Seismic Fragility Assessment of Canterbury Buildings

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ABSTRACT: Data from the 2010-2011 Canterbury earthquake sequence has been used to assess the damageability in earthquakes of the building types represented in the dataset. The damageability was represented as fragility functions which are probability distributions that indicate the likelihood that a building will be damaged to a minimum Damage State as function of a demand parameter, in this case peak ground acceleration (PGA).

The function derivation followed the methodology published in FEMA P-58-1, and used a database of 69,734 buildings. Building data, including damage assessments, had been collated by CERA and Christchurch City Council. Site PGAs were obtained from the Canterbury Geotechnical Database.

The data were derived from rapid building survey reports, detailed engineering evaluations and demolition records, which are in inconsistent formats. Algorithms were developed to transform these data to standardised Damage States.

There were sufficient data with a range of PGAs to calculate fragility functions for low-rise buildings. Buildings over three storeys were mainly confined to the Christchurch CBD area, which experienced a limited range of PGA's. There were therefore insufficient data over a range of ground motions to calculate meaningful functions for taller buildings. Options for improving the quality of data gathering in future earthquakes are discussed.

1 INTRODUCTION

Data from the 2010-2011 Canterbury earthquake sequence has been used to assess the damageability in earthquakes of the building types represented in the dataset. The damageability is represented as fragility functions, which are probability distributions that indicate the likelihood a building will be damaged to a minimum Damage State as function of an engineering demand parameter (EDP).

Fragility functions are useful for assessing and managing earthquake risk including predicting numbers of damaged buildings, costs and time to repair, numbers of casualties, and prioritising seismic strengthening. Empirical damage data are also useful to calibrate seismic rating systems such as the NZSEE new building design standard based method (NZSEE, 2016).

In this paper the processes of collating and analysing the damage data are described and fragility functions for a number of building types are presented. The limitations of the available data and options for improvement are discussed.

2 FORM OF FRAGILITY FUNCTIONS

Fragility functions used in this study have the form shown in equation 1 (ATC, 2012). $F_i(D)$ is the conditional probability that the building will reach damage level i as a function of the EDP, D. Φ denotes the standard normal (Gaussian) cumulative distribution function, with a median and logarithmic standard deviation for the EDP of θ_i and β_i, respectively.

$$F_i(D) = \Phi\left(\ln\left(\frac{D/\theta_i}{\beta_i}\right)\right) \tag{1}$$

Damage levels can be defined qualitatively (e.g. "minor", "moderate", "severe") or quantitatively (e.g. % drift, % repair cost). For this study, qualitative degrees of damage were used, and are referred to as Damage States. There are a number of options for the EDP (e.g. MMI, PGV, spectral acceleration), however peak ground acceleration (PGA) is most commonly used and has been adopted for this study.

The "bounding data" method presented in FEMA P-58-1 (ATC, 2012) was used to calculate the medians and dispersions from the collated data.

3 INFORMATION SOURCES

Three databases were used to obtain the information required for this study; the CEBA database (GNS Science 2015), the CCC database (Christchurch City Council 2015) and the Canterbury Geotechnical Database (Ministry of Business, Innovation and Employment 2011).

The CEBA and CCC databases provided building information enabling the Damage State, structural system and number of storeys of each building to be determined. They also provided information allowing each building to be located with GPS co-ordinates (either by providing the co-ordinates directly or by the building address). These two databases obtained their information through three different methods; Rapid Building Safety (RBS) evaluations, Detailed Engineering Evaluations (DEE's), and the CERA demolition list. A number of buildings had assessments in both the CCC and CEBA databases, as confirmed by address information and identification numbers. Where the databases had conflicting information the CEBA database was given priority as it appeared to be the more robust and complete database.

The O'Rourke (O'Rourke et al. 2012) estimates available in the Canterbury Geotechnical Database were used to provide the PGA through locating each building with its GPS co-ordinates.

