Report

Estimating the Risk to Life Safety during Earthquakes from Non-Structural Elements in Commercial Buildings in New Zealand

Prepared for Ministry of Business, Innovation and Employment (MBIE)

Prepared by Beca Ltd (Beca)

28 October 2016

Revision History

Revision Nº	Prepared By	Description	Date
1	**Andrew Baird** **Trevor Yeow**	Report	28/10/16

Document Acceptance

Action	Name	Signed	Date
Prepared by	**Andrew Baird** **Trevor Yeow**		28/10/16
Reviewed by	**Helen Ferner**		28/10/16
Approved by	**Helen Ferner**		28/10/16

Executive Summary

This report has been prepared for the Ministry of Business, Innovation and Employment (MBIE) by Beca Ltd (Beca) in conjunction with the University of Canterbury Quake Centre (UCQC) to estimate the risk of death and injury attributable to the failure of non-structural elements in earthquakes.

In New Zealand in the last six years, a total of 1,048 injuries were recorded as being directly attributable to earthquake damage of commercial buildings. 173 of these injuries were fatal. The majority of injuries in the last six years occurred during the earthquake that struck near Christchurch on the 22nd February 2011. Understanding what contributes to building-related earthquake injuries is essential for determining which components of a building require attention to reduce future earthquake injuries. The focus of this report is to determine the contribution that damage to non-structural elements has upon the total number of injuries in recent New Zealand earthquakes.

This research makes use of data collected by the "Researching the Health Implications of Seismic Events" (RHISE) Group from all major earthquakes in New Zealand since 4th September 2010. Such data has never been collected with such great detail or comprehensively before, allowing both the total number of injuries in each earthquake event and the cause and the severity of each injury to be quantified.

It was found that non-structural damage is the main contributor to earthquake injuries in commercial buildings, being the cause of 61% of all injuries. A further breakdown by non-structural element found that building contents were the dominant cause of injuries, making up 69% of all non-structural injuries (or 42% of all commercial building related injuries overall).

Damage to non-structural elements may cause more injuries than structural damage, however 90% of these injuries can be categorised as only 'requiring treatment', the lowest injury severity level considered in this study. There were no fatalities involving damage to non-structural elements of commercial buildings. This is compared with injuries attributable to structural or masonry damage, of which 58% and 37% were fatal, respectively. This result demonstrates that in order to reduce the risk to life-safety in earthquakes, effort should be focussed on reducing structural and masonry damage as a first priority, rather than non-structural elements. However, since non-structural elements contributed to a far greater number of minor injuries, it is possible that the overall injury costs attributable to non-structural element damage may be relatively high when compared to other earthquake caused direct injuries. Further research is required to quantify the total costs associated with non-structural and structural injuries.

The injury data obtained from the RHISE database was also used to propose a relationship between the number of injuries and the ground shaking intensity in the 2010-2011 Canterbury earthquakes. This relationship found that the rate of injury due to non-structural elements in a commercial building was up to 4.9 per 1,000 people, depending on the intensity of ground shaking. This relationship can potentially be used to estimate injury numbers in future earthquakes, however, its application is restricted due to the limited data available.

Contents

1 Introduction

This report has been prepared for the Ministry of Business, Innovation and Employment (MBIE) by Beca Ltd (Beca) and the University of Canterbury Quake Centre (UCQC) to estimate the risk of death and injury attributable to the failure of non-structural elements in earthquakes. This research forms part of a larger research programme that MBIE have commissioned to better understand the seismic performance of non-structural elements.

1.1 Scope

Our scope of work includes the following:

- Collection and processing of earthquake injury data to quantify the contribution of non-structural element damage to overall building related injuries; and the relative severity of such injuries;
- Development of an injury model that relates injuries from non-structural elements in an earthquake to the ground shaking intensity;
- Assembly of an expert panel to review and scrutinise our findings;
- A report summarising the findings of the research.

1.2 Methodology

The methodology used to estimate the risk of death and injury attributable to the failure of non-structural elements in earthquakes has been separated into two main sections. The first section is the processing of earthquake injury data to determine the total number of injuries due to building damage, the cause of these injuries, and their relative severity.

This was possible by making use of data collected by the "Researching the Health Implications of Seismic Events" (RHISE) Group from all major earthquakes in New Zealand since 4th September 2010. Such data has never been collected with such great detail or comprehensively before. This research is also the first to make use of the fully completed RHISE version 2.0 database. This section can be considered the factual representation of the processed RHISE data, and forms the majority of this report

The second section expands on the injury data obtained in the first section to propose a relationship between the number of injuries and the ground shaking intensity in the 2010-2011 Canterbury earthquakes. This relationship can potentially be used to estimate injuries numbers in future earthquakes, however, its application is restricted due to the limited data available.

1.3 Research Scope

The scope of this research includes direct injuries caused by damage of non-structural elements in commercial buildings in earthquake events in New Zealand since the 4th September 2010 Darfield earthquake. The definition of what is considered a non-structural element is expanded on in the following section. While not the focus of this research, injuries caused by damage of the primary structure are included for comparison purposes.

This research project is focussed on injuries related to commercial buildings. Examples include: office buildings, hospitals, schools, emergency service facilities and community facilities such as libraries, museums and auditoriums. All injuries that were deemed to have occurred in residential or farm buildings were excluded.

This research considers only direct earthquake injuries. Direct injuries are considered as being due to an unavoidable external force e.g. being hit by an object, as opposed to an indirect (or action) injury, e.g. spraining an ankle while trying to get under a desk. Research conducted following the 2010-2011 Canterbury earthquakes found that direct injuries accounted for 63% of injuries in the 22nd February 2011 Christchurch earthquake (Johnston et al., 2014).

1.4   Non-structural Element Definitions

While there is some confusion and inconsistency in definitions of what is a non-structural element, for the purposes of this research, non-structural elements have been considered parts of a building that are not part of the main structural gravity and seismic load resisting system and that are not engineered secondary structural elements such as stairs and precast panels.

Masonry (e.g. brick) has been purposefully separated into its own category in this research rather than being included as a non-structural element. This is due to the fact that masonry can serve either a non-structural or structural function in a building. Unreinforced masonry brick buildings often have both masonry parapets and masonry bearing walls for example. The RHISE data did not differentiate injuries caused by structural masonry from those caused by non-structural masonry.

For the purposes of this research, the categorisation of non-structural elements is highly dependent upon the descriptions used in the RHISE database. Difficulties arise in distinguishing the particular non-structural element that caused each injury. For example, it is often impossible to distinguish whether injuries from falling elements were the result of a particular service falling into or through the ceiling, or a result of failure of the ceiling itself. As a result of such difficulties, the categorisation of non-structural elements provided in Table 1 below was used for this research.

Table 1: Non-structural element categorisation.

Category	Description / Examples
Ceilings and Services	- suspended ceilings and tiles - HVAC equipment and ducting - pipework and plumbing - fire sprinkler systems - lighting systems - cable trays
Interior Walls	internal partitions
Contents	- furniture - shelving - electronics - generic items
Appendages	- signage - ornamentation
Exterior	- cladding systems - exterior glazing
Other	- plant - roof tiles - doors

2 Earthquake Injuries from Non-Structural Elements

2.1 Motivation

In New Zealand there have been approximately 480 recorded deaths attributed to earthquakes since the 1848 Marlborough earthquake. Prior to the 22nd February 2011 Christchurch earthquake, over 80 years had passed since an earthquake fatality as a result of building collapse (McSaveney, 2012; New Zealand Police, 2012). This result is in contrast with earthquakes worldwide, which have claimed the lives of over 500,000 people in the past three decades (Ramirez & Peek-Asa, 2005).

One of the main drivers for this result this can be attributed to the New Zealand Building Code requirement that even in a major earthquake, a building should not collapse and that the occupants can escape, even if the building itself is badly damaged (MBIE, 1992). This performance requirement is often referred to as a 'life-safety' objective of the Building Code. Improving the seismic performance of the structural system of buildings to ensure that this life-safety objective is met has been the focus of research in structural engineering worldwide for many decades (Wang, 1987).

