Vulnerability analysis of unreinforced masonry churches (EQC 14/660) - Final Report

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EXECUTIVE SUMMARY

We undertake the first (to our knowledge) seismic vulnerability method specifically designed for New Zealand Unreinforced Masonry (URM) churches. The vulnerability index (*VI*) methodology developed by Lagomarsino et al. (2003) for European churches and other monumental buildings has been the basis for our work. The technique entails a macro-seismic approach which is based on the use of vulnerability curves to correlate the post-seismic damage grade of the building to the shaking intensity experienced, using a discrete probabilistic distribution. The method has been redefined, with a new set of parameters and modifiers specifically created for New Zealand URM churches. This has been done by analysing the damage caused to 48 URM churches in the Canterbury region during the 2010–2011 Canterbury earthquake sequence.

This report shows the main achievements obtained during this project, funded by the Earthquake Commission (reference 14/660, January 2014-June 2016), which include: (a) the structural data compilation of a wider stock of 297 URM churches spread within New Zealand; (b) a specific typological classification for New Zealand unreinforced masonry (URM) churches; (c) a damage survey form for URM churches; (d) a macroseismic method to obtain the seismic vulnerability of URM churches using *VI* modifiers that have been developed specifically for New Zealand URM churches, using the damage data from the Canterbury earthquakes; and (e) the development of seismic scenarios for the URM churches in Wellington, Auckland and Dunedin, using the new parameters developed within this project.

The typological analysis of the New Zealand URM churches justified the need to develop a method specifically created for this country, as results show the great differences in typologies to European churches, with very simple architectural designs and a majority of one nave churches in New Zealand. The method has been applied to three cities in New Zealand, with very different seismic activity, from low (Auckland) to intermediate (Dunedin) and high (Wellington). Differences in the results due to the different characteristic scenarios show the need to develop specific scenarios for each city / region.

This project is seen as a first step towards the qualification of all the historical buildings in the country, in order to preserve New Zealand's cultural and historical heritage. Future work identified includes (a) the development of seismic scenarios for the URM churches in the rest of New Zealand, (b) addition of site effects to the seismic scenarios, to account for local differences in intensities experienced in each church, to be developed for the entire set of URM churches in the country, (c) development of a more sophisticated method based on the mechanical approach that analyses the structural behaviour of individual components of the building (macroelements) and (d) the addition of other buildings part of the cultural heritage in New Zealand.

1.0 INTRODUCTION

The 2010–2011 Canterbury earthquake sequence caused significant damage and disruption, with damage to Christchurch's architectural heritage being particularly extensive, as highlighted by different post-earthquake reconnaissance studies (Anagnostopoulou et al., 2010; Ingham et al., 2012; Leite et al., 2013; Lourenço et al., 2013). The consequences of the earthquake-induced damage to churches were severe with around 85% and 80% of the heritage unreinforced stone and clay brick masonry (URM) churches, respectively, becoming inaccessible to the local religion communities in the Canterbury region (Leite et al., 2013) following the earthquakes. Furthermore, after the Canterbury earthquakes significant issues have raised such as: (a) increased need to preserve New Zealand's cultural heritage; (b) high costs to strengthen churches and other heritage buildings; (c) lack of clarity on who should be responsible for covering the necessary costs; and (d) need to prioritise / rank the heritage buildings.

The issues described above emphasised the impelling need to define a systematic method to assess the seismic vulnerabilities of New Zealand (NZ) churches. Such a method should: (a) support the detection of the structural and construction weakness of each church, towards the identification of more appropriate retrofitting techniques; and also (b) allow for the assessment of the level of damage expected to different churches in a certain earthquake event, aiming to prioritise interventions and assess the benefit that a retrofitting campaign could bring.

The main aim of this project was to analyse and quantify the seismic vulnerability of New Zealand churches. The vulnerability index method developed by Lagomarsino et al. (2003) for European churches and other monumental buildings has been the basis for our work. The technique entails a macro-seismic approach based on the use of vulnerability curves to correlate the post-seismic damage grade of the building to the shaking intensity experienced, using a discrete probabilistic distribution. The method has been applied in Europe with successful results, especially for churches (e.g., Lantada et al., 2010; Goded et al., 2012b). Damage data collected by members of the scientific team (Ingham) for 48 URM churches in the Canterbury region following the February 2011 earthquake, has been used. Aims of the project are: (1) testing and calibrating the *VI* method on New Zealand churches by assuming a-priori that the seismic performance of New Zealand URM churches is similar to European ones; and (2) statistically processing and analysing the damage data of Canterbury URM churches to define a new set of parameters that are New Zealand specific to be included in the *VI* method.

