16TH EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING THESSALONIKI 18 - 21 JUNE 2018

DAMAGE, CASUALTY, AND LOSS SCENARIOS FOR NEW ZEALAND'S NORTH ISLAND CHURCHES

Shannon ABELING[1], Tatiana GODED[2], Nick HORSPOOL[3], Sonia GIOVINAZZI[4], Jason INGHAM[5]

ABSTRACT

The seismic vulnerability of 79 churches (65% timber, 16% reinforced concrete (RC), 13% unreinforced masonry (URM), and 6% concrete block) owned by the Anglican Diocese of Waikato and Taranaki, New Zealand has been assessed. Two types of seismic scenarios have been produced using the latest version of New Zealand's National Seismic Hazard Model and RiskScape tool. The seismic scenarios produced are (1) the most likely events at 500-, 1000- and 2500- year return periods for each church location, and (2) a series of large earthquakes affecting New Zealand's North Island. Expected global damage levels for each church have been derived for each of the proposed scenarios using the macroseismic method, where the seismic hazard is defined by the intensity and correlated to post seismic damage. The macroseismic method used has been recently developed, and is specifically designed for New Zealand URM churches, based on a widely tested approach for European historical buildings. Preliminary vulnerability curves generated for the URM churches estimate Modified Mercalli Intensities (MMI) between 6.5 and 9.0 and mean damage grades between 1 (light damage) and 3 (severe damage) based on the EMS-98 classification of damage to masonry buildings. Using the RiskScape tool, preliminary economic loss estimations have been obtained based on asset value data, and casualty estimations have been evaluated for each church. Given the design level earthquake for each church, all timber and concrete block churches were estimated to have either no damage or light damage. Using the median estimate, 15% (2) of the RC churches and 40% (4) of the URM churches were estimated to have moderate damage, and 50% (5) of the URM churches were estimated to have severe damage. No churches were estimated to cause a death when subjected to their design level earthquake, and 89% (70) of churches were estimated to have a ratio of repair cost to replacement cost of less than 10%.

Keywords: Churches; seismic vulnerability; risk and loss scenarios; seismic scenarios; loss estimations

1. INTRODUCTION

The inherent architectural characteristics of churches (and comparable temples and building forms where worship is performed) cause this general class of structures to be particularly vulnerable in earthquakes, when recognizing that they are often comprised of large open plans and thrusting structural elements. These architectural attributes, combined with non-ductile materials such as unreinforced masonry (URM) and early reinforced concrete (RC), have been shown to perform poorly in earthquakes worldwide (Sofronie, 1982; Montilla et al., 1996; Guerreiro et al., 2000; Lagomarsino & Podesta, 2004;

---

[1]PhD Candidate, Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand, sabe321@aucklanduni.ac.nz
[2]Seismic Hazard Modeller, GNS Science, Avalon, New Zealand, T.Goded@gns.cri.nz
[3]Risk Specialist, GNS Science, Avalon, New Zealand, N.Horspool@gns.cri.nz
[4]Senior Research Fellow, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, New Zealand, sonia.giovinazzi@canterbury.ac.nz
[5]Professor, Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand, j.ingham@auckland.ac.nz

Lagomarsino, 2012; Sorrentino et al., 2014). In New Zealand, the Canterbury earthquake sequence of 2010/11 caused heavy damage to several clay brick and stone URM churches (Leite et al., 2014; Cattari et al., 2015), with damage from these earthquakes resulting in the demolition of several churches having significant historic, architectural, and social importance. In an effort to prevent further destruction of church architecture in future New Zealand earthquakes, research has been undertaken in terms of cataloguing and assessing URM churches. This research activity included the development of a nationwide inventory of URM churches (Marotta et al., 2015) and the undertaking of seismic vulnerability assessment of URM churches in New Zealand (Leite et al., 2013; Goded et al., 2016; Marotta et al., 2017).

A pilot study was undertaken to identify the seismic risk of Anglican churches in the Waikato and Taranaki Regions of New Zealand, with the aim of this study being to develop a methodology to determine damage, casualty, and economic loss estimates for churches in several earthquake scenarios. To develop loss models, RiskScape (King & Bell, 2009), a loss modelling tool for natural hazards, was utilized as well as recently developed vulnerability curves for New Zealand URM churches (King & Bell, 2009; Goded et al., 2016). The church inventory is introduced, the selection of seismic scenarios is described, the RiskScape modelling procedure is explained, and results from the pilot study are presented herein.

1.1 North Island Church Inventory

An inventory has been developed that includes 79 buildings owned by the Anglican Diocese of Waikato and Taranaki which either currently or formerly served as a church. While not located in the most seismically active region of New Zealand, this building inventory was used to develop a methodology for the seismic risk assessment of New Zealand churches because the Diocese provided full access to archives and assisted in coordinating church inspections. The inventory includes churches of includes 65% (51) timber, 16% (13) reinforced concrete, 13% (10) unreinforced masonry, and 6% (5) concrete block churches. More information on the seismic screening procedure and statistics on the church inventory are provided in Abeling et al. (2018).

1.2 Seismicity of the Waikato and Taranaki Regions

The inventory is comprised of churches located primarily in the Waikato and Taranaki regions of New Zealand. These regions have moderate to low seismicity, but still pose some risk from earthquakes (Figures 1,2).

