0.64?

The series of capacities for buildings of a given typology in a given city can also be used to define a log-normal distribution. The uncertainty of this distribution represents only part of the overall uncertainty of the fragility curve. FEMA P695 (Federal Emergency Mangement Agency, 2009) provide four sources of uncertainty that must be considered within a building fragility distribution. They are:

1. Record-to-record uncertainty
2. Design requirements uncertainty
3. Test data uncertainty; and
4. Modelling uncertainty

Record-to-record uncertainty is calculated in accordance with Equation 7-2 of FEMA P695. As many of the buildings on the register are brittle structures, this value tends to be close to the minimum allowable value.

$$\beta_{\mathrm{RTR}} = 0.2 \leq 0.1 + 0.1\mu_{\mathrm{T}} \leq 0.4$$

The design requirements uncertainty has been set as zero for this investigation. Because this study is undertaken on existing buildings, assessment guidelines are assumed to capture all possible failure modes associated with a given damage state.

The test data uncertainty has been set to zero because the tested dataset is the same size as the dataset on which the fragility curve is expected to apply. In other words, all the buildings in the study are being considered in the data analysis to generate the fragility curves for those buildings.

The modelling uncertainty described in FEMA P695 is aligned to the variation of structural capacity identified by the series of building capacities forming the fragility curve for each city and typology.

Several sources have adopted consistent dispersion values to capture fragility curve uncertainty. Hulsey et al. [29] tested three values of beta and settled on using the largest value: β=0.45. Section 5.4.3 of HAZUS produces structural fragility curves for peak ground acceleration and also uses a consistent dispersion value of β=0.64. That value contains the uncertainty associated with the damage-state threshold of the structural system and the variability in response due to the spatial variability of ground motion demand.

To avoid presenting a false level of accuracy in the values of beta, the larger constant dispersion value of β=0.64 has been applied across all fragility curves in this study.

5.4.7 Plot four vertical lines for each of the four Damage States in ADRS

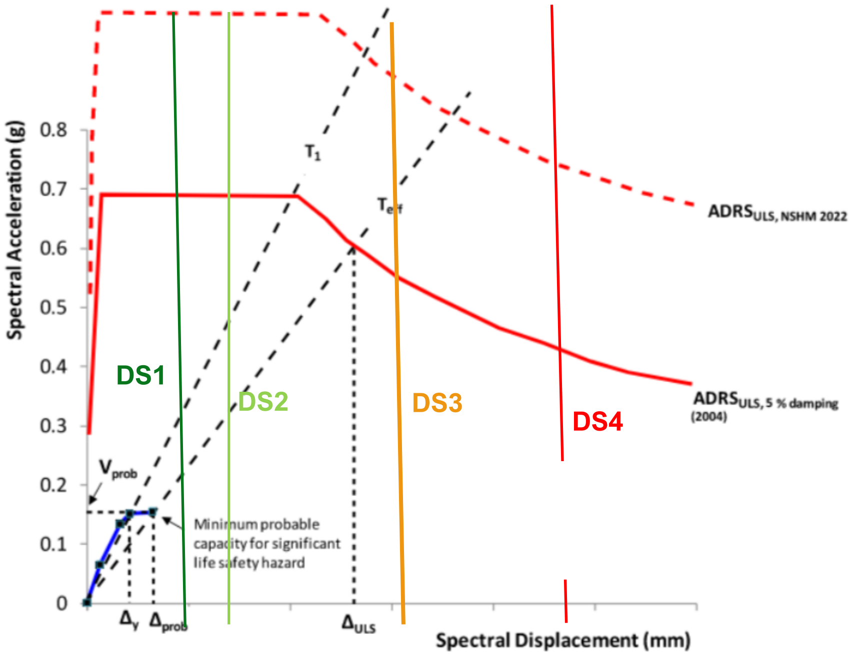


Figure 5.7: Example plot of the four damage states in ADRS

5.4.8 Plot the fragility S curves for each of the four Damage States

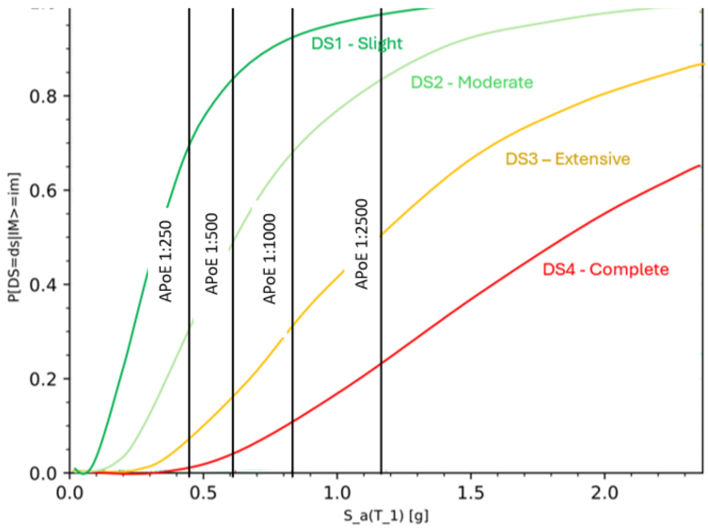


Figure 5.8: Example plot of four S fragility curves for each building type

5.4.9 How does ULS (basis for *%NBS*) compare against DS4 complete collapse state?

While the assessment criteria of existing buildings in New Zealand is for life-safety and based on ULS, the fatality risk assessment is based on collapse. Normalising the fragilities the model includes a collapse margin adjustment factor, a study-specific Inherent Capacity Factor (ICF), for these existing structures. Refer to Section 5.7 for further explanation.

5.4.10 How do our fragility curves compare against Hazus?

The Displacement-based method (DBM) based fragility curves of our study were compared against the Hazus fragility curves for each building type and was found to either match or be less conservative.

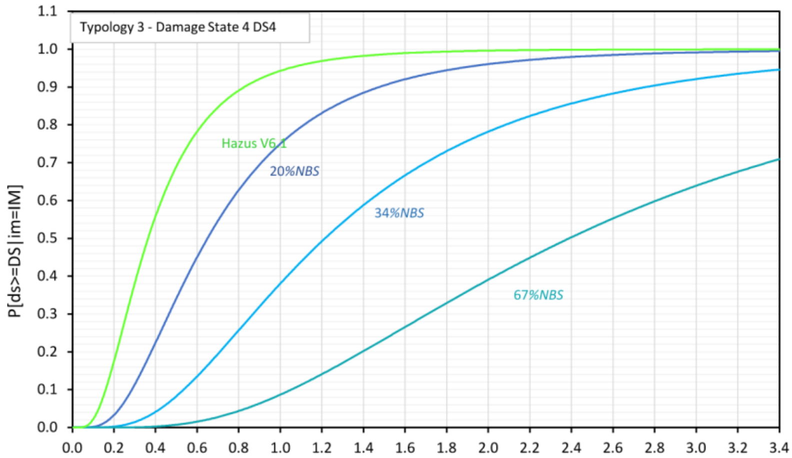


Figure 5.9: Comparison of DBM with Hazus curves for an unreinforced masonry building

5.4.11 How do our fragility curves compare against NZ experimental data or observed data from Christchurch 2011 event?

At the outset of the study, we engaged with universities and conducted a literature review to identify New Zealand-specific fragility curves supported by experimental test data or observed earthquake data for each building type. For each building type, a comparison of S-curves was performed against our fragility curves using the Displacement-Based Method (DBM). The DBM fragility curves were validated against observed damage data from the 2011 Christchurch earthquake (CEBA) or experimental data. Some types were less well-researched, requiring the use of older pre-2011 studies. However, literature was available for almost all types.

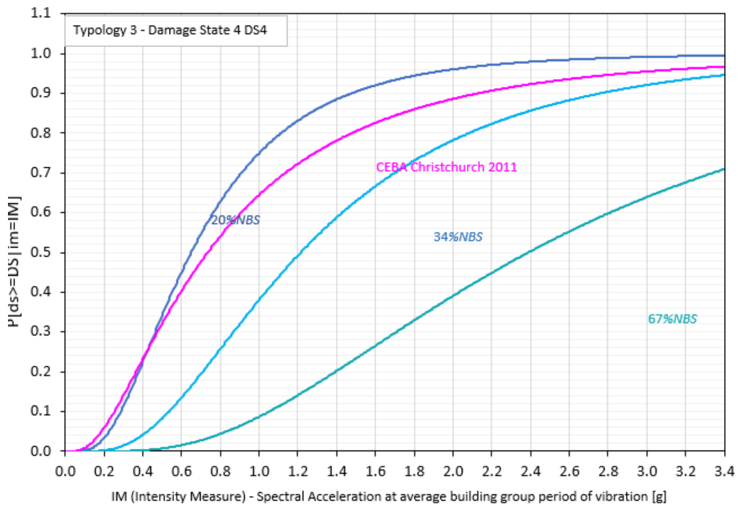


Figure 5.10: Comparison of DBM curves versus CEBA curve for an unreinforced masonry building

A complete set of comparison charts can be found in Appendix F.

5.4.12 What is the damage observed in each Damage State?

Assumptions for each damage state and each type are explained in the Table C6 in Appendix C under assumptions.

5.5 Step C – Shaking Intensity Hazard – APoE Levels

In New Zealand, a recent large-scale study by GNS Science was completed to create a National Seismic Hazard Model hereby referred to as the NSHM2022. The study characterizes the variation of seismic hazard throughout New Zealand based on updated ground motion models and seismic source models beyond those used for design codes such as NZS 1170.5:2004 that are used for assessing earthquake-prone buildings.

For this study, an estimate of spectral acceleration was required for a variety of earthquake APoE levels. GNS Science provides this data based on their NSHM2022 study dependent on input building and soil characteristics. The data can be extracted in the form of hazard curves or uniform hazard spectra. Because discrete hazard scenarios are sought, the uniform hazard data has been used in this study.

The characteristics of each structure, such as its estimated underlying V_{s30} and the benchmark period for the structure's building typology, are used to determine the spectral acceleration for each APoE level.

The V_{s30} of each structure was identified through QuakeCoRE's V_{s30} map by Foster et al. (2019). It is known that the map presents only a very low accuracy for the soil class of each structure, so it should not be relied upon for individual structures. Because this study aggregates the results of many buildings across a given typology and region, the V_{s30} results are only relied upon in a regional-sense. A possible error in the V_{s30} applied to an individual building are not expected to have a significant impact on the results.

Table 5.5: APoE shaking level when each damage state is initiated

Damage State	Approximate APoE when damage state is initiated (years)
DS1 (slight damage)	42
DS2 (moderate damage)	63
DS3 (extensive damage)	115
DS4 (complete collapse)	235

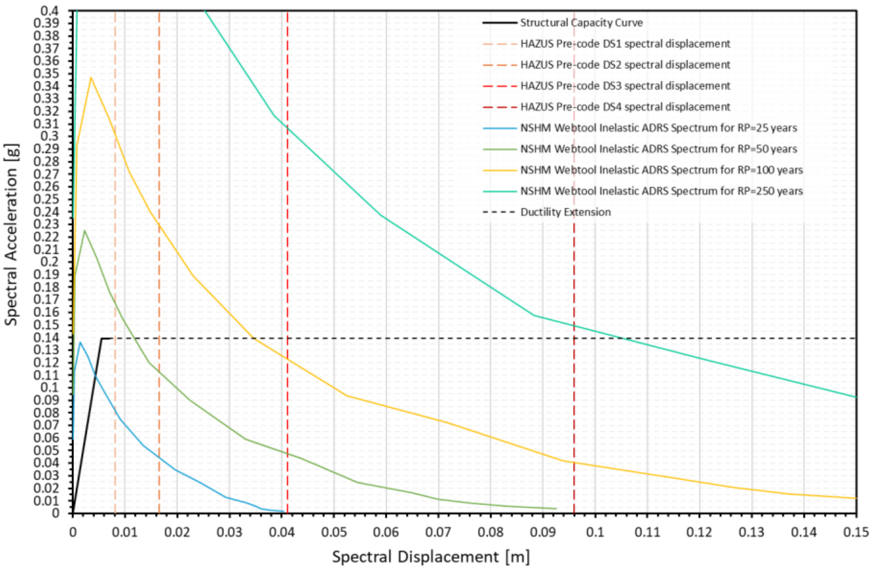


Figure 5.11: Example plot for URM single storey Dunedin building with NSHM2022 hazard spectrum

5.6 Step D – Consequence Model

Consequence models define the rates of the various loss types of conditional on the building damage state and are required to estimate the expected loss. The general workflow is shown Figure 5.12 and 5.13.

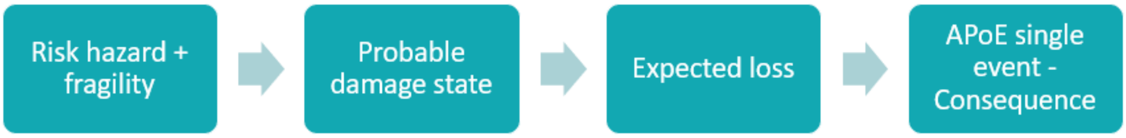


Figure 5.12: Example of workflow where consequence models are used to estimate expected loss based on damage state probabilities

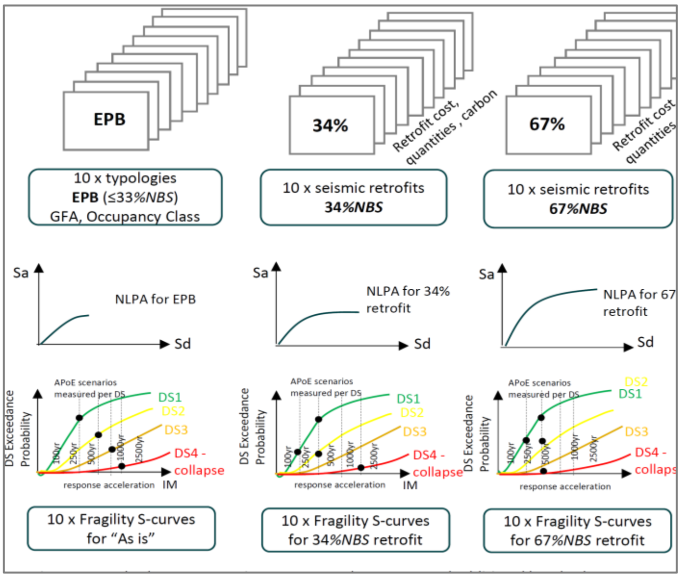


Figure 5.13: Outline process to integrate concept designs into consequence models

5.6.1 Casualty Consequence Models

The casualty consequence models estimate the rate of non-fatal injuries of different severity, and fatal injuries (deaths). There are four casualty states represented – Casualty State 2 (CS2) through to Casualty State 5 (CS5) and these are defined in Table 5.6. Casualty State 1 (CS1), minor injuries requiring first aid treatment are not considered due to very little information available to constrain and estimate the rate of these injuries as well as the likely very low economic and social impact of such minor injuries.

For each damage state and building type, the casualty consequence model has an associated rate of each casualty state. The rates have been determined based on analysis of ACC injury data and Coronial Enquiries into deaths from the 2010 Darfield Earthquake, the 2011 Christchurch Earthquake, the 2013 Cook Strait Earthquakes, the 2014 Eketahuna Earthquake, and the 2016 Kaikōura Earthquake (Horspool et al, 2020, Horspool, 2022). These studies found that the majority of deaths are due to structural collapse, while injuries are due to being hit by non-structural elements and buildings contents, or from falls and strains from strong ground shaking. The casualty rates can be multiplied by the number of occupants in the building to calculate the number of people in each casualty state. The rates represent the average for that building type and damage state. The casualty rates used in the model are shown in Table 5.6.

Furthermore, casualty rate models for URM, reinforced concrete and other types of buildings are also based on research paper by Ramos, Silva V, Martins. 2025 [20] Table 2.

Table 5.7: Casualty State Definitions after Horspool (2022)

Casualty State	Description	Abbreviated Injury Score
Minor CS1	First Aid: Minor injuries that can be treated by first aid such as minor scratches/abrasions, bruises, etc.	1
Moderate CS2	Community clinic: Injuries that require expert treatment (para-professional or doctor) but that are not immediately life-threatening if such treatment is not available. Examples include cuts requiring stitches, serious sprains, dislocations, significant burns (first degree, or second degree over small part of body), minor concussion (unconscious <1 hour).	2
Serious CS3	Hospital: Injuries requiring a greater degree of medical care and use of medical technology, such as X-rays or surgery, but not expected to progress to a life-threatening status; full recovery expected with suitable treatment. Examples include open head or face wounds, concussion (unconscious >1 hour), fractures (open, displaced), dehydration, exposure or serious burns (third degree over small part of body or second degree over large part of body).	3
Critical CS4	Hospital: Injuries that pose an immediate life-threatening condition or long-term disability if not treated adequately and expeditiously. Examples include brain damage; spinal-column injuries; nerve injuries; crush syndrome; internal-organ failures due to crushing, organ puncture or other internal injuries; uncontrolled bleeding; traumatic amputations of arms or legs.	4–5
Dead CS5	Fatal	6
Damage Ratio DR	Damage ratio as a % fraction of full replacement	
Downtime DT	Downtime (days) informing indirect and direct business disruption measure	

5.6.2 Repair Cost Consequence Models

The building repair cost consequence models define the damage ratio (DR) conditional on building damage state and building type. Damage ratio is defined as the ratio of the repair cost to the replacement costs of the building. The damage ratio can be multiplied by the replacement cost of the building to estimate the repair cost. The repair cost models are based on numerous studies investigating building damage and repair cost claims from insurance data from recent New Zealand earthquakes (Scheele, 2023). The assumed damage ratio and repair cost models are shown below in Table 5.8.

5.6.3 Business Interruption / Downtime Consequence Models

The downtime consequence models are conditional on the damage ratio which is a good proxy for the repair time. The downtime models reflect how long (in days) the building will be at reduced functionality. The models are primarily based on those in Hazus and have been modified based on observed building downtime from the 2010-2011 Canterbury Earthquake Sequence and 2016 Kaikōura Earthquake (Scheele et al, 2023). The downtime model is shown in last column of Table 5.8.

Table 5.8: Peak occupancy rates and time-specific rates for various use categories (Scheele et al, 2023)

Type		Damage State	DS Title	CS2 Moderate Injury	CS3 Serious Injury	CS4 Critical Injury	CS5 Fatality	DR Damage Ratio	DT Downtime
1	Light timber frame with URM element	DS1	Slight	0.01	0	0	0	0.1	1
		DS2	Moderate	0.04	0.002	0	0	0.3	10
		DS3	Extensive	0.1038	0.0013	0.0002	0.0007	0.8	180
		DS4	Complete	0.12	0.015	0.005	0.005	1	365
2	URM - 1 storey	DS1	Slight	0.01	0	0	0	0.1	1
		DS2	Moderate	0.04	0.002	0	0	0.3	270
		DS3	Extensive	0.07	0.035	0.05	0.1	0.8	365
		DS4	Complete	0.05	0.15	0.15	0.2	1	365
3	URM – 2-4 storey, GFA < $2000m^2$	DS1	Slight	0.01	0	0	0	0.1	1
		DS2	Moderate	0.04	0.002	0	0	0.5	270
		DS3	Extensive	0.07	0.035	0.05	0.1	0.8	365
		DS4	Complete	0.05	0.15	0.15	0.2	1	365
4	URM - 4 storey, GFA > $2000m^2$	DS1	Slight	0	0	0	0	0.1	5
		DS2	Moderate	0.04	0.002	0	0	0.5	270
		DS3	Extensive	0.07	0.035	0.05	0.1	0.8	365
		DS4	Complete	0.05	0.15	0.15	0.2	1	480
5	RC shear walls (low-rise)	DS1	Slight	0.01	0	0	0	0.1	5
		DS2	Moderate	0.04	0.002	0	0	0.3	270
		DS3	Extensive	0.07	0.01	0.05	0.05	0.8	365
		DS4	Complete	0.05	0.1	0.1	0.15	1	480
6	RC shear walls (mid-rise)	DS1	Slight	0.01	0	0	0	0.1	5
		DS2	Moderate	0.04	0.002	0	0	0.5	270
		DS3	Extensive	0.07	0.01	0.05	0.05	0.8	365
		DS4	Complete	0.05	0.1	0.1	0.15	1	480
7	RC frame + masonry infill	DS1	Slight	0.01	0	0	0	0.1	5
		DS2	Moderate	0.04	0.002	0	0	0.5	270
		DS3	Extensive	0.07	0.01	0.05	0.1	0.8	365
		DS4	Complete	0.05	0.15	0.15	0.2	1	480
8	Pre-1976 RC frame	DS1	Slight	0.01	0	0	0	0.1	10
		DS2	Moderate	0.08	0.005	0	0	0.5	270
		DS3	Extensive	0.07	0.01	0.0002	0.022	0.8	480
		DS4	Complete	0.23	0.01	0.02	0.15	1	560
9	Post-1976 RC frame with precast flooring	DS1	Slight	0.01	0	0	0	0.1	10
		DS2	Moderate	0.08	0.005	0	0	0.5	270
		DS3	Extensive	0.07	0.02	0.02	0.05	0.8	480
		DS4	Complete	0.23	0.05	0.05	0.18	1	560
10	Steel MRF with precast	DS1	Slight	0.01	0	0	0	0.1	5
		DS2	Moderate	0.08	0.005	0	0	0.3	90
		DS3	Extensive	0.07	0.01	0.01	0.02	0.8	270
		DS4	Complete	0.23	0.05	0.05	0.1	1	365

As an example, the number in the above table is the probability of the casualty state, as an example under column ‘CS5” for Type 4 and DS4 complete damage, the number 0.15 means that there is a 15% probability of being critically injured in a URM 4 storey building.

