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EMPIRICAL VULNERABILITY ASSESSMENT OF REINFORCED CONCRETE FRAME WITH MASONRY INFILL BUILDINGS IN THE CANTERBURY EARTHQUAKE SEQUENCE

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ABSTRACT

During the 2010/2011 Canterbury earthquakes, Reinforced Concrete Frame with Masonry Infill (RCFMI) buildings were subjected to significant lateral loads. A survey conducted by Christchurch City Council (CCC) and the Canterbury Earthquake Recovery Authority (CERA) documented 10,777 damaged buildings, which included building characteristics (building address, the number of storeys, the year of construction, and building use) and post-earthquake damage observations (building safety information, observed damage, level of damage, and current state of the buildings). This data was merged into the Canterbury Earthquake Building Assessment (CEBA) database and was utilised to generate empirical fragility curves using the lognormal distribution method. The proposed fragility curves were expected to provide a reliable estimation of the mean vulnerability for commercial RCFMI buildings in the region.

KEYWORDS: *empirical fragility curves, masonry infill, post-earthquake assessment*

INTRODUCTION

Christchurch, New Zealand was devastated by two destructive earthquakes in a period of six months. On 4 September 2010, the M_w 7.1 Darfield earthquake shook the Canterbury region with an epicentre located at a depth of 11-km and centred approximately 40-km west of central Christchurch [1]. Subsequently, the aftershock of the M_w 6.3 Lyttleton earthquake occurred on 22 February 2011 with an epicentre located at a shallow depth of 5-km and located 10-km south-east of central Christchurch [2]. This aftershock had a major impact on the region and generated significant ground motion forces in a densely-populated region [3]. As a result, many buildings

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experienced moderate to severe damage, and some completely collapsed. The 2010/2011 earthquake sequence in the region is hereafter referred to as the Canterbury earthquakes.

Unreinforced masonry (URM) buildings had an extensive level of damage and generally performed poorly in the Canterbury earthquakes, with the inadequate seismic performance of URM buildings having been thoroughly reported [4-9]. In addition, the seismic performance of reinforced concrete (RC) buildings has also been documented following the Canterbury earthquakes. Initially, reports by Kam et al. [10] showed evidence that RC buildings, in most cases, performed satisfactorily in the 2010 Darfield earthquake. However, the 2011 Lyttelton earthquake caused damage to some RC buildings, and Kam et al. [11] observed that many RC buildings were severely damaged.

In contrast to the URM and RC buildings, the seismic performance of reinforced concrete frame with masonry infill (hereafter referred to as RCFMI) buildings has not previously been specifically reported following the Canterbury earthquakes, even though these buildings constitute a significant proportion of existing buildings in the Canterbury region. It was recognised that some RCFMI buildings were constructed prior to the introduction of New Zealand's seismic code in 1935 and that these buildings might be vulnerable to earthquakes. Therefore, the study reported herein attempted to evaluate the seismic performance of commercial RCFMI buildings in the region following the Canterbury earthquakes and to quantify the earthquake impact on these buildings.

The initial phase of this study included cataloguing the RCFMI building stock in the Canterbury region. The Canterbury Earthquake Building Assessment (CEBA) database was acquired from Geological and Nuclear Science (GNS), that was developed based on post-earthquake data collected by Christchurch City Council (CCC), the Canterbury Earthquake Recovery Authority (CERA), and Tonkin and Taylor who exclusively provided land damage information [12]. The database provides information on damaged buildings, such as building addresses, the number of storeys, infill types, cavity construction, the year of construction, the lateral-load resisting system, building placards, the current state of buildings, peak ground acceleration (PGA) values, and other related information.

Based on the CEBA database, 10,777 damaged buildings were documented following the Canterbury earthquakes, with many of these buildings being residential buildings (6,062 out of 10,777; 56%). Commercial buildings were also reported (3,528 out of 10,777; 33%) and 191 out of 3,528 (5%) of the total commercial buildings were classified in the database as RCFMI buildings. It is suspected that this number of RCFMI buildings is low and that some RCFMI buildings were assigned an incorrect building type or were not surveyed because they exhibited no damage, but no effort was made in this study to revise the buildings entries in the CEBA database.