The Waikato Region is location on the North Island of New Zealand (Figures 1-2). It includes areas of low to moderate seismicity, with active faults in eastern and southern parts of the region. The most notable fault is the Kerepehi Fault, which has potential to produce M_w 5.5 to M_W 7.4 earthquakes (Figure 1) (Persaud et al., 2016). Previous earthquakes in this region include the M_L 4.6 Morrinsville earthquake in 1926, the M_L 5.1 Te Aroha earthquake in 1972, and the M_L 5.1 Korakonui earthquake in 1976 (GeoNet, 2017). All three earthquakes caused damage to houses and chimneys in areas near the epicentres and the Te Aroha earthquake caused minor damage to a URM church that required repairs (Eiby, 1968; Adams et al., 1972; Eiby, 1977).

The Taranaki Region is located south and west of the Waikato region (Figures 1-2), and also includes areas of low to moderate seismicity. There are several active faults in the western part of the region that lie in a northeast-southwest orientation, including the Inglewood Fault (Figure 1). The annual likelihood of a magnitude 6.0 earthquake is estimated to be 5% in South Taranaki and 3% in North Taranaki (Hull & Dellow, 1993). Previous earthquakes in this region include an M_L 6.8 earthquake near New Plymouth in 1853, an M_L 6.0 earthquake 30-40 km northeast of New Plymouth in 1912, and the M_L 6.1 Opunake earthquake in 1974 (Hull, 1994). These earthquakes caused shaking of MMVIII, MMVII, and MMVI respectively in parts of Taranaki and are reported to have caused cracked chimneys, walls, and ceilings (Robinson et al., 1976; Hull, 1994).

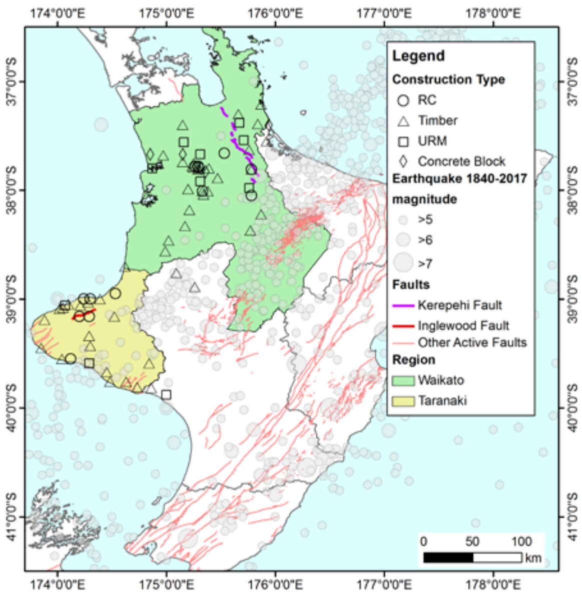

Figure 1. Location of inventory churches in relation to active faults and earthquake epicentres (fault data for image from Langridge et al. (2016))

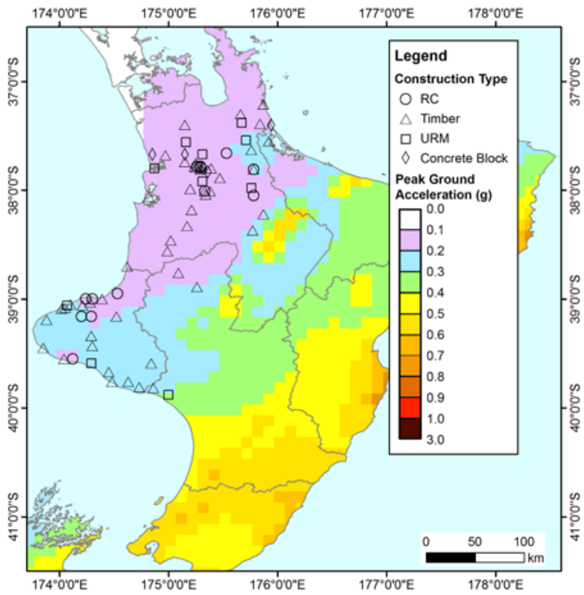

Figure 2. Location of inventory churches in relation to the 475 year return period, shallow soil PGA (source data for image from Stirling et al. (2012)).

2. SEISMIC SCENARIOS

Seismic scenarios were used to estimate damage, casualties and losses. Two types of seismic scenarios were used: 1) probabilistic scenarios (herein also referred to as design level earthquakes), based on the highest contributing sources at 500-, 1000- and 2500-year return periods, depending on the occupancy levels and the presence or absence of the church in the Heritage New Zealand listing; and 2) deterministic scenarios based on large potential events in the Taranaki and Waikato regions.

2.1 Design Level Earthquakes (probabilistic scenarios)

The scenarios were generated by choosing the fault source with the highest contribution to the seismic hazard for each location for 500-, 1000- and 2500-year return periods, using the latest version of New Zealand's National Seismic Hazard Model (Stirling et al., 2012). The highest contributors were chosen at Peak Ground Acceleration (PGA) level. The return periods were chosen using the criteria presented in Table 1 (Clark, 2017).

Table 1. Criteria for determining the mean return period of the design event for New Zealand churches

Church Location	Maximum Occupancy	Usage	Heritage Listing	Importance Level	Design event mean return period
Rural or suburban	<300	Infrequent	None	IL2	500-year
Rural or suburban	<300	Infrequent	Category 1 or 2	IL2	1000-year
Suburban or central	>300	Frequent	None	IL3	1000-year
Central	>300	Frequent	Category 1 or 2	IL3	2500-year

Once the seismic scenario has been selected, the magnitude of the fault source and its distance to the town centre are used to calculate the Modified Mercalli intensity, using New Zealand's current intensity attenuation equation (Dowrick & Rhoades, 2005). This intensity is used to estimate the expected damage using the individual vulnerability curve for each church.

