Which building components caused injuries in recent New Zealand earthquakes?

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ABSTRACT: In New Zealand in the last six years, a total of 1048 injuries were recorded as being directly attributable to earthquake damage of commercial buildings. 173 of these injuries were fatal. This paper investigates which building components caused these injuries and their relative severity. Understanding what contributes to building related earthquake injuries is essential for determining which building components require attention in order to reduce future earthquake induced injuries.

This investigation makes use of data collected by the "Researching Health Implications of Seismic Events" (RHISE) group's injury database sourced from Accident Compensation Corporation records, district health boards, and post-earthquake surveys. This database is one of the most detailed to have ever been collected worldwide, and allows insight into the cause of injuries and quantification of the severity of these injuries.

It was found that damage to non-structural elements was the cause of 61% of the 1048 recorded earthquake induced injuries with 90% of these being minor in nature. None were fatal. This contrasts with injuries related to structural building elements of which 58% were fatal. The two leading causes of non-structural element related injuries were from building contents and damage to ceiling and services which contributed to 69% and 16% of non-structural injuries, respectively.

This paper concludes by exploring the implications of these investigation findings in order to reduce the life safety risk from earthquakes.

1 INTRODUCTION

In New Zealand, approximately 480 recorded deaths have been attributed to earthquakes since the 1848 Marlborough event (McSaveney 2012). Mortality information is usually well documented following earthquakes. However, documenting non-fatal injuries is challenging as medical records created during emergencies often contain only very limited information (Petal 2004).

The 'Researching the Health Implications of Seismic Events' (RHISE) group of health researchers have collected data over the past six years across New Zealand from various sources to compile one of the most comprehensive earthquake induced injury databases in the world. This data covers the major seismic events in New Zealand in recent years starting with the Canterbury earthquake sequence. This data was collected from three main sources: (i) claims to the Accident Compensation Corporation (ACC), (ii) district health boards, and (iii) follow-up surveys.

This paper presents research commissioned by the Ministry of Business, Innovation, and Employment (MBIE) which used the RHISE database to examine the cause and severity of earthquake injuries caused by damage to commercial buildings in New Zealand. Injuries not directly caused by building damage (e.g. loss of balance and falling over) or which occurred in other building types (e.g. residential buildings) were outside the scope of this research. Categories of building components which caused more injuries were highlighted to identify areas of focus to reduce injuries in future earthquake events.

Figure 1: Non-structural damage following the 22nd February 2011 Christchurch earthquake

2 HISTORICAL EARTHQUAKE INJURIES

Only a small number of studies have detailed the causes of injuries from past seismic events. One study by Peek-Asa et al. (1998) investigated the cause of fatal and hospitalized injuries within the Los Angeles County following the 1994 Northridge event. They found that all 22 building damage-related deaths were due to occupants being struck by building parts; though no distinction was made between structural and non-structural elements. Movement of building contents, such as furniture, resulted in zero fatalities, but caused 21 hospitalizations compared to just 11 from other building components.

Telephone 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). Note, however, these findings were based on small sample sizes (149 sampled injuries from the 1994 Northridge event compared to 24,800 estimated non-self-treated injuries (Allen et al. 2009)) and may not be an accurate representation of all injuries.

A similar study conducted by Petal (2004) following the 1999 Izmit earthquake in Turkey found that 68% of non-fatal injuries and 26% of deaths were caused by non-structural elements. The injuries related to non-structural elements were identified as 70% being due to contents, 20% due to ceiling damage with the remainder caused by interior partitions, windows, doors and roofs. This study had similar limitations to Shoaf et al. (1998) as the findings were based on a small sample size (345 responses out of an estimated 61,100 total injuries (Allen et al. 2009)).

3 METHODOLOGY

3.1 Injury data

The first part of this research involved accessing the RHISE injury data. Due to the confidential nature of health data and the risk of breaching privacy, a rigorous approval process was undertaken which involved RHISE and the Health and Disability Ethics Committee. Protocols were agreed for the project which included addressing network security matters and providing specific authorisations for those accessing the extracted data. As part of this process, RHISE removed all identifiable data fields from the extracted data, such as victim’s name and all coronial data. Fatality information was sourced separately from the published Royal Commission Reports (Cooper et al. 2012a, 2012b, 2012c). 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 outside the scope of this research; such as injuries not caused by damage to commercial buildings. The cause of each injury was evaluated using the ACC injury descriptions (described in the following section) and the RHISE survey results. If the cause of the injury was not consistent in the two sources of data, judgement was used to categorise the injury.