It was also recognised that some of the information in the CEBA database that related to building characteristics and building damage was incomplete. Hence, a sidewalk survey was conducted in the region in order to compile any missing details for the 191 identified RCFMI buildings. In addition to the sidewalk survey, efforts were made to acquire post-earthquake documentation from CCC and Land Information New Zealand (LINZ).

The collected data was then compiled into the CEBA database, and the damaged buildings were grouped on the basis of the level of damage determined from Level 2 detailed assessments conducted by CCC [13]. The level of damage was grouped into five categories as Green 1 (G1), Green 2 (G2), Yellow 1 (Y1), Yellow 2 (Y2), and Red (R), and the buildings were assigned to damage states as Slight (DS1), Light (DS2), Moderate (DS3), Heavy (DS4), and Major (DS5). These categories are consistent with ATC-20 and EMS-98 [14] damage states, with some modifications defined based on the observed damage in the Canterbury earthquakes.

Subsequently, a Damage Probability Matrix (DPM) was created using compiled data to illustrate the effect of different ground motion intensities on the damage distributions of RCFMI buildings. Empirical fragility curves for the defined damage states were developed based on the lognormal cumulative distribution method, and the proposed fragility curves were compared with previous fragility curves generated by Rossetto and Elnashai [15] and by Del Gaudio et al. [16].

BUILDING POPULATION AND SURVEYED DAMAGED BUILDINGS

According to information obtained from CCC, the total number of commercial buildings in the region is approximately 28,394 properties. It is noted that this number includes vacant land, power kiosks, and 'other' and that the total number of properties counted includes both Christchurch city and its satellite towns, such as Akaroa, Lincoln and Lyttelton. Recently, a study conducted by Walsh et al. [17] has estimated the proportion of commercial RCFMI buildings in Christchurch to be about 14%. This estimation was obtained based on post-earthquake data collected by Kam et al. [11] in the Christchurch CBD following the Canterbury earthquakes. Thus, using the proportion estimated by Walsh et al. [17], there was thought to be roughly 3,900 commercial RCFMI buildings in the Christchurch region.

Figure 1 shows the location of damaged RCFMI buildings in the Christchurch region in conjunction with building placard status assigned from Level 1 assessments conducted by CCC following the 2011 Lyttelton earthquake [13]. Green placards indicate that the buildings have been inspected and were determined to be safe for reoccupation with no further structural intervention required, yellow placards represent the buildings having been inspected and assigned restricted entry, and red placards indicate the buildings that were considered unsafe and likely to have moderate to major level of damage.

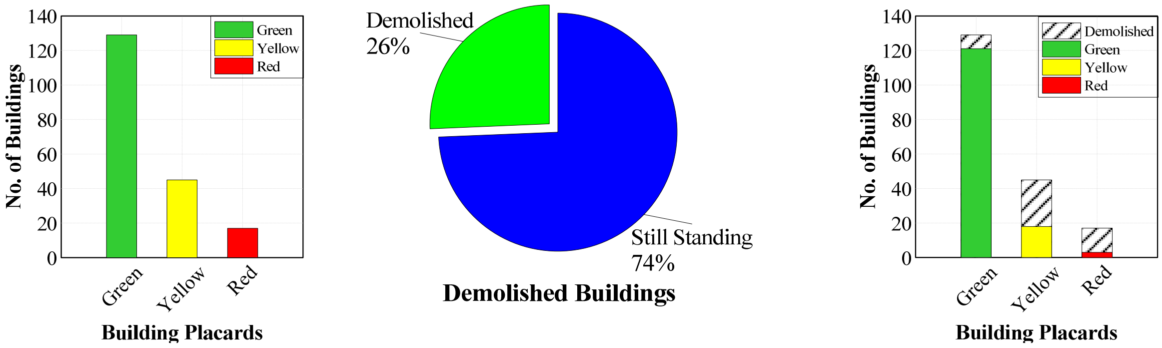
RCFMI buildings generally exhibited good performance during the Canterbury earthquakes, as it was established that the majority (129 out of 191 buildings; 68%) of the observed buildings were assigned green placards, (see Figure 2(a)). Recall also that it is suspected that additional RCFMI buildings were not surveyed because they exhibited no damage, such that the proportion of buildings meriting a green placard may well be significantly higher than 68%. In comparison, a comparatively small number of yellow placards, (45 out of 191 buildings; 24%), and red placards, (17 out of 191 buildings; 8%), were also identified.