4 DAMAGE STATE DEFINITIONS

Common damage definitions across all buildings in this study were limited by the available information for each building. Given the nature of the available data, it was decided the best representation of the damage was to classify against qualitative descriptors. Four Damage States were used in this study to qualify building damage: None, Minor, Moderate and Extensive/Complete. These are the states adopted by the well-known HAZUS loss modelling methodology (NIBS, 2003) and also mimic the levels that were available to assessors when they conducted the RBS evaluations ('None/Minor', 'Moderate', 'Severe').

The idealised meaning of each Damage State is shown in Table 1. For this study, the Extensive and Complete Damage States were combined as sufficient information was not available to distinguish between the two.

Table 1: Idealised Damage State definitions.

Damage State	Damage Ratio (%)	Likely Placard	Demolition	Collapse
None	0	Green	No	No
Minor	0-10	Green	No	No
Moderate	10-30	Yellow	Not expected.	No
Extensive	30-70	Red	Likely	Not expected.
Complete	70+	Red	Yes	10-15% expected to partially or totally collapse.

4.1 **Damage Indicators**

Each of the three assessment types (RBS, DEE's, demolition list) provided different information that could be used to qualify the Damage State of each building, noting that each building had a mix of information available from each assessment type. Useful information categories were referred to as a Damage Indicators. Algorithms were developed to use each building's Damage Indicators to determine its Damage State. The Damage Indicators used in the study are described below. Italicised words give the name of the Damage Indicator, words in single quotation marks give their available quantification. All Damage Indicators had the option of being blank.

4.1.1 *RBS Placard*

RBS assessments can be completed to one of two levels and resulted in a placard being assigned to the building to indicate its level of safety. The level 1 *placard status* could be 'Green', 'Yellow', 'Red'. The level 2 *placard status* could be: 'Green 1', 'Green 2', 'Yellow 1', 'Yellow 2', 'Red 1', 'Red 2', 'Red 3'.

4.1.2 *RBS Overall Damage Estimation*

Level 1 and 2 RBS assessments required assessors to estimate the damage suffered by a building to pre-defined, quantitative levels. The *estimated overall building damage (EOBD)* levels were 'None', '0-1%', '2-10%', '11-30%', '31-60%', '61-99%', '100%'.

4.1.3 *RBS Damage Descriptors*

RBS evaluations assessed aspects of particular categories of damage to pre-defined qualitative levels. The useful damage descriptors from RBS assessments were *Collapse, partial collapse, off foundation; Building or storey leaning; Wall or other structural damage; Foundations; Roof, floors (vertical load); Columns pilasters, corbels; Diaphragms, horizontal bracing; Pre-cast connections; Beams; Cladding, glazing; Interior walls, partitions*. Damage levels for all RBS damage descriptors were 'Minor/None', 'Moderate', 'Severe'.

4.1.4 *DEE Repair/Strengthening Recommendations*

DEE's required the level of repair and strengthening to be indicated to pre-defined qualitative levels. The *repair/strengthening recommendation* could be 'none', 'minor non-structural', 'minor structural', 'significant structural', 'significant structural and strengthening', 'demolition'.

4.1.5 *DEE Occupancy Recommendations*

DEE's required recommendations about building occupancy to be made to pre-defined levels. The *occupancy recommendation* could be 'full occupancy', 'partial occupancy', 'do not occupy'.

4.1.6 *DEE Pounding Damage Check*

DEE's required an indication of if pounding damage was suffered. The *pounding damage* level could be 'yes' (or blank).

4.1.7 *DEE Non-Structural Damage Check*

DEE's required an indication of if non-structural damage was suffered. The *non-structural damage* level could be 'yes' (or blank).

4.1.8 *CERA Demolition List*

Commercial buildings within the Christchurch CBD red zone were assessed following the earthquakes. Those determined to be dangerous required demolition to one of three levels. The *demolition extent* could be 'make safe', 'partial demolish', 'demolish'.