5.6.4 Occupancy Model

To calculate the number of injuries and deaths from the casualty consequence model, the number of occupants expected in each building must be estimated. Scheel et al (2023) developed a dynamic population model for estimating the number of people in buildings at different times of the day on different days of the week. The model uses a variety of data sources including, energy efficiency and use profiles, google maps business ‘business’ data, and corporate real estate occupancy data. The model incorporates two elements, first the m^2 per person for different building use categories which is used to estimate the peak occupancy, and second the time varying occupancy rate which defines the proportion of peak occupancy every hour for weekdays and weekends. For this study three time periods were used, peak occupancy, 10am weekday and 7pm weekday. These rates are shown in Table 5.9.

Table 5.9: Peak occupancy rates and time-specific rates for various use categories (Scheele et al, 2023).

Occupancy class	Description occupancy class	Peak occupancy [m^2 per person]	Beca adjusted rates	Proportion of peak at 10am weekday	Proportion of peak at 7pm weekday
RES1	Single-family Dwelling	30	30	0.4	0.7
RES3A	Apt., Multi-family Dwelling: Duplex	10	20	0.4	0.7
RES3B	Apt., Multi-family Dwelling: Triplex/Quad	10	20	0.4	0.7
RES3C	Apt., Multi-family Dwelling: 5-9 units	10	20	0.4	0.7
RES3D	Apt., Multi-family Dwelling: 10-19 units	10	20	0.4	0.7
RES3E	Apt., Multi-family Dwelling: 20-49 units	10	20	0.4	0.7
RES3F	Apt., Multi-family Dwelling: 50+ units	10	20	0.4	0.7
MULTI RES	Multi-use: Retail + RESID	10	20	0.4	0.7
COM1	Department store, shopping mall	2	4	0.8	0.2
COM3	Garage, Repair	20	30	0.8	0.1
COM4	Office	14	14	0.9	0.1
COM6	Hospital	20	20	1	1
COM7	Medical Office/Clinic	20	20	1	0.2
COM8	Restaurant	2	10	0.8	0.8
COM9	Movie theatre, Opera House, Galleries, Exhibitions	2	4	0.3	0.8
COM10	Parking Garage	10	18	0.05*	0.05*
COM11	Swimming pools, sport centre, community centres	10	15	0.9	0.2
COM12	Grandstand, Racecourse	2	4	0.01	0.8
COM13	Small retail shops, NZ corner shop	2	30	0.8	0.2
MULTI COM	Multi-use: Retail + COMM	15	25	0.6	0.8
UTI1	Substation, suburb	100	100	0.05	0.05
IND1	Factory	30	30	0.7	0.2

Occupancy class	Description occupancy class	Peak occupancy [m² per person]	Beca adjusted rates	Proportion of peak at 10am weekday	Proportion of peak at 7pm weekday
IND2	Industrial Warehouse, heavy	30	30	0.7	0.2
IND3	Lab, Food/Drugs/Chem 1-storey	30	30	0.7	0.2
REL1	Church	2	4	0.3	0.1
GOV1	Town hall, Main Railway station	4	4	0.8	0.2
GOV2	Police station, Fire stations	14	14	0.9	0.9
EDU1	High-school, Primary and Early childcare	2	4	0.95	0
EDU2	University classrooms	2	2	0.95	0.1

* The proportion of space associated with people in cars leaving or entering the building at the time of a 10am or 7pm even is assumed to be 1:20 (0.05)

The consequence model includes people inside and outside the building. Table 5.10 shows the multipliers that have been applied to the casualty states for building occupants to obtain those for people (pedestrians) outside a building.

Table 5.10: Assumed multipliers to relate building occupant casualties to those outside

Outside Casualty	CS2 Minor injury	CS3 Serious injury	CS4 Critical injury	CS5 (Fatality)
Daytime	1.04	1.12	1.14	1.1
Nighttime	1.01	1.03	1.03	1.03

5.6.5 Numbers of People Inside versus Outside a Building during Earthquakes

As part of our study, we reviewed our occupancy model and compared the data with pedestrian counts provided by Wellington City Council to validate assumptions regarding people outside buildings (refer Figure 5.14). This was a critical assumption, as URM (Unreinforced Masonry) building parapets and façades tend to fail outward onto the street, potentially affecting pedestrians. On average, there are typically 1–3 people outside a building at any given time, with numbers generally higher during the day. Pedestrian activity peaks near public transport stations or bus stops, during lunchtime near takeaway outlets, or before and after events. The number of people outside also varies significantly between urban centres and smaller towns, with less dense populations in smaller towns resulting in lower pedestrian counts similar to the outer suburbs of urban centres.

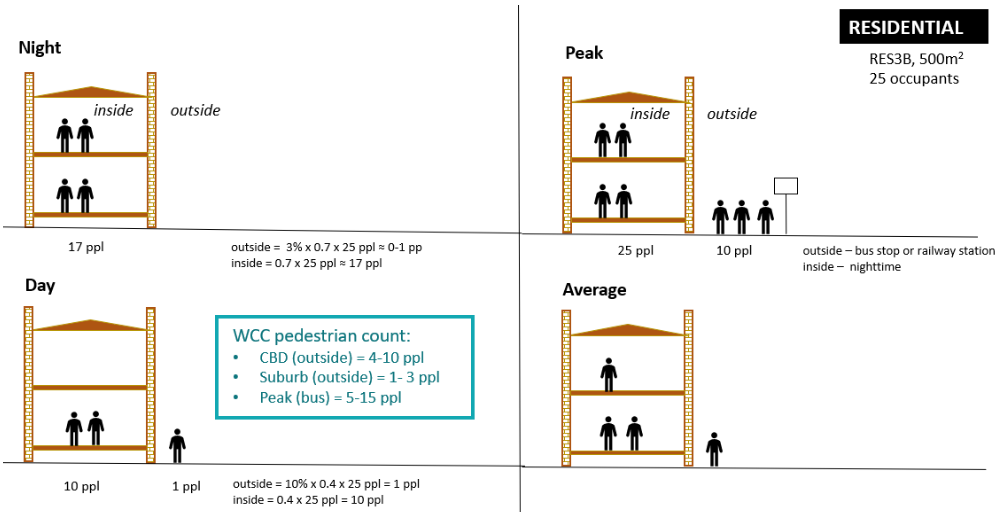


Figure 5.14: Occupancy model review – People inside and outside of a building

5.7 Step E – Applying ICF (overstrength) on Structural Backbone

What is ICF?

The Inherent Capacity Factor (ICF) is the 'overstrength' of the existing structure allowing to relate scaling from ultimate limit state to collapse margin. ICF is a study-specific term, and not referred elsewhere.

How was ICF derived?

To benchmark the ICF, we reviewed the CMR method as defined in FEMA P695 *Quantification of Building Seismic Performance Factors.*

FEMA P695 Section 7.1.2 'Acceptable Probability of Collapse' evaluates seismic performance by targeting a 10% probability of collapse at the Maximum Considered Earthquake (MCE) ground motion level as the target for acceptable performance for a 'performance group' and 20% for outliers. FEMA P695 is also noting that these limits were selected by judgement.

CMR is defined in Section 1.2.6 Figure 1-2 and Equation (1-8) of FEMA P695.

$$CMR = \frac{\hat{S}_{CT}}{S_{MT}} = \frac{SD_{CT}}{SD_{MT}}$$

Furthermore, the Adjusted CMR (ACMR) is defined in Equation (7-1) as per P695 Section 5.7.

$$ACMR = Spectral\ Shape\ Factor\ (SSF)\ x\ CMR$$

Therefore, applying FEMA P695 Acceptable ACMRs as per Table 7-3 and Table 7-2c

FEMA P695	*FEMA P695*T able 7 2c	*FEMA P695* Table 7 3	*ICF ACMR * 0.769*	*ICF adopted*
Model Quality- Fair Quality of Test data C - Fair Quality of Design Requirements C - Fair	β_{TOT1} = 0.675	$ACMR_{10\%}$ = 2.38	1.83	2.0
Model Quality- Poor Quality of Test data C - Fair Quality of Design Requirements C - Fair	β_{TOT1} = 0.800	$ACMR_{10\%}$ = 2.79	2.15	

In New Zealand, *%NBS* for existing structures is tied to the Ultimate Limit State (ULS).

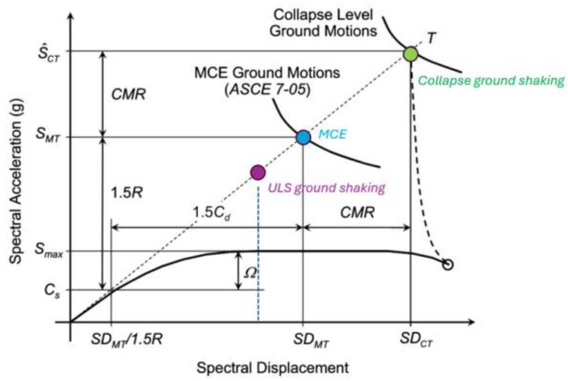


Figure 1-2 Illustration of seismic performance factors (R, Ω, and Cd) as defined by the Methodology.

Figure 5.15: Risk model settings

Noting that new structures are expected to achieve at least 130%*NBS* [*Engineering Assessment Guidelines* 2017], an inherent capacity factor (ICF) of about 2.0 was introduced as part of this project and applied to the ULS capacity curve determined for the existing structures to indicate the point of collapse.

Therefore, final ICF setting:

$$ICF = ACMR \cdot \frac{100\%}{130\%} = 2.0$$

How did we apply the ICF factor to the backbone curve?

The ICF factor of 2.0 was applied to both spectral displacement (yield/ultimate) and the spectral acceleration of the backbone curve of the structure. This way it keeps the stiffness the same and increases the yield displacement and spectral acceleration.

Ultimate spectral displacement was multiplied by ICF:

$$S_{du,ICF} = ICF \cdot S_{du,NBS}$$

Yield spectral displacement was multiplied by ICF:

$$S_{dy,ICF} = ICF \cdot S_{dy,NBS}$$

Spectral acceleration multiplied by ICF:

$$S_{a,ICF} = ICF \cdot S_{a,NBS}$$

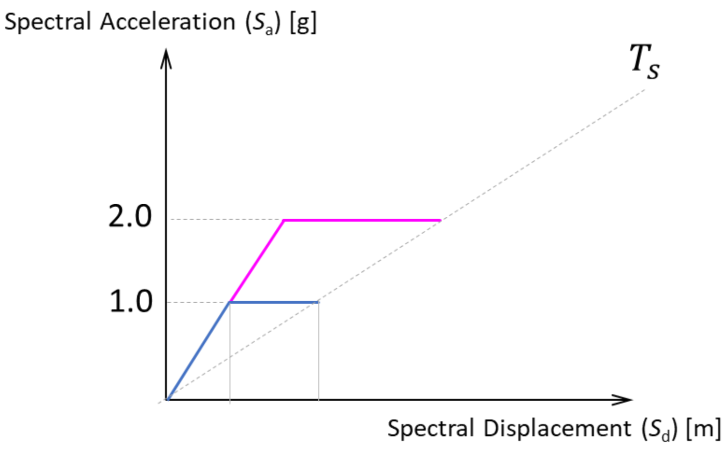


Figure 5.16: Implementation of inherent capacity factor (ICF) on the structural backbone

The Figure 5.16 shows the original backbone curve (*blue*), and the final ICF adjusted backbone curve (*pink*), by applying the multiplier of 3.0 to the spectral displacement and spectral acceleration with constant stiffness.

5.8 Step F – Sensitivity Testing of Risk Model over a Range of Assumptions

The most sensitive parameters influencing the results of this study were the fragility curves, consequence model and occupancy rates. As part of the sensitivity testing, we explored a range of input assumptions, considering both lower and upper bound ranges. The beta value of the fragility curves was also reviewed ranging from 0.64 (Hazus-recommended value) versus 0.45 as per displacement-based approach and used in many NZ based research papers.

Risk model 'tuning' and testing looking at several input settings:

1. Inherent Capacity Factor (ICF) from 1.0 to 4.0 - "overstrength" adjustments
2. Consequence model (e.g. CS5) using lognormal distribution range of 10, 50 and 90 percentiles
3. Beta factor of fragility curve 0.64 versus 0.45
4. Occupancy model – based on population and adjustments / reductions based on our review of stock
5. Hazard shaking levels across a city will vary; however, shaking levels were kept constant for this study and only varied depending on V_{s30} shear wave velocity of the city

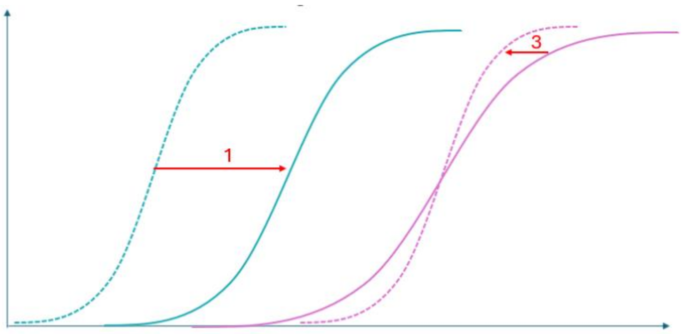


Figure 5.17: Sensitivity study of varying input parameter

5.9 Final Settings of Risk Model

The impacts across all buildings for each APoE were accumulated, and the risk model was calibrated at the city level following multiple sensitivity analyses and a thorough review of the results. As can be seen in Figure 5.18 (right) the total loss was compared against the Canterbury earthquake 2011 earthquake event, comparing shaking levels across the city with those in our study using an APoE of 1:500. Canterbury (Christchurch) 2011 earthquake event had an estimated loss of $52 billion and our study for APoE 1:500 for Christchurch concluded $45 billion total loss including also property loss and business interruption downtime. The final settings outlined below have been adopted for the risk model.

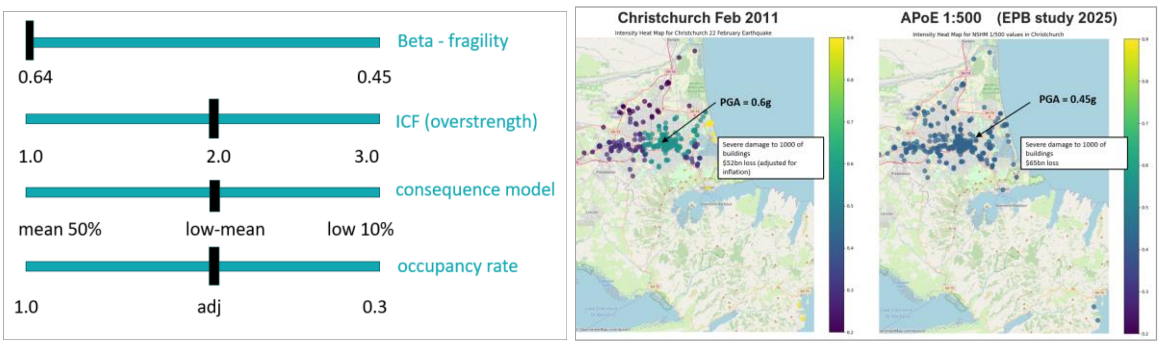


Figure 5.18: Risk model settings

Figure 5.18 (left) summarises the four key parameters for the risk model settings: ICF (Inherent Capacity Factor), consequences, occupancy rates, and fragility curves.

A sensitivity study was conducted using a pilot example – a single-storey unreinforced masonry (URM) office building in Dunedin. The study explored a range of values for each key input parameter (as shown in Table 5.11). For instance, it examined an ICF range from 1.0 to 3.0, a consequence model ranging from low to mean based on a lognormal distribution, and fragility curve assumptions with beta values of 0.64 and 0.45.

The final settings, detailed in Table 5.12, were derived following calibration through comparisons that assessed total loss for the Christchurch 2011 earthquake under similar APoE shaking levels (1:500 for Christchurch) and other major international earthquake events.

The final settings for this study include an ICF of 2.0, occupancy rates adjusted according to Beca's revised Table 5.8, and slightly amended consequence rates for unreinforced masonry (URM), as presented in Table 5.9. The complete final settings for the risk model are provided in Table 5.12.

Table 5.11: Sensitivity study of range of assumptions

Sensitivity study Range of assumptions				
Dunedin, URM 1 storey, office building				
	Case 1	**Case 2**	**Case 3**	**Case 4**
ICF	1.0	1.5	1.5	3.0
Fragility (Beta)	0.64	0.64	0.45	0.64
Casualty Rates (varying volume loss)	50 percentile (mean)	Lognormal distribution Beta = 0.6 URM, Beta = 0.8 (other typologies) Testing lognormal distribution range of 10, 50 and 90 percentiles.		50 percentile (mean)
V_{s30}	Site specific ranges from 200 m/s to 700 m/s			

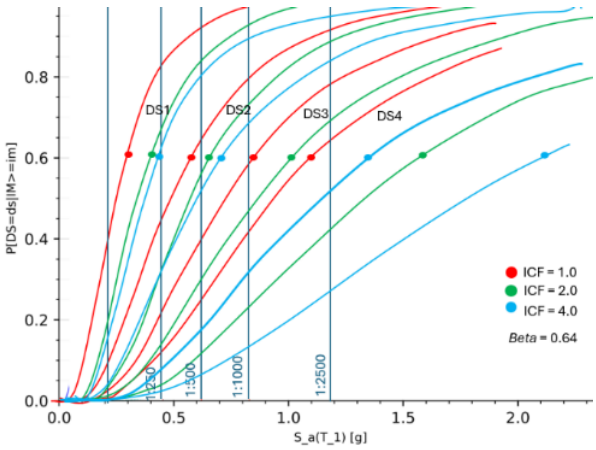


Figure 5.19: The median collapse intensities are defined by the inherent capacity factor (IFC) (1.0-red, 2.0-green, 4.0-blue), as a multiple of the Sa(T_1). Damage State DS1 to DS4. The slope of the fragilities is defined by Beta.

Yellow highlighted numbers in table above have been used as input for dashboard.

Table 5.12: Sensitivity study of range of assumptions

Final settings:			
ICF = 2.0	*Beta* = 0.64	Casualty model = 30% (low-mean) percentile	Occupancy model = Beca's adjusted rates
Reasoning explained in section 5.7 "Step E – Applying ICF"	Reasoning explained in section "Why did we adopt a Beta of 0.64"	The rational is to tune the risk model to address the issue when looking at loss across a city for a certain APoE.	Beca's adjusted occupancy rates as per Table 5.9. Rational is to adjust to this particular building stock.
Bpowereca's reference to final version: P:\527\5276358\1-WIP\SA-Structural\02-Working Calculations\Cost Benefit Tool Data\2025-05-15v - 6 Location, compromise settings w vosl 1p0 30pc cs5			

5.10 Cost Estimate Methodology for Building Replacement and Repair Works

Cost estimates for full building replacement have been calculated to provide a reference point.

The replacement costs have been determined based on the designated Occupancy Class and have been presented as a $/m^2 rate. Published resources from Quotable Value (QV) and Rider Levett Bucknall (RLB) have been referred to and then adjusted as appropriate based on recent market observations. The $/m^2 rates are then factored up to account for project related on-costs, including demolition, design fees, contingency and consents.