To provide a prompt and effective answer to the aforementioned needs a specific research project titled "Vulnerability analysis of unreinforced masonry churches" was launched and funded by the New Zealand Earthquake Commission, EQC 2014 (EQC Project 14/660) within the 2014 EQC Biennial Contestable Grants Programme. This project, which is now ending, was conceived as a multi-disciplinary, multi-agency and international effort, involving: GNS Science (leading institution, project PI Dr Tatiana Goded); University of Auckland; University of Canterbury; Heritage New Zealand Pouhere Taonga; University of Minho, Portugal; University of Genoa, Italy; New Zealand Ministry of Environment; Sapienza University, Rome (Italy); New Zealand Society for Earthquake Engineering. The project also benefitted from contributions by other researchers (see below). The objectives of this project are listed in Table 2.1.

Such a huge collaboration and effort allowed parallel activities to proceed, resulting in timely and significant outputs. This report presents the main results derived from this project, including (a) a detailed analysis of the earthquake-induced damage to a stock of 48 URM churches located in the Canterbury Region; (b) the seismic vulnerability analysis of a wider stock of 297 URM churches located all around New Zealand; a specific typological classification for New Zealand unreinforced masonry (URM) churches; (c) a damage survey form for URM churches; (d) a macroseismic method to obtain the seismic vulnerability of URM churches using vulnerability index modifiers that have been developed specifically for New Zealand URM churches, using the damage data from the Canterbury earthquakes; and (e) the development of seismic scenarios for the URM churches in Wellington, Auckland and Dunedin, using the new parameters developed within this project.

This project was benefitted by the addition of new members, at no extra cost to the project.

- Serena Cattari, assistant professor at Genoa University (Italy), part of Sergio Lagomarsino's team, responsible for the two conference presentations in New Zealand and the United Kingdom, supervisor (together with Sonia Giovinazzi) of the three Master students during their stay in Canterbury University, and one of the persons responsible for the new vulnerability method.
- Daria Ottonelli, PhD student of structural engineering from Genoa University (Italy), part of Sergio Lagomarsino's team, who spent six months at Canterbury University working for the project.
- Alessandra Marotta, PhD student of structural engineering at Sapienza University (Rome, Italy), together with her PhD supervisors, Domenico Liberatore and Luigi Sorrentino. Alessandra spent six months at University of Auckland working with Jason Ingham, and carried out a fieldwork to gather the data needed to develop the vulnerability curves for this project.
- Matilde Pinna, Arianna Bazzurro and Francesca Porta, Master students at Genoa University (Italy) who spent two months at Canterbury University analysing the damage caused to the URM churches during the Canterbury 2010–2012 earthquake sequence. Their results were published in a joint Master thesis in February 2015.

  In addition, three people have been added as collaborators to the project. They have been very supportive to the project and have provided very useful information and data.

- Alison Dangerfield (Heritage New Zealand)
- Barbara Rouse (Heritage New Zealand)
- Dave Mullin (Catholic Archdiocese of Wellington)

2.0 OBJECTIVES

The main objectives from this project, as described in the first phase of the funding application in April 2013, are summarised in Table 2.1.

Table 2.1 Project objectives (as listed in the EQC funding application, April 2013).

Ref.	Objectives
1	Compile structural data from URM churches in the Canterbury region and the cities of Wellington and Dunedin, including a field survey in Auckland to add the data from URM churches in that city.
2	Compile the damage data to URM churches in the Canterbury region during the 22 February 2011 earthquake.
3	Develop individual vulnerability curves for different URM church types identified, using the vulnerability index methodology developed for European monuments.
4	For Canterbury churches, obtain expected damage grades in New Zealand Modified Mercalli intensity (MMI) scale, and compare to the observed damage in the 22 February 2011 earthquake, to test the applicability of the Vulnerability Index (VI) methodology to New Zealand churches.
5	If there is a significant difference between expected and observed damage in the Canterbury churches, a statistical analysis of the damage data in Canterbury will be used. This way, new parameters will be developed and the vulnerability index methodology will be changed to match the specific building features of New Zealand churches.
6	The VI methodology will be applied to the churches in Dunedin, Wellington and Auckland, simulating a realistic earthquake scenario for each case, to obtain expected damage grades for each church.
7	The project outputs will provide a seismic damage evaluation procedure to help decision-makers (scientists, engineers and insurers) analyse the need for retrofitting interventions in URM churches.
8	The results will be presented at an international conference on Earthquake Engineering as well as at the New Zealand Society of Earthquake Engineering annual meeting.
9	The results will be included in a paper for publication in the Bulletin of Earthquake Engineering or a similar journal.

All the objectives have been fulfilled, and in several cases surpassed with new results obtained outside of the scope of the project. Table 2.2 summarises the status of each objective, together with the references of the journal papers, conference proceedings papers or Master thesis which have been published related to that objective.