(a) Location of buildings shown at region scale

(b) Surveyed buildings in the Christchurch CBD

Figure 1: Location of 191 damaged RCFMI buildings in the Christchurch region

The current state of the 191 RCFMI buildings as documented on 31 October 2016 reveals that there were 49 demolished buildings (26%), while the majority (74%) of these buildings remained standing, as shown in Figure 2(b). A high proportion of the RCFMI buildings assigned a red placard, (14 out of 17 buildings; 82%), and yellow placard, (27 out of 45 buildings; 60%), following the 2011 Lyttelton earthquake were demolished (Figure 2(c)) whereas only a small number of buildings having been assigned a green placard, (8 out of 129 buildings; 6%), were demolished, despite these 8 buildings having initially been assessed to have insignificant damage. The cost of repairing and strengthening these buildings to the minimum national standard of earthquake capacity is likely to have been the dominant factor dictating building demolition, with insurance companies perhaps deeming that replacement with a new building was more cost effective.



(a) Building placard assignments following the 2011 Lyttelton earthquakes

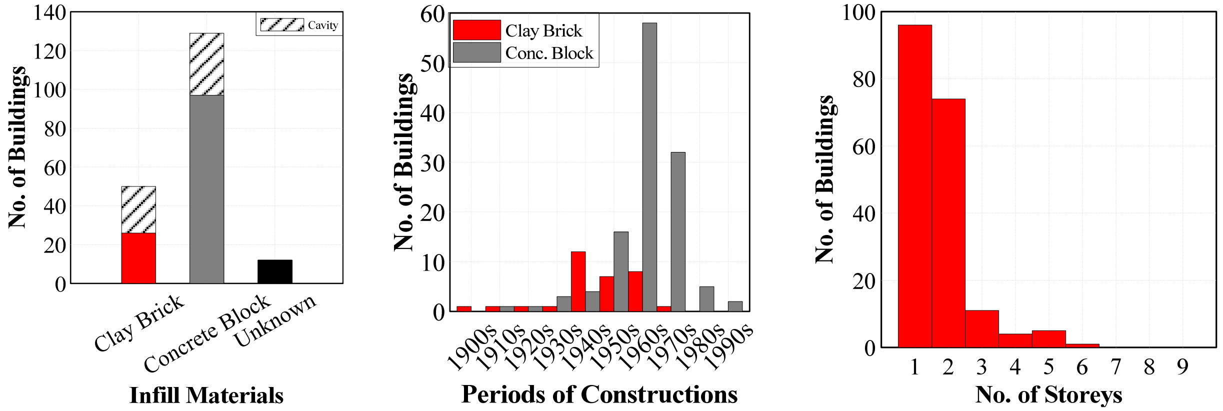
(b) The current state of buildings documented on 31 October 2016

(c) Proportion of demolished building for each building placard type

Figure 2: Damage and demolition statistics for RCFMI buildings

BUILDING CHARACTERISTICS

It was observed that the use of concrete block as infill was more prominent (68%) compared to clay brick infill (26%), as shown in Figure 3(a). Of the total surveyed buildings, there were 56 buildings (29%) having been determined as cavity-wall construction based upon the visible presence of air ventilation, weep holes and running bond patterns on the infill wall. The proportion of clay brick cavity-wall was observed to be 48% of the total surveyed clay brick infill construction, while concrete block cavity-wall construction was 25% of the total observed concrete block infill buildings.



(a) Infill material **(b) Year of construction of surveyed buildings** **(c) Number of storeys above ground**

Figure 3: RCFMI building attributes

The selection of infill material was strongly associated with the period of construction of the RCFMI building. As can be seen in Figure 3(b), clay brick infill buildings were initially constructed in the early 1900s, and these buildings were widespread from the 1940s to the early 1960s. However, the use of concrete block as infill substantially increased in the 1950s, and, commencing in the late 1950s, concrete block replaced the use of clay brick as infill material in the region.