5.11 Life-Cycle Carbon Assessment for Building Replacement and Repair Works

The following steps were undertaken to complete the carbon life cycle assessment (LCA):

- Quantity Determination: The Quantity Surveyor (QS) provided quantities required for carbon calculations related to full replacement and repair works.
- Carbon Calculation: Using these quantities, the BRANZ LCAQuick tool was applied to calculate the embodied upfront carbon emissions for each Building type.
- Reference Material: Findings from the MBIE research report titled "Understanding Potential Avoided Upfront Carbon Emissions Through Strengthening of Seismically Deficient Buildings" were referenced to provide additional context and support this analysis.

5.12 Benefit Inputs from Economic Analysis

The economic assumptions of the benefits follow two main references: the NIBS Report and the Research paper by Ilan Noy and Tomas Uher (December 2022) from Victoria University of Wellington, titled *"Cost-Benefit Analysis of a Building Code Change: Applying the NIBS 2019 Methodology in New Zealand."*

5.12.1 Benefits - Avoidance of Cost for Building Repair

Cost as fraction of building replacement cost as per *Table A-14 NIBS adopted for Occupancy classes as applicable for this study.* Repair costs were capped at 100% of replacement cost. The economic cost of the property damage is the lesser of damage repair costs or combined demolition and replacement cost. The assumed replacement cost was summarise in Table 5.13.

Our economic assumption focuses on immediate post-disaster reoccupancy rather than the longer-term full functional recovery. These assumptions consider downtime and disruption, partial replacement costs, including repairs to contents, non-structural elements, cosmetic damage, and reinstatement. However, they do not account for the complete restoration of regional utility services or infrastructure networks..

Table 5.13: Repair cost as a faction of building replacement cost

Building related damages NIBS/Hazus tables		Structures and Contents cost			
		GFA	Replacement cost x regional factors ($/m²)		
Label	Occupancy Class	(m^2)	Structure Replacement	Contents Value % of Replacement	Contents replacement
RES1	Single-family Dwelling	150	4990	50%	2495
RES3A	Apt., Multi-family Dwelling: Duplex	200	4460	50%	2230
RES3B	Apt., Multi-family Dwelling: Triplex/Quad	400	4860	50%	2430
RES3C	Apt., Multi-family Dwelling: 5-9 units	740	4860	50%	2430
RES3D	Apt., Multi-family Dwelling: 10-19 units	1400	6440	50%	3220
RES3E	Apt., Multi-family Dwelling: 20-49 units	3700	7490	50%	3745
RES3F	Apt., Multi-family Dwelling: 50+ units	7000	7490	50%	3745
MULTI-RES	Multi-use: Retail + RESID	7000	7490	50%	3745
COM1	Department store, shopping mall	10000	7880	100%	7880
COM3	Garage, workshop and repair	900	250	100%	250
COM4	Office	7000	6830	100%	6830
COM6	Hospital	5000	12750	150%	19125
COM7	Medical Office/Clinic	650	7490	150%	11235
COM8	Restaurant	500	6170	100%	6170
COM9	Movie theatre, Opera House, Galleries	1100	10510	100%	10510
COM10	Parking Garage	13000	3540	20%	708
COM11	Swimming pools, sport centre, halls	8000	14000	150%	21000
COM12	Grandstand, Racecourse	6000	6170	100%	6170
COM13	Small retail shops, NZ corner shop	200	4200	50%	2100
MULTI-COM	Multi-use: Retail + COMM	650	6570	100%	6570
UTI1	Substation, suburb	250	4500	100%	4500
IND1	Factory	2700	3150	150%	4725
IND2	Industrial Warehouse, heavy	2700	3540	150%	5310
IND3	Lab, Food/Drugs/Chem 1-storey	4100	8800	150%	13200
REL1	Church	1500	8800	100%	8800
GOV1	Town hall, Main Railway station	1000	10380	100%	10380
GOV2	Police station, Fire stations	1000	9460	150%	14190
EDU1	High-school, Primary and Early childcare	12000	7490	100%	7490
EDU2	University classrooms	4600	10120	150%	15180

5.12.2 Avoidance of People-Related Loss

5.12.2.1 VoSL for Earthquake casualties

Fragility and loss modelling generated the key quantities required for the economic analysis of costs and benefits. The key cost data are drawn from the Treasury's CABx, the NIBS and Noy & Uher 2022 paper as appropriate for each level. This included the monetary quantification of social loss (casualties, non-fatal injuries), based on Value of Statistical Life (VoSL) or fraction of VoSL as per Treasury CABx 2025.

5.12.2.2 Monetary Quantification of Human Loss (Casualties)

The VoSL has its origin in reflecting road accidents. In the New Zealand case, the Ministry of Transport (MoT) and The Treasury set it to NZ $17,519,531 (The Treasury New Zealand, 2025). Between 2021 and

2023 the VoSL was adjusted in New Zealand and increased in order of four times from NZ$4.3 million to NZ$17.5 million.

5.12.2.3 Monetary Quantification of Human Loss (Non-Fatal Injuries)

This aspect of the study was based on the research paper by Noy and Uher (2022). For injuries a fraction of VoSL as per Table 1 from Noy & Uher (2022) and summarised in Table 5.14.

Table 5.14: Monetary Quantification of Human Loss (Injuries/Casualties)

Casualty state		Fraction of VoSL	NZ$
Moderate	CS2	0.047	$823,418
Serious	CS3	0.105	$1,839,551
Critical	CS4	0.397	$6,955,254
Dead	CS5	1.00	$17,519,531

5.12.2.4 Post-traumatic stress disorder (PTSD)

This aspect of the study was based on the research paper by Noy & Uher (December 2022). Quantifying injuries related to mental health can be particularly challenging. The NIBS Report identifies PTSD as a significant mental health outcome following disaster events. Due to the lack of comprehensive data on the prevalence of PTSD after disasters, we propose that in New Zealand, the number of individuals expected to experience PTSD should be equivalent to those estimated to fall into the "serious" (AIS level 3) casualty category. The paper recommended determining an acceptable overall cost for preventing a statistical incidence of PTSD (V_{PTSD}) of NZD 140,000, following the NIBS report. This is based on Canterbury earthquake event 2011. The V_{PTSD} of NZD 140,000 has been applied to events with similar total loss as Christchurch e.g. APoE 1:500 Christchurch, Wellington, Dunedin, APoE 1:2500 Auckland.

5.12.3 Avoidance of Disruption and Downtime

5.12.3.1 Downtime losses (residential displacement and business interruption)

To quantify time-element losses (indirect losses over time, like business profit losses), both direct business disruption (V_{BI}) and indirect (Q) per day per occupant losses for each occupancy class (residential and commercial) must be calculated using the following methods as explained below.

The total time-element losses can then be quantified by combining the estimates of direct and indirect per day per occupant losses for each occupancy class with the number of indoor occupants and the mean duration of loss of function.

5.12.3.2 V_{BI} for residential occupancies

Time-element displacement costs for residential occupancy can be estimated using publicly available data. The multiplier (1.667) accounts for higher post-event housing costs, including temporary shelter expenses. Median monthly rent data per territorial authority (TA) is accessible (Tenancy Services, 2022).

Monthly house rental costs=Median monthly rent x 1.667

Household furniture hire costs are approximated at NZ$800/month (as per the NIBS Report) across all regions. Increased commuting costs can be estimated using NZ Transport Agency data or a standard value of NZ$160/month (from the NIBS Report). The average household size is projected at 2.6 people over the next two decades (StatsNZ, 2021). These factors are combined to calculate total per day per occupant residential displacement costs (V_{BI}) for family dwellings in each region using the provided equation.

$$V\_BI = \frac{(monthly\ house\ rental\ cost + monthly\ furniture\ hire\ cost + commuting\ costs)}{average\ household\ size\ x\ 30.4}$$

Using assumptions as follows:

- Median rent = $577.50 per week (*Wellington $650, Dunedin $575, Auckland $650, Whanganui $493, Christchurch $549, Feilding $548*)
- Furniture hire = $800 per month as per NIBS Report
- Commuting cost = $160 per month as per NZ Transport Agency
- Average number of household = 2.6 people as per StatsNZ 2021

5.12.3.3 VBI for non-residential occupancies

Business interruption costs can be calculated by determining the direct per-person economic sector interruption cost. This involves using the provided equation along with publicly available data on industry-specific earnings and employee numbers per industry (StatsNZ, 2022).

$$Direct\ loss\ (\$) = \frac{Wages\ and\ earnings\ in\ industry}{Number\ of\ employees\ in\ industry}$$

For wages and earnings, the 'income' as per StatsNZ has been used. Earnings from main wage and salary job by industry for all groups: Income Weekly as per STATSNZ

Refer to Appendix C for full table of data used for Business disruption.

5.12.3.4 Indirect output loss Q (indirect residential displacement/business interruption costs)

Calculating indirect losses associated with both residential displacement and business interruption is more challenging. Input-Output tables can estimate per dollar per person output loss (Q) for each occupancy class, as in the NIBS Report.

Assumption is per trapped victim of NZ$20,000. This value has been applied to a fraction of indoor occupants trapped in collapsed buildings following NIBS study 2019, section K.14. 25% of the area of the buildings with at least some collapse experiences collapse and estimated that 1 in 3 people occupying the collapsed are trapped, not fatally injured, and need extrication. Thus, the number for trapped people in collapsed buildings requiring extrication, as a fraction of indoor occupants was estimated by 0.083 times probability of collapsed building area as per Equation A-38 NIBS 2019 study. USAR cost is paid by government.

5.12.4 Retrofit Cost per Option and Building type

For Retrofit cost and carbon refer Appendix C.

5.13 Energy Efficiency Benefits

To determine the benefits associated with an energy efficiency upgrade a comparison of baseline building energy performance (and associated operational costs and carbon emissions) was compared to an upgraded building.

When considering the seismic upgrades, energy efficiency upgrades are only triggered when the extent of work associated with earthquake strengthening makes this a "relevant" scope. For example, in situations where the walls are being opened there is an opportunity for insulation to be installed to improve the energy efficiency. HVAC is not triggered by the retrofit scope and has therefore been considered as independent of the earthquake strengthening decision.

5.13.1 Baseline Energy Performance

The baseline energy performance is based on occupancy type (building loading and hours of use) and the assumed insulation and system attributes for the age of the study cohort.

The following overarching occupancy groups are suitable for the purposes of energy performance assessment for the earthquake-prone building inventory.

- Large/Multi-Unit Residential
- Commercial
- Industrial
- Hospitals

These group buildings into similar operational cohorts with the building attributes subject to upgrade (insulation, glazing, and lighting system efficiency) being consistent across the structural typologies assessed.

Table 5.15 below presents the baseline building attributes and the energy consumption of HVAC and lighting systems. The proposed energy efficiency upgrade only materially impacts on the energy from these two systems.

Table 5.15: Baseline energy performance

Metric	Residential	Commercial	Industrial	Hospital
Wall insulation performance	R1.2	R0.5	R0.1	R1.2
Roof insulation performance	R1.8	R1.2	R0.3	R1.8
Glazing performance	Clear single glazing (30% WWR)	Single Glazing with tint (50% WWR)	N/A	Clear single glazed (30% WWR)
Lighting system	Fluorescent battens	Fluorescent battens	Fluorescent battens	Fluorescent battens
Energy Consumption* (kWh/m²)	40	126	47	200

*HVAC and lighting systems only

Values in the table above have been developed from the following sources:

- Residential building energy consumption based on national average 11,410 kWh p.a for an average 121m² occupied dwelling with energy split of 34% for space heating and 8% for lighting as presented in the *BRANZ Study Report SR221 – 2010: Energy Use in New Zealand Households*. The selection of the 2010 study was appropriate as it is weighted towards aged building stock.
- Commercial building energy consumption was based on the *BRANZ Study Report SR297/1 – 2014 Building Energy End-Use Study (BEES)* which showed a 33% lighting load and 29% space conditioning load from a total of 203kWh/m² p.a.
- Industrial building energy was based on typical operating hours for a NZS 4243:2007 compliant lighting system. This has been correlated against Beca's database of existing industrial building energy consumption and is considered representative of a standard efficiency lighting system consistent with the age of buildings in the earthquake-prone cohort.
- Hospital energy consumption for HVAC and lighting was based on *Energy Performance of Medium-sized Healthcare Buildings in Victoria, Australia- A Case Study* (Deakin University) which provided a

breakdown of energy uses. This was correlated against the baseline energy performance for healthcare facilities presented in *Analysis to Inform a Review of Large Non-Residential and Apartment Building Thermal Performance Settings and Climate Zones - Beca 2021* (referred to henceforth as the *MBIE H1 Study*) which provided data points to account for NZ climatic conditions.

The assessment of energy costs and associated carbon emissions are based on the rates provided by the MBIE Energy Prices Tables [1] and the Ministry for Environments Measuring Emissions Guidance [2], reproduced in Table 5.16 and Table 5.17

[1] MBIE *Energy Price Data Tables 2024* - https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/energy-prices

[2] *Measuring Emissions Guidance 2023* https://environment.govt.nz/assets/publications/Measuring-Emissions-Guidance_DetailedGuide_2023_ME1764.pdf

Table 5.16: Energy Costs and HVAC System Fuel Mix

Building Type	Residential	Commercial	Industrial*	Hospitals
Electricity Costs	$0.33	$0.21	$0.21	$0.21
Gas Costs	$0.18	$0.10	N/A	$0.10
Heating Fuel Mix (Elec/Gas)	48% / 53%	33% / 67%	N/A	54% / 46%

*No HVAC consumption assumed for industrial buildings with electricity for lighting based on the "Commercial" price rate. The "Industrial" rate within the Energy Price data tables is intended for heavy industrial energy users such as manufacturers.

Table 5.17: Fuel Type Carbon Emissions

Fuel Type	Carbon Emissions (kgCO2e/kWh)
Grid Electricity	0.083
Network Gas	0.194

5.13.2 Benefits Assessment

Energy efficiency improvements have been estimated for each typology as follows:

- Residential building HVAC energy reduction is based on a 25% improvement in heating consumption due to the provision of double glazing and improved insulation as presented in the results of the *MBIE H1 study*. Lighting energy improvement is based on a 17% lumen per watt output improvement of LEDs over compact fluorescent lamps.
- Commercial building HVAC energy reduction is based on a 20% improvement in heating and cooling consumption due to the provision of double glazing and improved insulation as presented in the results of the *MBIE H1 study*. Lighting energy improvement is based on a 39% lamp wattage improvement from fluorescent battens (36W) to LEDs (22W).
- Industrial building energy improvement is based on the same lighting system performance improvement as presented for commercial buildings (39%) – this is significantly higher as a proportion of industrial energy use due to the limited use of HVAC.
- Hospital building energy improvement is based on a 20% improvement in heating and cooling consumption due to the provision of double glazing and improved insulation as presented in the results of the *MBIE H1 study*. Lighting energy improvement is based on a 39% lamp wattage improvement from fluorescent battens (36W) to LEDs (22W).

These levels of performance improvement are consistent with detailed existing building energy performance analysis previously undertaken by Beca for these building typologies.

The resulting building performance metrics and benefits are presented in Table 5.18 below:

Table 5.18: Energy efficiency performance and benefits

Performance	Residential	Commercial	Industrial	Hospital
Baseline energy (kWh/m² p.a.)	40	126	47	200
Baseline carbon emissions (kgCO2e/m² p.a.)	5.1	14.8	3.9	23.3
Baseline energy costs ($/m²)	$11	$36	$10	$53
Efficiency upgrade energy (kWh/m² p.a)	30	88	29	147
Efficiency upgrade carbon emissions (kgCO2e/m² p.a.)	5.1	14.8	3.9	23.3
Efficiency upgrade energy costs ($/m² p.a.)	$8	$24	$6	$38
Benefits				
Energy reduction (kWh/m² p.a.)	9	38	18	53
Energy improvement (%)	23%	30%	39%	27%
Carbon reduction (kgCO2e/m² p.a.)	1.2	4.0	1.5	5.7
Operational cost savings ($/m² p.a.)	$2	$11	$4	$16

5.13.3 EE Economic Analysis

The following economic analysis of the energy efficiency (EE) upgrades is provided to show how this option is not of benefit to the overall earthquake strengthening programme. It is really just an extended discussion and explores the boundaries of the economic performance with some extreme sensitivity settings to highlight this. The dashboard has the option to switch EE on presents the capital costs for energy efficiency upgrades (applied to the 67%*NBS* upgrade case only) and the operational costs and carbon emissions associated with each APoE level.

5.13.3.1 Time Period of Benefits

It is assumed that the time-period of benefits from the energy efficiency upgrade is 15 years. This is on the basis that only limited upgrades have occurred prior to any earthquake strengthening works and that without earthquake strengthening, other drivers (such as ceiling and cladding end of life, market expectations, etc.) would only trigger an efficiency upgrade by ~2040. For the presentation of scenario results the 15 year benefits are summed and presented as Year 1 benefits. This is analogous to an energy efficiency “option” where benefits are accrued at the same time as capital cost are incurred. This provides a similar basis to that used for earthquake events which are also assumed to occur in Year 1.

5.13.3.2 Energy Escalation

No allowance for energy escalation is included in the study.

5.13.3.3 Electrical Grid Decarbonisation

No allowance for grid decarbonisation is included in the study. This only benefits energy efficiency initiatives where there is significant fuel switching activities. The scope of this energy efficiency study excludes HVAC fuel changes (as this is not connected to earthquake strengthening works).

5.13.4 EE Cost Benefit Analysis

To determine the impact of energy efficiency upgrades for this project a discrete cost benefit analysis was undertaken prior to integration into the wider earthquake strengthening options. This explored the upper limit of benefits from an energy efficiency upgrade by testing:

- the lowest per m² upgrade cost to incorporate the energy efficiency retrofit scope across all typologies, against
- the highest level of energy efficiency improvement per m² across all building types.

The CBA inputs are shown in Table 5.19.

Table 5.19: CBA Inputs

CBA Inputs	
Lowest capital cost rate (across all typologies)	$327/m²
Highest annual benefit rate (across all typologies)	$15/m²
Discount rate	8%
Time period	15 yrs

These most optimistic capital and operational cost scenarios result in the cost benefit outcomes shown in Table 5.20.

Table 5.20: CBA Results

CBA Results	
NPV	-$170.11 /m²
BCR	0.41

5.13.5 EE Sensitivity Analysis

Sensitivity analyses on these CBA results were undertaken to further understand the key drivers.

5.13.5.1 Discount Rates

To further test the limits of the cost benefit analysis the analysis was also completed for discount rates of 0%, 2% and 5%.

Table 5.21 compares the results:

Table 5.21: Discount rate sensitivity test

Discount Rate Sensitivity	NPV ($/m²)	BCR
0% Discount Rate	-$94.43	0.71
2% Discount Rate	-$121.38	0.61
5% Discount Rate	-$150.53	0.49
8% Baseline Discount Rate	-$170.11	0.41
IRR	-4.48%	

The results in Table 5.20 highlights that even when selecting favourable capital and operational cost impacts, the BCR of an energy efficiency upgrade is significantly less than 1. This only becomes greater than one as the discount rate drops below -4.5%.

5.13.5.2 Capital and Operational Cost Accuracy and Escalation

To assess the impact of cost accuracy, the favourable capital cost selection was further reduced by 20% ($262/m²) with the most favourable operational benefits increased by 20% ($18.60). In addition, an energy cost escalation of 5% is applied. Table 5.22 shows the results of the sensitivity test at the baseline discount rate of 8%:

Table 5.22: Energy efficiency upgrade costs sensitivity test

Capital and Operational Cost Sensitivity	
NPV	-$17.78 /m²
BCR	0.86
IRR	6.76%

These sensitivity tests show that even at the most favourable boundaries of this cost benefit analysis, the BCR is less than 1.0. This highlights that the capital costs associated with the type of energy efficiency upgrades implemented in this study significantly outweigh the operational cost benefits. There are some intuitive reasons behind this when considering other studies of building energy performance. For example, the *MBIE H1 Study* presented similar outcomes, indicating that the cost optimal level of building insulation (when considering direct owner benefits) is significantly less than current building code settings in NZ.

By way of comparison, the EU's Energy Performance of Buildings Directive (EPBD), which sets the requirement for cost-optimal levels of energy performance for buildings, mandates much higher levels of insulation and other system efficiencies. This is however, in the context of colder climates, lower capital cost of building materials and higher energy costs.

The scenarios presented in the dashboard enable the energy efficiency benefits to be turned on and off and can be used to show the impact of this strategy.

6 Economic Analysis Results

The following section summarises loss and also APoE benefit-cost-ratios, the results of this study. These APoE benefit-cost-ratios are not the same as traditional BCR, as they are not discounted for time and also the benefits are not reduced by applying their probability factor.