Table 2.2 Project objectives: status and publications. Objectives that have been surpassed with new achievements not promised in the funding application are marked with a star, and the new achievements explained in the column for comments

Objectives	Status/Comments	References[1]
1 – Compile structural data in Canterbury, Wellington, Dunedin and fieldtrip in Auckland (*)	Completed and surpassed with data compiled in all New Zealand	A, B, C
2 – Compile damage data from 22/2/2011 Christchurch earthquake	Completed	A, B, D
3 – Develop Vulnerability Curves for each church using the Vulnerability Index (VI) method	Completed	A, B, D
4 – Compare the expected damage to the observed one in 22/2/2011 earthquake	Completed and surpassed with the proposal of an innovative approach to assess the damage	A, D
5 – New VI parameters for New Zealand URM churches	Completed	E
6 – Realistic seismic scenarios for Wellington, Dunedin and Auckland URM churches using the new VI method	Completed	E
7 – Provide a seismic damage evaluation procedure for local engineers to use	Completed	Appendices 2 and 3 of this report
8 – Present the results at the New Zealand Society of Earthquake Engineering (NZSEE) Conference and at an international conference (*)	Completed with NZSEE and SECED (UK) conferences	A, B
9 – Publish a paper with results from the project (*)	Completed and surpassed with an additional Master thesis, one journal paper accepted, one submitted and three more journal papers in preparation	C, D

[1]References: A: Cattari et al. (2015a); B: Cattari et al. (2015b); C: Marotta et al. (2015); D: Bazzurro et al. (2015)

3.0 CONFERENCES, PUBLICATIONS AND MEDIA RELEASES

3.1 CONFERENCES GIVEN IN NEW ZEALAND BY PROFESSOR LAGOMARSINO, FEBRUARY 2014

Professor S. Lagomarsino, from Genoa University (Italy) came to New Zealand for a 10 days stay from 13–22 February 2014, as part of the plan of the project. He visited more than 40 URM churches in Dunedin, Christchurch, Auckland and Wellington to understand the different types of construction for the NZ churches and also see how they differ from the European churches. Following the trip, the Genoa team has already started gathering some ideas on the changes to be made in the VI method to adapt to the New Zealand URM churches.

Professor Lagomarsino's trip caught great interest. He gave 3 talks on vulnerability assessment to masonry buildings in Christchurch, Auckland and Wellington, with the following titles:

- "Seismic vulnerability of ancient masonry structures: post-earthquake actions and preventive mitigation strategies", Canterbury University, Christchurch, Tuesday 18th February, 6.00pm.
- "Seismic assessment of existing masonry buildings", University of Auckland, Auckland, Wednesday 19th February, 6.00pm.
- "Preservation of cultural heritage masonry structures in seismic areas: displacement-based assessment procedures for single monuments and vulnerability models for risk analysis on territorial scale", Old St Paul's church, Wellington, Thursday 20th February, 6.15pm.

3.2 CONFERENCE PAPERS

Results from this project were presented in one national and one international conference. The national conference was the New Zealand Society for Earthquake Engineering Annual Meeting (Rotorua, April 2015), where a talk was given by Serena Cattari. In July 2015, results from the project were presented in a poster at the *Earthquake Risk and Engineering towards a Resilient World* Conference in Cambridge (United Kingdom). Both presentations were published in conference papers. Part of the team also presented in Italy the new procedure developed to analyse the damage caused to churches. The details are as follows:

Cattari, S., Ottonelli, D., Pinna, M., Lagormarsino, S., Clark, W., Giovinazzi, S., Ingham, J. M., Marotta A., Liberatore D., Sorrentino L., Leite, J., Lourenço, P. B., Goded, T. (2015). Towards the definition of a New Zealand specific approach for the seismic vulnerability analysis and post-earthquake damage assessment of URM churches *NZSEE 2015 Conference, 10–12 April 2015, Rotorua, New Zealand,* 10pp.

Cattari, S., Ottonelli, D. Pinna, M., Lagormarsino, S., Clark, W., Giovinazzi, S., Ingham, J. M., Marotta A., Liberatore D., Sorrentino L., Leite, J., Lourenço, P. B., Goded, T. (2015). Damage and Vulnerability Analysis of Unreinforced Masonry Churches after the Canterbury (New Zealand) Earthquake Sequence 2010–2011. *SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World 9–10 July 2015, Cambridge UK,* 10pp.

Lagomarsino S., Cattari S., Ottonelli D., Giovinazzi S. (2015). Sviluppo di una nuova procedura per il rilievo del danno delle chiese nella fase di post-terremoto, in: Atti del XVI Convegno ANIDIS "L'Ingegneria Sismica in Italia", L'Aquila, 13–17 September 2015, 10 pages (In Italian).

3.3 PUBLICATIONS

In addition to the above conference papers, there have been two publications on results from the project. One of them is related to the URM churches inventory database collected during the project. Second, a Master thesis was presented at the Genoa University (Italy) which included the damage evaluation of the churches damaged in the Canterbury earthquakes. Details of these publications are shown below.

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

Bazzurro, A., M. Pinna and F. Porta (2015). Seismic damage and vulnerability assessment of churches in New Zealand: proposal of a survey form for emergency management and models for the safety verification (in Italian). Master thesis. Genoa University (Italy), 434pp.