However, elements of a building that are termed 'non-structural' have received far less consideration from the structural engineering community. The implications of this inequity are now gaining attention, with extensive failures of non-structural elements, like those shown in Figure 1, contributing significantly to the overall damage in an earthquake (Filiatrault et al., 2002). The economic consequences of such damage can be substantial due to the cost and downtime associated with repair; however, less is understood regarding the life-safety risk posed by such damage. This report aims to quantify the risk to life-safety posed by damage to non-structural elements by examining the cause of injuries in recent New Zealand earthquakes.

Figure 1: Non-structural damage following the M_W 6.1 2011 Christchurch earthquake

2.2 Historical Earthquake Injuries

Fatal and non-fatal injury numbers for several recent earthquake events are shown in Table 2. Non-fatal injuries outweigh fatal injuries in most events. The notable exceptions are Haiti in 2010 due to the poor construction quality of buildings, and Chile in 2010 and Japan in 2011 due to secondary hazards (i.e. fires or tsunami).

Table 2: Fatal and non-fatal injury numbers from recent events

Year	Event	Fatal (F)	Non-fatal (NF)	NF/F ratio	Reference
1994	Northridge, United States	33	24,600	745	Allen et al. (2009)
1995	Hanshin-Awaji, Japan	6,400	43,800	6.84	Allen et al. (2009)
1999	Kocaeli, Turkey	17,400	44,000	2.53	Allen et al. (2009)
1999	Chichi, Taiwan	2,500	11,300	4.52	Allen et al. (2009)
2003	Bam, Iran	26,300	30,000	1.14	Allen et al. (2009)
2009	L'Aquila, Italy	305	1,500	4.92	Calvi et al. (2009)
2010	Leogane, Haiti	316,000	250,000	0.79	Harris et al. (2010), USGS (2014)
2010	Pelluhue, Chile	799	500	0.63	European Commission (2010)
2011	Canterbury, New Zealand	185	7,200	38.9	Johnston et al. (2014), New Zealand Police (2012)
2011	Tohoku, Japan	15,900	6,200	0.39	National Police Agency of Japan (2015)

Surveys to investigate the main causes of non-fatal injuries for various Californian earthquakes found that 50-55% of non-fatal injuries during the 1987 Whittier Narrows and 1994 Northridge earthquakes were caused by non-structural elements (Shoaf et al., 1998). A similar study conducted by Petal (2004) following the 1999 İzmit earthquake in Turkey found that non-structural damage was the cause of approximately 75% of the direct earthquake injuries. Further details on the type of structural or non-structural elements considered, or whether masonry was included in either category was not provided. Therefore these statistics may not be directly comparable to those presented in this report.

Johnston et al. (2014) used an early version of the RHISE database to examine the cause of injuries from the 2010-11 Canterbury earthquakes. The classification system adopted in their study was not sufficient to determine which non-structural elements caused injuries. However, the categories most likely attributable to non-structural elements, such as projectiles (i.e. items falling from height) and broken glass, caused 13% and 18% of all injuries during the 4th September 2010 and the 22nd February 2011 events, respectively. It should be noted that many of the injuries of the Johnston et al. (2014) study were deemed to have action-related causes (i.e. cleaning up debris) or unknown causes. Consequently, the percentages above are not directly comparable with those presented in this report.

2.3   Earthquake Events Causing Injury

Injury data has been collected from all major seismic events within New Zealand since the 4th September 2010 Darfield earthquake. The key event information of the seven major events that resulted in injuries is shown in Table 3, and the location of each earthquake identified in Figure 2. This includes the four major Canterbury shaking events (4th September 2010, 22nd February 2011, 13th June 2011, and 23rd December 2011), and the three major shaking events located near the Cook Strait and lower North Island, referred to here as the three Wellington shaking events (21st July 2013, 16th August 2013, and 20th January 2014).

Table 3: Major earthquake event information

Date	Primary Location	Magnitude (M_W)	Depth	Maximum Intensity
4th September 2010	Darfield	7.0	12 km	MM 9
22nd February 2011	Christchurch	6.1	5 km	MM 9
13th June 2011	Christchurch	5.9	6 km	MM 8
23rd December 2011	Christchurch	5.9	7 km	MM 7
21st July 2013	Cook Strait	6.5	17 km	MM 8
16th August 2013	Lake Grassmere	6.5	8 km	MM 7
20th January 2014	Eketahuna	6.1	28 km	MM 7

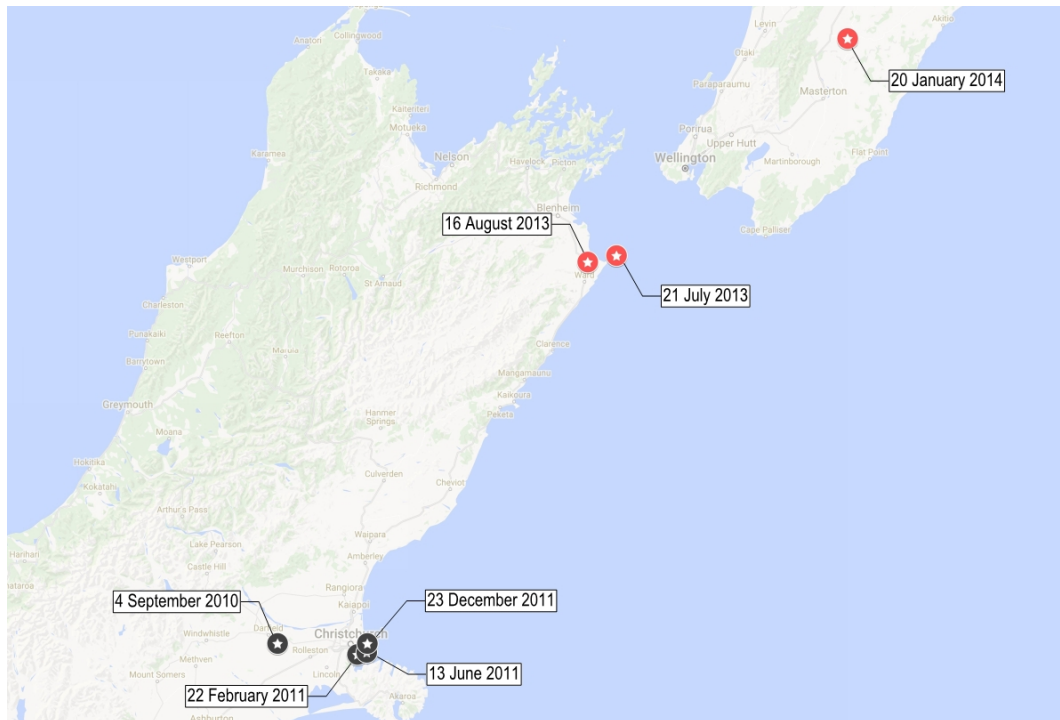Note: M_W = Moment Magnitude, MM = Modified Mercalli

Figure 2: Location of major earthquake events

2.4 Earthquake Injury Data

The data collected by the "Researching the Health Implications of Seismic Events" group (RHISE) has been processed to quantify both the cause and severity of injuries attributable to non-structural elements. This data was collected from three main sources: Accident Compensation Corporation's (ACC) injury claims, district health board information and RHISE surveys. The survey data contains much greater detail than the ACC data but the survey only had a 10% response rate.

A rigorous approval process was undertaken which involved RHISE and the Health and Disability Ethics Committee (HDEC) to ensure confidentially of the data. Part of this process involved RHISE removing identifiable information, such as names of the victims and coronial data, from the extracted dataset. To further prevent the potential for individuals to be identified from this research, any injury totals equal to one were assigned as being two injuries. RHISE also applied filters at our request to remove data that was outside the scope of this research. These filters removed injuries which occurred in residential or farm buildings; and/or were obviously not caused by building or non-structural element damage, such as motor accidents, animal attacks, or during clean-up.

The cause of each injury was evaluated using the ACC injury descriptions and the RHISE survey results, where available. If the cause of injury was not consistent in the two sources of data, judgement was used to categorise the injury.