3.2 **Injury cause**

Definitions of what is considered a non-structural element varies somewhat between different countries and research projects. The descriptions within the RHISE database naturally influenced the definition of non-structural elements and the categorisations within the non-structural element grouping. For the purposes of this research, non-structural elements have been considered as parts of a building that are not part of the main structural gravity and seismic load resisting system and are not engineered secondary structural elements such as stairs and precast panels.

Building components were identified in the categories as listed in Table 1. Masonry (e.g. brick) was purposefully separated into its own category due to the RHISE database not being detailed enough to differentiate between structural (e.g. brick load-bearing walls) and non-structural (e.g. brick parapets) masonry elements. The RHISE data also did not identify whether injuries from falling elements were the result of a particular service falling onto or through the ceiling, or a result of failure of the ceiling itself. The unknown category was used for any injuries deemed to be directly caused by building damage, but where the information in the RHISE database lacked sufficient detail to assign it to one of the other categories.

Table 1: Categorization of building components

Building Component Category		Examples
Non-structural elements	Ceilings and Services	• Suspended ceilings and tiles • HVAC equipment and ducting
	Interior Walls	• Internal partitions
	Contents	• Furniture • Shelving
	Appendages	• Signage • Ornamentation
	Exterior	• Cladding systems • Exterior glazing
	Other	• Plant • Roof tiles
Structural elements		• Beams • Columns
Masonry		• Bricks • Infill walls
Unknown		• Debris • Rubble

3.3 **Injury severity classification**

The severity of an injury is subjective and can be quantified in several different ways. This research defined injury severity according to the level of treatment received. The categories were: (i) received treatment (outside hospital); (ii) attended the emergency department (ED); (iii) admitted to hospital; and (iv) fatal. This approach avoided the need to access detailed health records which contained confidential information and posed a possible privacy breach risk, a significant issue when working with health related data. 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 were under reported.

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.

4 RESULTS

4.1 Injuries by seismic event

The New Zealand events covered by the RHISE database are listed in Table 2. A total of 1048 commercial building damage-related injuries were directly attributable to these seven major events, or the aftershock periods between these major events. The time periods between major events include numerous aftershocks since no single aftershock caused a significant number of injuries. Note, this study was conducted prior to the 2016 Kaikoura earthquakes.

Table 2: Major earthquake event information

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

The earthquake on 22nd February 2011 generated by far the most number of injuries as shown in Figure 2. Consequently the injury statistics presented in this paper will be distorted by this single event. The number of injuries in the 4th September 2010 earthquake was comparatively low despite the magnitude of the earthquake. This is likely due to the earthquake occurring at 4:35am, when the majority of commercial buildings were unoccupied.

The low number of injuries in the subsequent Canterbury events may be attributed to: (i) the Red Zone cordon, a public exclusion zone established in the Christchurch CBD following the 22nd February 2011 earthquake; and (ii) buildings vulnerable to causing injury may have been damaged in the 4th September 2010 or 22nd February 2011 events, or may have been otherwise cordoned off so they were not occupied during subsequent events.