6.1 Loss Estimates – Results

Loss tables are split into three components as follows:

- ***People***: Includes the loss due to injuries and death (casualty states CS2-5) and urban and search efforts for trapped victims.
- ***Function***: includes the loss related to downtime and business disruption indirect and direct (displacement cost for accommodation, business disruption).
- ***Property***: Includes loss related to earthquake repair works as a function of Damage rate (DR) of full replacement, non-structural elements and content replacement.

Refer also Economic assumptions in Appendix C.

6.1.1 Loss Tables per centres - nighttime

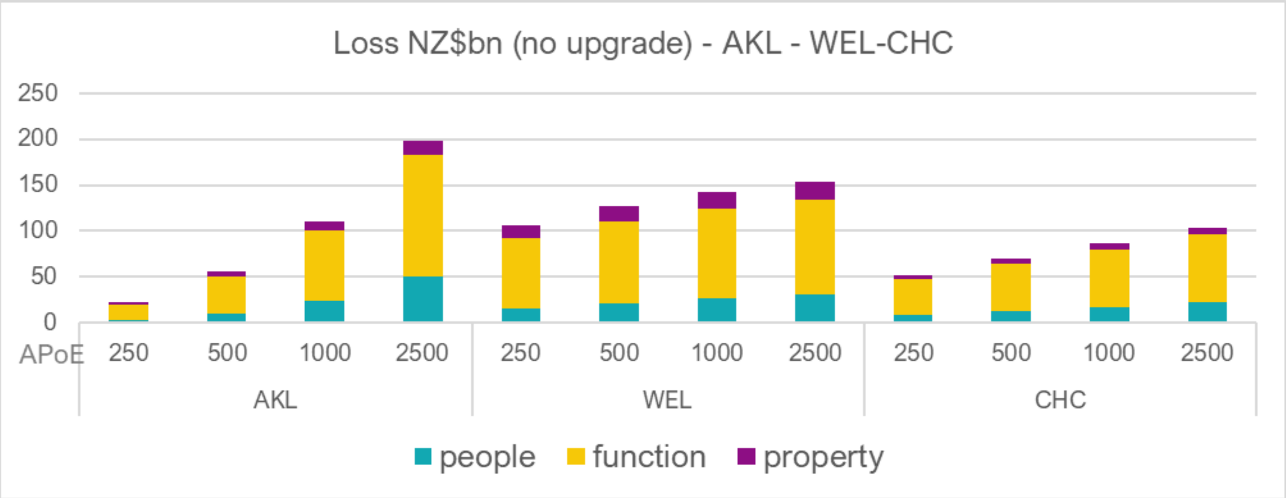


Figure 6.1: Total loss for ‘No upgrade’ for Auckland, Wellington, Christchurch

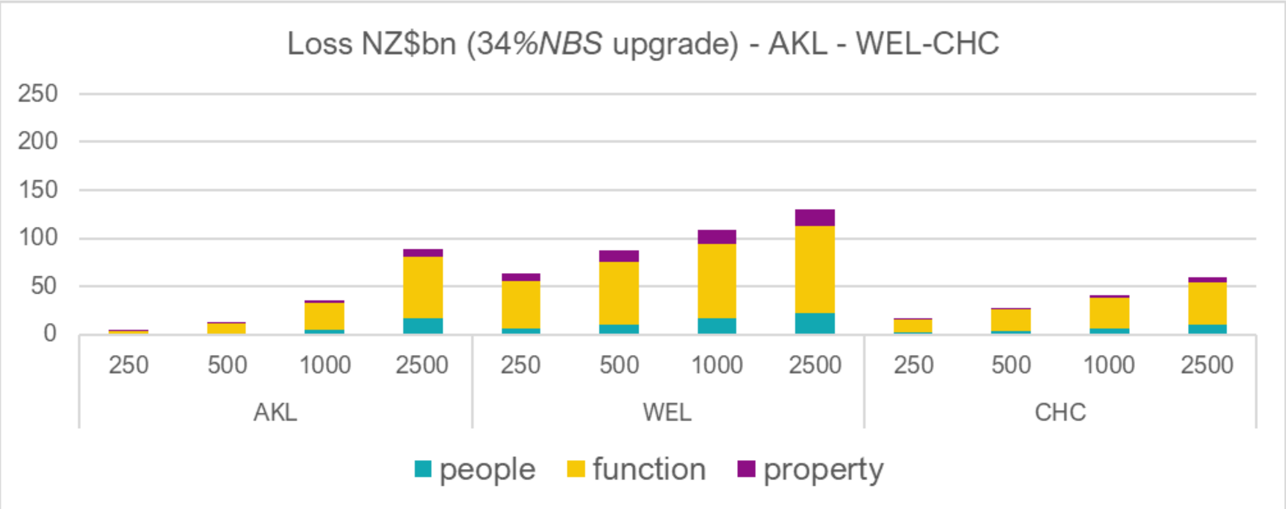


Figure 6.2: Total loss for 34%*NBS* upgrade for Auckland, Wellington, Christchurch

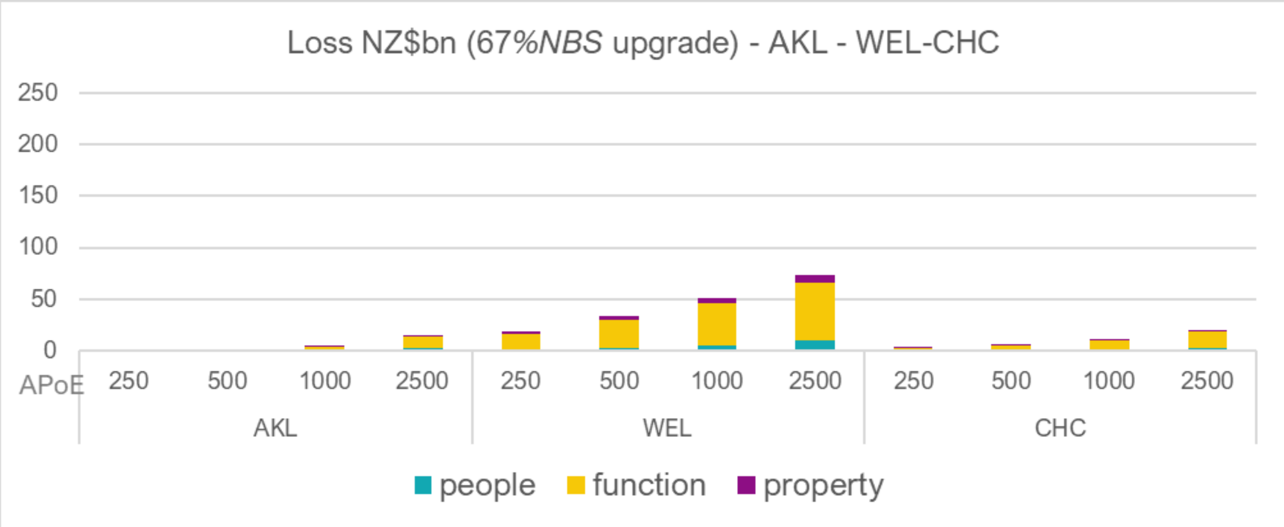


Figure 6.3: Total loss for 67%*NBS* upgrade for Auckland, Wellington, Christchurch

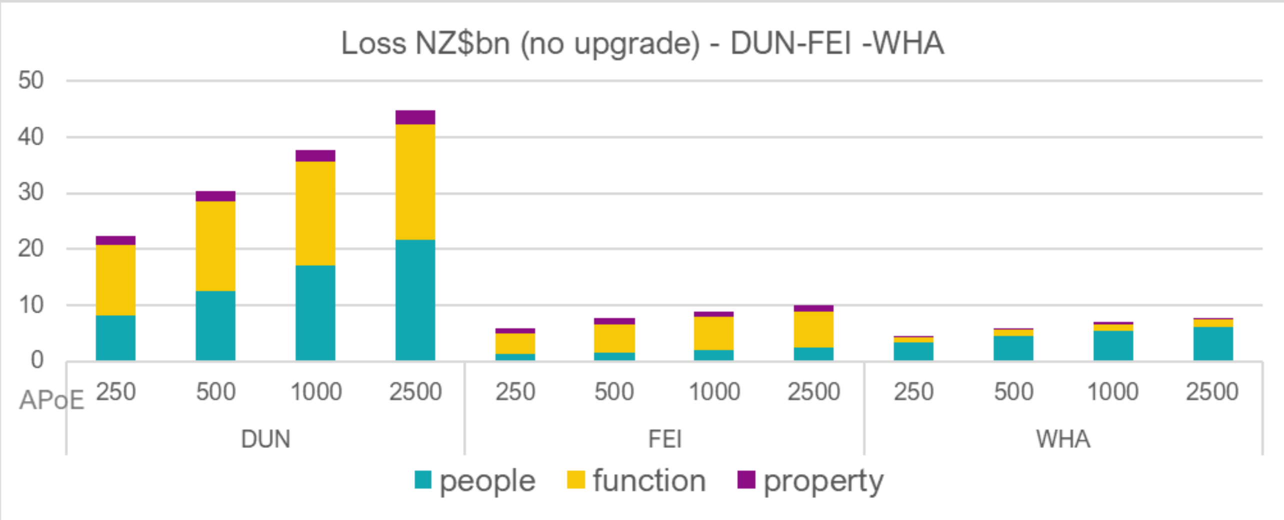


Figure 6.4: Total loss for 'No upgrade' for Dunedin, Feilding, Whanganui

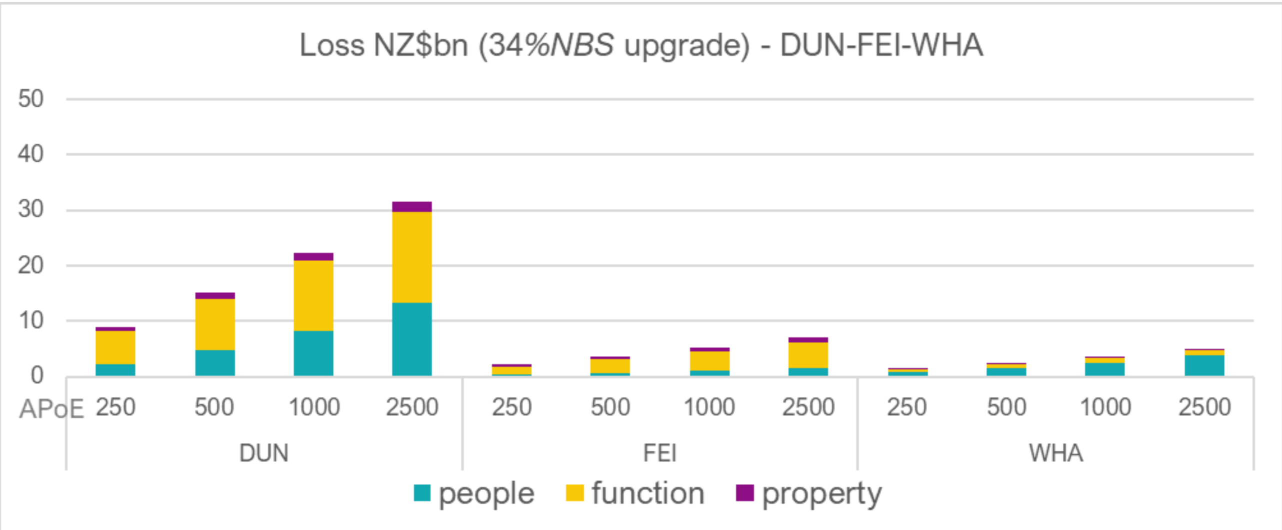


Figure 6.5: Total loss for 34%*NBS* upgrade for Dunedin, Feilding, Whanganui

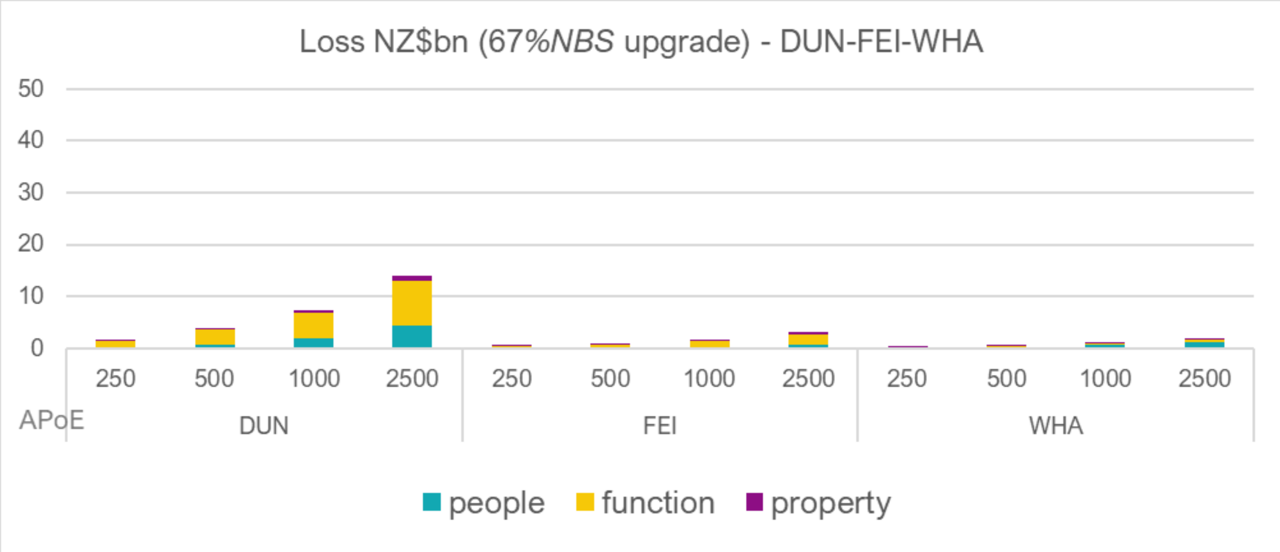


Figure 6.6: Total loss for 67%*NBS* upgrade for Dunedin, Feilding, Whanganui

6.1.2 Loss estimate for each of the six centres – No upgrade option

Table 6.1: No upgrade – Loss estimate for each of the six cities at nighttime [NZ$ bn]

APoE	Location	No of Buildings	Loss total	People	Function	Property
1:500	Auckland	1351	56.1	9.4	41.3	5.4
	Wellington	540	126.8	21.1	89.3	16.4
	Christchurch	415	69	11.7	52.4	4.9
	Dunedin	160	30.4	12.6	16.0	1.8
	Feilding	77	7.6	1.7	5.0	0.9
	Whanganui	27	5.9	4.4	1.2	0.3
1:1000	Auckland	1351	109.9	23.4	76.9	9.6
	Wellington	540	142.2	26.8	97.4	18.0
	Christchurch	415	85.9	16.8	63.3	5.8
	Dunedin	160	37.7	17.1	18.5	2.1
	Feilding	77	9.1	2.1	5.9	1.1
	Whanganui	27	7	5.4	1.3	0.3
1:2500	Auckland	1351	198.7	50.6	131.9	16.2
	Wellington	540	153.7	31.0	103.6	19.1
	Christchurch	415	103.5	22.2	74.5	6.8
	Dunedin	160	44.8	21.8	20.6	2.4
	Feilding	77	10	2.3	6.5	1.2
	Whanganui	27	7.8	6.1	1.4	0.3

6.2 Loss Estimate for Each of the Six Centres – 34%*NBS* Option

Table 6.2: 34%*NBS* upgrade – Loss estimate for each of the six cities at nighttime [NZ$ bn]

APoE	Location	No of Buildings	Loss total	People	Function	Property
1:500	Auckland	1351	13.5	1.4	10.6	1.5
	Wellington	540	87.7	11.0	65.1	11.6
	Christchurch	415	27.9	3.4	22.4	2.1
	Dunedin	160	15	4.7	9.3	1.0
	Feilding	77	3.6	0.7	2.4	0.5
	Whanganui	27	2.5	1.6	0.7	0.2
1:1000	Auckland	1351	35.9	5.2	27.1	3.6
	Wellington	540	108.8	16.7	78.0	14.1
	Christchurch	415	41	6.0	32.0	3.0
	Dunedin	160	22.3	8.2	12.7	1.4
	Feilding	77	5.3	1.1	3.5	0.7
	Whanganui	27	3.5	2.5	0.8	0.2
1:2500	Auckland	1351	89	16.3	64.6	8.1
	Wellington	540	129.4	22.8	90.1	16.5
	Christchurch	415	59	9.8	45	4.2
	Dunedin	160	31.6	13.3	16.4	1.9
	Feilding	77	7.1	1.5	4.7	0.9
	Whanganui	27	5.7	0.9	3.7	1.1

6.3 Loss Estimate for Each of the Six Centres – 67%*NBS* Option

Table 6.3: 67%*NBS* upgrade – Loss estimate for each of the six cities at nighttime [NZ$ bn]

APoE	Location	No of Buildings	Loss total	People	Function	Property
1:500	Auckland	1351	0.9	0.1	0.7	0.1
	Wellington	540	33.8	2.7	27.6	3.5
	Christchurch	415	6.1	0.5	5.1	0.5
	Dunedin	160	3.9	0.8	2.8	0.3
	Feilding	77	1	0.2	0.7	0.1
	Whanganui	27	0.6	0.3	0.2	0.1
1:1000	Auckland	1351	3.8	0.5	2.9	0.4
	Wellington	540	51.1	5.5	40.5	5.1
	Christchurch	415	11	1.1	9.0	0.9
	Dunedin	160	7.5	2.0	5.0	0.5
	Feilding	77	1.7	0.3	1.2	0.2
	Whanganui	27	1	0.6	0.3	0.1
1:2500	Auckland	1351	15.6	2.2	11.8	1.6
	Wellington	540	73.5	9.8	56.7	7.0
	Christchurch	415	19.8	2.3	16.0	1.5
	Dunedin	160	13.9	4.4	8.6	0.9
	Feilding	77	3.1	0.6	2.2	0.3
	Whanganui	27	1.9	1.3	0.5	0.1

6.4 APoE Benefit-cost Ratios – 34%*NBS* Option

The APoE benefit to cost results as summarised below include the following:

Costs

- Building seismic upgrade costs for two upgrade options
- Building energy efficiency upgrade costs

Benefits - Avoidance of

- Building repair or replacement costs
- Content replacement costs
- Deaths, injuries and post-traumatic stress disorder (PTSD)
- Time-element losses (residential displacement and direct and indirect business interruption)
- Search and rescue costs
- Carbon emissions

Table 6.4: APoE benefit-cost ratios for 34%*NBS* option (nighttime)

APoE	Location	No of Buildings	Cost [NZ$ Million]	Benefit [NZ$ Million]	APoE benefit cost ratio	Loss no upgrade [NZ$ Million]	Loss 34% upgrade [NZ$ Million]
1:500	Auckland	1351	4,522	42,420	9	56,018	13,598
	Wellington	540	1,715	39,040	23	126,719	87,679
	Christchurch	415	1,127	41,178	37	69,046	27,868
	Dunedin	160	394	15,302	39	30,379	15,077
	Feilding	77	88	3,975	45	7,612	3,637
	Whanganui	27	46	3,490	76	5,901	2,411
1:1000	Auckland	1351	4,522	73,950	16	109,904	35,954
	Wellington	540	1,715	33,319	19	142,114	108,795
	Christchurch	415	1,127	45,042	40	85,979	40,937
	Dunedin	160	394	15,481	39	37,750	22,270
	Feilding	77	88	3,752	43	8,980	5,228
	Whanganui	27	46	3,381	74	6,964	3,582
1:2500	Auckland	1351	4,522	109,674	24	198,745	89,071
	Wellington	540	1,715	24,261	14	153,742	129,482
	Christchurch	415	1,127	44,626	40	103,552	58,926
	Dunedin	160	394	13,263	34	44,813	31,549
	Feilding	77	88	2,970	34	10,051	7,081
	Whanganui	27	46	2,717	59	7,755	5,038

6.5 APoE Benefit-cost Ratios - 67%*NBS* Option

Table 6.5: APoE benefit-cost-ratio results for 67%*NBS* option (nighttime)