4.2 **Damage State Algorithms**

The algorithms outlined in this Section were used to determine each building's Damage State based on its available Damage Indicators. The algorithms were based around the *placard status* of the building as this was considered to be the most correctly applied Damage Indicator by assessors. Other Damage Indicators were then examined, such as the *estimated overall building damage* and the RBS damage descriptors. The damage descriptors of *collapse, partial collapse, off foundation* and b*uilding or storey leaning* were given particular consideration due to their encompassing of a whole-of-building damage scenario. Buildings that were demolished were considered to be in only the Moderate or Extensive/Complete Damage States. The DEE Damage Indicators were only useful confirming that damage to a building had occurred, but not for quantifying it.

4.2.1 *Excluded*

Buildings that had insufficient date to determine whether or not they had suffered damage were excluded from the analyses. There needed to be at least one non-blank status from either the *placard status, estimated overall building damage,* any RBS damage descriptor, or the *repair/strengthening recommendation.*

4.2.2 *None*

If a building was not excluded it was assumed that some level of damage had occurred during the earthquakes unless it could be shown otherwise. By this rationale, only buildings with a *placard status* of 'G', G1' or blank were considered for this Damage State. One of the available choices/combinations in each boxed-out column of Table 2 needed to be satisfied to deem a building to be in the None Damage State.

Table 2: Algorithm table for determining Damage State None.

Placard Status	**EOBD**	**DEE Repair/ Strengthening**	**All RBS Damage Descriptors**	**DEE Pounding Damage**	**DEE Non-Structural Damage**	**DEE Occupancy Recommendation**
G, G1, Blank	None	None, Blank	Minor/None, Blank	Blank	Blank	Full Occupancy, Blank
	Blank	None				

4.2.3 *Minor Damage*

If a building was not in the Excluded, None, Moderate or Extensive/Complete Damage State, then it was deemed to be in the Minor Damage State.

4.2.4 *Moderate Damage*

If a building was not in the Excluded, None or Extensive/Complete Damage State, then it was checked for the Moderate Damage State.

When checking for the Moderate Damage State, if any of the following Damage Indicators were present, then the Damage State was deemed to be achieved: *Placard status* is 'R', 'Y2' or 'Y1'; *Estimated overall building damage* is '61-99%' or '31-60%'; *Demolition extent* is 'make safe'; *Collapse, partial collapse, off foundation* is 'Moderate'; *Building/storey leaning* is 'Moderate'. If at least one of these Damage Indicators was not present then the criteria of Table 3 were referred to. For the given placard statuses, if the *estimated overall building damage* and RBS damage descriptor criteria were met, the building was deemed to be in the Moderate Damage State.

Table 3: Algorithm table for determining Damage State Moderate for the placard statuses shown.

Placard Status	Estimated Overall Building Damage	All RBS Damage Descriptors
Y	11-30%	
	2-10%	>1/2 Moderate or Severe
	0-1%	>2/3 Moderate or Severe
	Blank	Blank
G, G2, Blank	11-30%	
		>1/2 Moderate or Severe

4.2.5 *Extensive/Complete Damage*

If a building was not in the Excluded or None Damage State, then it was checked for the Extensive/Complete Damage State.

When checking for the Extensive/Complete Damage State, if any of the following Damage Indicators was present, then the Damage State was deemed to be achieved: *Placard status* is ‘R2’ or ‘R1’; *Estimated overall building damage* is ‘100%’; *Demolition extent* is ‘full’ or ‘partial’; *Collapse, partial collapse, off foundation* is ‘Severe’; *Building/storey leaning* is ‘Severe’. If one of these Damage Indicators was not present, then for the placard statuses shown in Table 4, if the conditions across one full row were met, the building was deemed to be in the Extensive/Complete Damage State.

Table 4: Algorithm table for determining Damage State Extensive/Complete for the placard statuses shown.