In addition, as a first approximation of the site effects at each of the buildings, intensity amplification factors have been obtained from a site class map for the whole country (Perrin et al., 2015). The site classes have been obtained from the average shear-wave velocity to 30 m depth, or Vs30 values, which were calculated from available geotechnical data (e.g. seismic cone penetration tests, microtremor measurements). The site classes correspond to the New Zealand Loading Standard, NZS 1170.5 (Standards New Zealand, 2004) being classes A (Strong Rock), B (Soft Rock), C (Shallow Soil), D (Deep or Soft Soil) and E (Very Soft Soil). Once site classes were assigned to each church, intensity amplification factors were derived from the amplification factors for each New Zealand site class obtained by Dowrick and Rhoades (2005). However, it should be noted that the site class maps used to calculate intensity amplifications were obtained through broad-scale modelling, and are not site-specific. Thus, vulnerability results derived using site effects from these site class assignments should be treated with caution and only be used as an indication of the areas where significant site effects may appear.

2.2 Scenario Earthquakes

In addition to the seismic scenarios for design level earthquakes, two deterministic scenario earthquakes were chosen: Kerepehi Central Fault and Inglewood Fault ruptures (Russ Van Dissen, GNS Science, personal communication). Both earthquake scenarios correspond to active faults having the potential to generate high magnitudes within the Taranaki and Waikato regions, where the churches are located, and represent the largest potential events in the area of this study. The Kerepehi Central Fault is the segment of the Kerepehi Fault with the largest predicted magnitude (M_w 6.9), and corresponds to a normal mechanism event with a recurrence interval of 5400 years. The Inglewood Fault (M_w 6.5) has a normal with strike slip component mechanism and a recurrence interval of 4200 years.

3. RISKSCAPE

RiskScape is a multi-hazard loss modeling tool that has the ability to model the impacts of scenarios, events, or probabilistic ensembles using hazard-exposure models that are either built into the program or user input (King & Bell, 2009). The building inventory was modified so that it may be input into RiskScape software as an inventory of assets. The asset inventory included a number of building characteristics (e.g., construction type, year of construction, floor area, presence/absence of parapets), building occupancy numbers, and asset replacement cost. RiskScape assigned each item in the inventory to a vulnerability class and each vulnerability class to the corresponding fragility function. The fragility function related the MMI to the damage state for each inventory item. The assigned damage state was then used to estimate casualties and economic loss.

3.1 Fragility Functions

RiskScape uses the following equations to determine the mean damage ratio (MDR) for a given shaking intensity (MMI):

$$\text{MDR} = \text{A} \times 10^{\left(\frac{\text{B}}{\text{MMI-C}}\right)} \quad \text{for MMI} \geq \text{M, and} \tag{1}$$

$$\text{MDR} = \text{A} \times 10^{(\text{D} \times \text{MMI} + \text{E})} \quad \text{for MMI} < \text{M} \tag{2}$$

where A, B, C, D, and E are constants defined for each building class, and M is the Modified Mercalli Intensity at which the functional form changes (Cousins, 2004; King & Bell, 2009). The equations are based primarily on New Zealand data for intensities MM5.0 to MM7.9 and a combination of New Zealand and California data for intensities MM8.0 to MM11.0 (Rojahn & Sharpe, 1985; Dowrick, 1991; Dowrick & Rhoades, 1993; Dowrick et al., 2001).

Cambridge Architectural Research Ltd. developed the following formula to estimate the probability of loss exceeding any given loss ratio (LR), given the MDR:

$$\phi^{-1}(\text{R}) = \text{a}\ \phi^{-1}(\text{MDR}) + \text{b}\ \phi^{-1}(\text{LR}) \tag{3}$$

where ϕ^{-1} refers to the inverse of the standard cumulative Gaussian distribution, R is the proportion of the sample with a loss ratio exceeding LR, and a and b are constants that are dependent on the building class (Cousins et al., 2014).

RiskScape uses the loss ratio to determine the damage state of an asset. The damage states and loss ratio ranges used by RiskScape for buildings in earthquakes are shown in Table 2 (Cousins et al., 2014) and an example of the derived relationship between MMI and the probability of a building being in a defined damage state is shown in Figure 3.

Table 2. Damage states and loss ratios

Loss Ratio	Damage State	Description
1 to 10%	DS1	Light
10 to 35%	DS2	Moderate
35 to 75%	DS3	Severe
75 to 90%	DS4	Partial Collapse
>90%	DS5	Collapse

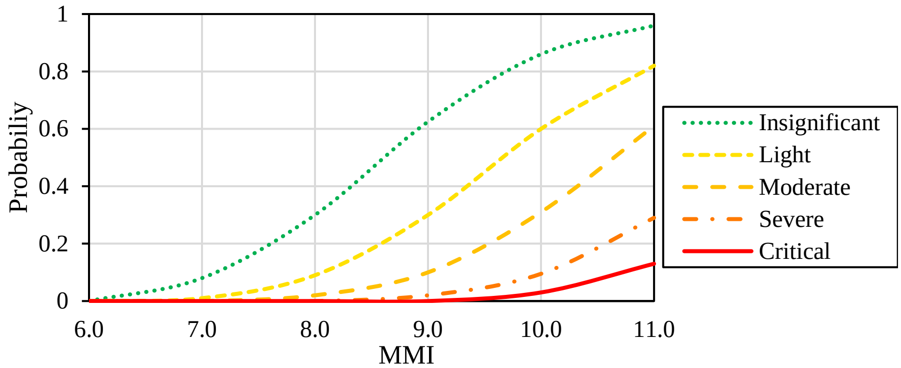

Figure 3. Example RiskScape fragility functions for shaking intensity and probability of being in one of the defined damage states, adapted from Cousins et al. (2014)

The RiskScape fragility functions are not specific to churches. As there are few existing fragility functions for New Zealand churches of construction types other than URM, the RiskScape fragility functions corresponding to timber, RC and concrete block materials have been used for the corresponding churches in this study. Fragility functions corresponding to the URM churches have been included in RiskScape. The process used to determine the MDR for URM churches is described in the following section.