Figure 3(c) shows the number of stories for the surveyed RCFMI buildings in Christchurch. The majority (95%) of surveyed buildings were 1 to 3 storeys, where 1-storey buildings constituted the greatest proportion (50%) of the total 191 observed buildings. 2-storey buildings had a proportion of 39% and 3-storey buildings accounted for 6% of the total surveyed buildings. It should be considered that RCFMI construction was generally not used in New Zealand for mid to high-rise buildings, explaining the small number of buildings (5%) having 4+ storeys.

DETERMINATION OF DAMAGE STATES

Damage states are commonly used to empirically describe the seismic vulnerability of buildings following an earthquake. In this study, damage states were defined based on the Level 2 detailed assessments documented by CCC after the 2011 Lyttelton earthquake. Initially, CCC conducted

Level 1 rapid assessments assigning the level of damage into three building placards of green, yellow, and red on the basis of estimated building damage that was observed from the exterior of buildings. Level 2 detail assessments categorise the level of damage into five categories in line with general rapid assessment methods used worldwide, such as ATC-20 and EMS-98[14]. The damaged buildings were assigned to damage states of Slight (DS1), Light (DS2), Moderate (DS3), Heavy (DS4), and Major (DS5), as defined in Table 1. The number of observed damaged buildings associated with each damage state are presented in Figure 4.

Table 1: Definition of damage states

Damage States	**Level 2 assessment**	**Estimated building damage**	**Description**
DS1 – Slight	Green 1 (G1)	0 – 1%	Insignificant damage, repair is not required, the buildings can be occupied immediately
DS2 – Light	Green 2 (G2)	2 – 10%	Insignificant damage, repair or strengthening is required, the buildings can be occupied immediately
DS3 – Moderate	Yellow 1 (Y1)	11 – 30%	Significant damage, repair or strengthening is required, short-term entry to some parts of buildings
DS4 – Heavy	Yellow 2 (Y2)	31 – 60%	Significant damage, repair or strengthening is required, some parts of buildings were restricted to entry until secured or demolished
DS5 – Major	Red (R)	61 – 100%	Severe damage or collapse, the buildings were unsafe

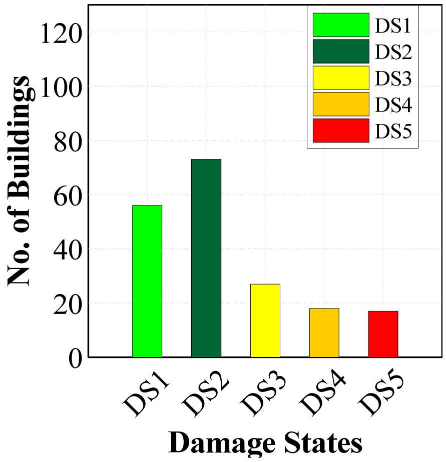
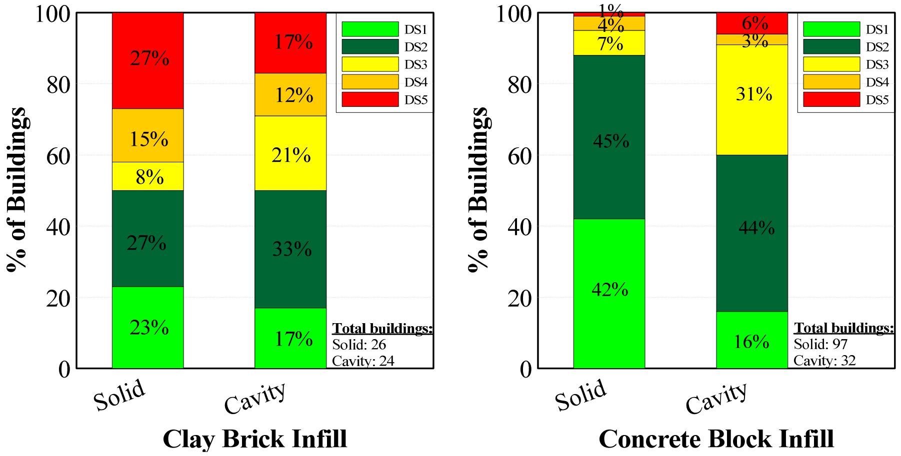