2.4.1 Total Injuries

A total of 1,048 injuries were directly attributable to earthquake building damage, according to the earthquake events as shown in Figure 3 below. The injuries have been either attributed to the seven major earthquake events defined in the previous section, or to the time period between these major events. The time periods between major events include numerous aftershocks since no single aftershock event caused a significant number of injuries.
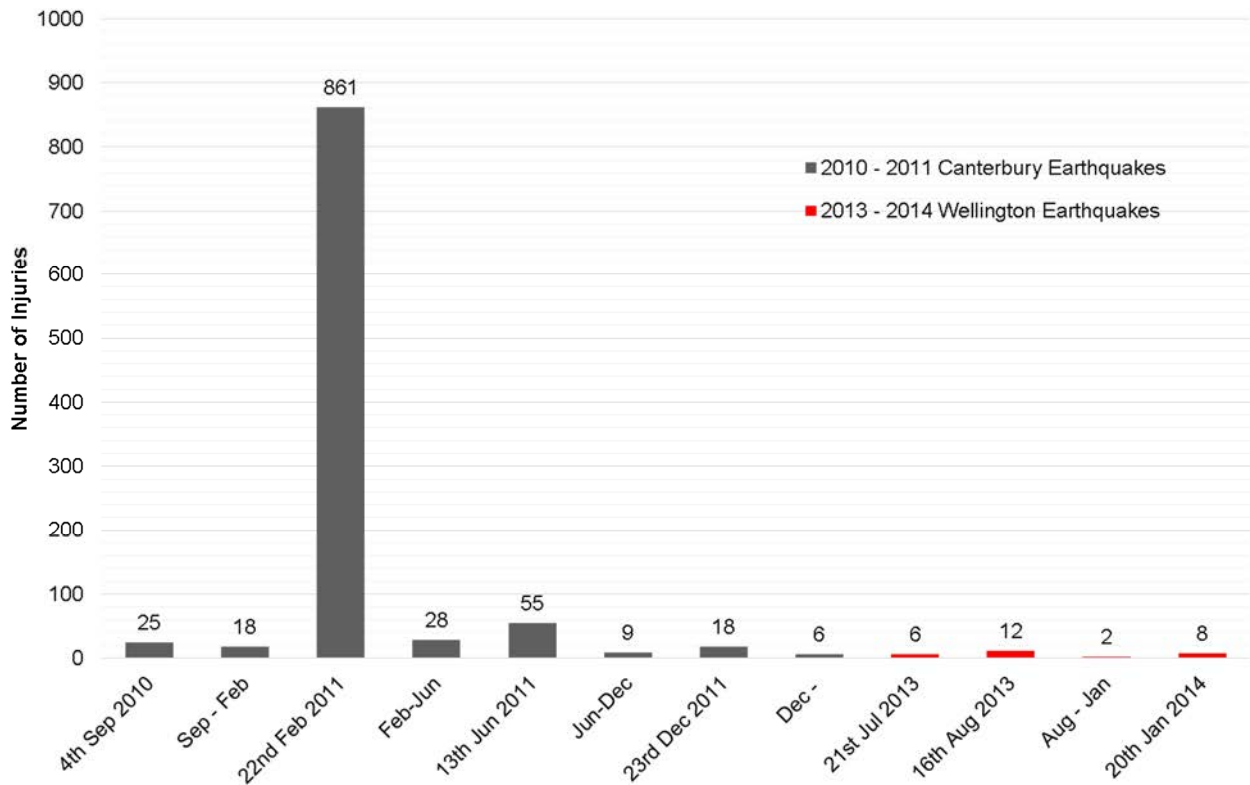
Figure 3: Total number of injuries for each earthquake event

The earthquake on 22nd February 2011 generated by far the most number of injuries. Overall injury statistics subsequently presented in this report are consequently distorted by this single earthquake event. The number of injuries in the 4th September 2010 earthquake was comparatively low for the magnitude of this earthquake. This is likely due to the earthquake occurring at 4:35am, when it would be expected that the majority of commercial buildings are unoccupied.

2.4.2 Injury Cause

A breakdown of the cause of injury between the following categories: non-structural, structural, masonry and unknown, for the total 1048 identified injuries in the RHISE database for the earthquake events from 4 September 2010 is shown in Figure 4. Non-structural damage is the main contributor to earthquake injury, being the cause of 61% of all injuries.

The contribution of structural and masonry damage to injuries was most noticeable in the 22nd February 2011 earthquake, with a significant number of injuries being attributed to the two reinforced concrete building collapses and the numerous unreinforced masonry failures (CERC, 2012a). This may have also been attributed to the instatement of the Central City Red Zone cordon which was a public exclusion zone established in the Christchurch CBD following the 22 February 2011 earthquake.
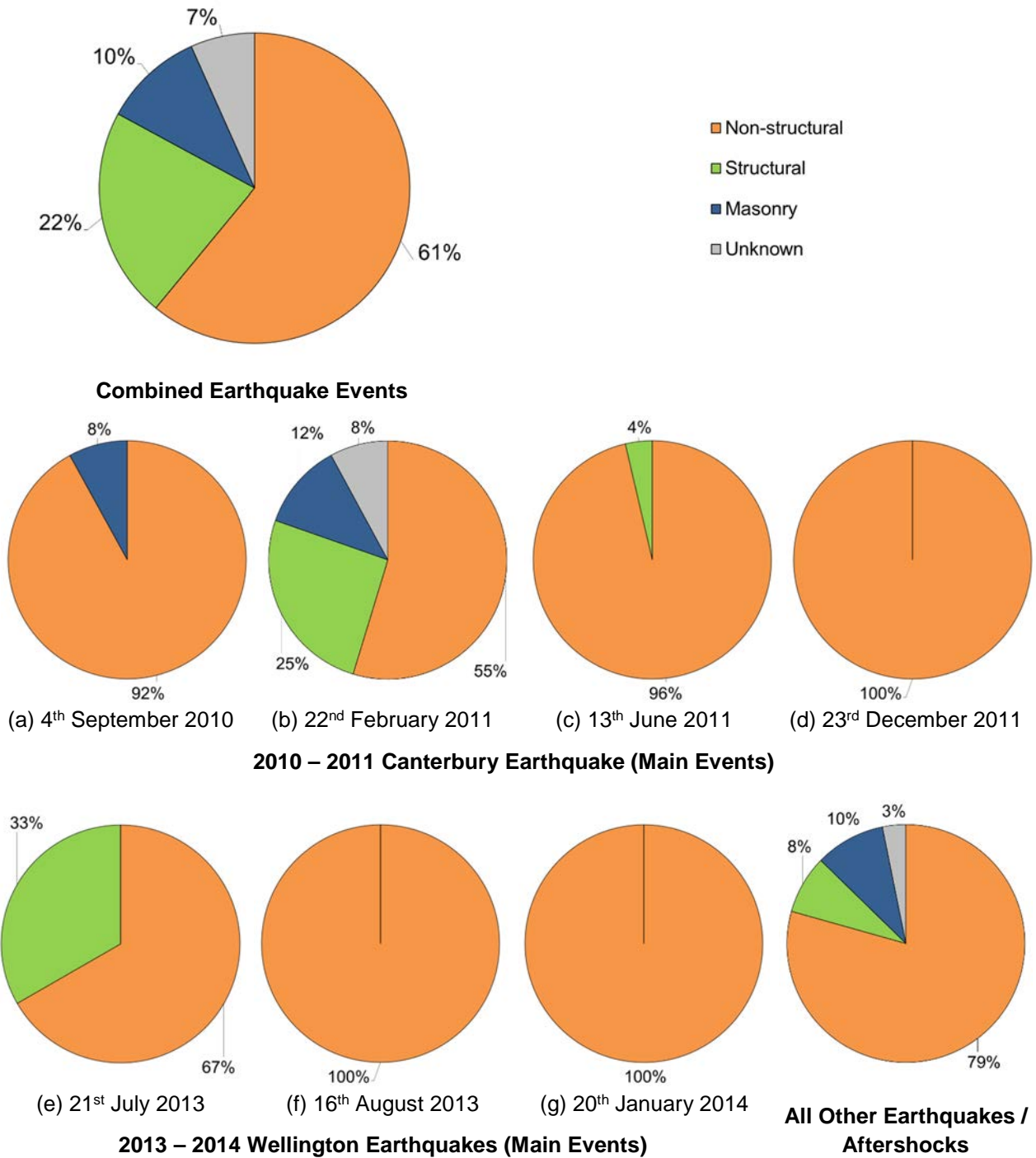
Combined Earthquake Events