Part of the team (Sapienza University, Rome, Italy and Auckland University) has further developed research related to this project, and has had one accepted journal paper and one submitted. Details of these two publications are as follows:

Marotta, A., Sorrentino L., Liberatore D., Ingham, J. M. (2016). Vulnerability assessment of unreinforced masonry churches following the 2010–2011 Canterbury (New Zealand) earthquake sequence. *Journal of Earthquake Engineering* (accepted).

Marotta, A., Sorrentino L., Liberatore D., Ingham, J. M. (2016). Territorial seismic risk assessment of New Zealand unreinforced masonry churches. *Earthquake Spectra* (submitted).

In addition, there are other three publications in preparation. One of them is focused on the new damage survey forms developed by the research group of Genoa University and its application to the damage observed during the Canterbury earthquakes on New Zealand URM churches. A second one contains the new Vulnerability index method developed for New Zealand URM churches and the modifiers calibrated on basis of dataset of churches damaged by the Canterbury earthquakes. S. Lagomarsino, S. Cattari and D. Ottonelli (Genoa University) are responsible for these two publications. The third paper (being T. Goded responsible for it) will present the results on the seismic scenarios in Auckland, Wellington and Dunedin churches. They are planned to be submitted to an international journal within the next six-eight months.

3.4 MEDIA RELEASES

GNS Science and the University of Canterbury send media releases to make the EQC project known by the public. The project caused great interest and appeared in several media, including the Canterbury University and GNS Science webpages, the Dominion Post in Wellington and an interview to Sonia Giovinazzi in TVNZ in Christchurch. The links to these four media releases are provide below:

http://www.comsdev.canterbury.ac.nz/rss/news/?feed=news&articleId=1201

http://www.gns.cri.nz/Home/News-and-Events/Media-Releases/seismic-fitness-churches

http://www.stuff.co.nz/dominion-post/news/wellington/9733641/Churches-quake-safety-under-the-microscope

http://tvnz.co.nz/breakfast-news/study-quakeproof-nz-s-heritage-video-5843644

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4.0 METHOD AND RESULTS

4.1 RESEARCH METHOD

Most of the seismic vulnerability studies developed in the past years are focused on ordinary buildings, which, when combined with site effects and loss estimations studies, can provide a realistic seismic risk analysis in a region or urban area. Ordinary buildings' failure during an earthquake is one of the main causes of human losses, as well as being responsible for the majority of the government support to restoring normal life after a big seismic event. Nevertheless, historical and monumental buildings should not be forgotten in seismic risk studies as earthquakes represent the main cause for the loss of our cultural and historical heritage. For this reason, several recent studies have been focused on this kind of building (Augusti et al., 2001, 2002; Irizarry et al., 2002; Lagomarsino et al., 2003; Sousa, 2003; Irizarry et al., 2004; Lagomarsino and Podestà, 2004a, 2004b, 2004c; Lagomarsino et al., 2004; Lagomarsino, 2006; Cassinello, 2007; Goded et al., 2007; Lagomarsino and Resemini, 2009; Goded et al., 2012b). Nevertheless, such studies are still very scarce in most countries. The April 2009 L'Aquila earthquake in Italy, (Modena et al., 2010; Binda et al., 2011; Lagomarsino, 2011) and the Christchurch earthquakes in 2010–2011 (Anagnostopoulou et al., 2010; Ingham et al., 2012; Leite et al., 2013; Lourenco et al., 2013) reminded us of the invaluable loss seismic events can cause to the present heritage and the need to study these buildings in order to take the necessary measures to avoid their failure during an earthquake.

The majority of the historical monuments are masonry structures that are very difficult to model due to their technological and constructive complexity. Their big dimensions make them vulnerable even if they are built with high quality materials (Giovinazzi, 2005). Churches have proven to be especially vulnerable. Notable damage to churches in previous earthquakes occurred in Guatemala (1976), Irpinia (Italy, 1980) and Mexico (1999), where around 600 churches suffered heavy damage. The 1997 Umbria-Marche (Italy) earthquake sequence caused serious damage to monumental buildings leaving more than 2,000 churches with significant damage (Lagomarsino, 1998). A large quantity of damage information was compiled from these events and used to develop a method to study monuments' vulnerability within the European Risk-UE project (Mouroux and Le Brun, 2006). We will apply this method to our project.

The vulnerability index method is based on the fact that certain building classes with the same mechanical behaviours and loading patterns usually exhibit the same kind of damage pattern during an earthquake. In this way, buildings can be classified in different types and vulnerability functions can be developed for each of them based on observed damage patterns. This method, both for ordinary and monumental buildings, has been developed for the past 25 years within the *Grupo Nazionale per la Difesa dai Terremoti* (Italian National Group for the Defense from Earthquakes, GNDT, Corsanego and Petrini, 1994). The technique has been widely applied and tested in several studies carried out in Italy (Benedetti and Petrini, 1984; Bernardini, 1997; Dolce, 1997; Bernardini, 2000). It is a robust and versatile method where building vulnerability is characterised in a very simple way, being very detailed in the single features of each building (Lantada, 2007).