3.1.1 New Zealand URM Church Vulnerability Functions

A macroseismic method was developed by Goded et al. (2016) to determine the seismic vulnerability of New Zealand URM churches, in which the following equation was used to determine the mean damage grade of a URM church:

$$\mu_D = \left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \quad (4)$$

where μ_D is the damage grade, I is the Modified Mercalli Intensity, V is the Vulnerability Index, and Q is the Ductility Index and is equal to a value of 3. The equation was originally proposed by Lagomarsino (2006) for churches and vulnerability index modifiers were specifically developed for New Zealand URM churches based on damage observed in the Canterbury earthquakes of 2010/2011 (Goded et al., 2016). The vulnerability index for a specific URM church was calibrated based on the building characteristics, such as masonry quality, state of maintenance, existing building damage, structural transformations, etc., and structural features such as the number of naves or the height of the lateral walls. More details of the development of the vulnerability curves and associated methodology for URM churches are described in Cattari et al. (2015) and Goded et al. (2016). An example vulnerability function for a New Zealand URM church is shown in Figure 4. The damage grade output from this generated vulnerability curve was based on the masonry damage grades suggested by EMS-98 (Grünthal, 1998). For compatibility within RiskScape, it has been assumed that the RiskScape Damage States 0-5 are directly interchangeable with EMS-98 Damage Grades 0-5.

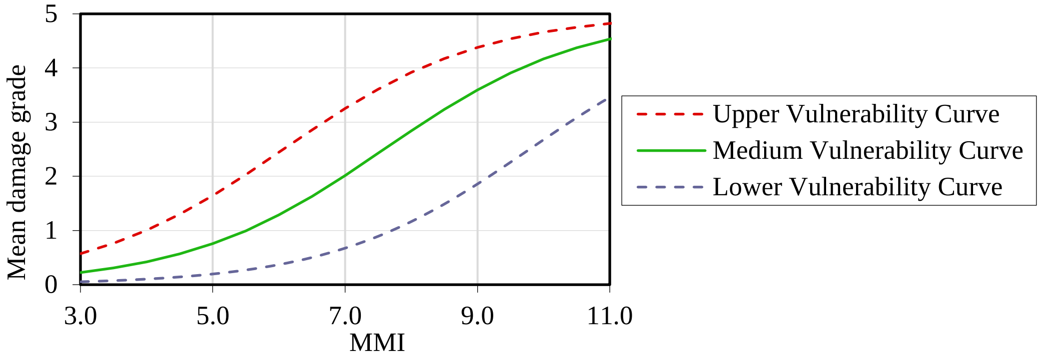

Figure 4. Example of New Zealand URM church vulnerability function for mean damage grade due to shaking intensity, adapted from Goded et al. (2016)

The probability of a URM church being within a particular damage state was determined based on a binomial distribution defined by the mean damage grade, μ_D (Braga et al., 1982). The probability, p_k, associated with being in damage grade k is represented by the following equation:

$$p_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_d}{5}\right)^k \left(1 - \frac{\mu_d}{5}\right)^{5-k} \quad (5)$$

3.2 Casualty Modelling

RiskScape uses a simplified model to estimate casualties based on the building construction type and the assigned damage state. The model that RiskScape uses is based on worldwide data and assigns a casualty state to each occupant of a building. Casualty states include no injury or light injury, moderate injury, serious injury, critical injury, and death. An example of a model that RiskScape uses to determine casualty states is presented in Table 3. The numbers provided in the example model are probabilities, and RiskScape uses a random number to assign an occupant to a casualty state.

The described procedure only accounts for casualties that occur as a result of building collapse. RiskScape accounts for other causes of casualties (e.g., fire, landslides, falling glass, parapets and gables, and panic reaction) separately and adds them to the casualty count.

The building occupancy used for the results presented herein was the typical number of people that attend Sunday morning service at a given church. The occupancy of a church would be expected to be much lower on a typical weekday and would be expected to be zero on a typical night.

Table 3. Damage states and damage ratios (Cousins et al., 2014)

Casualty State	**Building Type: URM**				
	DS1	**DS2**	**DS3**	**DS4**	**DS5**
CS1: No injury, or Light Injury	1	1	0.9576	0.8883	0.736
CS2: Moderate Injury	0	0	0.07	0.07	0.12
CS3: Serious Injury	0	0	0.0024	0.035	0.08
CS4: Critical Injury	0	0	0	0.0007	0.004
CS5: Death	0	0	0	0.006	0.06

3.3 Economic Loss Modelling

The following equation is used by RiskScape to determine economic loss (King & Bell, 2009):

Loss = MDR x Replacement Value (6)

where loss is the repair cost and MDR is the 'Mean Damage Ratio' as determined by the fragility or vulnerability function. The replacement value used was the Improvement Value provided by the

Quotable Value (QV) report for each property (QV, 2017). It is noted that the repair cost estimates for churches will likely be low due to the often high cost of labour required to repair these structures. RiskScape can also use a similar formula to determine contents repair cost. However, due to a large amount of uncertainty regarding the economic value of items owned by the churches, contents value was not considered as part of this study.

4. SCENARIO RESULTS

The described method was used to select scenario earthquake events. A hazard map was created to match a church with the corresponding MMI for the church's design level earthquake. This evaluation was used to help identify churches that would likely sustain the most damage and that represent the highest risk given a design level earthquake. To simulate the impact of a single event on the entire building inventory, hazard models were run for the Inglewood Fault and the Kerepehi Central Fault earthquakes. Each scenario was performed using RiskScape numerous times until a stable distribution of results was obtained. The results of the scenarios are presented in the following sections.