Placard Status	EOBD	All RBS Damage Descriptors	Collapse, Partial Collapse, Off Foundations	Building or Storey Leaning	Demolition Extent
R	61-99%, 31-60%, 11-30%				
	Blank	Blank, >1/3 Severe			
			Moderate		
				Moderate	
					Make Safe
Y2	61-99%				
	31-60%	>2/3 Severe			
			Moderate	Moderate	
					Make Safe
Y	61-99%				
	31-60%	>2/3 Severe			
			Moderate	Moderate	
Blank	61-99%, 31-60%				
		>1/2 Severe			
			Moderate	Moderate	

5 BUILDING TAXONOMY

Buildings were categorised according to the type of system used for their lateral-load-resisting structure (LLRS) and their number of storeys. The LLRS types were based on those used in the CCC and CEBA databases (taken from RBS assessments and DEE's). The LLRS types listed below were used.

- *Concrete Frame*. Reinforced concrete moment frames. Could be ductile or non-ductile.
- *Concrete Frame – Infilled*. Reinforced concrete moment frames with infill.
- *Concrete Wall*. Reinforced concrete shear walls. Could be ductile or non-ductile. Includes precast ("tilt-up") construction.
- *Confined Masonry*. Masonry infill between reinforced concrete frames. Infill acts to resist lateral loads while concrete frames confines it to improve performance. Infill may be reinforced or unreinforced.
- *Masonry – Reinforced*. Reinforced hollow block masonry. Could be partially or fully filled.
- *Steel Frame*. Steel frames of all forms (e.g. moment frame, braced frame) and connection types (e.g. welded, bolted, riveted).
- *Timber Framed*. All buildings with timber structure. Typically timber-framed residential houses but also includes commercial buildings (e.g. with post-and-beam construction and plywood shear walls).
- *URM*. Unreinforced clay brick masonry. Typically loading-bearing brick shear walls with timber floors.

6 RESULTS

Figure 1: Fragility data and curves for all buildings. From left to right; 1-3 storeys, 4-7 storeys and 8+ storeys.Figure 1, Figure 2 and Figure 3 show the fragilty curve results for this study.

For Figure 1 and Figure 2 the green, orange and red data are for the Minor, Moderate and Extensive/Complete Damage States, respectively. The data points shown represent the precentage of buildings that achieved at least the Damage State of interest over the PGA range for that data point. The PGA range for each data point was determined according to the methodology of FEMA P-58-1.

Figure 2 and Figure 3 show fragility curves for 1-3 storey buildings only. There were insuffcient data over a range of PGA's to produce meaningful fragility functions for buildings taller than this. This can be seen in the scarcity of data points for the 4-7 storey and 8+ storey plots of Figure 1.

The vertical axis for all figures shows the conditional probabiltiy of being at least in the Damage State. The horizontal axis for all figures shows the PGA (in *g*) in a range from zero to one.

Figure 1: Fragility data and curves for all buildings. From left to right; 1-3 storeys, 4-7 storeys and 8+ storeys.