The *VI* method that will be used in this project was proposed by Lagomarsino et al. (2003) within the Risk-UE project for historical and monumental buildings (Lagomarsino, 2006). It consists of a macroseismic approach where the seismic hazard is defined by the macroseismic intensity. The technique is based on the use of vulnerability curves that correlate the post seismic damage grade or condition of the building (using the mean damage grade μ_d, a continuous parameter where $0 \leq \mu_d \leq 5$), to the intensity suffered, using a discrete probabilistic distribution.

This technique classifies historical buildings in 13 different types: palaces, monasteries, castles, churches, chapels, mosques, theatres, towers, bridges, walls, triumphal arches, obelisks and statues. Each type is characterised by two parameters: its vulnerability index (V_I) and its parameter ϕ, which represents the slope of the vulnerability curve.

The vulnerability index for each building is obtained by the sum of two components: a vulnerability index due to its type (V_{it}), and some vulnerability index modifiers that depend on the state of the monument (V_{im}). These modifiers are classified in two types: general modifiers for all the types, V_{ig} (masonry quality, state of maintenance, structural transformations, recent interventions…), and specific modifiers for each type, V_{is} (for a church, these modifiers would be the number of naves, the height of its lateral walls, the existence of domes or vaults, etc.).

The seismic behaviour characterisation for each building type, and thus the vulnerability index values, were obtained by Lagomarsino (2006) from a statistical analysis of the seismic damage to Italian monuments observed during the past 30 years, especially after the Friuli (1976) and Umbria-Marche (1996, 1997) earthquakes. From the vulnerability index, mean damage grades (μ_d) can be obtained for each building using vulnerability curves that represent the expected damage distribution for each intensity value. The vulnerability function to obtain μ_d recommended by Lagomarsino (2006) for monumental buildings was proposed by Sandi and Floricel (1994) as a vulnerability curve representation, and was used by Lagomarsino and Giovinazzi (2006) for ordinary buildings (see more details in Section 4.5).

Once the vulnerability curve is obtained for each building, damage probabilities can be estimated that represent the probability of suffering a specific damage level as a consequence of the action of an earthquake of certain intensity. These probabilities are obtained based on the fact that the expected damage can be fitted to a binomial distribution defined by a unique parameter: the mean damage grade μ_d (Braga et al., 1982). In this way, each monumental building is first characterised by its type and its vulnerability index that depends on its actual condition. Then, a certain seismic scenario is supposed where the building would experience a specific intensity. By using the vulnerability curve, the expected mean damage grade μ_d is obtained as well as its damage probabilities. As three vulnerability index values are given for each building, lower, mean and upper damage distributions will be obtained with its correspondent probabilities.

With the *VI* method, it is possible to study individually the monuments' vulnerability in a certain region and to compare that with the damage observed due to past earthquakes. In this way, it is possible to test the feasibility of applying the method to a certain region. In this project, the method will be checked for New Zealand using the information from the churches damaged during the Canterbury earthquakes, where expected and observed damage will be compared.

The vulnerability analysis of churches in several New Zealand cities will assist decision-makers to determine appropriate retrofitting strategies for this building type, and will consequently mitigate damage in future earthquakes. In addition, the project outputs will assist decision-makers in the process of identifying and ranking the seismic vulnerability of

URM churches and the prioritising of seismic retrofitting interventions. Successful application of this method to URM churches in several New Zealand cities will enable subsequent use of the method nationwide, plus potential application to other types of historical architectural monuments.

4.2 TYPOLOGICAL CLASSIFICATION OF NEW ZEALAND URM CHURCHES

Earthquake damage that occurred to churches in Italy has been systematically assessed and interpreted from the structural point of view, after the many earthquakes during the last 40 years, such as the 1976 Friuli earthquake (Doglioni et al., 1994), the 1980 Irpinia event (Liberatore et al., 2009), the 1997 Umbria-Marche earthquakes (Lagomarsino and Podestà 2004a-b), the 2002 Molise earthquake (Lagomarsino and Podestà 2004c), the 2009 L'Aquila earthquake (Lagomarsino 2012), and the more recent 2012 Emilia earthquake (Sorrentino et al., 2014). These analyses have demonstrated that the seismic response of churches may be described according to recurrent phenomenologies, traceable to the damage modes and mechanisms of collapse of the different parts, called macroelements (e.g., presbytery, apse, bell tower), which demonstrate a structural behaviour almost autonomous. The classification into macroelements and collapse mechanisms has allowed the definition of methods to assess damage and to quickly acquire useful information for handling emergencies (first aid interventions, fitness for use, economic damage estimates, planning support and project management). In this project, macroelements have been used to obtain a new method to obtain the damage index of a church, by adding up the damage indexes of each individual macroelements. This method is describen in Section 4.1. After the 1997 Umbria Marche earthquake, a damage survey form was developed, consisting of four structured pages. Later on it has been officially adopted (G.U. no. 55, 2006) by the Italian Civil Protection Department and the Ministry for Cultural Heritage and Activities, for the post-earthquake emergency management. In the following this tool is named as ISF (Italian Survey Form).