4.1 Design Level earthquakes

A hazard map that matched each church to the corresponding MMI for its design level earthquake was introduced as input into RiskScape. The probability of a church being in each damage state is shown in Figure 5. Figures 6 and 7 show the median and 84th percentile estimates, respectively, for damage grade distribution of the churches for their design level earthquakes. All timber churches and concrete block churches were estimated to remain in DS1. Most RC churches were estimated to remain in DS1, but a few were estimated to be in DS2 and DS3 for the median and 84th percentile estimates, respectively. URM churches were estimated to have the worst performance given a design level earthquake. Figure 8 shows the number of churches that were estimated to have at least one person in the specified casualty state given Sunday morning occupancy and the design level earthquake. Most churches (93% for median estimate and 87% for 84th percentile estimate) were projected to not cause any moderate or worse injuries given their design level earthquake. Using the 84th percentile estimate, 2 churches (2.5%) were estimated to cause at least one death. The median and 84th percentile estimates for the ratio of repair cost to replacement cost are shown in Figure 9. Most churches (89% for median estimate and 87% for 84th percentile estimate) were estimated to have a ratio of repair cost to replacement cost less than 10%.

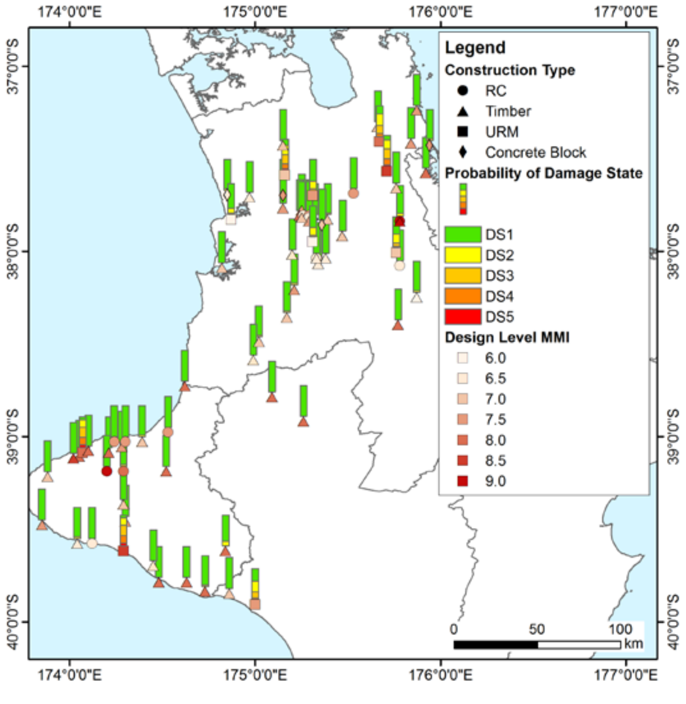

Figure 5. Probability of church in the inventory being in each damage state given the extimated MMI for its design level earthquake

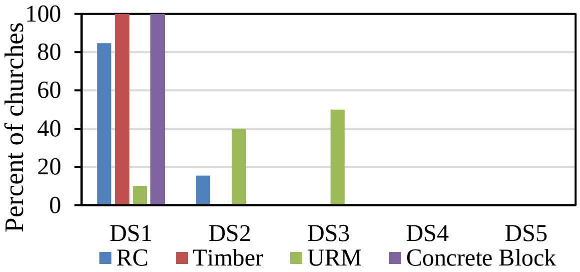

Figure 6. Median damage grade distribution for design level earthquake

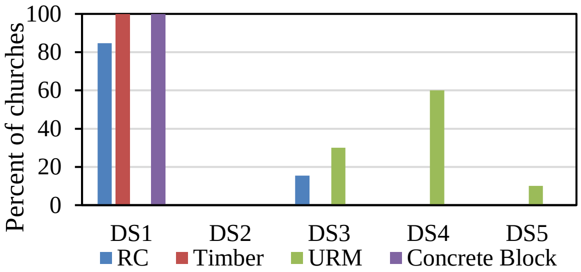

Figure 7. 84th Percentile damage grade distribution for design level earthquake

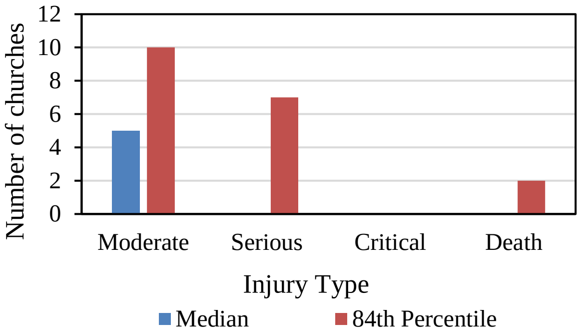

Figure 8. Median and 84th percentile distributions of churches that cause at least one injury in the specified injury state for design level eathequake

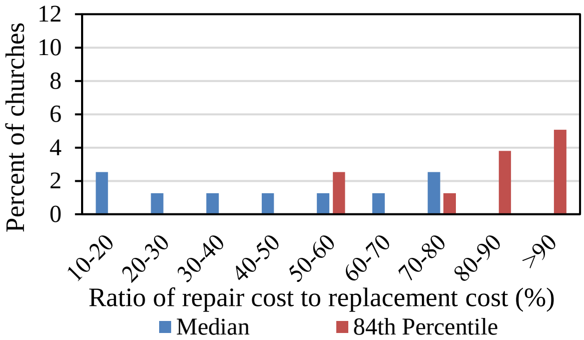

Figure 9. Median and 84th percentile distributions of ratio of repair cost to replacement cost for design level earthquake

4.2 Kerepehi Central Fault Earthquake

Damage states, casualties and losses were estimated for the church inventory in the Kerepehi Central Fault earthquake scenario. The probability of a church being in each damage state is shown in Figure 10, and the median and 84th percentile estimates for damage states, casualties, and losses are shown in Table 4. Given the median estimates, 6 churches (all URM) along the fault like are likely to be in DS3 or DS4. One death was estimated to occur, as well as four serious injuries and sixteen moderate injuries. The inventory was estimated to require just over NZ$1.6 million dollars in repair costs.