APoE	Location	No of Buildings	Cost [NZ$ Million]	Benefit [NZ$ Million]	APoE benefit cost ratio	Loss no upgrade [NZ$ Million]	Loss 34% upgrade [NZ$ Million]
1:500	Auckland	1351	9,186	55,069	6	56,018	949
	Wellington	540	3,770	92,990	25	126,719	33,729
	Christchurch	415	2,475	62,875	25	69,046	6,171
	Dunedin	160	764	26,446	35	30,379	3,933
	Feilding	77	184	6,654	36	7,612	958
	Whanganui	27	94	5,353	57	5,901	548
1:1000	Auckland	1351	9,186	106,053	12	109,904	3,851
	Wellington	540	3,770	91,076	24	142,114	51,039
	Christchurch	415	2,475	74,925	30	85,979	11,055
	Dunedin	160	764	30,252	40	37,750	7,498
	Feilding	77	184	7,225	39	8,980	1,754
	Whanganui	27	94	5,908	63	6,964	1,055
1:2500	Auckland	1351	9,186	183,143	20	198,745	15,602
	Wellington	540	3,770	80,251	21	153,742	73,491
	Christchurch	415	2,475	83,661	34	103,552	19,891
	Dunedin	160	764	30,868	40	44,813	13,945
	Feilding	77	184	6,978	38	10,051	3,073
	Whanganui	27	94	5,800	61	7,755	1,955

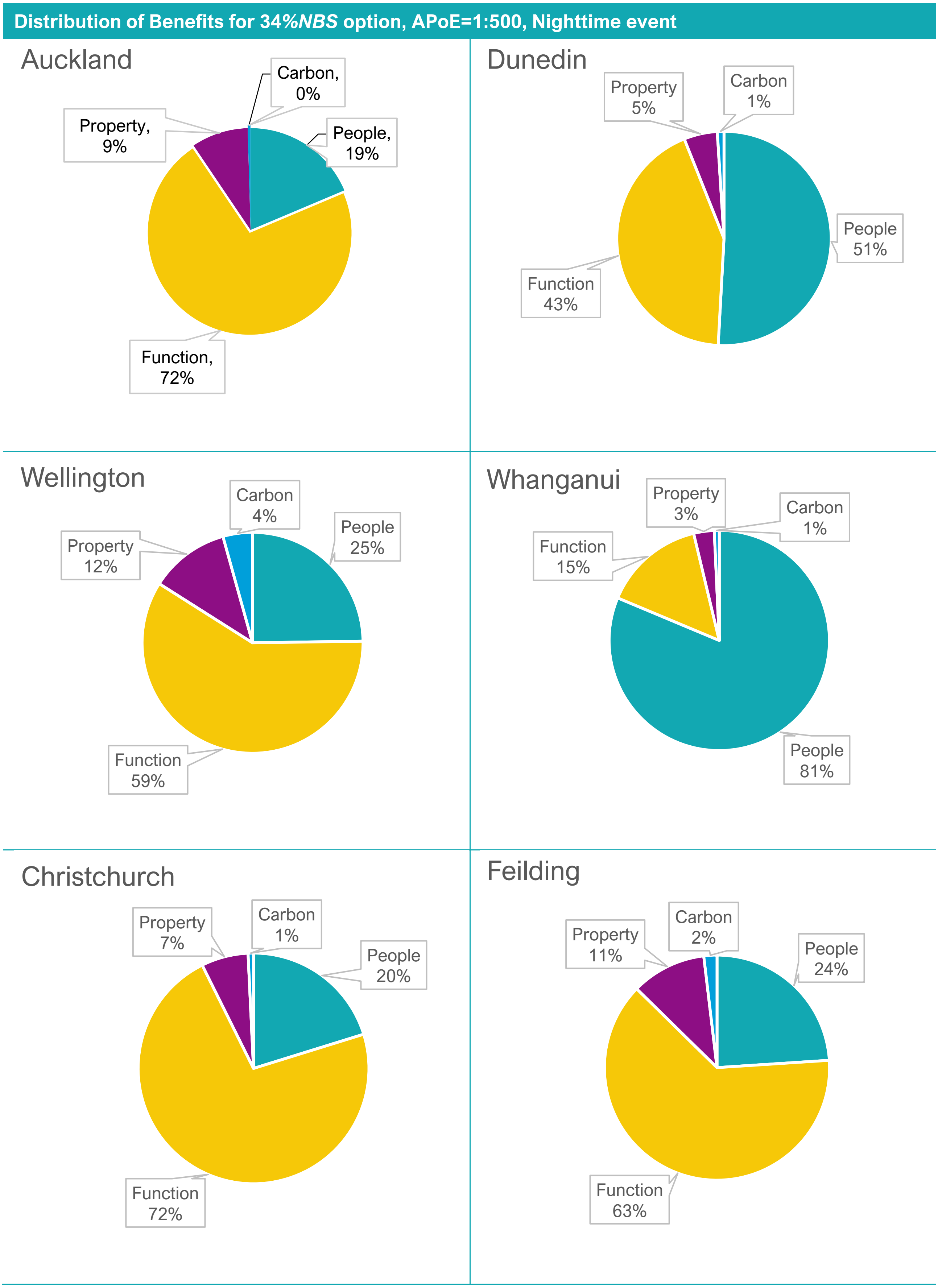


Figure 6.7: Distribution of benefits for APoE 1-in-500 and 34%*NBS* option

7 Key Findings

This project has been a research-focused investigation to provide the means to enable others to understand the implications of the current EPB settings and to provide the ability to "test" the implications of potential policy changes. It does not include a detailed EPB policy review.

A dashboard has been developed to allow the impact of various decisions to be investigated. This dashboard must be used with caution by those who are aware of the underlying assumptions and on the assumption that the results indicated are reliant on these assumptions. The short time period available for this project has not allowed the dashboard to be exhaustively tested for all possible combinations of available inputs, which again emphasises the need for caution when interpreting the outputs.

Although the project necessarily restricted consideration to a sample of locations, with care the findings can be extrapolated to other locations where there is a similar inventory of EPBs (numbers and distribution of typology type).

Some key findings that have been observed for the six locations are summarised below for consideration:

Vulnerable Building Types

There are two main vulnerability types: Unreinforced masonry buildings and multi-storey non-ductile concrete buildings.

Retrofitting the unreinforced masonry (URM) buildings alone, even to the minimum 34*%NBS*, provides the greatest contribution to potentially saving thousands of lives.

Due to mostly URM and stone buildings in Dunedin and two storey URM buildings in Whanganui, these locations experience the largest percentage benefit to preventing people related losses, with over 90% attributed solely to URM retrofitting.

About half of the people related loss in Wellington is related to pre-1976 concrete buildings, the other half to URM buildings.

Location

This study highlights elevated vulnerability in Dunedin due to the new hazard estimates.

Dunedin is historically considered a low seismicity zone; however, this study highlights that the increased hazard due to nearby fault lines (NSHM2022) that are triggered for the rare (higher APoE) shaking levels, combined with brittle masonry buildings, significantly elevates the city's vulnerability. Wellington is the highest-hazard area, with five times the hazard compared to other centres, and has the greatest people - related losses at APoE shaking levels of 1:500.

Auckland (1,351 EPBs) has 2.5 times more earthquake-prone buildings than Wellington; however, the study found that Wellington (535 EPBs) experiences three times greater human-related losses in a 1:500 earthquake event.

In Auckland, the low probability earthquake events reveal benefits of strengthening buildings to 34*%NBS*, primarily due to the impact of reducing downtime and business disruption costs. The BCR (24) for Auckland for APoE of 1:2500 is similar to the BCR for Wellington (23) for APoE of 1:500 with 2.5 times the number of buildings.

Annual Probability of Exceedances APoE

A significant step change in losses occurred between Annual Probability of Exceedance (APoE) 1:500 and the larger shaking events of 1:1000 and 1:2500, with losses tripling and quadrupling in Auckland.

Increase in losses from 1:500 to 1:1000:

- 1.5 x times in Wellington, Christchurch, Dunedin, Whanganui, Fielding
- 2 x times in Auckland.

Increase in losses from 1:500 to 1:2500:

- 1.5 x times in Wellington
- 2 x times in Dunedin and Christchurch, Whanganui, Fielding
- 5 x times Auckland.

This is considered to be due to the proximity to 1:2500 occurrence fault lines in Auckland and Dunedin that are acknowledged in the new NSHM2022.

Figures 6.1 - 6.6 compare the estimated loss for the various locations for all of the APoE levels investigated for no upgrade, 34%*NBS* and 64%*NBS* respectively.

Strengthening Level 34%*NBS* and 67%*NBS*

Across most centres, achieving the minimum strengthening level of 34%*NBS* reduces losses by at least two-thirds, except for Wellington where a higher level of strengthening than 34% would be required to achieve a similar reduction in losses.

The cost for 67% vs 34% mitigation is double (2x) but the effect on loss reduction is four times (4x).

For all cites (except Wellington) there is a higher benefit-cost-ratio for 34%*NBS* when compared to 67%*NBS*.

For Auckland the benefit-cost-ratio is relatively low at APoE 1:500 to strengthen to a level of 34%*NB*S due to high cost ($4.5bn) versus benefit ($42bn).

Retrofitting 34%*NBS* option could potentially provide the following:

- 80% reduced people-related losses in Auckland compared to 'No upgrade' for all APoE levels.
- 60% reduced people-related losses in Christchurch, Dunedin, Feilding compared to 'No upgrade' for APoE up to 1:500.
- 40% reduced people-related losses in Wellington compared to 'No upgrade' for APoE up to 1:500.

Retrofitting 67%*NBS* option could potentially provide the following:

- 30% additional reductions in people-related losses for the high APoE 1:2500, for Wellington, Dunedin, Whanganui and Feilding in the rare, higher APoEs.

Building Purpose

Priority buildings such as schools (43), hospitals (34), and FENZ fire or police stations (13) are part of the EPB stock across the 6 locations.

These structures play a critical role in earthquake response and contribute to the resilience of our communities and minimising disruptions to these services when they are needed most. Many of these buildings are publicly owned and might carry a higher duty of care. Many of these buildings are already classified as potential 'Priority Buildings' with shorter time frames for carrying out seismic work.

Over a third of the stock are identified as for residential purpose; many of these are of unreinforced-masonry construction.

These buildings serve as homes for numerous people and also potentially provide shelter in place for residents following earthquakes.

Timeframes

Our study did not review timeframes specifically. However, a review of timeframes for certain building types or location might be determined as a justified mitigation measure using the Traditional CBA method.

Accuracy of EPB stock

Not all EPBs are potentially captured yet in the inventories available (e.g. Auckland may identify more non-ductile concrete buildings once their identification processes are complete). Not all TAs have identified a full set of EPBs yet, in particularly in low seismic areas.

Certain buildings of Type (1, 5, 9, 10) have been added under the 'any time pathway'. Territorial Authorities (TAs) currently identify potentially earthquake-prone buildings using the EPB methodology through two pathways: either an active approach within defined time frames based on the level of hazard and 'profile categories' for specific building types, or at any time that the TA might suspect a building meets the EPB criteria, requiring owners to provide engineering assessments to confirm or otherwise the status. The completeness of the inventories for buildings under this latter category is unknown.

People Inside versus Outside URM Building

This study revealed an elevated risk to those outside unreinforced masonry buildings on higher foot traffic routes, in locations with increased hazard levels.

The project identified high risks to people outside the building due to falling parapets or facades across all APoE levels.

Socio Economic Impacts

Future decision-making should not solely focus on BCRs but also incorporate socio-economic aspects and recovery potential, which were not explored in this study. Historically, marginalised and vulnerable communities have faced disproportionate impacts from earthquakes and other natural hazards (as well as the earthquake-strengthening itself). There is a need to link this study with socio-science research like the work by Sabine Loos (University of Michigan) and studies by NZ socio scientists.

New Knowledge

The new National Seismic Hazard model 2022 (NSHM2022) introduces an aspect of new knowledge (when compared with the current Engineering Assessment Guidelines, and the definition of *%NBS*, which is based on the current seismic hazard from 2004). The NSHM2022 is indicating increased earthquake hazard and therefore risks in many areas, raising questions about how this updated data should influence health and safety decision-making for owners and tenants of earthquake-prone buildings.

Currently, the updated NSHM2022 results do not influence the requirements for application of the earthquake-prone building system. The earthquake-prone building system for assessing and strengthening to 34%*NBS* which came into effect July 2017 uses the seismic hazard model from 2004 as specified in New Zealand's Building Code B1/VM1. Uncertainty remains around how these updated risks should impact health and safety decisions for workplace tenants. This study could potentially inform work on a review of how the EPB system should respond to new knowledge.

Sustainability Considerations

Retrofitting buildings where practicable can save up to 85% of embodied carbon compared to new construction. Owners of earthquake-prone buildings must strengthen or demolish them within compliance timeframes as required by New Zealand's legislation. Strengthening rather than replacement achieves sustainability goals.

Policy recommendations could consider mechanisms and settings that prioritise retaining existing building stock. Addressing earthquake risks to acceptable levels under the Earthquake-Prone Building (EPB) system provides an opportunity to integrate such incentives into current frameworks. Avoided embodied emissions offer significant benefits, potentially lowering the cost of meeting New Zealand's climate change targets.

Additionally, incentives promoting "green" refurbishments—such as energy-efficient mechanical systems and enhanced thermal performance—could deliver co-benefits by reducing operational carbon emissions and improving the commercial viability of reuse.

Costs

The scope of work required and therefore the cost of retrofitting URM buildings to achieve 34%*NBS* is approximately 30% greater in high seismic zones than for low to medium seismic zones.

The relative cost for similar retrofit in Auckland, Wellington, Christchurch, Dunedin, Whanganui and Feilding was found to be in the ratio of 0.87, 1.18, 1.00, 0.76, 0.94 and 1.08 respectively.

It costs approximately twice as much to achieve 67%*NBS* than 34%*NBS*. This was found to be valid for all centres.

When there is a step change in structural scope to achieve 34%*NBS* and 67%*NBS*, such as foundation work, this has a significant impact on costs.

Caution needs to be applied when reviewing the costs as data outliers can significantly skew the results. This applies, in particular, to buildings with large gross floor area (GFA) and those that have a specific use, such as hospitals and education facilities.

The spread of costs per building type for our reference buildings was large. For example, the current costs to achieve 34%*NBS* in Wellington was estimated to range between NZ$700-$3,000/m^2.

Disruption and Downtime

Direct and indirect business disruptions due to downtime following an earthquake were predominantly observed in urban centres like Wellington and Christchurch. And the smaller towns such as Whanganui and Dunedin experienced more significant losses related to people. This difference may be attributed to the prevalence of URM buildings and residential structures in smaller towns, whereas urban areas feature a mix of residential and commercial uses and larger buildings, often a mix of concrete and unreinforced masonry (URM), which take longer to repair.

8 Uncertainties

It will be apparent that there are many assumptions made in such a methodology and uncertainties and ranges in inputs at every step, some large for critical inputs. Caution is recommended when interpreting the actual costs and benefits that have been determined. It is the relative results and trends observed between different options for increasing severity of the shaking, the characteristics of different centres, and different types of structure that are the valuable output from this project.

Each assumption and step of this investigation includes a level of uncertainty in aspects such as:

- Building inventory could have a variable in number of buildings or allocation of structural form or GFA.
- This project presents results specifically focuse solely on the small portion of earthquake-prone buildings (most vulnerable buildings). It does not include every building within our cities.
- It is only related to the six locations, and it does not encompass all of New Zealand.
- Cost estimates are based on concept sketches only for one case study building per building type, but the costs can vary greatly between strengthening projects.
- Carbon calculations are generally only an estimate and are not precise.
- Fragility model dispersion. Models are assumed in the critical direction of shaking.
- V_{s30} soil shear wave velocities for each site.
- Consequence models such as occupancy rates during peak and average hours.
- Risk model.
- Loss estimation results should be interpreted with caution due to significant uncertainty in the baseline values. There is a lack of comprehensive data from past earthquake events, particularly for the larger events, and limited data available to estimate damage based on different measures of hazard severity.
- The project methodology is based on APoE shaking levels therefore are the same for all buildings in the inventory for a city (with varying only the soil type V_{s30}). Hence, this is not the same as an actual scenario event where the shaking will vary across the city (e.g. intensity dropping off with distance to epicentre).
- During real earthquakes, not all buildings are similarly affected, and they do not all perform the same. The APoE-based approach is not the same as an actual earthquake event where the shaking will vary across the location. Some allowance of this observation has been made by representing a range of results allowing different effect factors.
- The capacities of the buildings were based on a simplified method using a single degree of freedom for the weak direction of the structure, this simplicity has uncertainties. The cost estimates for the strengthening were based on concepts with margins. Cost of retrofit project can vary based on many factors such as removal of hazardous materials, removal of building services, etc.

To address this complexity and data limitations, buildings and system components have been grouped into categories based on key characteristics. The relationship between hazard severity measures and the average degree of damage, along with associated losses for each building category, relies on current limited data and existing theories.

The results of a natural hazard loss analysis should not be looked upon as a prediction. Instead, they are only an estimate, as uncertainties inherent to the model will be influenced be quality of inventory data, assumptions and the hazard parameters. Nevertheless, it is still considered reasonable to use the methodology outlined to determine the relative impact of various measures/decisions.

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A

Appendix A

Traditional Cost – Benefit Analysis

Appendix A – Traditional Cost Benefit Analysis

Indicative Cost Benefit Analysis

This project has primarily used an ApoE-based approach which abstracts from time in the sense that the capital investment for the seismic upgrade and the earthquake event were modelled *as if* they both occur in the same year. Implicit within the APoE approach, however, are all the elements required to undertake a Cost Benefit Analysis (CBA). This annex includes the results of a more traditional CBA based on the data generated for the APoEs.

CBA and APoE approach compared

A CBA approach recognises that the benefits arise over time – in this case the 75-year design life. The benefits in any one year are *the expected value* of avoided costs of damage, casualties and economic disruption i.e. the total benefits multiplied by the probability of the earthquake event occurring in that year. For simplicity we have assumed that all the costs of the building upgrade are incurred in the first year. This will overestimate the costs for centres which currently have longer legislative timeframes for retrofit to above 34*%NBS*.

Sources for estimates of costs and benefits

In summary, costs and benefits are analysed by using the sum of quantities times the prices and multiplied by the probabilities of each of the five APoE per year. APoEs that have been used are 1:100, 1:250, 1:500, 1:1000, 1:2500. For 1 in 500 year then full costs are known and met now while benefits have a 0.002 hance of happening in a year, so the benefits of an event re multiplied by 0.002 and entered for each year, for discounted.

On the benefits side, the key quantities required for the CBA used New Zealand data generated by the fragility and loss modelling discussed above. The key shadow prices[3] were drawn from the Treasury's CABx and the Noy & Uher 2022 paper as appropriate. The costs of seismic strengthening for representative building types were multiplied by the number of buildings in the typology to generate total costs for each centre.

For residential buildings we looked at disruption cost e.g. residents have to vacate and live elsewhere while retrofitting occurs. Same applies for commercial buildings, alternative office space has to be arranged unless upgrade works is scheduled between lease renewals.

Details on the costing methodology and the benefits were discussed in Section 6 so will not be repeated here. The key point to emphasise is while there can be a high degree of reliance on the estimated costs of seismic strengthening, estimation of the potential benefits is much more complex with correspondingly lower reliability and wider confidence intervals. The difficulties of aggregating the loss modelling at the representative building level to generate plausible values at the overall town or city levels were previously highlighted. Accordingly, the CBA results at the urban centre level should be treated as indicative rather than definitive.

Moreover, this study has focused on six urban centres – three main cities (metropolitan) and three regional towns. Undertaking a full national cost benefit analysis would require additional analysis of the remaining stock of EPBs and the location specific seismic risk they pose. This analysis was out of scope for this project. Accordingly, summing up the findings for 6 centres does not provide the robust analysis required

[3] In economic terms, "shadow prices" refer to the implicit or imputed value of a good, service, or resource that is not directly priced in the market. These prices are used in cost-benefit analyses and economic evaluations to reflect the true opportunity cost of resources when market prices are distorted

to prepare a full national CBA. The later would require estimating the benefits and costs for each region, then aggregating them to the national level.

Comparable CBAs – Martin Jenkins 2017

Two previous CBAs have focused on seismic strengthening of existing buildings as precursors for this project.

The “Indicative CBA Model for Earthquake-prone building review” was prepared by Martin Jenkins for MBIE in 2012. The study examined all pre-1976 buildings in New Zealand, estimating 82,000 out of a total 194,000 buildings, with earthquake-prone buildings (EPBs) making up about 10% or 19,000. The analysis faced challenges due to the lack of a comprehensive EPB register in 2012, relying on estimates and data from QV and discussions with engineers.

The cost-benefit analysis (CBA) was conducted over 75 years and assessed the net present value of costs and benefits for different policy options, focusing on *%NBS* targets and compliance timelines. The model evaluated scenarios including maintaining or increasing the *%NBS* target and considered additional costs like fire safety improvements, producing outputs such as present value net cost/benefit and "per event" analyses. The study found very low-cost benefit ratios for the options reviewed.