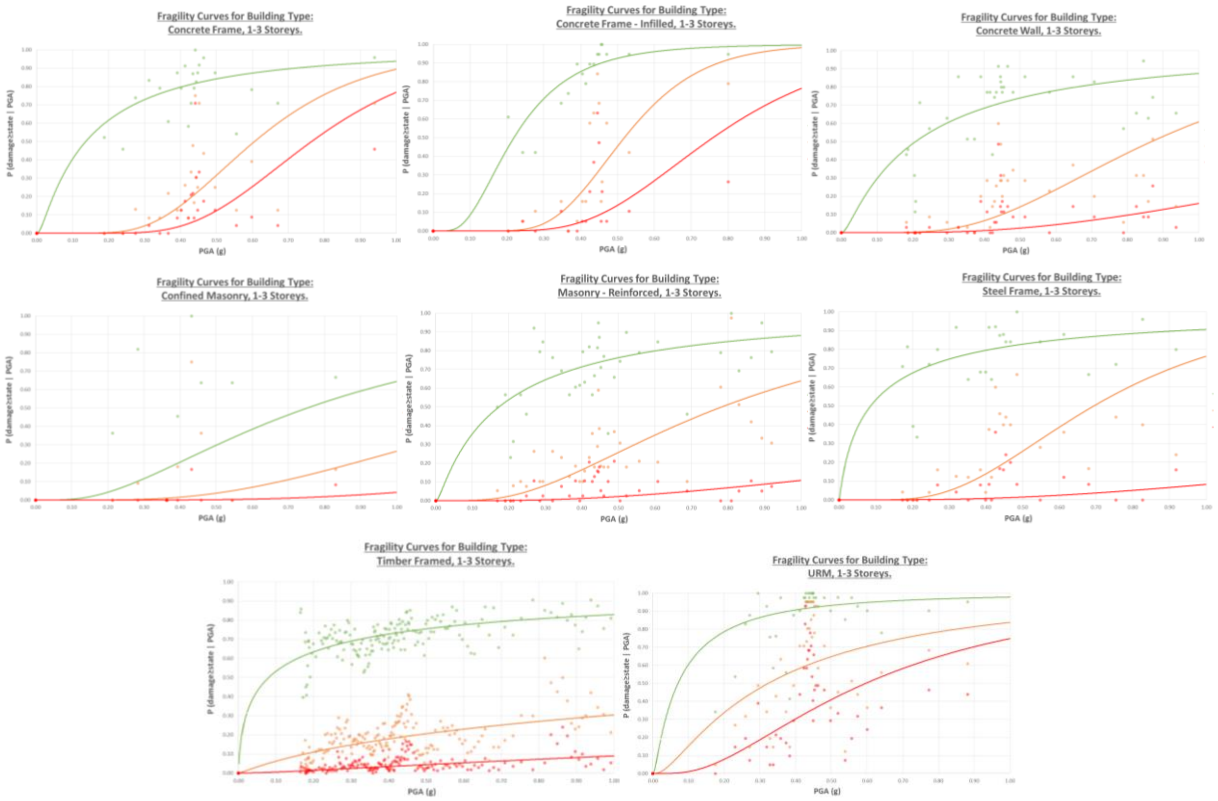

Figure 2: Fragility data and curves for 1-3 storey buildings of different LLRS types. From top-left; Concrete Frame, Concrete Frame - Infilled, Concrete Wall, Confined Masonry, Masonry - Reinforced, Steel Frame, Timber Framed and URM.