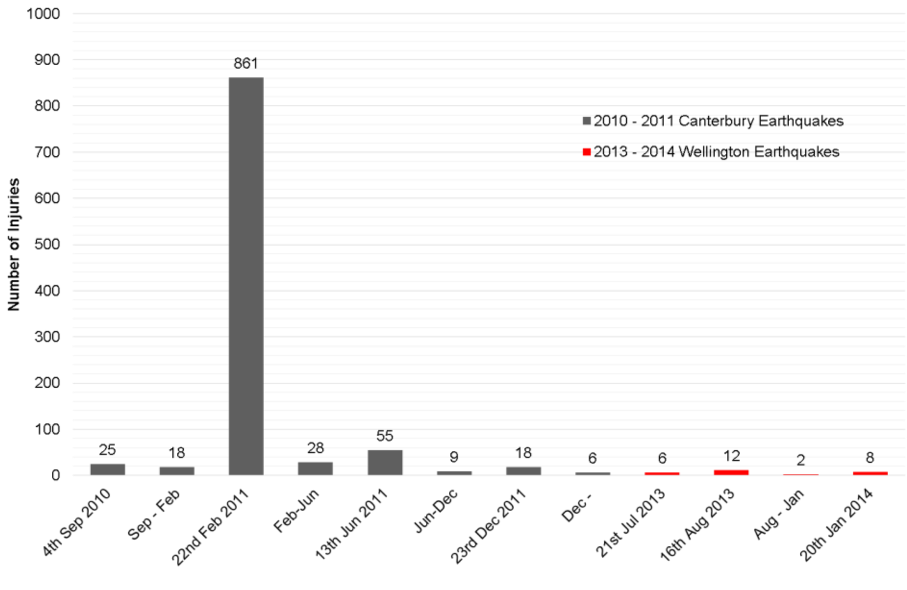


Figure 2: Total number of injuries for each earthquake event

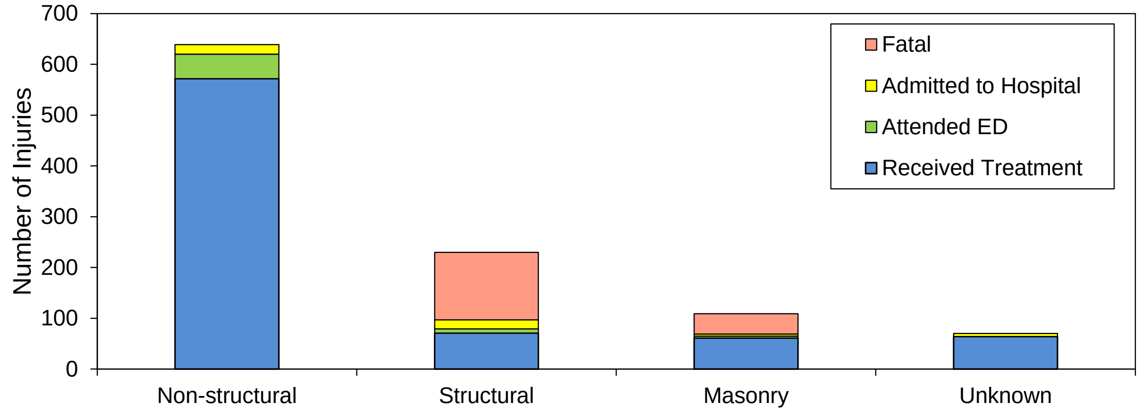
4.2 Injuries by building component

A breakdown of the cause and severity of injuries between the different building component categories: non-structural, structural, masonry, and unknown is shown in Figure 3.

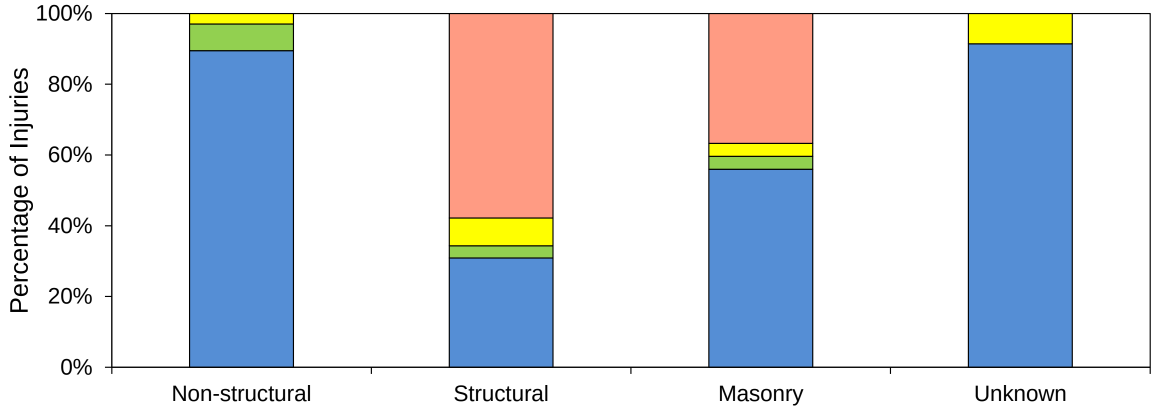
Non-structural damage was identified as the cause of 61% of injuries overall. 90% of these non-structural injuries were at the lowest injury severity level. The majority of injuries requiring ED treatment, or hospitalisation were also due to non-structural damage, highlighting the large proportion of non-fatal injuries caused by non-structural element damage.

There were 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 (Cooper et al. 2012b). In contrast, structural and masonry damage caused 133 and 40 fatalities, respectively. All structural damage related fatalities, and a portion of non-fatal injuries (insufficient details in the RHISE database to determine an exact number), were caused by the collapse of the Pyne Gould Corporation (PGC) building and the Canterbury Television (CTV) building. Masonry damage-related fatalities were spread out among 16 different locations within the central business district, confirming the widely recognised risk posed by unreinforced masonry. This emphasises the critical role that structural and masonry collapse prevention plays in life safety protection.