(a) 4th September 2010   (b) 22nd February 2011   (c) 13th June 2011   (d) 23rd December 2011

2010 – 2011 Canterbury Earthquake (Main Events)

(e) 21st July 2013   (f) 16th August 2013   (g) 20th January 2014   **All Other Earthquakes / Aftershocks**

2013 – 2014 Wellington Earthquakes (Main Events)

Figure 4: Cause of injuries by building component

An injury categorised as 'Unknown' was deemed to be the direct result of damage to a building (as opposed to an indirect injury), however, categorising the component of the building that caused the injury was not possible due to lack of information. Cases where the injury cause was unidentifiable were excluded. The total number of injuries can therefore be considered to be a lower bound estimate, since it is likely more injuries were attributable to direct building damage, but the description was insufficient to conclude this with certainty.

The sequence of earthquake events appears to have a strong influence on the type of injuries. For example, no injuries were attributed to masonry damage for earthquakes that occurred following the 22nd February

2011 earthquake. We surmise this is because the masonry vulnerable to falling and causing injury had fallen in the 22nd February 2011 earthquake (or earlier 4 September 2010 earthquake) and was therefore no longer a falling risk.

A breakdown of the cause of injury by non-structural elements for the earthquake events from 4 September 2010 is shown in Figure 5.

Combined Earthquake Events

(a) 4th September 2010   (b) 22nd February 2011   (c) 13th June 2011   (d) 23rd December 2011

2010 – 2011 Canterbury Earthquake (Main Events)

(e) 21st July 2013   (f) 16th August 2013   (g) 20th January 2014   **All Other Earthquakes / Aftershocks**

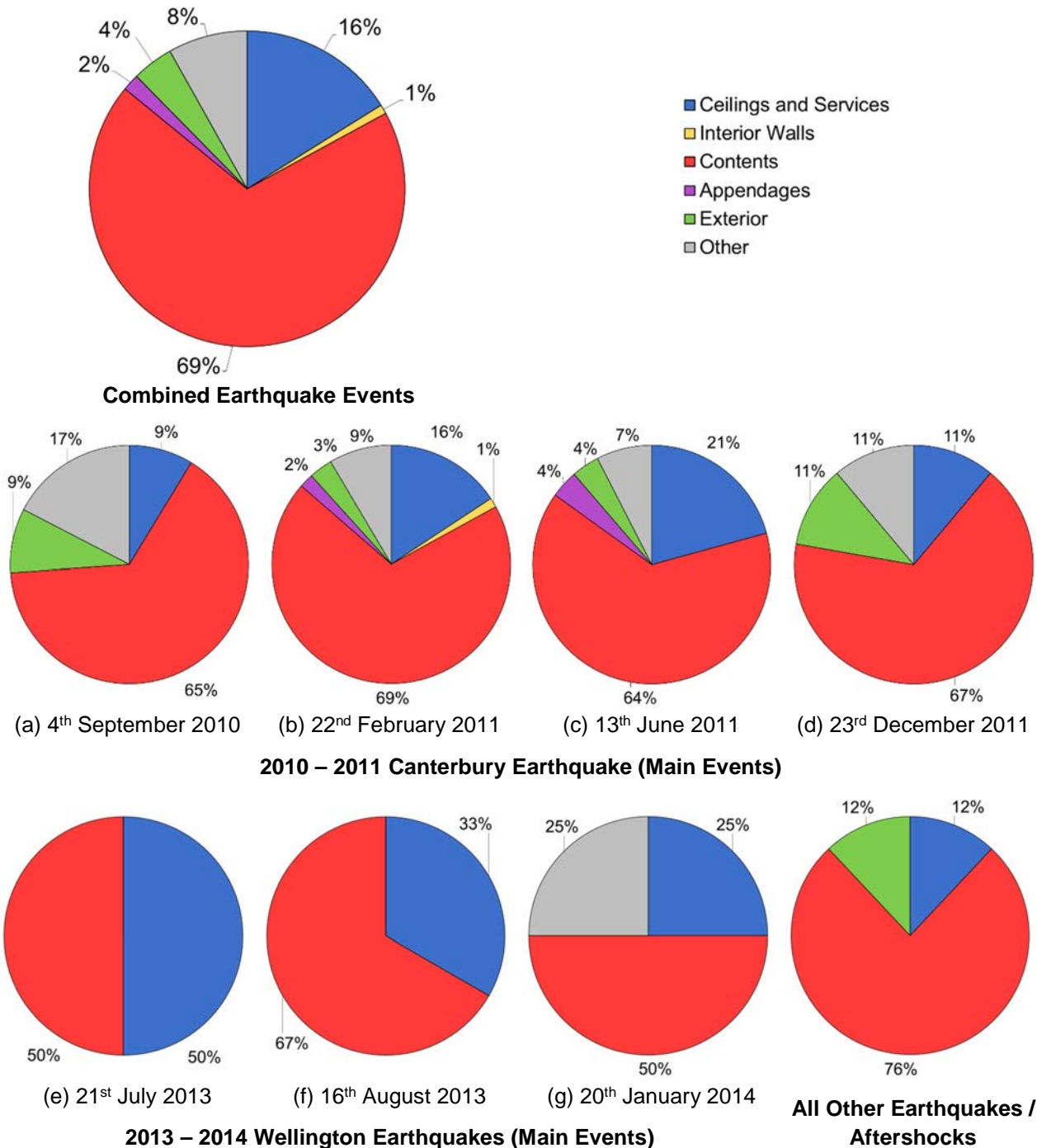**2013 – 2014 Wellington Earthquakes (Main Events)**

Figure 5: Cause of non-structural element related injuries

Contents related injuries were the dominant cause of injuries, making up 69% of all non-structural injuries (or 42% of all building related injuries overall). The proportions of injuries between the different non-structural categories was relatively consistent for all earthquake events, with contents always being the dominant

contributor. Ceilings and services were the second largest injury contributor. Appendages, exterior elements and other non-structural elements made a minor contribution to total injuries. Interior walls caused very few injuries, as damage to these elements rarely resulted in fall-out of the interior wall, hence not posing a significant injury hazard.

The breakdown of types of non-structural elements causing injury and the proportion of non-structural elements causing injury in the sequence of earthquakes studies suggests that injuries suffered in an earthquake event are dependent both on the position (and characteristics) of the earthquake within the earthquake sequence and whether the type of component is relatively easily and quickly repaired or not including of whether the building is in an area where access can be gained for repairs to be carried out. The data suggests structural and masonry building components are unlikely to be quickly repaired and therefore are not likely to injure someone in a subsequent earthquake in the sequence while non-structural elements including building contents may be relatively quickly repaired and thus capable of causing injury in further earthquakes in a sequence of earthquakes.

2.4.3   Injury Severity

The severity of an injury is subjective and can be quantified in several different ways. This research defines the measure of injury severity using the level of treatment received as per the following treatment categories:

- received treatment (outside hospital)
- attended emergency department (ED)
- hospitalised
- fatal

The severity of injuries due to damage from all building components (structural and non-structural) for all earthquake events considered is shown below in Figure 6. As would be expected, the majority of injuries were more minor in nature, with injuries receiving treatment outside of hospital contributing to 73% of injuries within the research scope. Since self-reported injuries (i.e. people who were injured but did not seek any form of treatment) are not represented in the data, it is likely that minor injuries are under reported. Fatal injuries comprise the second highest number of injuries, totalling 173. This can be attributed to the deaths that resulted from the two building collapses and the numerous unreinforced masonry failures the 22nd February 2011 earthquake.