The interpretation of vulnerability and seismic damage in terms of macroelements, as proposed via the ISF, has been applied to Christchurch churches. It was observed that, from an architectural point of view, some macroelements (such as domes) are rarely present in New Zealand. In fact New Zealand churches show typological and dimensional data different from Italian churches, with the New Zealand ones having generally a more regular plan configuration. Therefore, as a first step, a typological classification for New Zealand unreinforced masonry churches (URM), based on the plan and spatial features of these structures (Figure 4.1 and Figure 4.2), has been developed in order to group the structures that are considered to have similar seismic behaviour and to define NZ specific macroelements. The classification has been defined on the basis of a field survey of churches located throughout New Zealand, according to the following categories:

- **A**, one nave, buttresses (possibly), and sloping roof;
- **At**, one nave with transept, buttresses (possibly) and sloping roof;
- **B**, three naves with transept, apse (eventually), buttresses (possibly) and sloping roof;
- **C**, central-plan;
- **D**, a large hall without internal walls, with "box type" behaviour and exteriors as a building;
- **E**, Basilica, similar to B but much larger.

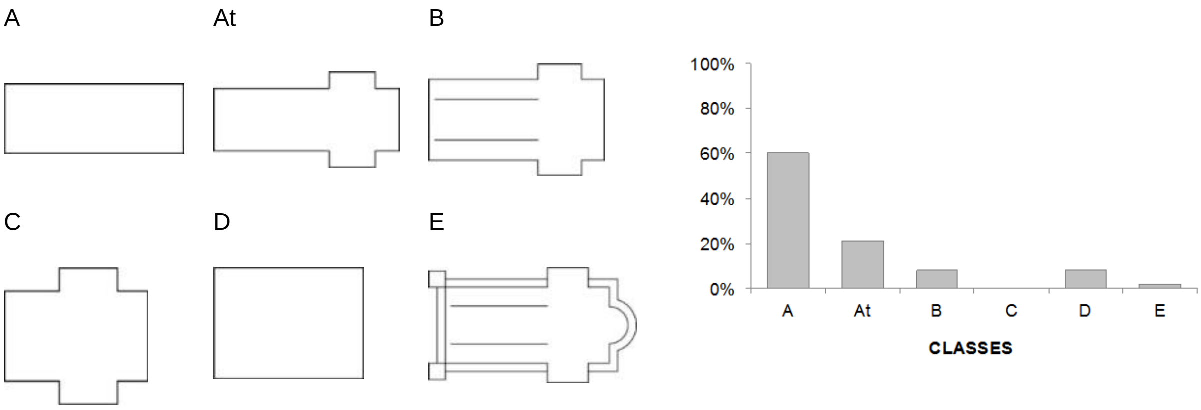


Figure 4.1 Classification of URM churches in New Zealand: a-left) recurring types (plan view); and b-right) their frequency within the stock of the 48 Christchurch churches analysed as part of the project.

The histogram in Figure 4.1 shows the frequency of the typological classes for the Christchurch stock (48 URM churches), whereas in Section 4.3 the statistics are extended to the entire stock of New Zealand URM churches.

According to the typology classification of URM churches in New Zealand into six types shown in Figure 4.1, examples of churches from different typologies are shown in Figure 4.2.

Figure 4.2 Examples of different URM churches typologies in New Zealand.

It is worth noticing from Figure 4.1 that the majority of the churches fall in the A Class, meaning that a typical NZ church is mainly composed of the following macroelements: nave, presbytery, sloping timber roof, buttresses (possibly). The At Class includes the same macroelements as for the Class A, but in the presence of the transept. The combined percentage of A and A_t types covers 80% of the analysed stock from Christchurch. This result outlines the simplicity of the architecture of New Zealand churches. The most recurring macroelements, as a consequence of the predominance of Class A, are the central nave, façade, and presbytery, which are present in almost 100% of the churches (3). A further macroelement that characterizes the sample is the Atrium (Narthex), is present in 80% of the churches. In some cases there is more than one atrium along the nave or in proximity of the apse (respectively classified as AN1 and AN2 in the proposed classification). A similar subdivision is proposed for the chapels. A considerable number of macroelements are present in less than 25% of the surveyed churches, related to the lateral naves, transept and dome, as illustrated in Figure 4.3.