Figure 4: Damage state assessment for observed damaged buildings

BUILDING DAMAGE STATISTICS

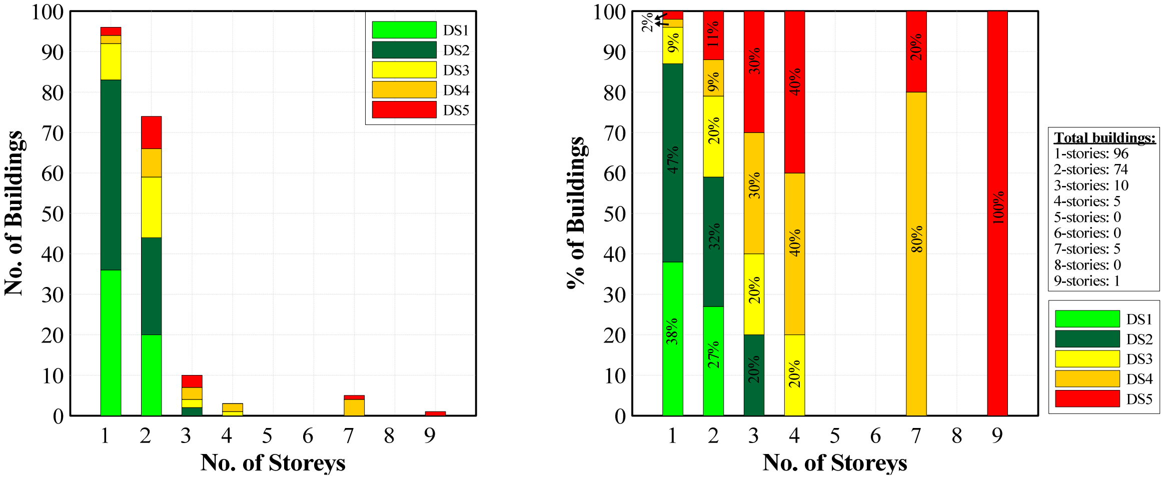
Figure 5 illustrates the damage sustained by infill material for different wall morphology (solid and cavity-wall construction) in accordance with the level of damage following the 2011 Lyttelton earthquake. In general, it was observed that clay brick infill experienced considerable damage compared to concrete block infill. Clay brick RCFMI buildings sustained a similar performance in the 2011 Lyttelton earthquake for both solid and cavity-wall construction as 50% of the total surveyed clay brick buildings experienced moderate to major damage (DS3-DS5) for both wall morphologies. Despite 40% of the concrete block RCFMI buildings that had cavity-wall construction sustaining moderate to major damage, the majority of RCFMI buildings (82%) constructed using solid concrete block infill showed an adequate performance during the 2011 Lyttelton earthquake.



(a) Clay brick **(b) Concrete block**

Figure 5: Extent of damage to infill material

It was observed that the level of damage to RCFMI buildings following the 2011 Lyttelton earthquake was higher with an increased building height (see Figure 6). The majority (more than 80%) of RCFMI buildings having 3+ stories sustained moderate to major damage, while most of the buildings having 1 to 2 stories experienced less damage.