The previous section demonstrated that non-structural elements caused the greatest number of injuries, however Figure 6 reveals that 90% of these non-structural injuries were at the lowest injury severity level. There were also no fatalities from damage to non-structural elements in commercial buildings, though there were recorded fatalities which occurred in residential buildings and from the failure of secondary structural elements (CERC, 2012b). The majority of injuries requiring ED treatment, or hospitalisation were also due to non-structural damage, which highlights the large proportion of overall injuries due to non-structural damage causes, as shown earlier in Figure 4.

Combined Injury Severity Breakdown

(a) Non-structural (b) Structural (c) Masonry (d) Other

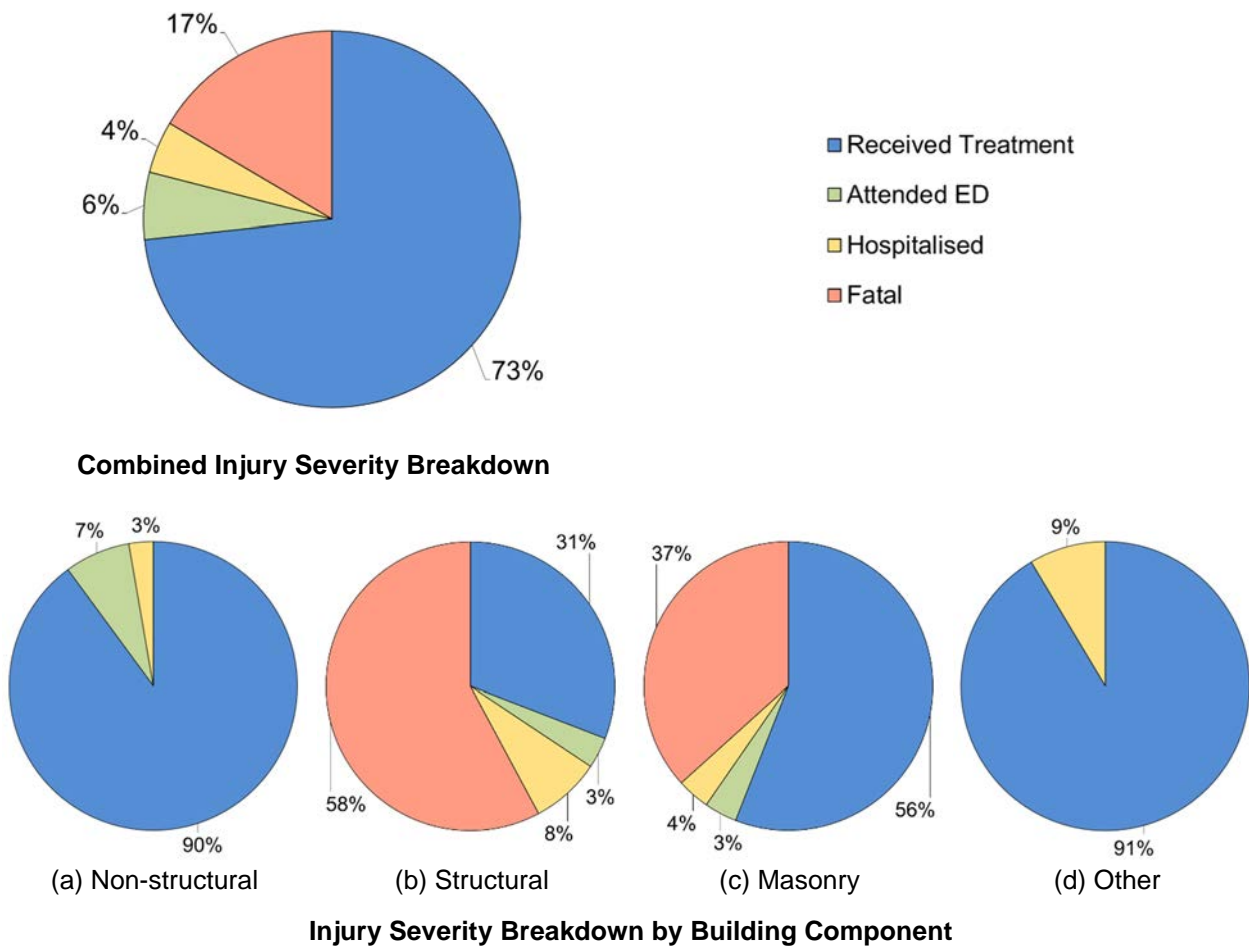**Injury Severity Breakdown by Building Component**

Figure 6: Breakdown of injury severity by building component

It is shown in Figure 6b that the majority (58%) of structural building component related injuries were fatal. All of the fatalities resulting from structural damage were a result of the two building collapses that occurred on the 22nd February 2011. Of the non-fatal injuries caused by structural damage, many of these injuries could also be attributed to the collapse of these two buildings. This emphasises the critical role that structural collapse prevention plays in life-safety protection. A large proportion of masonry related injuries also resulted in fatalities, demonstrating that this also poses a significant life-safety hazard.

The proportion of injury severity can be further broken down by non-structural element type, as presented in Figure 7. The proportions are generally similar for each type, and since contents are the dominant injury cause, the breakdown of content injuries is nearly identical to that of the combined non-structural injury breakdown.

It can be seen in Figure 7 that exterior elements caused the greatest proportion of injuries that required emergency department treatment, or admission to hospital. Such injuries are likely attributable to glass falling from height, which was widely reported following the Canterbury earthquakes (Baird et al., 2011).

Appendages also caused several injuries requiring emergency department treatment, which is likely related to being heavy non-structural elements falling from height similarly to exterior elements. Injuries attributed to interior walls were rare, and also only ever minor in severity. Such elements evidently do not present a significant issue from a life-safety viewpoint based on the research data.

Combined Non-structural Injury Breakdown

Legend:
- ■ Received Treatment
- ■ Attended ED
- ■ Hospitalised
- ■ Fatal

(a) Ceilings and Services
(b) Interior Walls
(c) Contents
(d) Appendages
(e) Exterior
(f) Other NSE

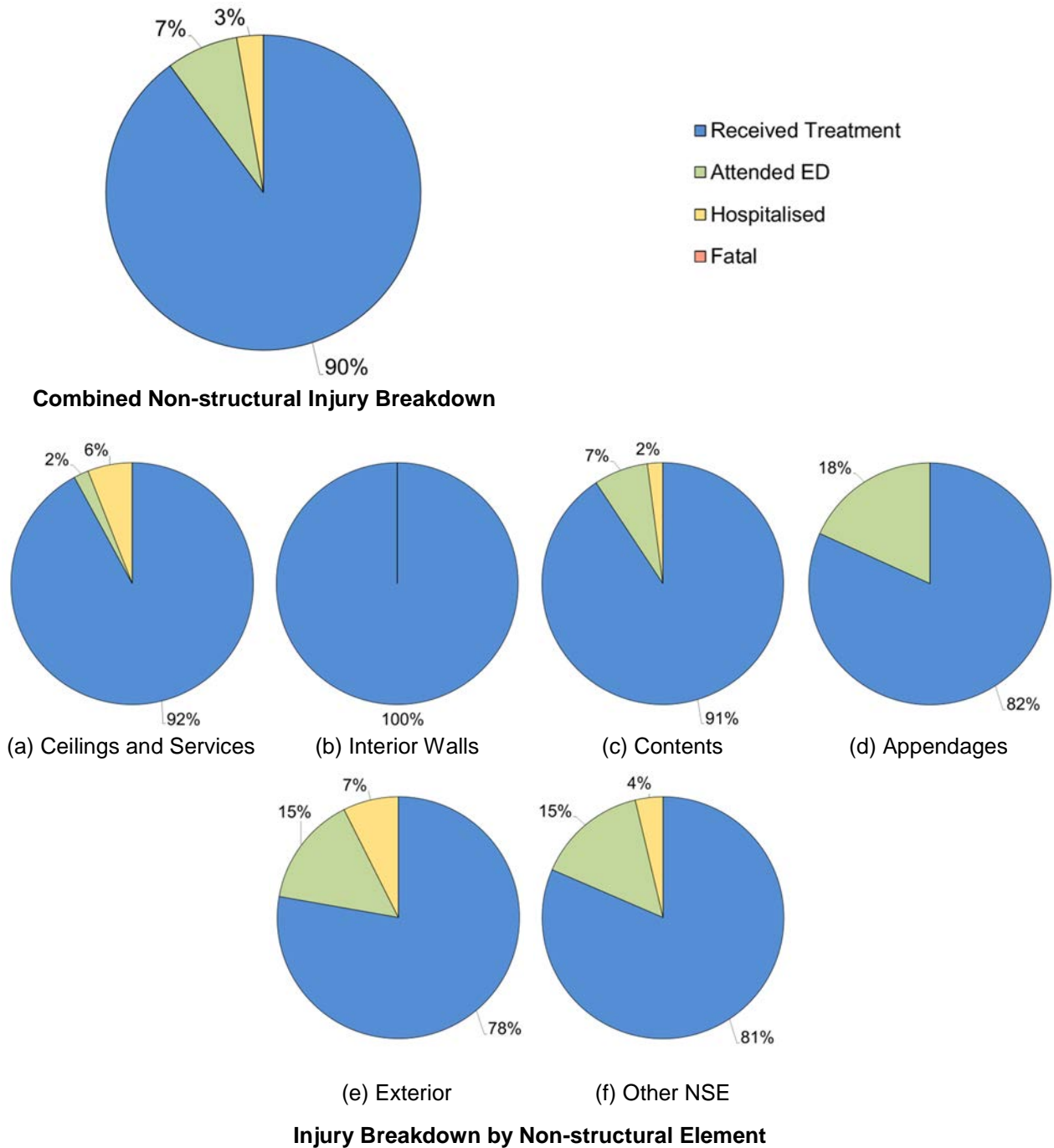**Injury Breakdown by Non-structural Element**