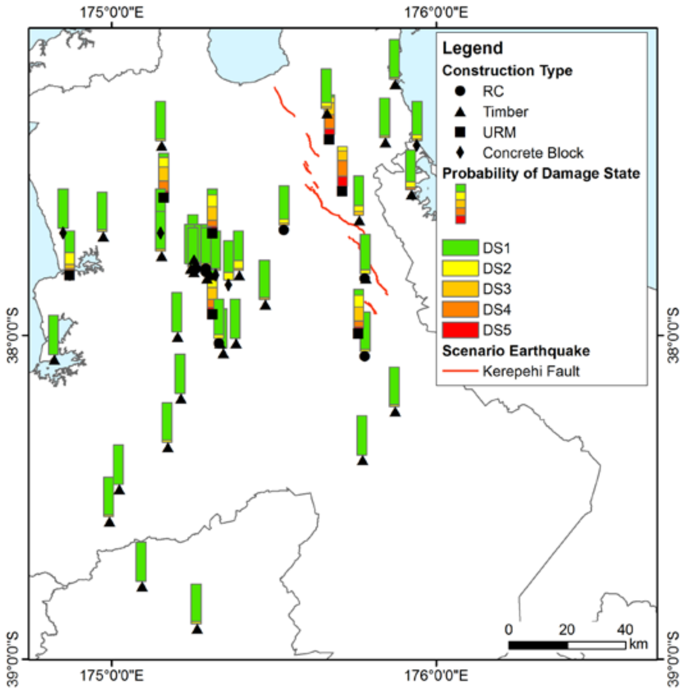

Figure 10. Probability of church being in each damage state in the Kerepehi Central Fault scenario earthquake

Table 4. Kerepehi Central Fault scenario earthquake losses

	50th Percentile (Median) Losses	84th Percentile Losses
Number of Buildings	79	79
DS5 - Collapse	0	4
DS4 – Partial Collapse	2	3
DS3 – Severe Damage	4	0
DS2 – Moderate Damage	1	7
DS1 – Light Damage	72	65
Occupants - Sunday	2660	2660
CS5 - Deaths	1	12
CS4 - Critical Injuries	0	1
CS3 - Serious Injuries	4	18
CS2 - Moderate Injuries	16	28
Value (NZD)	22,604,500	22,604,500
Repair Cost (NZD)	1,621,144	3,289,337

4.3 Inglewood Fault Earthquake

Damage states, casualties and losses were also estimated for the church inventory in the Inglewood Fault earthquake scenario. The probability of a church being in each damage state is shown in Figure 11, and the median and 84th percentile estimates for damage states, casualties, and losses are shown in Table 5. Given the median estimates, only one church was estimated to be in DS2 and one church was estimated to be in DS3. Seven moderate injuries were estimated to occur, and the inventory was estimated to require approximately NZ$1.9 million dollars in repair costs. The reason that the repair cost for the church inventory was estimated to be higher in the Inglewood Fault earthquake than in the Kerepehi Central Fault earthquake even though fewer buildings are forecast to be damaged in the Inglewood Fault earthquake is because the church that is likely to sustain severe damage is a large cathedral.

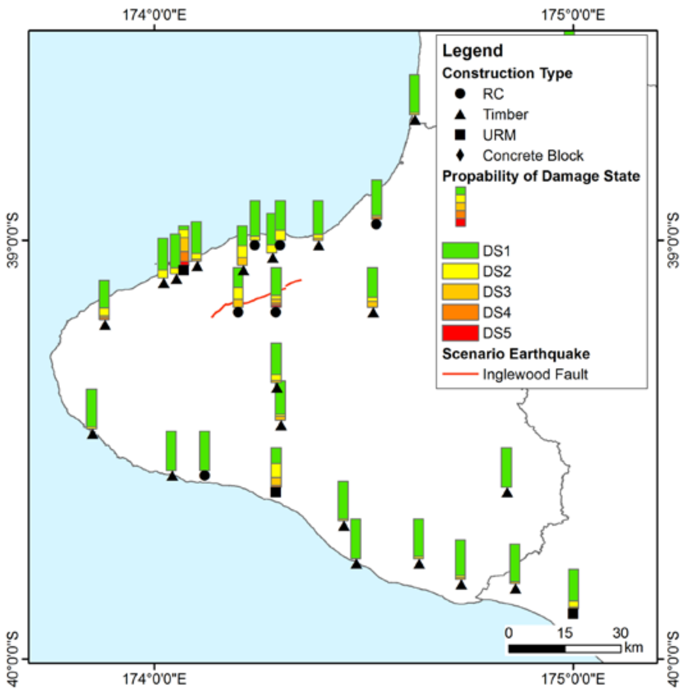

Figure 11. Probability of church being in each damage state in the Inglewood Fault scenario earthquake