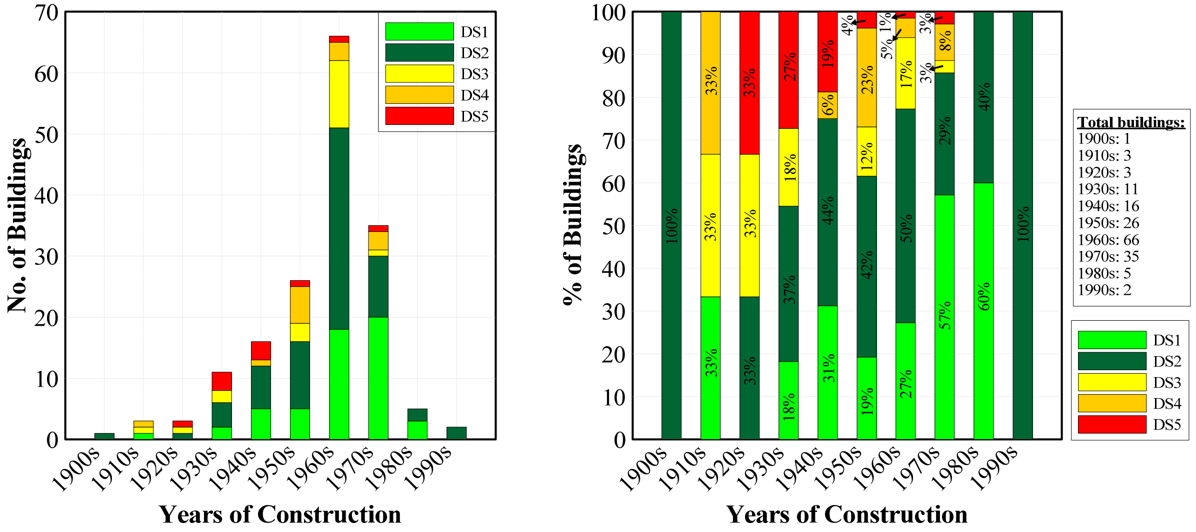


(a) Total number of buildings **(b) Percentage of buildings**

Figure 6: The influence of RCFMI building height on damage

Figure 7 presents the recorded level of damage sustained by RCFMI buildings following the 2011 Lyttelton earthquake, correlated against period of construction. It was observed that RCFMI building constructed between the 1910s and the 1930s (more than 45% of the total number of surveyed buildings) had considerably more damage because these buildings were constructed before the introduction of the first New Zealand seismic code in 1935. It was documented that a large number of these buildings experienced moderate to major damage, and, as expected, the buildings constructed in that era were likely prone to earthquakes.

In contrast, RCFMI buildings constructed from the 1940s onwards exhibited better performance compared to the buildings constructed between the 1910s to the 1930s, as seismic requirements would have been incorporated into the design process (see Figure 7). It is considered that the New Zealand seismic code had a significant elevation in seismic criteria in 1976, which required seismic detailing and ductility [18]. As a result, it is unsurprising that RCFMI buildings constructed in the late 1970s onwards performed satisfactorily during the earthquakes.



(a) Number of damaged buildings **(b) Damage state as a percentage**

Figure 7: The influence of period of construction on damage

DAMAGE PROBABILITY MATRIX (DPM)

A Damage Probability Matrix (DPM) is commonly utilised to illustrate the effect of seismic ground motion intensities on the level of damage sustained by buildings during an earthquake. The recorded PGA values obtained from the CEBA database were sorted into a number of range, and the buildings associated with damage states were assigned to the range of PGA values (see Table 2). As shown in Table 2, the majority of RCFMI buildings (about 93% of the total number of surveyed buildings) experienced PGA values from 0.3*g* to 0.6*g*. However, no clear trend regarding the influence of PGA on the level of damage was observed. Some of the PGA values were well above the levels that these buildings would have been designed to.

Table 2: Damage Probability Matrix (DPM) illustrating the effect of damage to Peak Ground Acceleration (PGA) following the 2011 Lyttelton earthquake

Damage states	**Peak Ground Acceleration (%*g*)**									**Total**
	0.1 – 0.2	**0.2 – 0.3**	**0.3 – 0.4**	**0.4 – 0.5**	**0.5 – 0.6**	**0.6 – 0.7**	**0.7 – 0.8**	**0.8 – 0.9**	**0.9 – 1.0**	
DS1		5	16	26	8	1				**56**
DS2		7	14	34	17				1	**73**
DS3			13	13	1					**27**
DS4			3	15						**18**
DS5			3	14						**17**

EMPIRICAL FRAGILITY CURVES

Fragility curves can be defined as the probability of buildings being in or exceeding a specific damage state as a function of peak ground acceleration (PGA). In this study, the lognormal cumulative distribution method was utilised to derive empirical fragility curves as this method was generally used to represent fragility relationship [19-21]. The cumulative lognormal distribution can be computed as follows:

$$P\left(\mathrm{DS} \geq \mathrm{DS}_i \middle| \mathrm{PGA}\right) = \Phi\left(\frac{\ln\left(\mathrm{PGA}/\theta_{DS_i}\right)}{\beta_{DS_i}}\right) \tag{1}$$

where:

Φ is the standard normal cumulative distribution function;

θ_{DS_i} is the expected median value of PGA when buildings reach a certain damage state;

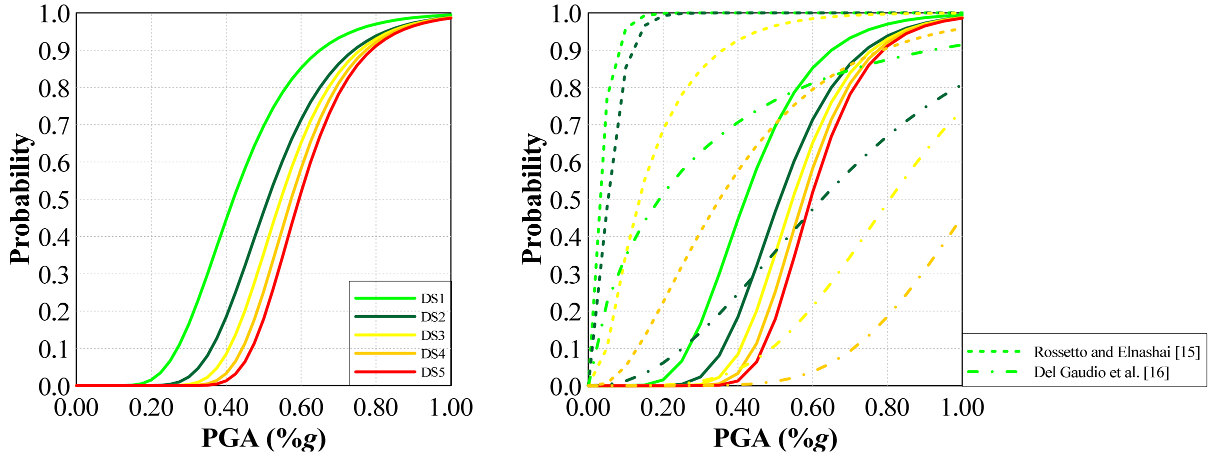
β_{DS_i} is the natural logarithm standard deviation of PGA for different damage states.

The empirical fragility curve for each damage state was generated through the corresponding value of median $\left(\theta_{DS_i}\right)$ and standard deviation $\left(\beta_{\mathrm{DS}_i}\right)$, which were calculated based on the Maximum Likelihood Estimation (MLE) method as this method has been widely utilised to generate fragility functions from post-earthquake data [22-24]. The estimated median and log standard deviation values are presented in Table 3, and the fragility curves for RCFMI buildings following the 2011 Lyttelton earthquake for each damage state are shown in Figure 8(a).

Table 3: Estimated median value and log standard deviation at different levels of damage for deriving fragility curves

Damage states	Median (θ)	Standard deviation (β)
DS1	0.419	0.343
DS2	0.431	0.337
DS3	0.412	0.277
DS4	0.431	0.265
DS5	0.431	0.269

The empirical fragility curves were subsequently compared with previous empirical fragility curves for RCFMI buildings generated by Rossetto and Elnashai [15] and Del Gaudio et al. [16] (see Figure 8(b)). Rossetto and Elnashai [15] generated empirical fragility curves based on a large post-earthquake data set obtained from 19 events, including European and non-European earthquakes, while Del Gaudio et al. [16] derived empirical fragility curves based on damage data following the 2009 L'Aquila, Italy earthquake. The fragility curves were derived for each damage state, adopted from EMS-98 [14] as Slight (DS1), Light (DS2), Moderate (DS3), and Extensive (DS4). It is considered that Extensive (DS4) damage in the previous studies was consistent with the definition of Heavy (DS4) and Major (DS5) damage in this study. The comparison of empirical fragility curves between this study and previous studies can be seen in Figure 8(b).