Figure 7: Injury Breakdown by Non-structural Element Type

Ceilings/services injuries and contents injuries had a similar proportion of injuries that required emergency department treatment or hospitalisation. However, contents had a greater number of injuries overall, so the number of contents related injuries requiring treatment is greater. Based on the data we can conclude that if an occupant of a commercial building in New Zealand is injured in an earthquake, the most likely cause of the injury is building contents, however, the severity of the injury is most likely to be minor.

3 Relating Earthquake Shaking to Injuries from Non-structural Elements.

This section describes the approach taken to relate earthquake shaking with the injury data quantified in the previous section of this report. This relationship requires two additional inputs to supplement the injury data: (i) estimation of the size of population exposed to ground shaking to derive injury rates, and (ii) earthquake shaking intensity information. This has been undertaken focusing solely on the 2010-2011 Canterbury earthquakes due to significantly more injury data and ground shaking data being available for these earthquakes, compared to the other earthquake events included in the previous section.

3.1 Injury Model Background

There are two main types of models which exist for modelling injuries; mechanics-based and event-tree approach. Mechanics based models generally consider the non-structural elements contained within a room, the interior room layout, the position of occupants within the building, and predict the sequence of events which may lead to injuries within the room. Examples of mechanics-based approaches include Yeo and Cornell (2003), Okada et al. (2012), and Yeow et al. (2013). Such models clearly require a wealth of information not easily obtainable; including occupant behaviour, room layouts, and detailed behaviour of non-structural elements. As such, this approach is too complex for use in regional-scale injury modelling in its current form.

The most commonly used event-tree approach is shown in Figure 8; where (i) the population present within each building type are estimated, (ii) the global damage level for each building type is predicted, and (iii) injury rates are assigned for each damage level. Examples of models which follows this approach include the Cambridge University Casualty Model (Coburn et al., 1992), HAZUS® (FEMA, 2015), and Mitrani-Reiser (Mitrani-Reiser, 2007). While this approach may be adapted to consider non-structural element failure rather than the building's damage level, no studies exists linking non-structural element failure to injury severity.
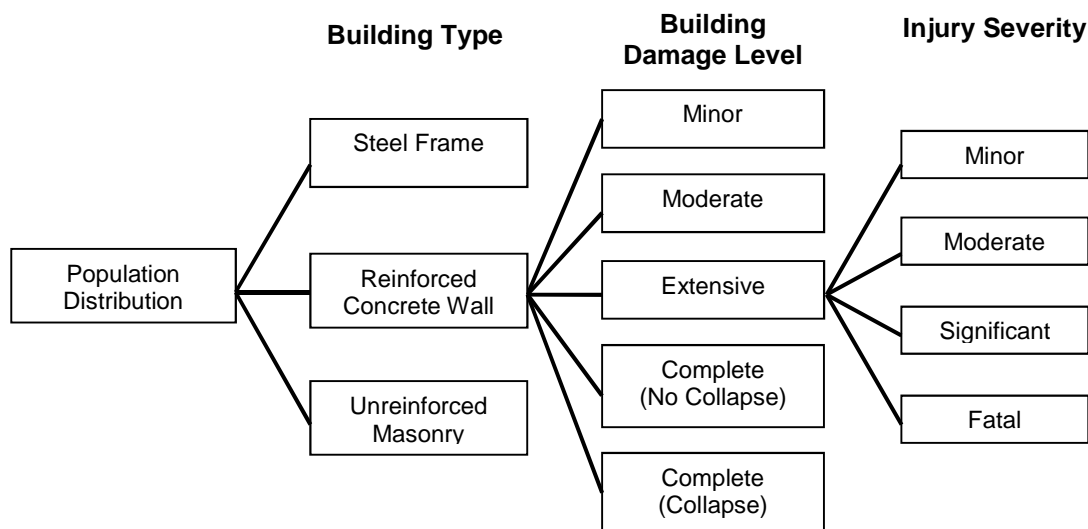

Figure 8. Event tree model for indoor casualty prediction HAZUS® (FEMA, 2015)

An alternate approach to considering damage to the building or non-structural elements is to use the intensity of shaking instead. Examples of this includes Nichols and Beavers (2003) considering earthquake magnitude, and Jaiswal and Wald (2010) considering Modified Mercalli Intensity (MMI) (Wald et al., 1999). A limitation of the former is that a large number of other factors can influence the shaking severity at a given

site, such as (i) source-to-site distance, (ii) rupture depth, and (iii) soil class, among others. MMI on the other hand is a direct measure of the effect of site-specific shaking intensity. The number of injuries caused by non-structural element failure from existing data can then be correlated against MMI to assess its significance. This allows for such failure to be implicitly considered without incorporating the uncertainty and unknowns of (i) predicting the percentage of non-structural elements which failed, and (ii) estimating the severity of injury for a given element failure.

3.2 Injury Rate Derivation

In its simplest term, the earthquake injury rate can be defined by the number of injuries normalised by the population exposed to earthquake shaking. The following methodology was used to establish the relationship for linking injury rates caused by non-structural earthquake damage to shaking intensity:

1. Extract injury data from RHISE database for different types of non-structural elements

2. Use existing data to estimate ground shaking intensity (i.e. Modified Mercalli Intensity)

3. Estimate the number of people exposed to level of shaking intensity

4. Combine injury data with population exposure

The first step has been covered in the previous section of this report. A detailed description of steps two and three, as well as a full description of assumptions used, is provided in Appendix A. The outcome of step four is the relationship between injury rate and ground shaking, called the injury model, and is described in the following section.