All the key parameters have shifted significantly in the 13 years since the MJ study was completed: the number of EPBs is known to be much lower, construction costs have escalated significantly relative to general inflation, more is known about the capital costs of seismic strengthening and more robust estimates are available about potential damage and casualties. Accordingly, it is difficult and not very productive to compare the MJ study with the results presented below.

The NIBS study.

The gold standard for natural hazard risk is the Natural Hazard Mitigation Saves 2019 Report from the National Institute of Building Sciences (NIBS, 2019). This study reviewed the economics of mitigation for multiple hazards including seismic strengthening for both new and existing buildings. The approach highlights three main benefits drivers – avoidance of damage, economic disruption and casualties. It also factored in other benefits (search and rescue, insurance cost) but these proved to be third order as shown by the pie chart in Figure A1 for the breakdown of seismic retrofitting existing residential buildings.

Figure A1: Breakdown of benefits from NIBS study (Source NIBS 2019 Page 8 Figure 3)

Accordingly, in this CBA an approach was applied that is consistent with the NIBS study and which draws on the findings of Noy and Uher (2022), who scoped the application using the NIBS approach to New Zealand. The NIBS methodology has been followed while tailoring for New Zealand by using NZ loss modelling data and drawing parameter values wherever they were available from the Treasury’s CABx and the Noy & Uher 2022 study.

The dashboard developed to illustrate the scenarios includes the potential economies of scope from undertaking an energy efficiency upgrade as part of seismic strengthening. This was not something included in the NIBS methodology.

Under a conventional CBA approach, the energy efficiency analysis would not be included in the costs or benefits streams of seismic strengthening. This is because energy efficiency upgrades stand alone as a matter that requires a discrete separate decision. The results presented In Section 9 of this report suggest that, in the New Zealand context, energy efficiency savings do not cover the extra costs associated with the upgrade. As such energy efficiency upgrade would simply reduce the value of the net benefit steam. Accordingly, energy efficiency has not been included in the assessment of the economic costs and benefits of seismic strengthening.

The choice of discount rate – a key parameter

The CBA uses the Treasury new 2% real default discount rate for non-commercial investments as the base case augmented by sensitivity analysis using the Treasury's commercial rate (8%), zero and 5%. The model calculates the breakeven Internal Rate of Return (IRR). As the BCR tipping point (>1) is sensitive to the discount rate and period of assessment. The IRR calculate the breakeven discount rate at which the present value of the costs and benefits are equalised.

The counterfactual

A key element of any CBA is to set a credible base that can be used to assesses the difference between the outcome state following an intervention with a counterfactual based on the continuation of the status quo. This provides an assessment of the incremental impact of the intervention compared to the base case. In this case, the benefits of the proposed seismic strengthening of EPBs are compared to the counterfactual where no seismic strengthening is undertaken.

Cautions and caveats

It is important to bear in mind the following caveats when interpreting the results presented below.

Reliability

The estimates of the costs of remediation have been undertaken at a detailed representative building level and have been externally peer reviewed. By contrast the estimates of the benefits from avoided damage, disruption, fatalities and injuries have been undertaken at a less granular level and while they have also been subject to review are necessarily more speculative. Aggregating the potential losses from the individual building level to the overall location is particularly challenging as discussed in Section 8 in the report. These caveats are important as it suggests that greater reliance can be placed on the relative values (measured by BCR and IRR) than the absolute values measured by the NPV.

Economic not Commercial Returns

The focus of the analysis is on the wider economic costs and benefits. Understanding the commercial returns to building owners from investment in earthquake strengthening across a range of building use types and locations is a separate study. Understanding the commercial returns required acquiring structured data which is not readily available. There has been some empirical work relevant to this in New Zealand. Grimes et al (2015) study of earthquake liquefaction risk found an initial risk premium after the Christchurch Earthquake sequence but that it failed to persist. (Filippova et al. 2017) suggests that while an earthquake risk premium exists for office accommodation in Wellington, there is no corresponding commercial return in Auckland. Whether any risk premium that might exist is adequate to cover the costs of building remediation is also unknown New Zealand evidence on any earthquake risk premium in other centres or building use types is also lacking. The results presented below suggest – consistent with the NIBS study, that the majority of benefits from building remediation arise from avoided direct and indirect disruption. It requires a separate study to assess the extent that any earthquake rental premium is adequate to recoup the costs of earthquake strengthening over time through increased rental streams (or implicit rental from owner occupied buildings from investments in seismic remediation).

The Findings

In the CBA tables below are representing economic results from various perspectives are shown by location, by building group (e.g. all URM's combined) and by likelihood. Net present values (NPVs) are calculated using a range of discount rates (0, 2, 5 and 8%). The NPV, Benefit Costs Ratio (BCR) as well as the breakeven Internal Rate of Return moving from a base case of no retrofit to 34*%NBS* and 67*%NBS* are shown.

In this case adopting a more conversative approach is proposed. Given the higher reliability of the data on remediation costs relative to expected benefits discussed above, the options that yield the highest IRR and BCR are focused on. This is akin to a cost effectiveness analysis which focuses attention on where the 'bang for buck' is highest by focusing any available resources on the interventions with the highest returns.

The Results

The Table A1-A4 below the economic returns from the CBA as measured by the BCR, Net Present Value (NPV) and Internal Rate of Return (IRR). It shows the results for each of the 6 locations and then by building type in each location.

Key Insights are

- By focus area - disruption dominated damage and death (consistent with the NIBs study)
- By Location – Auckland versus the rest
- By Building type – URM and concrete buildings and others
- By Likelihood
- By return

Sensitivity analysis

The sensitivity analysis has been conducted using a range of variables and has focused on the benefit stream as the reliability of this data is lower and the confidence intervals are wider as well.

As part of the sensitivity analysis, increasing VoSL (*2) for mass casualty events as per (Taig 2022) has been considered but for the final study and after discussion with the wider project team VoSL (*1) has been assumed.

Table A1: Economic Return for each of the 6 locations (average night/day)

Wellington			
Option	**NPV**	**BCR**	**Break even IRR**
34%NBS	$100,214M	5.85	15%
67%NBS	$155,676M	4.11	10%
Christchurch			
Option	**NPV**	**BCR**	**Break even IRR**
34%NBS	$50,338M	4.70	14%
67%NBS	$52,331M	2.57	7%
Auckland			
Option	**NPV**	**BCR**	**Break even IRR**
34%NBS	-$27,386M	0.48	-%
67%NBS	-$80,005M	0.29	-%
Dunedin			
Option	**NPV**	**BCR**	**Break even IRR**
34%NBS	$16,150M	4.40	13%
67%NBS	$19,853M	2.95	8%
Whanganui			
Option	**NPV**	**BCR**	**Break even IRR**
34%NBS	$3,785M	7.87	25%
67%NBS	$4,425M	4.46	13%
Feilding			
Option	**NPV**	**BCR**	**Break even IRR**
34%NBS	$5,634M	6.31	19%
67%NBS	$6,608M	3.58	10%

Table A2: Economic Return results for Building Types for 6 locations (average night/day)

Wellington			
Results	**NPV**	**BCR**	**Break even IRR**
34%NBS	$100,214M	5.85	15%
URM (2,3,4)	$23,910M	4.87	14%
RC (6,7,8)	$29,879M	4.65	14%
Other (1,5,9,10)	$33,037M	6.24	19%
67%NBS	$155,676M	4.11	10%
URM (2,3,4)	$38,385M	3.85	11%
RC (6,7,8)	$44,690M	3.10	9%
Other (1,5,9,10)	$49,914M	4.25	12%
Christchurch			
Results	**NPV**	**BCR**	**Break even IRR**
34%NBS	$50,338M	4.70	14%
URM (2,3,4)	$11,558M	5.68	17%
RC (6,7,8)	$13,559M	4.28	12%

Other (1,5,9,10)	$25,220M	4.61	13%
67%NBS	$52,331M	2.57	7%
URM (2,3,4)	$14,822M	3.79	11%
RC (6,7,8)	$12,832M	2.24	6%
Other (1,5,9,10)	$24,676M	2.40	7%
Auckland			
Results	**NPV**	**BCR**	**Break even IRR**
34%NBS	-$27,386M	0.48	0%
URM (2,3,4)	-$3,707M	0.77	1%
RC (6,7,8)	-$22,148M	0.28	0%
Other (1,5,9,10)	-$1,529M	0.69	1%
67%NBS	-$80,005M	0.29	0%
URM (2,3,4)	-$15,513M	0.52	0%
RC (6,7,8)	-$55,149M	0.18	0%
Other (1,5,9,10)	-$9,342M	0.32	-1%
Dunedin			
Results	**NPV**	**BCR**	**Break even IRR**
34%NBS	$16,150M	4.40	13%
URM (2,3,4)	$13,494M	4.60	13%
RC (6,7,8)	$1,885M	4.05	12%
Other (1,5,9,10)	$770M	3.00	8%
67%NBS	$19,853M	2.95	8%
URM (2,3,4)	$17,366M	3.31	9%
RC (6,7,8)	$1,627M	1.89	5%
Other (1,5,9,10)	$858M	2.01	5%
Whanganui			
Results	**NPV**	**BCR**	**Break even IRR**
34%NBS	$3,785M	7.87	25%
URM (2,3,4)	$3,606M	7.89	25%
RC (6,7,8)	$66M	5.98	18%
Other (1,5,9,10)	$112M	8.89	30%
67%NBS	$4,425M	4.46	13%
URM (2,3,4)	$4,236M	4.61	13%
RC (6,7,8)	$97M	4.12	12%
Other (1,5,9,10)	$90M	2.20	6%
Feilding			
Results	**NPV**	**BCR**	**Break even IRR**
34%NBS	$5,634M	6.31	19%
URM (2,3,4)	$1,148M	5.76	17%
RC (6,7,8)	$519M	6.17	19%
Other (1,5,9,10)	$3,966M	6.51	20%
67%NBS	$6,608M	3.58	10%
URM (2,3,4)	$1,402M	3.57	10%
RC (6,7,8)	$559M	2.93	8%
Other (1,5,9,10)	$4,646M	3.68	10%

B

Appendix B

Example Calculation – Case Study Building: Dunedin URM typology 2

Appendix C

Assumptions And Exclusions

Appendix C – Assumptions and Exclusions

C1 Inventory Assumptions

The basis for the building inventory used in this study is from the publicly available earthquake-prone building register (https://epbr.building.govt.nz/) as dated 25 November 2024 in the six study locations.

Following review of the publicly available list on MBIEs website, it has become apparent, through confirmation by the TAs, this list includes all addresses that have ever been on the EPB register, including those that have since been removed from the EPB register either through demolition, further engineering assessment, or seismic strengthening. We understand this study is targeted at those addresses that currently have an EPB status.

We approached all the individual TAs responsible for the six locations to confirm the list of current EPB and seek any further information they may hold on to the buildings, such as: structural system type, age of construction, GFA, number of storeys and those currently with EPB status.

The following number of buildings will be used:

Table C1: Summary of inventory per location

Location		MBIEs EPB Register	TAs EPB lists	Final inventory	Difference in registers (MBIE TA)
		Both remediated and EPB status	EPB status	Converted into number of buildings	
Auckland	AKL	1,708	1,413	1,351	+295
Feilding	FEI	76	77	77	-1
Whanganui	WHA	22	28	27	-6
Dunedin	DUN	237	230	160	+7
Christchurch	CHC	1,359	514	415	+845
Wellington	WEL	978	540	540	+438
		4380	2802	**2570**	+1578

C1.1 Difference between MBIE register and TA list:

As we understand it, there is one source of EPB register that both the TA and the MBIE website refer to. However, the TAs have more features to allow filtering of data, whereas the MBIE register has limited features. The MBIE list includes a check box to 'turn off' buildings which *may* have been remediated.

The adopted data source for this study is the list provided by the TAs for those address that currently have EPB status. The EPB notice is per title entry, hence some buildings may have several notices. This study focuses on number of buildings.

C1.2 Final inventory numbers:

We have concluded the difference between the TA list and the final inventory is because some buildings have been demolished or buildings had multiple entries per unit.

In total there are 2,570 buildings with an EPB notice that will be adopted for this study across the six locations.

C1.3 Distribution of Occupancy Class per GFA

Table C2 summarises the occupancy classes observed by GFA across the building inventory. The average GFA is defined as the mean value (not median) calculated by summing all values in a dataset and dividing by the number of values.

Table C2: Summary of the GFA across each of the occupancy classes

	RES1	RES3A	RES3B	RES3C	RES3D	RES3E	RES3F			
MIN GFA	200	200	200	200	200	300	500			
MAX GFA	6,400	700	1,000	3,000	4,600	7,400	14,600			
AVER GFA	400	300	300	700	1,800	3,600	5,400			
	COM1	COM3	COM4	COM6	COM7	COM8	COM9	COM11	COM12	COM13
MIN GFA	300	300	300	1,600	100	100	100	200	200	200
MAX GFA	45,000	3,700	31,000	50,000	1,500	900	5,000	8,000	2,000	4,100
AVER GFA	4,200	500	1,200	22,500	500	200	900	500	1,300	300
	UTI1	IND1	IND2	IND3	GOV1	GOV2	EDU1	EDU2		
MIN GFA	100	350	200	600	100	100	100	500		
MAX GFA	5,000	25,000	16,400	3,000	3,000	15,000	5,000	11,400		
AVER GFA	500	1,800	1,900	2,200	1,100	2,500	1,200	3,600		

Table C3 summarises the occupancy classes split by building typology.

Table C3: Summary of the GFA across each of the occupancy classes

	RES	COM	UTI	IND	REL	GOV	EDU
1	32%	56%	0%	2%	4%	1%	5%
2	12%	72%	1%	5%	8%	1%	1%
3	70%	24%	0%	2%	2%	1%	1%
4	40%	33%	0%	16%	5%	5%	0%
5	21%	65%	3%	7%	3%	0%	1%
6	39%	43%	4%	10%	2%	1%	0%
7	24%	52%	1%	17%	2%	1%	3%
8	19%	61%	2%	14%	1%	1%	2%
9	8%	88%	0%	4%	0%	0%	0%
10	4%	51%	2%	39%	1%	2%	1%

	Occupancy Allocation
1	30%RES+60%COM+5%EDU
2	10%RES+70%COM
3	70%RES+25%COM
4	40%RES+35%COM+15%IND
5	20%RES+65%COM
6	40%RES+45%COM+10%IND
7	25%RES+50%COM+15%IND
8	20%RES+60%COM+15%IND
9	10%RES+85%COM
10	50%COM+40%IND

Table C4: Distribution of building typology by GFA.

	1	2	3	4	5	6	7	8	9	10
	Light timber frames + URM	URM 1-story, GFA < 2000m^2	URM 2-story, GFA < 2000m^2	URM 1-4-story, GFA > 2000m^2	RC block walls, 1-storey (low-rise)	RC walls (mid-rise)	RC frame with masonry infill,	Pre-1976 RC Frame	Post-1976 RC Frame with precast	Steel MRF + heavy cladding
MIN GFA	200	200	200	2,030	40	200	200	200	350	200
MAX GFA	3,500	2,000	2,000	18,800	5,600	31,000	11,400	50,000	45,000	10,500
AVER GFA	300	300	500	4,500	500	1,100	1,100	4,000	9,100	1,700

C2 Cost Estimate Assumptions

The following list of assumptions and variables allowances have been compiled.

These are listed as:

This estimate is for the purpose of identifying the comparative costs for various seismic strengthening works across the building typology and regions for the purposes of providing construction costs inputs for modelling purposes.

Notes:

- The cost estimate summary has been developed to identify the differences in seismic strengthening costs for 34*%NBS* and 67*%NBS* for each building type.
- The base rate has been calculated based upon Christchurch cost data, derived from average tender pricing for each of the itemised structural scope requirements as defined within the structural drawing details.
- The base cost rates are Q4 2024 located in Christchurch.
- The cost values includes within the summary for each typology are provided as an indicative guide for the scope of seismic improvement works for each building type.

There are many variables that can impact the out-turn cost of a seismic upgrade project, including issues such as:

- Site constraints - access and limitations around delivery and materials delivery logistics
- Use of the building
- Occupancy use and standard of fit out
- Staging and phasing of works to larger buildings.

Variable Impacts/Cost factors

The assessment of the rates and expected project costs are subject to a number of variables:

These are:

- Regional cost differences
- Contractor management and supervision and margins
- Seismic design requirements across different regions
- Building use
- Internal fit out and quality of fit out
- Heritage status
- General assumptions.

Regional Cost Impact - This is the change in the base rate due to the location of the project regionally. This is based upon the table in the summary page document.

The regional cost impacts are a mixture of positive and negative percentage impacts.

They are derived from evaluation of regional cost indices from QV and the RLB Digest 2024 - and have been weighted using Christchurch as the base i.e. 1.00 The indices adjustments are only used as a comparative guide.

Contractor Margins and On-Site Overheads (Contractor preliminary costs) and Off-site overheads (contractors offsite overheads and margins) have been derived from tender data received from each of the main regions.

Seismic Design Requirements - These have been derived by the structural engineers - based upon the seismic regional zone. They have been expressed as a percentage difference across each typology for the different structural remediation requirements.

Building Use - This has an impact upon the cost of enabling (soft strip and demolition of finishes and fixtures, and the making good to the fit out and services after the seismic strengthening.

The basis of the cost exercise has assumed that floor coverings, wall linings and ceilings will be removed to uncover the elements requiring strengthening, and that the building services will be carefully removed and reinstated with minor allowances for replacement of unserviceable components. No upgrade of services has been allowed for.

C3 General Cost Assumptions

Refer to Appendix E for a full list of Cost Estimate Assumptions and Exclusions.

Fit Out Reinstatement

Assumes a quality of localised removal and reinstatement of impacted finishes and services for building functions as follows:

Architectural GFA Rates \$100-\$400/m^2

- Basic – Minimal architectural finishes such as, carpark, warehouse, industrial type buildings. (\$100-\$250/m^2)
- Medium – Moderate architectural finishes such as low-grade offices and retail type buildings. (\$200-\$400/m^2).

Building Services GFA Rates \$100-\$600/m^2

- Low – Low density such as, carpark, warehouse, industrial type buildings. (\$100-\$200/m^2)
- Medium – Moderate density such as low-grade offices and retail type buildings. (\$200-\$400/m^2)
- High – High density such as residential apartments, medium grade office space and retail. (\$400-\$600/m^2).

Energy Efficiency (EE) upgrades are only relative to the areas effected by structural scope, but will not apply to others.

For example, if there is structural work proposed to two out of the four sides of the building, only two sides that have the structural work will have an additional EE component.

Energy efficiency upgrades are limited to increased wall and roof insulation measures and replacement window joinery only to those elements directly impacted by the strengthening work.

Exclusions:

Exclusions listed below are in addition to those listed in Appendix E.

- No allowance for asbestos removal - the impact of asbestos contamination to existing buildings and buildings that may have been removed previously.
- No allowance for resource consent constraints that impact the methodology or scope for seismic repairs (i.e. noise restrictions, traffic movements etc).
- No allowance to address requirements of heritage buildings

Sitewide/Infrastructure Allowances

- No allowance for dealing with land complexities - Issues such as flood risk (where surface water drainage may be impacted - or raising levels); Steeply sloping sites where retaining structures may be needed.
- No allowance for additional hard landscaping paths and access more than 1m from the face of the building.
- No allowance for infrastructure services upgrades.
- No allowance for providing temporary access and its removal and reinstatement.

Project On-Costs

- Fees - professional consultancy and management fees - expected at 15% but can range from 10% to 25% depending upon the project size (smaller project values often have a higher percentage in professional fees) and complexity, particularly where there are significant existing building services alterations required to open up main structural elements.
- Owner Costs - This is cost of owner management, supervision and internal project reporting and management, legal costs etc - this can vary between 2% to 5%.
- Consent Fees - vary between 1% and 2% depending upon value and consent requirements.

Contingency

Base Rate Contingency applied to the combined value of construction costs and project on-costs - This is for construction contingency risk - relating to unknowns and costs associated with the construction stage of a project.

It is a sum that is includes to provide a risk reserve to cover costs associated with discovery of damaged components, hidden asbestos, methodology impacts and the like.

For the cost exercise at the concept is the general allowance for contingency at 15%. This allowance can vary from 5% to 30% and is subject to the design maturity and knowledge of the project requirements, and benchmarked costs of similar projects.

A Design Risk Contingency has been allowed for within the elemental costs. This ranges from 10% to 20% depending upon the complexity of the works and the maturity of the design information.