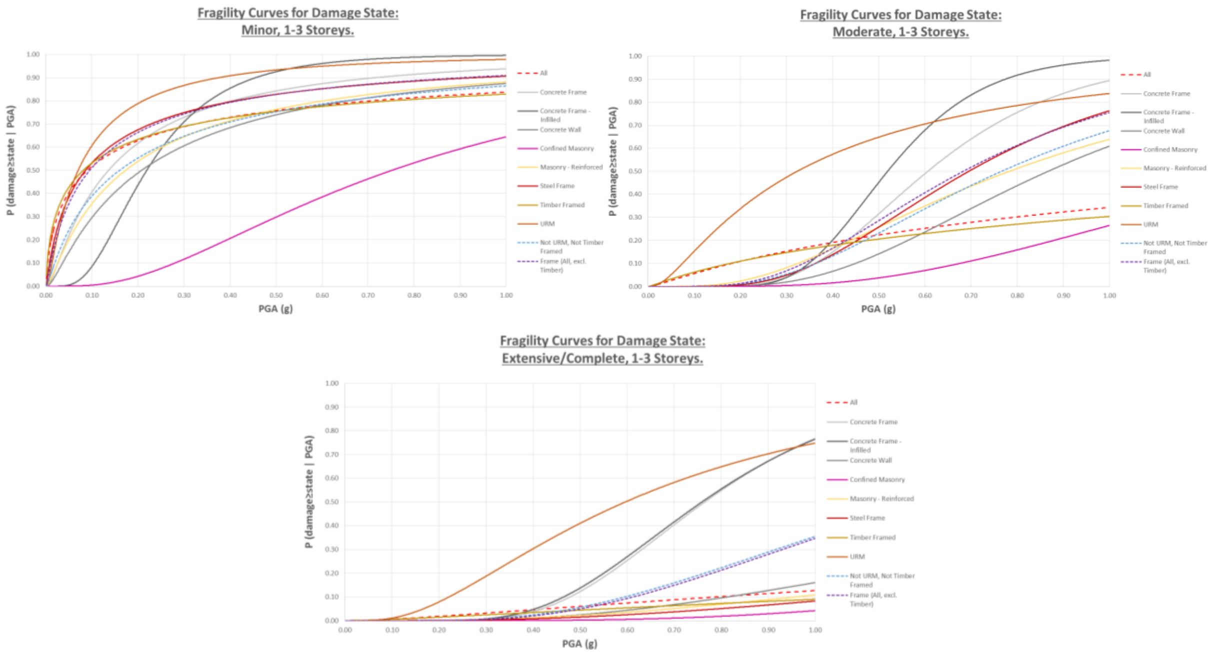

Figure 3: Fragility curves for 1-3 storey building of different Damage States. From top-left; Minor, Moderate and Extensive/Complete.

Table 5 shows the calculated fragility curve parameters from the FEMA P-58-1 method for 1-3 storey buildings of each LLRS type. For brevity, only 1-3 storey results are shown as lack of data meant meaningful curves could not be developed for taller buildings. Note that the number of buildings in column three of the table is the number that met or exceeded that Damage State.

Table 5: Fragility curve parameters for 1-3 storey buildings.

LLRS Type	Damage State	No. Buildings	Median, θ (g)	Log. Std. Dev., β
All	None	36,644		
	Minor	26,508	0.090	2.450
	Moderate	7,720	2.196	1.946
	Extensive/Complete	2,497	6.839	1.682
Concrete Frame	None	544		
	Minor	424	0.136	1.297
	Moderate	145	0.606	0.401
	Extensive/Complete	81	0.765	0.366
Concrete Frame - Infilled	None	322		
	Minor	264	0.219	0.572
	Moderate	107	0.519	0.312
	Extensive/Complete	50	0.759	0.382
Concrete Wall	None	1225		
	Minor	833	0.208	1.367
	Moderate	236	0.867	0.513
	Extensive/Complete	104	2.027	0.711
Confined Masonry	None	113		
	Minor	52	0.752	0.769
	Moderate	18	1.456	0.599
	Extensive/Complete	3	2.888	0.613
Masonry - Reinforced	None	1470		
	Minor	1,033	0.173	1.486
	Moderate	369	0.783	0.688
	Extensive/Complete	95	2.998	0.889
Steel Frame	None	593		
	Minor	457	0.086	1.861
	Moderate	149	0.695	0.508
	Extensive/Complete	46	3.416	0.885
Timber Framed	None	28,597		
	Minor	20,626	0.081	2.646
	Moderate	5,572	3.165	2.248
	Extensive/Complete	1,412	12.853	1.903
URM	None	1686		
	Minor	1,477	0.070	1.312
	Moderate	966	0.323	1.147
	Extensive/Complete	647	0.596	0.773

Table 6 shows the total number of data available for this study and the number of buildings determined to be in each damage state.

Table 6: Number of buildings with available data and total buildings in each Damage State.

Data Category		No.
Total Buildings		69,734
With available LLRS information.		53,344
With available storey no. information.		42,391
Damage State:	Excluded	3142
Damage State:	None	19,181
Damage State:	Minor	35,312
Damage State:	Moderate	8,260
Damage State:	Extensive/Complete	3,839

7 DISCUSSION

7.1 Data Quality

The largest and most useful source of damage data for this study was from RBS survey results. In terms of inferring damage, the RBS data suffered from a lack of consistency of application. There were instances of significantly different data for buildings in both the CCC and CEBA databases. E.g. an *estimated overall building damage* of '0-1%' in one database and '61-99%' in the other. If the RBS assessments were to be slightly modified then data from future earthquakes would be much more reliable for future fragility studies in New Zealand. For example, a range of damage options could be provided on assessment forms (e.g. Minor, Moderate, Severe, Complete) with one sentence descriptors given for each option to ensure consistency of application.