3.3 Non-structural Injury Models

The non-structural injury model represents the relationship between the ground shaking intensity with the injury rate. It consists of a data point that relates these two variables for each earthquake event considered, as shown in Figure 9. The injury model presented in Figure 9 considers injuries from all non-structural elements. The relationship shows that the injury rate increases with ground shaking intensity which is reasonable. The injury rate varied between 0.1 and 4.9 injuries attributable to non-structural damage per 1,000 people, depending on the intensity of ground shaking.
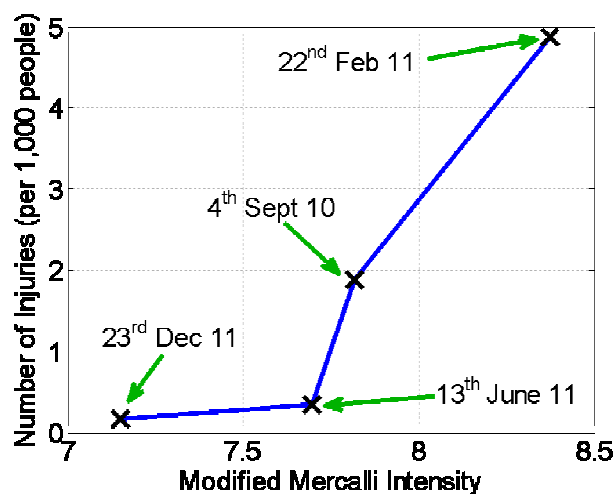

Figure 9: Non-structural element injury rate versus ground shaking

The two lowest injury rates were the last two significant events of the four Canterbury earthquake sequence events considered. It is likely that these injury rates may have been higher had they had not followed larger

previous earthquake events which we surmise would have damaged the most vulnerable non-structural elements and which may not have been repaired by the time these later significant events in the Canterbury earthquake sequence occurred.

This injury model can be used as a tool for estimating the number of injuries in other earthquakes. However, the model is implicitly Christchurch specific, meaning that the factors linking MMI to injury severity, such as soil type, building typology, non-structural element types, building populations, etc., are representative of Christchurch in the years 2010-2011. Any further application therefore assumes that these 'filters' are an appropriate representation of the place that they wish to estimate injuries for. That's not to say that such a model is unusable, as it will likely provide a better estimate of possible injury numbers compared to equivalent models developed outside of New Zealand, which have been passed through their own local filter. Further data will help in improving the validity of the model and widen its application.

The injury rate can also be broken down to show the individual contribution of each non-structural element type considered, as shown in Figure 10. As would be expected, contents injuries are the main contributor to the overall non-structural injury rate. The contribution of each non-structural component to the overall injury rate appears to be relatively consistent for different levels of ground shaking. It appears that interior wall and appendage injuries only register under large shaking.
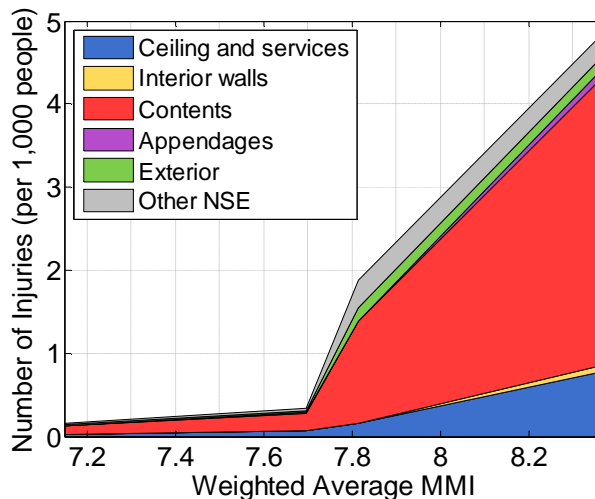

Figure 10: Breakdown of non-structural element injury rate versus ground shaking

4   Conclusions

This research focussed on quantifying the number of injuries due to damage of non-structural elements in commercial buildings in recent New Zealand earthquakes. The research was based on injury information from earthquakes collected by the RHISE Group from 4th September 2010 onwards. The key findings from this research are as follows:

- Non-structural damage contribute to 61% of all commercial building related earthquake injuries
- The contribution of non-structural damage to all commercial building related earthquake injuries can be as high as 96-100% in smaller aftershocks
- Contents related injuries contribute to 42% of all commercial building related earthquake injuries
- Damage to internal walls, appendages and exterior non-structural elements only contributed to 7% of overall earthquake injuries
- 90% of non-structural injuries were at the lowest injury severity level considered (received treatment)
- 58% of structural injuries, and 37% of masonry injuries were fatal
- 82% of all building related earthquake injuries occurring since 4th September 2010 were a result of the 22nd February 2011 earthquake.

The injury data obtained from the RHISE database was also used to propose a relationship between the number of injuries and the ground shaking intensity in the 2010-2011 Canterbury earthquakes. This relationship found that the rate of injury due to non-structural elements in a commercial building can be up to 4.9 per 1,000 people, depending on the intensity of ground shaking. Although somewhat limited in its further application, the injury model developed can still give a rough indication of possible injury numbers. Data from future events will help to validate the usefulness of the injury model as a rapid assessment tool or information on the state of non-structural elements for life-safety.

5   Acknowledgements

We are very grateful to the following RHISE Group members for their willingness to allow the data they have collected to be used as the basis of this research:

Joanne Deely
Finn Sigglekow
Kenny Daly
Michael Ardagh

As part of this research project, an expert panel was assembled to scrutinize the available injury data, apply engineering judgement where data was limited or missing, and to discuss the approach of relating injuries to ground shaking. The workshop was held on the 26th of August 2016 and we wish to acknowledge the following participants of the workshop for their valuable feedback on the findings of this research:

Nick Locke (MBIE)
David McGuigan (MBIE)
Bill Holmes (Rutherford and Chekene)
SR Uma (GNS)
Andrew King (GNS)
Rob Jury (Beca)
Matthew Lander (Beca)

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Appendix A   Adjusted Population Derivation

A.1 Ground Shaking Intensity

The Modified Mercalli Intensity parameter, MMI, was selected as the qualitative shaking intensity measure for this research. This is because MMI is a better descriptor of the effect of ground motion on the population. While there are attenuation relationships available for estimating the distribution of MMI across Christchurch City, these are either not representative of New Zealand, or are not readily available for usage. Instead, MMI was estimated using shaking intensities that are more descriptive of the ground's response; namely peak ground acceleration, PGA, and peak ground velocity, PGV. This was done following Wald et al. (1999) as shown in the following equations:

$$MMI = 3.66 \log(PGA) - 1.66 \qquad \textbf{(1)}$$

$$MMI = 3.47 \log(PGV) + 2.35 \qquad \textbf{(2)}$$

PGA and PGV spatial distribution data across Christchurch City by Bradley (2014) was used to estimate the shaking intensity for each of the four major events. A contour map showing the PGA across Canterbury based on these studies is shown in Figure 11. Since the majority of commercial buildings are located within the four main avenues of Christchurch (Deans, Bealey, Fitzgerald, and Moorhouse), the average PGA and PGV within this region is taken as the representative shaking intensity of the respective events. Two values of MMI was then calculated for each event; one using PGA and the other using PGV. The larger MMI of the two was used as the representative shaking intensity value of each respective shaking event.
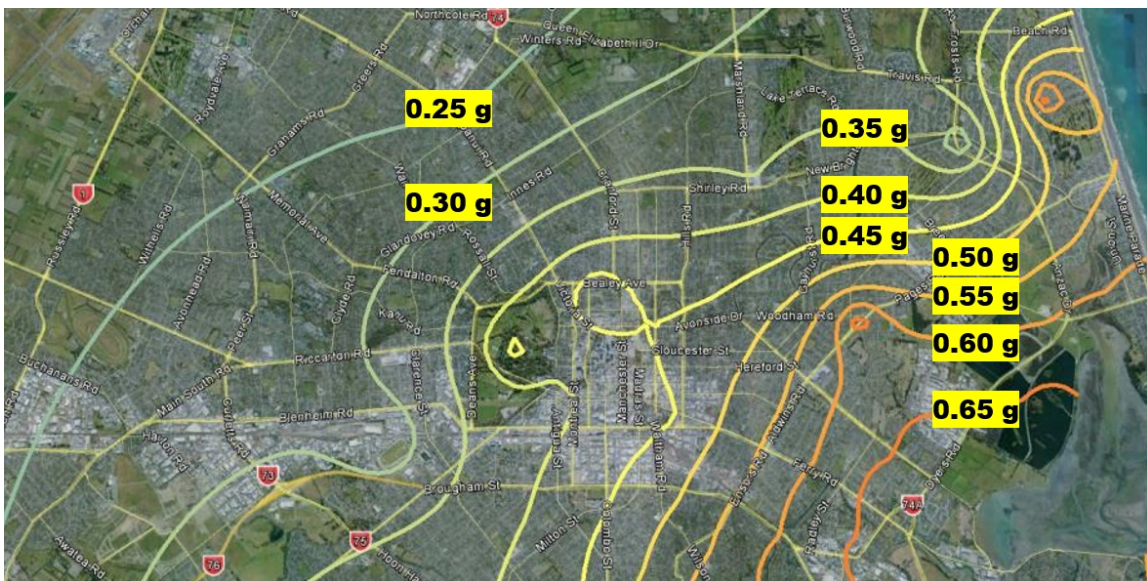