The sequence of earthquake events appears to have a strong influence on the type of injuries sustained. 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 4th September 2010 earthquake), or was adequately cordoned off and was therefore no longer at risk of causing injury.



(a) Number of relevant injuries caused by building component



(b) Percentage of injuries caused by building component

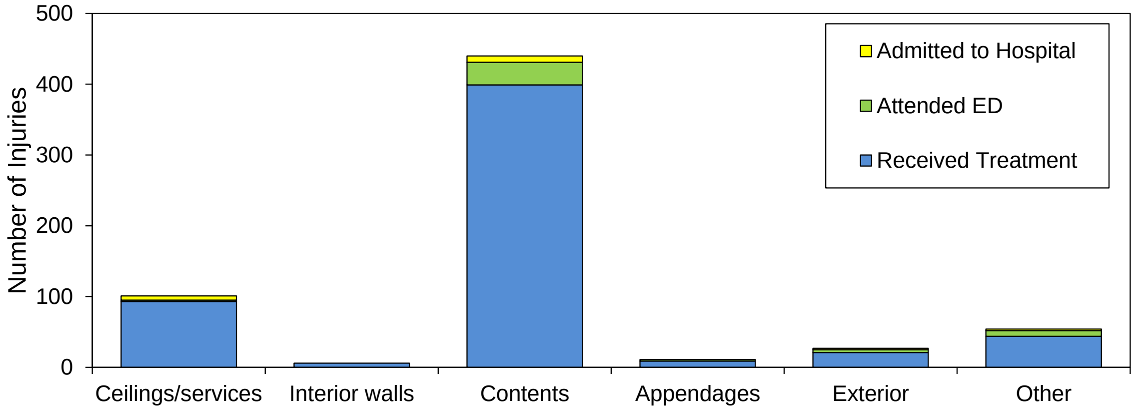
Figure 3: Injuries by building component category damage disaggregated by injury severity

4.3 Injuries by non-structural component

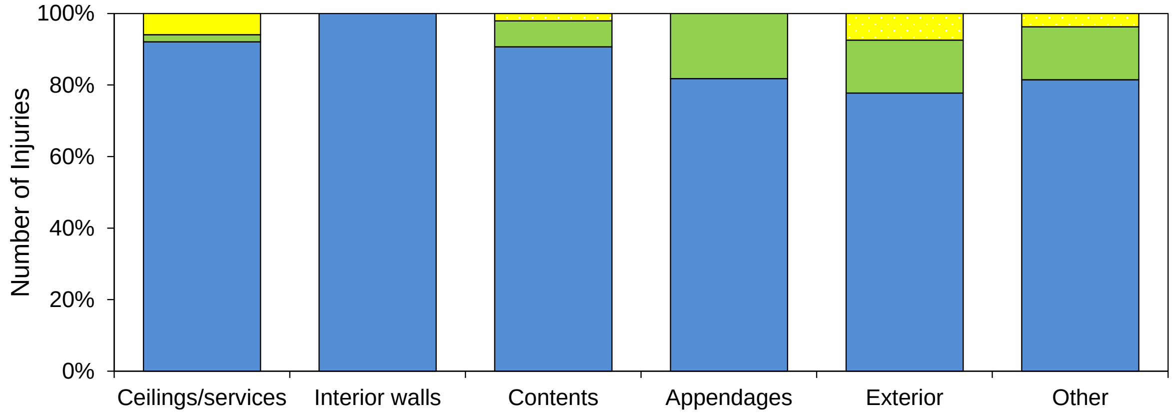
The number and severity of injury can be further broken down within the non-structural category by element type as shown in Figure 4. Contents contributed to 69% of all non-structural element related injuries, or 42% of all injuries considered in this research. Damage to ceilings and services was identified as the second greatest cause of non-structural elements related injuries (16%), followed by 'other' non-structural elements (8%). Damage to interior walls was rare, and only ever minor in severity. This indicates interior walls are not a significant issue from a health-and-safety perspective based on the research data compared with other non-structural elements.

Ceilings/services injuries and contents injuries had a similar proportion that required emergency department treatment or hospitalisation, as shown in Figure 4b. However, contents had a greater number of injuries, so overall the number of contents related injuries requiring treatment was 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 injury is building contents, however the severity of the injury is most likely to be minor.