Nc	CENTRAL NAVE
NI_{LEFT}	LEFT LATERAL NAVES
NI_{RIGHT}	RIGHT LATERAL NAVES
F	FAÇADE
T_{LEFT}	LEFT TRANSEPT
T_{RIGHT}	RIGHT TRANSEPT
D	DOME
TA	TRIUMPHAL ARCH
P	PRESBYTERY
A	APSE
AN_1	ATRIUM/NARTHEX (1st group)
AN_2	ATRIUM/NARTHEX (2nd group)
C_1	CHAPELS (1st group)
C_2	CHAPELS (2nd group)
BT	BELL TOWER
PR	PROJECTIONS

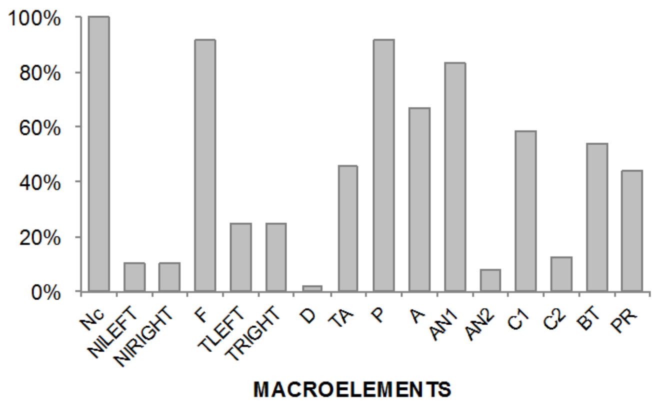


Figure 4.3 Frequency of the macroelements on the stock of 48 URM churches from Christchurch.

4.3 AN INVENTORY OF UNREINFORCED MASONRY CHURCHES IN NEW ZEALAND

The first churches in New Zealand were built mainly with timber, because of the ease of construction in terms of time and material availability. However, stone and clay-brick (URM) masonry buildings started being used largely from around 1880, when clay became readily available and prosperity increased. The 1931 Hawke's Bay earthquake (M_w 7.8) demonstrated the poor performance of URM and marked the beginning of the decline in use of URM. Despite this, unreinforced masonry (URM) is one of the construction materials most frequently used in New Zealand's early built heritage, and URM churches represent a significant proportion of the heritage building stock of New Zealand. It is also widely known that URM churches frequently perform poorly even in moderate earthquakes, because of their intrinsic structural vulnerability (e.g., D'Ayala, 2000). URM churches are particularly vulnerable to earthquakes because of their open plan, large wall height-to-thickness and length-to-thickness ratios, and the use of thrusting horizontal structural elements for vaults and roofs. Their use of low strength materials often causes decay and damage due to poor maintenance, and the connections between the various structural components are often insufficient to resist loads generated during earthquakes (Ingham et al., 2012; Lagomarsino, 2012; Sorrentino et al., 2014). The 2010–2011 Canterbury earthquakes caused widespread damage to stone and clay-brick URM churches (Leite et al., 2013). An accurate documentation of the architectural heritage in a country is the first step in understanding the relevance of the damage observed and in the implementation of effective conservation strategies.

Given the aim of EQC project, it was necessary to apply the survey form to a large set of New Zealand churches. In the absence of a complete list of churches present across the country, several reference sources were utilised, leading to the identification of 297 URM churches currently existing in New Zealand (Figure 4.4). This total does not account for 12 URM churches demolished in Christchurch because of heavy damage suffered during the Canterbury earthquake sequence. This made it impossible to gather all the structural data from these churches needed to apply the method. The first identification source considered was the Heritage New Zealand (HNZ) List (Heritage New Zealand webpage, http://www.heritage.org.nz/the-list), formerly referred to as the Register. Approximately half of the identified churches are recorded therein. Some of the non-registered buildings were identified through the online inventories of the different religious denominations in New Zealand, archive documentation, architectural books (Warren, 1957; Fearnley, 1977; Anonymous 1979a, 1979b; Wells and Ward, 1987; Kidd, 1991; Knight, 1993; Donova, 2002; Wells, 2003) and other reports. Such research led to acquiring knowledge of churches constructed of different types of structural materials. Hence, a subsequent filtering was performed by preliminary observation using Google Street View, to check if they corresponded to URM churches. Finally, additional churches were identified during the field survey along the 10 000 km itinerary that was planned based on the previously identified sites. This field survey aimed to acquire technical information for all URM churches, and to appropriately identify numerous non-registered buildings considered to be potentially significant examples of early New Zealand architecture. Despite the care and effort put into the definition of this inventory, the existence of other churches along routes not explored during the field trip cannot be excluded.

Figure 4.4 Geographical distribution of URM churches in New Zealand.

Almost 70% of the inventory is concentrated in the South Island, with a prevalence of churches located in the Otago (30%) and Canterbury regions (29%), as shown in Figure 4.5.

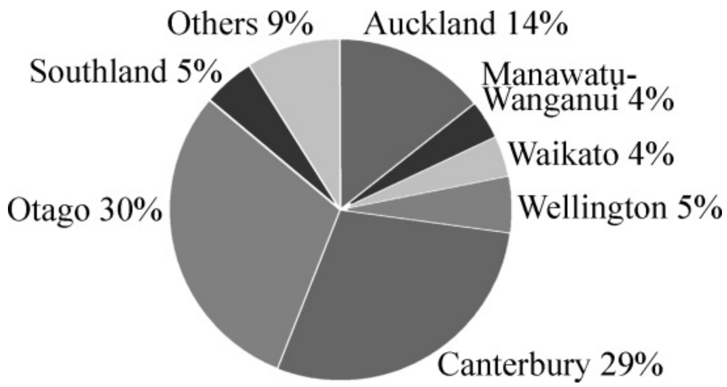


Figure 4.5 Estimated provincial distribution of URM churches in New Zealand.