C4 Comparison of New Zealand's Case Study Buildings versus Types as per Hazus methodology (US)

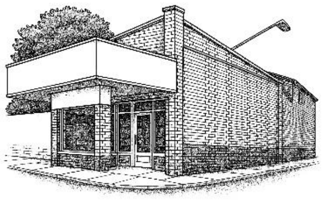
C4.1 New Zealand's EPB - Type Descriptions

Type 1 - Light-timber frames with URM elements

Narrative

Type 1 represents 463 (18%) nonirregular, single, two- or three-storey light timber frame buildings mostly at least three-unit residential buildings. Many of these buildings were built pre-1935 and have brick party walls and chimneys. The lateral load resisting system consists of light timber frame wall system. Floor system is typical wooden floors. Loads are light and spans are small. Majority of buildings have light metal roofs, only a few heavy tile roofs. The case study building chosen has two-storeys, a GFA of 200 m^2, height of 6.0m and both brick chimney and one central party wall.

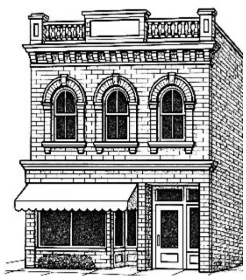
Type 2 –URM building 1-storey



Narrative

Type 2 represents 500 (19%), single storey unreinforced masonry buildings. Most of these are dairy corners shops or light retail. Most of these structures are characterised by load bearing masonry walls to the sides and rear and an open shop front. The case study building is single storey, with a building height of 4.8m supported on shallow foundations. The structure is open along the street frontage and has cavity brick walls on the sides and the back with a brick parapet.

Type 3 – URM 2-4 storey building with smaller GFA < 2000m^2



Narrative

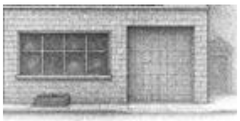
Type 3 represents 634 (25%), mostly two to three storey unreinforced masonry wall buildings. Most of these are mixed-use with retail at the ground floor and residential in the upper levels. Most of these buildings are pre-1935 and internal brick partition walls separating rooms. Based on a past survey, most of these will have cavity exterior walls, parapet and flexible, wooden diaphragms (not rigid). The case study building is a two-storey, stand-alone building (not a raw building) with exterior cavity walls and single wythe partition brick walls and a 1.2m tall brick parapet towards street frontage which wraps partially around to the sides. Diaphragms consist of wooden floors.

Type 4 – URM 1-4 storey building with large GFA > 2000

Narrative

Type 4 represents 58 (2%) three or more storeys, unreinforced masonry structures. Typical building use across the inventory is multi-unit apartments or public buildings. The lateral load resisting system consists of unreinforced masonry walls. For the case study building it was assumed that exterior walls are cavity construction and internal partition walls are single wythe brick walls. The building has a parapet and timber floors.

Type 5 - RC shear walls (low-rise)



Narrative

Type 5 represents 326 (13%) of single-storey low-rise concrete wall buildings. Common use is for workshops or utility plant rooms. Most buildings are constructed 1950 – 1960 with light reinforcing content. The case study building is a single storey, lightly reinforced blockwork wall system with a light roof structure and sits on shallow foundations.

Type 6 - RC shear walls (mid-rise)

Narrative

Type 6 represents 61 (2%) reinforced concrete shear wall buildings. Common building use is commercial. Most buildings are constructed pre-1976 with non-ductile detailing. These structures are heavy in self-weight.

Case study buildin is a 4-storey structure, 17m by 17m in plan dimensions. The lateral load resisting system consist of non-ductile reinforeced concrete shear walls which lacking in confinement detailing and are reinforeced with plain round bars.

Type 7 - RC frame with masonry infill

Narrative

Type 7 represents 179 (reinforced concrete frame with masonry infill buildings. Common building use is commercial. Most buildings are constructed pre-1935. The case study building is a four-storey building with a floor area of 800 m^2. Typical storey height of 3.5m for each storey. Frame detailing is non-ductile. These the building has three bays in the transvers direction with typical bay length of 3m and have 5 bays in longitudinal direction with 3.8m bay length. A thickness of 230mm for the masonry infill wall was adopted

Type 8 - Pre-1976 RC Frame

Narrative

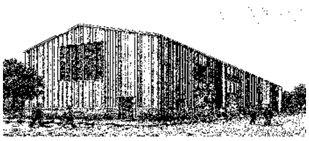
Type 8 represents 152 (6%) reinforced concrete frame buildings built pre-1976 with non-ductile detailing. Common building use is commercial, tertiary education or hospital buildings. The case study building is only three storeys, to reflect the EPB stock. With cast-in situ diaphragms, non-ductile detailing and common pre-capacity design characteristics e.g. weak column strong beams, not well confined columns.

Type 9 - Post-1976 RC Frame with precast flooring

Narrative

Type 9 represents 26 (1%) reinforced concrete frame buildings built post-1976, characterised with ductile detailing of frames and applied capacity design principles. These structures are heavy in self-weight. What lets these buildings down is the incompatibility between ductile frames and elements low in displacement capacity like stairs, cladding panels and brittle floor units and often the lack of diaphragm ties. There are often only internal beams in one direction, but none in the other (no beams in span of the hollow-core direction). The case study building is a 9-storey structure with concrete frames and hollow-core precast floor system. The ductile RC frames are typically well detailed and expected to score high. The building is clad with precast panels characterised by lack of displacement capacity. The internal stairs are precast with limited inter-storey displacement capacity.

Type 10 - Steel MRF + precast parts governed



Narrative

Type 10 represents 171 (7%) steel moment frame buildings with or without heavy cladding panels. Most of these are used for industrial production or storage. Over 60% of these buildings are in Christchurch. Typically, steel portal frames in transverse direction and steel cross bracing in the longitudinal direction.

C4.2 Hazus types and difference to NZ types as per EPB study typology

The Hazus manual 6.1 (USA) includes 36 specific building types that are used in the Hazus methodology and listed in Table 5-1 of Hazus v6.1. These types are based on classification system of FEMA-178, NEHRP *Handbook for the Seismic Evaluation of Existing buildings*. The below table shows the 10 types of our EPB study compared with selected Hazus types which are similar (not equivalent) to the types. Differences are explained. The Hazus types were used to compare the Hazus fragility curves with this study's DPM fragility curves. For the purpose of this study, there was a benefit of trying to match and use as much as possible predefined types from Hazus for this task.

Table C5: The 10 types of this study compared with Hazus types

Type # (NZ)	Types as per Hazus (USA)	Difference of New Zealand types
1	**W1** These are typical single-family or small, multi-family dwellings of not more than 5,000 square feet of floor area. The essential structural feature of these buildings is repetitive framing by wood rafters of joists on wood stud walls. Loads are light and spans are small.	Very similar structure to NZ NZ timber houses typically has a smaller floor area. Brick chimneys - both in NZ and US US has masonry veneer, while NZ has mainly timber cladding within the EPB stock, some veneer NZ has brick partition walls, not specified in US
2 3 4	**URML and URMM** These buildings include structural elements that vary depending on the building's age and, to a lesser extent, its geographic location. In buildings built before 1900, the majority of floor and roof construction consists of wood sheathing supported by wood framing. In large multi-storey buildings, the floors are cast-in-place concrete supported by the unreinforced masonry walls and/or steel or concrete interior framing. In unreinforced masonry constructed built after 1950 outside California, wood floors usually have plywood rather than board sheathing. In regions of lower seismicity, buildings of this type constructed more recently can include floor and roof framing that consists of metal deck and concrete fill supported by steel framing elements. The perimeter walls, and possibly some interior walls, are unreinforced masonry. The walls may or may not be anchored to the diaphragms. Ties between the walls and diaphragms are more common for the bearing walls than for walls that are parallel to the floor framing. Roof ties are usually less common and more erratically spaced than those at the floor levels. Interior partitions that interconnect the floors and roof can reduce diaphragm displacements.	Most URM structures in NZ were built between 1910 and 1935. In NZ, timber floor structures are predominant, with rigid concrete floors being rare. In the US, some larger URM buildings typically have concrete floors. NZ floors are primarily constructed using board sheathing. In the US, some regions use board sheathing. Both NZ and the US feature interior masonry partition walls in URM buildings. In the US, modern low-seismic design may include metal deck with concrete fill or steel framing for interior walls; however, this is not typical in NZ. Most URM buildings in NZ are pre-1935 constructions. Walls may or may not be anchored to floors in both NZ and the US. Connections between walls and floors are more common for load-bearing purposes in both countries. Parapets present in both NZ and US URM buildings. Cavity walls found in colder zones of both countries. In NZ, about 50% of URM buildings have cavity walls.

Type # (NZ)	Types as per Hazus (USA)	Difference of New Zealand types
5 6	**C2L and C2M** The vertical components of the lateral force-resisting system in these buildings are concrete shear walls that are usually bearing walls. In older buildings, the walls often are quite extensive, and the wall stresses are low, but reinforcing is light. In newer buildings, the shear walls often are limited in extent, generating concerns about boundary members and overturning forces.	The C2 damage state descriptions are applicable to NZ as well. Pre-1976 walls in NZ typically feature lighter reinforcement, a lack of confinement, and minimal boundary reinforcing. Floors in these buildings are often cast-in-situ. Many of these structures include non-ductile columns supporting the floors, which were not designed to resist lateral loads. The extensive damage state DS3 is also relevant to NZ, characterised by features such as "visibly buckled wall reinforcement" and "partial collapse due to failure of non-ductile columns."
7	**C3M** These buildings are similar to steel frame buildings with unreinforced masonry infill walls except that the frame is of reinforced concrete. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behaviour of the system.	Very similar geometry and construction methodology in both – US and NZ Most buildings were constructed pre-1976, with some dating back to pre-1935, featuring non-ductile column detailing. In NZ mostly cast-in situ slabs. Similar deficiency issues are observed in NZ as described in the damage state descriptions: Infill walls can form a compression strut under stress, or Infill walls may disintegrate, leading to frame instability. And concrete columns may suffer shear failure due to reduced effective height and high shear forces imposed by infill deformation.
8 9	**C1M and C1H** These buildings are similar to steel moment frame buildings except that the frames are reinforced concrete. There are a large variety of frame systems. Some older concrete frames may be proportioned and detailed such that brittle failure of the frame members can occur in earthquakes, leading to partial or full collapse of the buildings. Modern frames in zones of high seismicity are proportioned and detailed for ductile behaviour and are likely to undergo large deformations during an earthquake without brittle failure of frame members or collapse.	Damage state description similar. Pre-1976 frames characterised by non-ductile detailing of columns and beams, lack of confinement reinforcement, limited displacement and rotation capacity, weak column/strong beam behaviour, which contributes to structural vulnerabilities under seismic loading.
10	**S1L** These buildings have a frame of steel columns and beams. In some cases, the beam-column connections have very small moment resisting capacity but, in other cases, some of the beams and columns are fully developed as moment frames to resist lateral forces. Usually, the structure is concealed on the outside by exterior	This building Type S1 and characteristics might be slightly different for New Zealand. In New Zealand a weakness or lower *%NBS* score as per *Engineering Assessment Guidelines* of these buildings is often due to the heavy cladding (precast cladding panels) which are defined in NZBC as 'parts' that poses life safety risks. It was

Type # (NZ)	Types as per Hazus (USA)	Difference of New Zealand types
	non-structural walls, which can be of almost any material (curtain walls, brick masonry, or precast concrete panels), and on the inside by ceilings and column furring. Diaphragms transfer lateral loads to moment-resisting frames. The diaphragms can be almost any material. The frames develop their stiffness by full or partial moment connections. The frames can be located almost anywhere in the building. Usually, the columns have their strong directions oriented so that some columns act primarily in one direction while the others act in the other direction. Steel moment frame buildings are typically more flexible than shear wall buildings. This low stiffness can result in large inter-storey drifts that may lead to relatively greater non-structural damage.	recommended to review with NZ research and test data.

Damage State assumptions for each Building type

Table C6: Damage State Assumptions per type

Type #	Damage state		Damage state description
1	DS1	Slight	Small plaster or gypsum-board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer.
1	DS2	Moderate	Large plaster or gypsum-board cracks at corners of door and window openings; small diagonal cracks across shear wall panels exhibited by small cracks in stucco and gypsum wall panels; large cracks in brick chimneys; toppling of tall masonry chimneys.
1	DS3	Extensive	Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of “room-over-garage” or other “soft-storey” configurations; small foundations cracks.
1	DS4	Complete	Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load-resisting system; some structures may slip and fall off the foundations; large foundation cracks. Approximately 3% of the total area of W1 buildings with Complete damage is expected to be collapsed.
2,3,4	DS1	Slight	Diagonal stair-step hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; movements of lintels; cracks at the base of parapets
2,3,4	DS2	Moderate	Most wall surfaces exhibit diagonal cracks; some of the walls exhibit larger diagonal cracks; masonry walls may have visible separation from diaphragms; significant cracking of parapets; some masonry may fall from walls or parapets.
2,3,4	DS3	Extensive	In buildings with relatively large area of wall openings, most walls have suffered extensive cracking. Some parapets and gable end walls have fallen. Beams or trusses may have moved relative to their support.

Type #	Damage state		Damage state description
2,3,4	DS4	Complete	Structure has collapsed or is in imminent danger of collapse due to in-plane or out-of-plane failure of walls. Approximately 15% of the total area of URM buildings with Complete damage is expected to be collapsed.
5, 6	DS1	Slight	Diagonal stair-step hairline cracks on masonry wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; movements of lintels; cracks at the base of parapets.
5, 6	DS2	Moderate	Most wall surfaces exhibit diagonal cracks; some of the walls exhibit larger diagonal cracks; masonry walls may have visible separation from diaphragms; significant cracking of parapets; some masonry may fall from walls or parapets.
5, 6	DS3	Extensive	In buildings with relatively large area of wall openings, most walls have suffered extensive cracking. Some parapets and gable end walls have fallen. Beams or trusses may have moved relative to their support.
5, 6	DS4	Complete	Structure has collapsed or is in imminent danger of collapse due to in-plane or out-of-plane failure of walls. Approximately 15% of the total area of URM buildings with Complete damage is expected to be collapsed.
7	DS1	Slight	Diagonal (sometimes horizontal) hairline cracks on most infill walls; cracks at frame-infill interfaces.
7	DS2	Moderate	Most infill wall surfaces exhibit larger diagonal or horizontal cracks; some walls exhibit crushing of brick around beam-column connections. Diagonal shear cracks may be observed in concrete beams or columns.
7	DS3	Extensive	Most infill walls exhibit large cracks; some bricks may dislodge and fall; some infill walls may bulge out-of-plane; few walls may fall partially or fully; few concrete columns or beams may fail in shear resulting in partial collapse. Structure may exhibit permanent lateral deformation.
7	DS4	Complete	Structure has collapsed or is in imminent danger of collapse due to a combination of total failure of the infill walls and nonductile failure of the concrete beams and columns. Approximately 15% (low-rise), 13% (mid-rise) or 5% (high-rise) of the total area of C3 buildings with Complete damage is expected to be collapsed.
8	DS1	Slight	Flexural or shear type hairline cracks in some beams and columns near joints or within joints.
8	DS2	Moderate	Most beams and columns exhibit hairline cracks. In ductile frames some of the frame elements have reached yield capacity indicated by larger flexural cracks and some concrete spalling. Nonductile frames may exhibit larger shear cracks and spalling.
8	DS3	Extensive	Some of the frame elements have reached their ultimate capacity indicated in ductile frames by large flexural cracks, spalled concrete and buckled main reinforcement; nonductile frame elements may have suffered shear failures or bond failures at reinforcement splices, or broken ties or buckled main reinforcement in columns which may result in partial collapse.
8	DS4	Complete	Structure is collapsed or in imminent danger of collapse due to brittle failure of nonductile frame elements or loss of frame stability. Approximately 13% (low-rise), 10% (mid-rise) or 5% (high-rise) of the total area of C1 buildings with Complete damage is expected to be collapsed.
9	DS1	Slight	Hollowcore early cracking.
9	DS2	Moderate	Hollowcore major cracking and to precast cladding panels top floors.
9	DS3	Extensive	Hollowcore failure leading to loss of floor and precast panels of top floors.

Type #	Damage state		Damage state description
9	DS4	Complete	Hollowcore failure and panels .
10	DS1	Slight	Diagonal hairline cracks on concrete shear wall surfaces; larger cracks around door and window openings in walls with large proportion of openings; minor concrete spalling at few locations; minor separation of walls from the floor and roof diaphragms; hairline cracks around metal connectors between wall panels and at connections of beams to walls.
10	DS2	Moderate	Most wall surfaces exhibit diagonal cracks; larger cracks in walls with door or window openings; few shear walls have exceeded their yield capacities indicated by larger diagonal cracks and concrete spalling. Cracks may appear at top of walls near panel intersections indicating “chord” yielding. Some walls may have visibly pulled away from the roof. Some welded panel connections may have been broken, indicated by spalled concrete around connections. Some spalling may be observed at the connections of beams to walls.
10	DS3	Extensive	In buildings with relatively large area of wall openings most concrete shear walls have exceeded their yield capacities and some have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visibly buckled wall reinforcement. The plywood diaphragms may exhibit cracking and separation along plywood joints. Partial collapse of the roof may result from the failure of the wall-to-diaphragm anchorages sometimes with falling of wall panels.
10	DS4	Complete	Structure is collapsed or is in imminent danger of collapse due to failure of the wall-to-roof anchorages, splitting of ledgers, or failure of plywood-to-ledger nailing; failure of beams connections at walls; failure of roof or floor diaphragms; or, failure of the wall panels. Approximately 15% of the total area of PC1 buildings with Complete damage is expected to be collapsed.

C5 Structural Retrofit Concept Design Assumptions

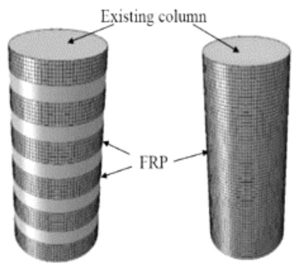
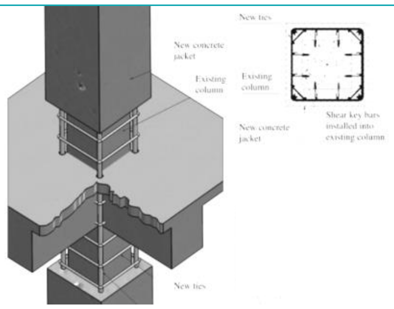
C5.1 Summary of seismic vulnerabilities and strengthening scope

A summary of the typical seismic vulnerabilities and how these have been addressed in the representative building strengthening schemes for both 34%*NBS* and 67%*NBS* is summarised in the table below.

Table C7: Typical seismic vulnerabilities for each typology and how this is addressed in the 34%*NBS* and 67%*NBS* design.