7.2 Data Availability

It can be seen from the data points in Figure 1 and Figure 2 that, with the exception of timber buildings the data is largely centred in the 0.4g – 0.5g PGA range. The Christchurch CBD and adjacent commercial/industrial areas, with high concentrations of non-residential buildings, were generally in that range. Also noticeable is that the data points show a higher percentage of buildings exceeding each Damage State in this PGA range. The reason for this is not obvious, it could be that the earthquakes effects were more severe in that zone, that the buildings in this zone were more fragile than other zones, or that the Damage Indicators applied to the CBD buildings were biased on the higher side.

The calculated fragility functions are strongly influenced by the 0.4g - 0.5g data and may lead to the damage probabilities being under-estimated for low PGA's and over-estimated for higher. Further analysis of the Christchurch data for construction date, seismic ratings and soil class may shed light on this matter, although the available data of these type are limited. Since the majority of higher-rise (four storey plus) buildings were located in the CBD, and therefore experienced a narrow range of PGA's, there are insufficient data to calculate fragility functions for them.

The damage state of most interest for risk of harm and regulatory earthquake prone building classification purposes is Collapse. There were insufficient data to calculate fragility curves for a Collapse Damage State as only two non-URM buildings are recorded as having collapsed (Pyne Gould Corporation and Canterbury Television buildings). Given the number of buildings exposed, it follows that the probability of collapse of non-URM buildings in moderate to strong ground shaking of the type experienced in Christchurch is very low.

More data from other earthquakes are required if robust, evidence-based fragility functions for New Zealand buildings are to be developed. Damage data from all (or a representative sample of) buildings

subject to ranges of shaking are required, not just those that were significantly damaged (ATC, 2012). At present the most useful source of these data, the RBS evaluations, are generally only initiated and collated when a Civil Defence Emergency is in declared. Consequently, opportunities to collate very useful data from the 2013 Cook Strait and Seddon and 2016 Kaikoura earthquakes for example, where buildings in Wellington City and elsewhere were subjected to moderate to strong shaking, were missed. Given the value of these data it would appear to be desirable to implement a system to collect them, possibly managed by GNS Science.

8 CONCLUSIONS

- This study demonstrates how data collected by CERA and Christchurch City Council in the process of managing the risk of harm from buildings damaged in the Canterbury earthquake sequence can be used to calculate empirical damageability models, in this case "Fragility Functions". These models are useful tools for society to assess and manage risk posed by its building stock in future earthquakes.
- The data were dominated by the February 2011 event. As such, some structural typologies had limited ranges of PGA over which to develop empirical curves. Meaningful curves were therefore only able to be developed for low-rise buildings of various structural typologies. Even then, structural typologies other than timber framed and masonry - reinforced lacked data across a wide range of PGA's. Augmenting the Canterbury data with data from future earthquakes would close these gaps and improve the relevance of these curves.
- It is proposed that readily implementable changes to the ways that building and damage data are recorded in the Rapid Building Safety evaluations could allow more accurate fragility curves to be developed.
- RBS evaluations are generally only undertaken and collated in a comprehensive way when a Civil Defence Emergency is in place. It is proposed that a system to collect comprehensive building and damage data in non-emergency events (e.g. the 2013 Cook Strait and 2016 Kaikoura earthquakes) is required.

9 ACKNOWLEDGEMENT

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A full report on the study titled *Seismic Fragility of Older New Zealand Buildings* and numbered *PROP-29151-HAZCHCH-OPS* is available and expands on the data presented in this paper.

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