Exterior non-structural elements were identified as having the greatest proportion of injuries requiring admission to hospital or treatment at the emergency department out of all non-structural element categories. This is likely to be attributable to glass falling from height, the occurrence of which was widely reported during the Canterbury events (Baird et al. 2011). Damage to appendages also resulted in proportionally more severe injuries compared with other non-structural element categories.



(a) Number of relevant injuries caused by non-structural element category



(b) Percentage of injuries caused by non-structural element category

Figure 4: Injuries by non-structural element damage disaggregated by injury severity

5 DISCUSSION

5.1 Comparison with past studies

A review of the outcomes of this study compared with previously completed studies on the injury risks from non-structural elements indicates significant similarities in findings. The proportion of non-fatal injuries from non-structural and structural elements were found to be 61% and 22% respectively from the recent New Zealand earthquakes and 68% and 22% from the Izmit event (Petal 2004).

Contents were found to have caused few, if any, deaths in the 1994 Northridge (Peek-Asa et al. 1998), 1999 Izmit event (Petal 2004), and from the New Zealand events. Most deaths in the latter two events were due to structural damage, while the first was undetermined as the causes of deaths were not differentiated between structural or non-structural building components. The similarity in findings from this research and those from literature gives confidence that they may be also applicable to other events.

5.2 Implication of findings

The results of this study are limited by the relatively short data collection period and the particular seismic events that occurred during this time. For example, approximately 80% of the injuries considered were a result of a single event. Such a limited dataset means it is not appropriate to solely base building code performance on this data. Even so, the results do provide useful insights.

One pertinent question this research raises is whether the life-safety objective of the building code was met. The term 'life-safety' is often associated with a level of performance that avoids fatalities, however, from a regulatory viewpoint, this association is not entirely accurate. One of the primary objectives of the New Zealand Building Code (NZBC) is to "safeguard people from injury caused by structural failure". Evidently, the requirement is to protect people from minor/major injuries as well as death that may result from earthquake damage.

6 CONCLUSIONS

This research aimed to quantify the cause and severity of injuries caused by damage to commercial buildings in recent New Zealand earthquakes. By identifying the main contributors to earthquake injuries, it is hoped that effort in future can be focussed on reducing the risk these elements pose.

For the earthquakes considered in this research, it was found that all fatalities that occurred were a result of structural or masonry damage. Structural damage related fatalities were attributed to two building collapses, whereas masonry damage related fatalities were spread among sixteen different locations within the Christchurch central business district.

Non-structural element damage was found to be the main contributor (61%) to earthquake injuries in commercial buildings and was the greatest cause of injuries across all non-fatal severity categories. Considering that the New Zealand Building Code requires people to be safeguarded against both injury and death, it is vital that that non-structural elements are not neglected when considering the risk to life-safety. Perhaps to further emphasise the importance of 'safeguarding people from injury' the term 'life-safety' should be replaced by a new term such as 'injury-prevention' that better conveys this requirement.

A further breakdown of injury cause by non-structural elements found that building contents were the dominant cause of injuries (although these tended to be at the low end of severity), making up 69% of all non-structural injuries (or 42% of commercial building related injuries overall). This indicates that building tenants and users of commercial buildings also have a role in reducing the life safety risk to building occupants by considering the risk posed by building contents moving or falling and mitigating these risks.

While damage to exterior non-structural elements and appendages only caused a small number of injuries, the proportion of these injuries requiring treatment at the emergency department or hospital admission was the greatest across all non-structural elements types. This appears to be largely attributable to glass falling from height, the occurrence of which was widely reported during the

Canterbury events and was also observed during the recent 2016 Kaikoura earthquake.

As damage to non-structural elements caused the greatest number of injuries across all non-fatal injury categories, this research suggests that efforts to reduce future earthquake injuries should focus on improving the seismic performance of non-structural elements. This conclusion is in alignment with the very significant contribution non-structural elements have to overall building damage repair costs following an earthquake (Filiatrault et al. 2002).

Suggestions of pragmatic approaches to minimise damage of non-structural elements have been previously proposed (Ferner et al. 2016). These concepts extend to minimising future earthquake injuries from non-structural elements. Practical and pragmatic approaches that consider the seismic restraint of non-structural elements as part of a holistic design approach for the entire building are, we believe, likely to be the most effective at reducing both damage and injuries from non-structural elements in earthquakes.

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