Typology	Typical seismic vulnerabilities	Vulnerabilities addressed within reference building strengthening scope	
		34%*NBS*	67%*NBS* (in addition to 34%*NBS* scope)
1	• Heavy elements, such as concrete roof tiles, masonry veneers, parapets, chimneys and party walls • Lack of sufficient lining walls to provide bracing • Lack of sub-floor bracing • Timber floor diaphragms for higher seismic loading demands	• Remove chimney • Out of plane restraints to URM party wall	• Additional supplementary plasterboard lining walls and adjacent floor/roof diaphragm tie in • Additional supplementary sub-floor bracing • Timber floor diaphragm upgrade
2	• Overarching problem is that New Zealand's URM building stock is not designed for earthquake loads and often lack a basic degree of connection between structural elements to allow all parts to act together (C8.12 *Engineering Assessment Guidelines*) • Unrestrained parts including parapets, chimneys and ornaments • Poor wall to diaphragm connections and diaphragms • Out of plane capacity of URM walls • Lack of in-plane bracing elements, particularly at ground floor for open street frontage • Specific structural issues	• New supplementary bracing adjacent to street frontage and associated pad foundations • Restraining URM parapet to street frontage • Top of URM wall out of plane restraints and modest diaphragm upgrades	• Cavity ties for those with brick cavities • RC overlay to improve both in-plane and out-of-plane restraints to discrete locations adjacent to openings • Out of plane restraints to URM walls • Upgrade of street front canopy
3		• As per Typology 2, with the following additions or modifications: • Additional floor diaphragm upgrades to reflect higher force demands at Level 1 and Roof	• As per Typology 2, with the following additions or modifications: • Additional RC overlay to transverse wall (opposite to street frontage end) and associated foundations • Foundations extent increased for transverse bracing to street frontage
4		• Upgrades of lateral force resisting system through RC wall overlays. • Timber floor diaphragm upgrades with localised plywood overlays • Out of plane restraints to internal URM walls in upper levels • Restraint to roof top parapets to building perimeter	• Nominal upgrades to the egress stairs to improve mid floor landing seating • Extent of timber floor upgrades increased to entire floor plate including localised steel drag elements to lateral force resisting system • Entire roof bracing system to distribute roof level loads to lateral force resisting system
5	• Lack of force resisting system in the transverse direction adjacent to the street frontage	• New supplementary bracing in transverse direction and associated pad foundations	• Increase in foundation extent for new transverse bracing • New roof bracing system to transfer heavy cladding/shear wall out of

<table>
<tr><th rowspan="2">Typology</th><th rowspan="2">Typical seismic vulnerabilities</th><th colspan="2">Vulnerabilities addressed within reference building strengthening scope</th></tr>
<tr><th>34%NBS</th><th>67%NBS (in addition to 34%NBS scope)</th></tr>
<tr><td></td><td>• Can be governed by brittle (shear) mechanisms, rather than ductile (flexure)
• Lack of roof level diaphragms to resist heavy cladding/structural walls
• Prescence of heavy components, such as internal walls, parapets and claddings
• Lack of hold down to resist over turning forces</td><td>• Out of plane restraints to top of shear walls
• Out of plane restraints to internal URM walls</td><td>plane loads to lateral load resisting system
• Parapet restraints to street frontage
• Nominal upgrades to street frontage canopy
• Extent of timber floor upgrades increased to</td></tr>
<tr><td>6</td><td>• Heavy buildings with lack of capacity in the lateral load resisting system. Can be governed by brittle (shear) mechanisms, rather than ductile (flexure)
• Ill configured floor diaphragms (large openings or limited roof level system).
• Lack of roof level diaphragms to resist heavy cladding/structural walls
• Prescence of URM components, typically internal walls
• Lack of hold down to resist over turning forces</td><td>• Enhancement of existing RC wall capacity through RC overlays to existing walls at lower levels
• Parapet upgrades on street frontage</td><td>• Foundation upgrades by improving overturning hold down
• Diaphragm upgrades with localised steel drag elements fixed to existing floor
• Vertical steel plates to existing shear walls to improve ductility capacity</td></tr>
<tr><td>7</td><td>• Out of plane performance of masonry infill panels
• In-plane performance of masonry infill panels and their effects on adjacent RC frames
• Shear capacity of frames in the direction of the infill panels or by effects of by strong beam/weak-column mechanisms
• Roof top elements not designed for modern ‘parts and components’ amplification of earthquake forces</td><td>• Improvement of shear and confinement to transverse direction columns
• Enhance out of plane capacity of masonry infill panels in upper levels</td><td>• New supplementary transverse lateral load resisting system and associated foundations through a new steel braced frame to street frontage and RC overlay walls at rear of building
• Improvement of diaphragm tie members adjacent to new transverse lateral load resisting system
• Where applicable, to the perimeter, improvement of tie back of outer brick veneer to masonry infill substrate
• Where applicable, supplementary upgrade of longitudinal walls through RC overlays
• New steel roof bracing system
• Parapet restraint
• Nominal roof top plant room upgrades</td></tr>
</table>

<table>
<tr><th rowspan="2">Typology</th><th rowspan="2">Typical seismic vulnerabilities</th><th colspan="2">Vulnerabilities addressed within reference building strengthening scope</th></tr>
<tr><th>34%NBS</th><th>67%NBS (in addition to 34%NBS scope)</th></tr>
<tr><td rowspan="5">8</td><td>Non-ductile columns
Flexible frames, typically poorly detailed RC elements (beams, columns and beam-column joints)
Floor diaphragms generally of more robust in-situ concrete, however can often be poorly tied together particularly adjacent to openings
Flat slab floor systems in some instances. Often limited by shear capacity of slabs adjacent to columns when subject to lateral movements
Roof top elements not designed for part loads</td><td>Fibre reinforced polymer (FRP) wrap to potential plastic hinge zones of columns
Supplementary steel bracing system to high seismic areas only
Enhanced shear capacity of slabs for flat slab buildings</td><td>Supplementary steel bracing system to all seismic zones
Foundation upgrades including piles for new bracing system
Localised diaphragm upgrades to improve capacity adjacent to floor openings and new bracing members</td></tr>
<tr><td colspan="3">Non-Ductile Concrete Column – Typical retrofit mitigations</td></tr>
<tr><td>Fibre-reinforced polymer (FRP) wrapping</td><td>Steel Jacketing</td><td>Reinforced Concrete jacketing</td></tr>
<tr><td>
</td><td></td><td>
</td></tr>
<tr><td>The fibres (unidirectional flexible sheets or fabrics can be woven or unwoven) are then wrapped to the concrete using the resin to apply to concrete columns</td><td>This application uses a steel cage surrounding the existing concrete column
The cage is consisting of four steel angles, placed at the corners of RC column and steel straps/battens are used horizontally, welded to the angles with a specific interval along the height of the column. The gap is filled up with non-shrink cement mortar or epoxy grout</td><td>The application of a thin layer (150-200mm) of reinforced concrete around the existing column. For ensuring the proper bond anchored bars/shear keys and adhesive materials are added.</td></tr>
</table>

Typology	Typical seismic vulnerabilities	Vulnerabilities addressed within reference building strengthening scope	
		34%*NBS*	67%*NBS* (in addition to 34%*NBS* scope)
	• Advantage: Includes easy to application in limited space, cut the necessity of intensive surface preparation that result reducing the labour costs and provide the substantial ductility	• Advantage: It increases lateral strength, axial load carrying capacity, the ductility and shear capacity of structural member. It is generally regarded as easy to install, and relative cost effective	• Advantage: Improves the ductility, confinement, shear capacity and axial load carrying capacity
	• Disadvantage: The fibres and resign are relative expensive as compared to steel or concrete, however less labour intensive. It requires special approval, on site testing and trained site personal for the installation.	• Disadvantage: Cage requires lots of welding which is labour intensive and increases the onsite works	• Disadvantage: Architecturally the section enlargement is often not accessible. There are programme increases due to drilling starter bars and preparing the surface area. It often needs dowelling the reinforcing bars to the footing.
9	• Flexible and ductile reinforced concrete frames with high lateral drift • Precast concrete floors with low deformation capacity, in particular Hollowcore floors • Stairs and inability to withstand high drifts	• New steel seating angles at ends • Flexible and ductile reinforced concrete frames with high lateral drift • Retrofit of stairs to enable differential inter-storey to occur while also providing additional stair seating • Stairs and inability to withstand	• Upgrade to precast concrete floors to address positive moment, 'Alpha' and 'Beta' units as defined within the EAG • Column ties to address intermediate columns not adequately laterally restrained at floor levels • Retrofit of infill panels to building perimeter where applicable • Upgrades to roof top plant rooms
10	• Connection details of heavy perimeter cladding (precast panels or masonry walls), typically not contributing to the capacity of lateral load resisting system • Steelwork details often lacking to perform in a ductile manner	• Upgrade precast panel connections at base and top of panels • Upgrade of cross bracing connections to vertical bracing and roof bracing system	• Improvement of portal frame detailing including connection upgrades and new lateral restraint to avoid flexural buckling • Further retrofit of steel roof bracing system to enhance strut (compression) members • Replacement of existing vertical cross bracing system • Nominal improvements to secondary elements with incomplete load paths, such as an external canopy

C6 Economic Assumptions

Table C8: Economic Assumptions for BCR analysis

Costs	Benefits Avoidance of
• Building seismic upgrade costs for two upgrade scenarios • Building energy efficiency upgrade costs	• Building repair or replacement costs • Content replacement costs • Deaths, injuries and PTSD • Time-element losses (residential displacement and direct and indirect business interruption) • Search and rescue costs • Building upgrade capital carbon for two upgrade scenarios • Non-financial: culturally significant including heritage sites, social aspects etc

Repair costs were capped at 100% of replacement cost. The economic cost of the property damage is the lesser of damage repair costs or combined demolition and replacement cost.

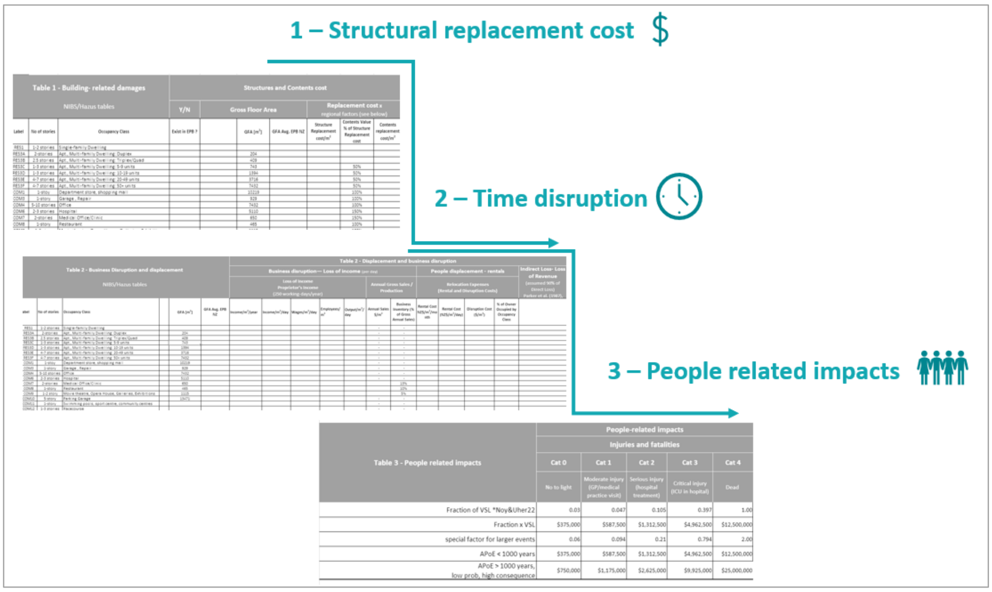


Figure C1: Benefits - Economic input

VoSL for earthquake

Fragility and loss modelling generated the key quantities required for the economic analysis of costs and benefits. The key shadow prices are drawn from the Treasury's CABx and the NIBS/Noy & Uher 2022 paper as appropriate for each scenario. This included the monetary quantification of social loss (casualties, non-fatal injuries), based on Value of Statistical Life (VoSL) or fraction of VoSL as per Treasury CABx 2025.

Why 2% discount rates?

The economic analysis uses the Treasury new 2% default discount rate for non- commercial investments augmented by sensitivity analysis. However, the use of a APoE approach essentially abstracts from time so the analysis of economic costs and benefits so no discount rates were used and the internal Rate of Return (breakeven discount rate) was calculated.

Table C9: Business Disruption Cost (indirect and direct)

z		StatsNZ Ref.	GFA (m^2)	Direct Loss					Business inventory	People displacement	% Owner occupied	Indirect Loss Loss of Revenue[4]		Direct Loss V_{BI} [$/m²/day]	NIBS Tab 4 15 Q [$/m²/day]	Indirect Loss [$/m²/day]
				Loss of Income												
				Income		No of employee	250 working days/year			Rental cost						
				NZ$/year	NZ$/day		NZ$/day/ employee	NZ$/day	Hazus Tab 6 12	NZ$/m²/day	Hazus Tab 6 15	NZ$/day/m²	NZ$/day			
RES1	Single-family Dwelling	7	1300							24.33	75%	24.33	24.33	24.33	0.47	11.44
RES3A	Apt., Multi-family Dwelling: Duplex	7	650							24.33	35%	24.33	24.33	24.33	0.47	11.44
RES3B	Apt., Multi-family Dwelling: Triplex/Quad	7	1000							24.33	35%	24.33	24.33	24.33	0.47	11.44
RES3C	Apt., Multi-family Dwelling: 5-9 units	7	1260							24.33	35%	24.33	24.33	24.33	0.47	11.44
RES3D	Apt., Multi-family Dwelling: 10-19 units	7	2000							24.33	35%	24.33	24.33	24.33	0.47	11.44
RES3E	Apt., Multi-family Dwelling: 20-49 units	7	1400							24.33	35%	24.33	24.33	24.33	0.47	11.44
RES3F	Residential	7	1850							24.33	35%	24.33	24.33	24.33	0.47	11.44
COM1	Department store, shopping mall	7	1850	50,076	193	347	0.56	192.60	13%		55%		192.6	192.60	0.04	7.13
COM3	Garage/ Workshop repair	3	1985	78,000	300	215	1.40	300.00			55%		300	300.00	0.37	112.20
COM4	Office	12	2000	91,988	354	264	1.34	353.80			55%		353.8	353.80	0.02	5.66
COM6	Hospital	15	1770	76,544	294	287	1.03	294.40			95%		294.4	294.40	0.50	147.20
COM7	Medical Office/Clinic	15	1500	76,544	294	287	1.03	294.40			65%		294.4	294.40	0.50	147.20
COM8	Restaurant	7	885	50,076	193	348	0.55	192.60			80%		192.6	192.60	0.64	122.69
COM9	Movie theatre, Opera House, Galleries, Exhibitions	16	1750	65,884	253	146	1.74	253.40			45%		253.4	253.40	0.64	161.42
COM10	Parking Garage	7	800	50,076	193	348	0.55	192.60			25%		192.6	192.60	0.37	72.03
COM11	Swimming pools, sport, community centres	16	2000	65,884	253	146	1.74	253.40			25%		253.4	253.40	0.37	94.77
COM12	Racecourse	16	2000	65,884	253	146	1.74	253.40			25%		253.4	253.40	0.37	94.77
COM13	Smaller retail / NZ corner shops	7	1800	50,076	193	348	0.55	192.60			80%		192.6	192.60	0.04	7.13
UTI1	Suburb substation	4	1400	102,076	393	30	13.22	392.60			80%		392.6	392.60	0.26	102.08
IND1	Factory	1	2000	71,292	274	89	3.09	274.20	5%		75%		274.2	274.20	0.26	71.29
IND2	Industrial Warehouse, heavy	3	1765	78,000	300	215	1.40	300.00	4%		75%		300	300.00	0.44	131.40
IND3	Lab, Food/Drugs/Chem 1-storey	3	565	78,000	300	215	1.40	300.00	5%		75%		300	300.00	0.06	19.20
REL1	Church	16	2000	65,884	253	146	1.74	253.40			90%		253.4	253.40	0.05	11.40
GOV1	Town hall, Main Railway station	16	1765	65,884	253	146	1.74	253.40			70%		253.4	253.40	0.05	11.40
GOV2	Police station, Fire stations	13	1770	91,208	351	213	1.65	350.80			95%		350.8	350.80	0.05	15.79
EDU1	High-school, Primary and Early childcare	14	2000	72,436	279	203	1.37	278.60			95%		278.6	278.60	0.04	9.75
EDU2	University classrooms	14	1400	72,436	279	203	1.37	278.60			90%		278.6	278.60	0.04	9.75

[4] Assumed 90% of direct loss as per Parker et al 1987 RiskScape

Embodied Carbon - Retrofit vs Demo & full replacement

34%*NBS* Strengthening

Table C10: Embodied Carbon (Whole-of-Life LCA)– 34%*NBS* retrofit

Building Type		GFA (m^2)	Embodied Carbon ($kgCO2e/m^2$)			
			Residential	Commercial	Industrial	Hospital
1	Light-timber frames with URM elements	200	99	164	99	198
2	URM -1 storey	200	152	217	152	304
3	URM ≥ 2 storeys, < 2000m^2	500	120	185	120	240
4	URM 1-4 storeys > 2000m^2	4400	167	232	167	334
5	RC Shear wall – low-rise	340	141	206	141	282
6	RC shear wall – mid-rise	1150	105	170	105	210
7	RC frame with masonry infill	830	105	170	105	210
8	Pre-1976 RC frame	1500	102	167	102	227
9	Post-1976 RC frame with precast	5200	92	157	92	184
10	Steel moment frame with heavy cladding	900	89	154	89	178

67%*NBS* Strengthening

Table C11: Embodied Carbon (whole-of-Life LCA) – 67%*NBS* retrofit

Building Type		GFA (m^2)	Embodied Carbon ($kgCO2e/m^2$)			
			Residential	Commercial	Industrial	Hospital
1	Light-timber frames with URM elements	200	109	174	109	218
2	URM -1 storey	200	202	267	202	404
3	URM ≥ 2 storeys, < 2000m^2	500	188	253	188	376
4	URM 1-4 storeys > 2000m^2	4400	316	381	316	632
5	RC Shear wall – low-rise	340	265	330	265	530
6	RC shear wall – mid-rise	1150	157	222	157	314
7	RC frame with masonry infill	830	200	265	200	400
8	Pre-1976 RC frame	1500	229	294	229	354
9	Post-1976 RC frame with precast	5200	134	199	134	268
10	Steel moment frame with heavy cladding	900	96	161	96	192

Table C12: Embodied Carbon – Full replacement incl NSE

Building use	Carbon Full Replacement incl. NSE [$kgCO_2e/m^2$]
Residential	335
Commercial	940
Industrial	470
Hospitals	1000

Table C13: Embodied Carbon – Regional adjustment factors

Location	Regional carbon adjustment factor
Auckland	0.78
Wellington	1.09
Christchurch	1.0
Dunedin	0.76
Whanganui	0.95
Feilding	1.07

Table C14: Cost for Capital Carbon (NZ$) – [Benefit workstream]

Environmental amenity Shadow Emission Value $CO_{2/}$	
202 – Central path (Present to 2030)	- 155

Note: The current cost of carbon under the emissions trading scheme is $52 CO_2/kg, with prices fluctuating between $40 and $90 CO_2/kg, over the past four years. For this analysis, we assumed the CBAx central price path projected to 2030 ($155). This approach aligns with our methodology of treating all scenarios as occurring within a "nominal year," assuming that the works are completed and the earthquake occurs in the near future.

Energy Efficiency Upgrade Cost

Table C15: Energy Efficiency Upgrade cost [Cost workstream]

Building Type		GFA (m2)	Cost for EE Upgrade 67%NBS option		
			Commercial	Industrial	Hospital
1	Light-timber frames with URM elements	200	580	580	580
2	URM -1 storey	200	515	515	515
3	URM ≥ 2 storeys, < 2000m^2	500	455	455	455
4	URM 1-4 storeys > 2000m^2	4400	340	295	340
5	RC Shear wall – low-rise	340	475	475	475
6	RC shear wall – mid-rise	1150	405	355	405
7	RC frame with masonry infill	830	495	435	495
8	Pre-1976 RC frame	1500	410	355	175
9	Post-1976 RC frame with precast	5200	345	335	345
10	Steel moment frame with heavy cladding	900	350	305	350

Table C16: Wages and Earnings as per StatsNZ for Business Disruption assumptions:

Occupancy Class		StatsNZ description	Average Income		Employee
			Year	Day	No.
COM1	Department store, shopping mall	7. Retail Trade and Accommodation	50,076	193	347
COM3	Garage, Repair	3. Manufacturing	78,000	300	215
COM4	Office	12. Offices	91,988	354	264
COM6	Hospital	15. Health	76,544	294	287
COM7	Medical Office/Clinic	15. Health	76,544	294	287
COM8	Restaurant	7. Retail Trade and Accommodation	50,076	193	347
COM9	Movie theatre, Galleries	16. Art and Recreation and other	65,884	253	146
COM10	Parking Garage	7. Retail Trade and Accommodation	50,076	193	347
COM11	Swimming pools, sport centres	16. Art and Recreation and other	65,884	253	146
COM12	Racecourse, Grandstands	16. Art and Recreation and other	65,884	253	146
COM13	Smaller retail / NZ corner shops	7. Retail Trade and Accommodation	50,076	193	347
UTI1	Suburb substation	4. Electricity, Gas, Water	102,076	393	29
IND1	Factory	1. Agriculture, forestry, and fishery	71,292	274	89
IND2	Industrial Warehouse, heavy	3. Manufacturing, 6. Wholesale trade	78,000	300	215
IND3	Lab, Food/Drugs/Chem 1-storey	3. Manufacturing, 6. Wholesale trade	78,000	300	215
REL1	Church	16. Art and Recreation and other	88,192	339	146
GOV1	Town hall, Railway station	13. Public Admin, 16. Art, Recreation	65,884	253	146
GOV2	Police station, Fire stations	13. Public Administration and Safety	91,208	351	213
EDU1	Highschool, Primary, Early childcare	14. Education and Training	72,436	279	203
EDU2	University classrooms	14. Education and Training	72,436	279	203

Beca