Table 5. Inglewood Fault scenario earthquake losses

	50th Percentile (Median) Losses	84th Percentile Losses
Number of Buildings	79	79
DS5 - Collapse	0	0
DS4 – Partial Collapse	0	2
DS3 – Severe Damage	1	5
DS2 – Moderate Damage	1	13
DS1 – Light Damage	77	59
Occupants - Sunday	2660	2660
CS5 - Deaths	0	1
CS4 - Critical Injuries	0	0
CS3 - Serious Injuries	0	6
CS2 - Moderate Injuries	7	18
Value (NZD)	22,604,500	22,604,500
Repair Cost (NZD)	1,912,449	3,334,261

5. CONCLUSIONS

The research presented herein was used to develop a method to determine the seismic risk of churches in New Zealand. RiskScape was used to develop damage, casualty, and economic loss estimation for churches given their design level earthquake and two scenario fault rupture earthquakes. Given the design level earthquake for each church, all timber and concrete block churches were estimated to remain in DS1 (no or light damage). The median estimates for RC churches were that 15% (2) would be in DS2 (moderate damage) and the remaining churches would be in DS1. The median estimates for URM churches were that 50% (5) would be in DS3, 40% (4) would be in DS2, and only 10% (1) would be in DS1. No churches were estimated to cause a death in their design level earthquake using the median estimate, and approximately 2% of the churches (2) were estimated to cause at least one death using the 84th percentile estimate. In the Kerepehi Central Fault earthquake, 6 churches (all URM) were estimated to be in DS3 or DS4 given the median estimates. One death was estimated to occur, and the inventory was estimated to require approximately NZ$1.6 million dollars in repair costs. In the Inglewood Fault earthquake, 2 churches were estimated to be in DS2 or DS3 given the median estimates. No deaths were estimated to occur, and the inventory was estimated to require approximately NZ$1.9 million dollars in repair costs. Further research will estimate damage, casualty, and losses for other likely scenario earthquakes in the area of the church inventory. Data collection on churches throughout New Zealand is also being undertaken to expand the inventory and develop a clearer estimate of earthquake risk to churches throughout New Zealand.

6. ACKNOWLEDGMENTS

This project was supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre. This is QuakeCoRE publication number 0234. We thank Russ Van Dissen (GNS Science) for providing recommendations on the faults to use for the deterministic scenarios. We acknowledge the New Zealand GeoNet project and its sponsors EQC, GNS Science and LINZ, for providing data/images used in this study.

7. REFERENCES

Abeling S, Vallis S, Galvez F, Goded T, Horspool N, Giovinazzi S, and Ingham J (2018). Seismic Screening of Anglican Churches in the Waikato and Taranaki Regions of New Zealand. *Proceedings of the New Zealand Society for Earthquake Engineering NZSEE 2018 Conference*, Auckland, New Zealand.

Adams RD, Muir MG, and Kean RJ (1972). Te Aroha Earthquake, 9 January 1972. *Bulletin of the New Zealand Society for Earthquake Engineering*, 5(2): 54-58.

Braga F, Dolce M, and Liberatore D (1982). A statistical study on damaged buildings and an ensuing review of the MSK-76 scale. *Proceedings of the 7th European Conference on Earthquake Engineering*, 20-25 September, Athens, Greece.

Cattari S, Ottonelli D, Pinna M, Lagomarsino S, Clark W, Giovinazzi S, Ingham JM, Marotta A, Liberatore D, Sorrentino L, Leite J, Lourenco PB, and Goded T (2015). Damage and vulnerability analysis of URM churches after the Canterbury earthquake sequence 2010-2011. *Proceedings of the SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World*, 9-10 July, Cambridge UK.

Clark W (2017). [Executive officer of the New Zealand Society for Earthquake Engineering], personal communication.

Cousins WJ (2004). Towards a first-order earthquake loss model for New Zealand. *Proceedings of the Conference of the New Zealand Society for Earthquake Engineering*, 19-21 March 2004, Rotorua, New Zealand.

Cousins WJ, Deligne NI, and Nayyerloo M (2014). Estimated damage and casualties for earthquakes affecting Auckland, Lower Hutt, New Zealand, GNS Science.

Dowrick DJ (1991). Damage costs for houses and farms as a function of intensity in the 1987 Edgecumbe earthquake. *Earthquake Engineering and Structural Dynamics*, 20(5): 455-469. 10.1002/eqe.4290200506.

Dowrick DJ, and Rhoades DA (1993). Damage costs for commercial and industrial property as a function of intensity in the 1987 Edgecumbe earthquake. *Earthquake Engineering and Structural Dynamics*, 22(10): 869-884. 10.1002/eqe.4290221004.

Dowrick DJ, and Rhoades DA (2005). Revised models for attenuation of modified mercalli intensity in New Zealand Eathquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, 38(4): 185-214.

Dowrick DJ, Rhoades DA, and Davenport PN (2001). Damage ratios for domestic property in the magnitude 7.2 Inangahua, New Zealand, earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, 34(3): 191-213.

Eiby GA (1968). An annotated list of New Zealand earthquakes, 1460-1965. *New Zealand Journal of Geology and Geophysics*, 11(3): 630-647. 10.1080/00288306.1968.10420275.

Eiby GA (1977). Anomalous intensities due to the Korakonui earthquake, 5 December 1976. *Bulletin of the New Zealand Society for Earthquake Engineering*, 10(4): 167-169.

GeoNet (2017). GeoNet Quake Search. Retrieved from https://quakesearch.geonet.org.nz/

Goded T, Giovinazzi S, Liberatore D, Pinna M, Cattari S, Ingham JM, Sorrentino L, Clark W, Langomarsino S, Marotta A, and Ottonelli D (2016). Vulnerability assessment of unreinforced masonry churches (EQC 14/660) - Final Report, GNS, 132 pp.