(a) The 2011 Lyttelton earthquake

(b) Comparison with previous fragility curves in different countries

Figure 8: Empirical fragility curves for RCFMI buildings

As shown in Figure 8(b), the fragility curves generated by Rossetto and Elnashai [15] (dashed line) for each damage state indicated significantly higher expected levels of damage for a prescribed PGA value when compared to the fragility curves proposed in this study (solid line). This discrepancy might be caused by the nature of the building characteristics, in which Rossetto and Elnashai [15] considered a considerable extent of building data, including European and non-European buildings, that might lead to large uncertainties associated with empirical relationships between the ground motion data and building damage state due to the scarcity of observational data. In addition, the structural details and quality of construction are likely to be distinctly different to the building characteristics for New Zealand RCFMI buildings, leading to greater earthquake vulnerability.

Despite indicating a higher probability at the DS1 (Slight) damage state, the fragility functions derived by Del Gaudio et al. [16] revealed a lower probability for DS2 (Light) to DS4 (Heavy) damage states compared to the fragility curves developed in this study. The difference between the two fragility curves for the DS1 (Slight) damage state would be further amplified if efforts were made in the New Zealand study to account for the suspected number of undamaged buildings that were omitted from the CEBA data set because surveys were not conducted for some undamaged buildings. These uncounted buildings might induce large uncertainties regarding the total number of existing RCFMI buildings that were subjected to the Canterbury earthquakes. Furthermore, the difference between the DS2 (Light) to DS4 (Heavy) damage states might be affected by site effects, earthquake parameters (such as depth, soil type, and 'other'), and the natural characteristics of buildings. It was also considered that a lower probability for the DS4 (Extensive) damage state from the Del Gaudio et al. [16] study may be the result of different definitions of damage states for DS4 (Heavy) and DS5 (Major) when compared to the definitions adopted in this study.

The discrepancies between empirical fragility curves in the different studies are acknowledged, as the reliability of empirical fragility functions is highly dependent on the quality of the post-earthquake data. This reliability is linked to the survey method used to define the level of damage and to estimate the ground motion intensity level. Because the CEBA database was utilised in this study to determine the level of damage based on Level 2 detailed assessment, the quality of data is thought to be reliable. However, it is highlighted that the level of damage of some RCFMI buildings was not reported in the CEBA database, which introduced some uncertainties regarding the accuracy of the developed fragility relationships. Despite these uncertainties, the proposed empirical fragility curves from the Canterbury earthquakes provide a reliable insight regarding the seismic vulnerability of commercial RCFMI buildings in New Zealand because it is assumed that the characteristic of buildings is relatively similar across the country.

CONCLUSIONS

There were 191 RCFMI buildings having been assessed following the 2010/2011 Canterbury earthquakes. It was observed that the majority of RCFMI buildings revealed an adequate performance during the earthquakes, with a considerable number of these buildings having been assigned into green placards (68%). In addition, their current state showed that a comparatively small number of RCFMI buildings had been demolished (26%), while the majority of these buildings remained standing (74%).

Observations indicated that buildings with clay brick infill sustained more damage when compared to building having concrete block infill, but there was no clear evidence that wall morphology (solid or cavity-wall construction) had a significant impact on building performance. With increasing building height, damage levels were shown to increase and a large percentage of RCFMI buildings having 3+ stories experienced moderate to major damage. RCFMI buildings constructed during the period between the 1910s and the 1930s were more likely to be earthquake-vulnerable as it was shown that many buildings from this era had a high level of damage compared to more modern buildings.

A Damage Probability Matrix (DPM) was used to illustrate the effect of peak ground acceleration (PGA) on the level of damage in the Canterbury earthquakes. During the earthquakes, most

RCFMI buildings were subjected to PGA values of between 0.3*g* and 0.6*g*. Empirical fragility curves adopting a lognormal distribution were generated, and the fragility functions were estimated based on the Maximum Likelihood Estimation (MLE) method. The proposed empirical fragility curves presented herein were compared to previous empirical fragility curves developed in different countries. The comparison revealed that the empirical fragility curves were different due to the discrepancies of ground motion recordings, site effects, earthquake parameters, and the natural characteristics of RCFMI buildings in each country. Despite empirical data having a large uncertainty due to the reliability of ground motion and building damage data, the proposed empirical fragility curves were thought to provide a reliable insight regarding the seismic vulnerability of RCFMI buildings in New Zealand.

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