Figure 11: Median PGA contour map from 22nd February 2011 Canterbury earthquake event

A.2 Population Exposure

There is significant uncertainty around quantifying the actual population numbers exposed to earthquake shaking. The method used here utilises working population data obtained from New Zealand census data which is subsequently modified to provide the best estimate of population exposed to the earthquake event in commercial buildings within Christchurch, called the adjusted population. Since the focus of this research is on injuries within commercial buildings, the population exposed to shaking used in deriving injury rates are based on working population data within Christchurch City.

The modifications made to the working population data were based upon addressing the following limitations identified in the data:

- Data is only collected every four years during the national census;
- Data excludes non-workers, e.g. visitors, shoppers, children;
- Data does not differentiate between indoor and outdoor workplaces;
- Data does not include information about the time-of-day a worker is at workplace;
- Data does not differentiate between the occupational type of workplace (commercial building versus working from home).

The adjusted population, P_{adj}, is expressed as follows:

$$P_{adj} = F_1.F_2.F_3.P_{working} \qquad \textbf{(3)}$$

where $P_{working}$ is the working population obtained from census data,
F_1 is the event factor,
F_2 is the work shift factor, and
F_3 is the time factor.

Based on the methodology discussed, the values estimated for F_1, F_2, F_3, and the $P_{working}$ data source implemented, are shown in Table 4. These can then be paired with Eq 3 to adjust the population numbers within each unit boundary.

Table 4. Modification factors for estimating exposed population numbers

Event	F_1	F_2	F_3	P_{adj} / $P_{working}$	$P_{working}$ source
4th Sept 2010	1.04	0.071	1.00	0.074	2006 census data
22nd Feb 2011	1.05	0.893	0.60	0.562	2006 census data
13th Jun 2011	1.02	0.893	1.00	0.911	2013 census data
23rd Dec 2011	1.01	0.893	0.72	0.649	2013 census data

Event Factor

One complication with estimating the working population during each event is that census data is only available for 2006 and 2013. However, estimates of the dwelling population on the 30th of June are available on an annual basis. Therefore, a key assumption made for estimating the event factor is that the working population is directly proportional to the dwelling population over time.

The annual dwelling population trend is shown in Figure 12. The following assumptions were made to determine F_1 for each of the four major events:

1. The 4th September 2010 event was not significant enough to result in major changes to the population trend, and as such the population numbers during this event and during 22nd February 2011 follows the nearly constant trend between 2006 and 2010.

2. There is a significant decrease in population numbers following 22nd February 2011.

3. The decrease in population numbers following this event up until 30th June 2012 is relatively constant.

Based on these assumptions, F_1 is estimated by dividing the estimated dwelling population at the time of each event by the dwelling population from either 2006 or 2013. Since many businesses during the 22nd of February 2011 event were forced to relocate, the working population distribution for events after the 22nd of

February 2011 is likely to be more consistent with the 2013 census data. In contrast, the working population distribution up until the 22nd of February 2011 event is likely to be more consistent with the 2006 census data. As such, the 2006 dwelling population was used to estimate F_1 for 4th September 2010 and 22nd February 2011 events, while the 2013 dwelling population was used for the other two events.
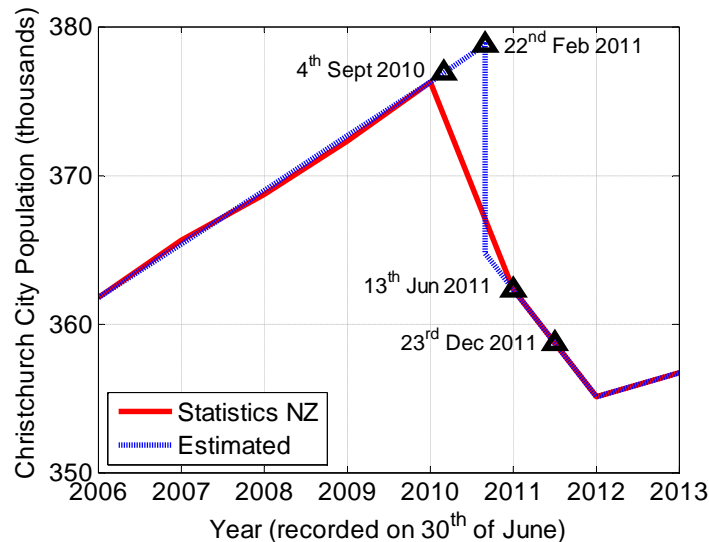

Figure 12. Dwelling population trends from 2006 to 2013 (Statistics New Zealand)

Working Population Characteristics

The working population data may underestimate the actual population exposed as it excludes (i) residential population who might be visiting commercial buildings during the day (i.e. supermarkets), and (ii) school-children population. In contrast, the data does not differentiate between indoor and outdoor population, which may have resulted in an overestimate of the population exposed since most risk from non-structural elements would be to indoor occupants. It is assumed here that both of these limitations mitigate each other, and that usage of the working population data is the best estimate that can be achieved.

One further complication is the type of work-shift which is more greatly affected during each event. For example, the 4th September 2010 event occurred early morning, where else the others occurred during working hours, and as such the population present within commercial buildings will be different. A survey done in 2008 by Statistics New Zealand showed that around 89.3% of employed people in New Zealand mainly working during daytime hours. As such, the working population during the events following 22nd February 2011 was multiplied by 0.893.

The same survey also showed that just 1.1% of employees worked night-shifts. However, this is likely to underestimate the exposed population as there will be a sizeable tourist population who might be in hotels which is also classified as a commercial building. In addition, a further 6.0% of the working population have flexible work shifts, some of whom may have also been working during the time of the earthquake. While part of this extra working population may have also been working during daylight hours in events following the 22nd of February as well, this would have relatively smaller effect due to the difference in daytime and night-time working population numbers. For simplicity, it will be assumed that the entire working population with flexible working shifts are present during the event, while the hotel guest population is ignored. As such, F_2 in this case is 0.07.

Time Factor

The 4th September 2010 events occurred in the early morning, while the 13th June 2011 event occurred during peak work hours. As such, these two events do not need further modifications to adjust for time.

The 22nd February 2011 event occurred at 12:55pm, which is near the end of lunch-break. Based on several studies on transient occupancy numbers (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2004; D'Oca & Hong, 2015; Duarte et al., 2013; Wong & Mui, 2011), the percentage of occupants present during lunch break ranges from 47% to 80%. The average from these studies however is around 60%, and as such F_3 is assumed to be 0.60 for this case.

The 23rd December 2011 event occurred close to Christmas, and as such the working population would be lower during this period. However, information on effect of holidays on population numbers is sparse. Nonetheless, Keith (1997) showed that the monthly average occupancy for December is about 72% of peak values, and as such, F_3 is assumed to be 0.72 for this case.

Other

A final modification was made to filter out unit boundaries with small working populations. This is because the density of commercial buildings is far lower for these unit boundaries, and as such the working population within these boundaries are far less likely to be exposed to hazards within commercial buildings compared to other boundaries. In this case, unit boundaries with a working population less than 250 are ignored. This value was selected as the largest working population observed in any unit boundary was 26,000, and thus commercial buildings are unlikely to have a noticeable presence in unit boundaries which have 100 times smaller working populations. This adjustment reduced population estimates by around 10%.