Grünthal G (1998). European Macroseismic Scale 1998. Cahiers du centre Européen de Géodynamique et de Séismologie, 15: 1-99.

Guerreiro L, Azevedo J, Proença J, Bento R, and Lopes M (2000). Damage in ancient churches during the 9th of July 1998 Azores earthquake. *Proceedings of the 12th World Conference on Earthquake Engineering*, 30 Jan - 4 Feb, Auckland, New Zealand.

Hull AG (1994). Past earthquake timing and magnitude along the Inglewood Fault, Taranaki, New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering*, 27(2): 155-162.

Hull AG, and Dellow GD (1993). Earthquake Hazards in the Taranaki Region, GNS Science Consultancy Report 1993/03, GNS Science,

King A, and Bell RPM (2009). RiskScape Project: 2004 - 2008, GNS Science Consultancy Report 2009/247, GNS Science, 162 pp.

Lagomarsino S (2006). On the vulnerability assessment of monumental buildings. *Bulletin of Earthquake Engineering*, 4(4): 445-463. 10.1007/s10518-006-9025-y.

Lagomarsino S (2012). Damage assessment of churches after L'Aquila earthquake. *Bulletin of Earthquake Engineering*, 10(1): 73-92. 10.1007/s10518-011-9307-x.

Lagomarsino S, and Podesta S (2004). Damage and vulnerability assessment of churches after the 2002 Molise, Italy earthquake. *Earthquake Spectra*, 20(S1): 271-283. 10.1193/1.1767161.

Langridge RM, Ries WF, Litchfield NJ, Villamor P, Van Dissen RJ, Rattenbury MS, Barrell DJA, Heron DW, Haubrock S, Townsend DB, Lee JA, Cox S, Berryman KR, Nicol A, and Stirling M (2016). The New Zealand active faults database: NZAFD250. *New Zealand Journal of Geology and Geophysics*, 59(1): 86-96. 10.1080/00288306.2015.1112818.

Leite J, Ingham JM, and Lourenco P (2014). Damage inspection in churches - The Canterbury earthquake (New Zealand) experience. *Proceedings of the Cultural Heritage and Loss Prevention (HELP) 2014*, 6-7 Oct, Porto, Portugal.

Leite J, Lourenco P, and Ingham JM (2013). Statistical Assessment of Damage to Churches Affected by the 2010-2011 Canterbury (New Zealand) Earthquake Sequence. *Journal of Earthquake Engineering*, 17(1): 73-97. 10.1080/13632469.2012.713562.

Marotta A, Goded T, Giovinazzi S, Lagomarsino S, Liberatore D, Sorrentino L, and Ingham J (2015). An inventory of unreinforced masonry churches in New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering*, 48(3): 171-190.

Marotta A, Sorrentino L, Liberatore D, and Ingham J (2017). Vulnerability assessment of unreinforced masonry churches following the 2010-2011 Canterbury (New Zealand) earthquake sequence. *Journal of Earthquake Engineering*, 21(6): 912-934. 10.1080/13632469.2016.1206761.

Montilla PJ, Uzcategui AI, and Hernandez SM (1996). Damages occurred to churches due to earthquake of February 8, 1995 in Pereira, Colombia. *Proceedings of the 11th World Conference on Earthquake Engineering*, 23-28 June, Acapulco, Mexico.

Perrin ND, Heron D, Kaiser A, and Van Houtte C (2015). Vs30 and NZS1170.5 site class maps of New Zealand. *Proceedings of the New Zealand Society for Earthquake Engineering NZSEE 2015 Conference*, 10-12 April, Rotorua, New Zealand.

Persaud M, Villamor P, Berryman KR, Ries W, Cousins J, Litchfield N, and Alloway BV (2016). The Kerepehi Fault, Hauraki Rift, North Island, New Zealand: active fault characterisation and hazard. *New Zealand Journal of Geology and Geophysics*, 59(1): 117-135. 10.1080/00288306.2015.1127826.

QV (2017). Property Report. Retrieved January-September 2017, from https://www.qv.co.nz/

Robinson R, Calhaem IM, and Thomson AA (1976). The Opunake, New Zealand, earthquake of 5 November 1974. *New Zealand Journal of Geology and Geophysics*, 19(3): 335-345. 10.1080/00288306.1976.10423563.

Rojahn C, and Sharpe RL (1985). Earthquake damage evaluation data for California, Redwood City, California, United States, Applied Technology Council, 492 pp.

Sofronie R (1982). Behaviour of eastern churches in earthquakes. *Proceedings of the 7th European Conference on Earthquake Engineering*, 20-25 Sept, Athens, Greece.

Sorrentino L, Liberatore L, Decanini LD, and Liberatore D (2014). The performance of churches in the 2012 Emilia earthquakes. *Bulletin of Earthquake Engineering*, 12(5): 2299-2331. 10.1007/s10518-013-9519-3.

Standards Australia and Standards New Zealand (2002). Structural design actions - Part 0: General principles. Wellington: Standards New Zealand.

Standards New Zealand (2004). Structural Design Actions Part 5: Earthquake actions–New Zealand. Wellington: Standards New Zealand.

Stirling MW, McVerry GH, Gerstenberger MC, Litchfield NJ, Van Dissen RJ, Berryman KR, Barnes P, Wallace LM, Villamor P, Langridge RM, Lamarche G, Nodder S, Reyners ME, Bradley B, Rhoades DA, Smith WD, Nicol A, Pettinga J, Clark KJ, and Jacobs K (2012). National seismic hazard model for New Zealand : 2010 update. *Bulletin of the Seismological Society of America*, 102(4): 1514-1542. 10.1785/0120110170.