The comparatively low proportion of URM churches in the Auckland region (14%), despite the region being the most populated of New Zealand (Statistics New Zealand, 2013), can be justified because of the larger use of timber in construction. There are at least two explanations for this fact. First, stone was less readily available in the area, whereas Kauri trees were common, especially on the Coromandel Peninsula and in the northern areas (Orwin, 2012). Consequently most early constructions, including churches, were made with timber. Second, at the time of the 1848 Marlborough and 1855 Wairarapa (M_w 8.2) earthquakes, it was observed that masonry buildings were susceptible to destruction while wooden buildings appeared more resistant to withstand such forces (Schrader, 2013). Wooden churches, sometimes intended as temporary buildings, are in general still standing today and in good condition (Tonks and Chapman, 2009). This resilience was also proven by the Canterbury earthquakes, during which timber churches had the best overall performance, with no cases of structural damage (Leite et al., 2013).

New Zealand URM churches tend to have similar characteristics, in terms of both architectural features and construction details. This similarity occurs because most of the structures were built over a relatively short time span, and were often designed by the same architects. Focusing on the architectural characteristics of the churches, it has already been observed that the religious heritage is mainly represented by longitudinal plan churches, with a long nave eventually crossed by a transept (technical terminology is explained in Figure 4.6). The body of the building is arranged in naves. The main nave is at times flanked by lower aisles, and rows of piers or columns separate them. The main nave can end with a circular or polygonal apse.

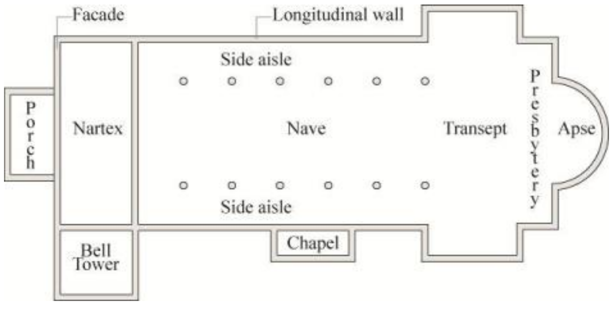


Figure 4.6 Schematic plan showing the common parts of a church.

In terms of the building material, 55% of the inventory (i.e., 297 URM churches) is constructed of clay-brick URM and 39% is constructed of natural-stone URM. In 3% of cases, building stones were limited to facings, basement walls, and the main façade, probably because stone was more expensive than clay brick those days. For the remainder of the inventory the presence of plaster hampered a positive identification of the masonry type, although the date of construction indicates a traditional building technique and response to simple percussion excludes the use of timber. The construction types were connected to local geology, with almost all stone URM buildings in New Zealand being constructed in areas where the material was available nearby from local quarries, fields and rivers (e.g., the volcanic rocks of Auckland, New Plymouth, Christchurch, Timaru and Dunedin, the limestone in Oamaru, and the schist in central Otago) (Nathan and Hayward, 2012). The natural-stone buildings are mostly concentrated in the South Island, in Canterbury and Otago regions, characterised by metamorphic rocks (such as schist) and sedimentary rocks (such as limestone), respectively. Igneous rocks are widely distributed throughout the country with a prevalence of basalt (Giaretton et al., 2013).

More details on the inventory of New Zealand URM churches can be found in Marotta et al. (2015). The complete list of the 297 URM churches is shown in Appendix 1.

4.4 DAMAGE ANALYSIS OF THE CHURCH STOCK HIT BY THE CANTERBURY 2010–2011 EARTHQUAKE SEQUENCE

Post-earthquake damage assessment represents a fundamental step to analyse the actual seismic response and seismic vulnerability of URM churches. In this work, the damage analysis was carried out according to three different approaches:

i. The computation of the damage index (i_d, see below) starting from the ISF (Italian Survey Form, see Section 4.2 and Appendix 3), in particular in the part of the Fitness For Use classification (FFU), and the method of collapse mechanism identification and classification, as described in Leite et al*.* (2013).

ii. The definition of a damage grade D_k (k = 1...5), based on expert judgment, for the overall church and/or for the different macroelements of the church. The damage grade D_k was defined coherently with damage scale proposed within the European Macroseismic Scale (EMS98 – Grunthal 1998), i.e., D_0 no damage, D_1 negligible to slight damage, D_2 moderate damage, D_3 substantial to heavy damage, D_4 very heavy damage, D_5 destruction.

iii. The computation of the damage index (i_d) through an innovative method, based on the macroelement approach, briefly described in Section 4.4.1

Figure 4.7 shows the comparison among the abovementioned methods. As Approach (ii) is the most qualitative, it usually overestimates damage with respect to the other two methods. Approach (i), on the contrary, tends to underestimate damage when compared to Approach (iii), as the latter is calibrated to the actual macroelements present in the church, assigning a weight to them and also considering the peak of damage.

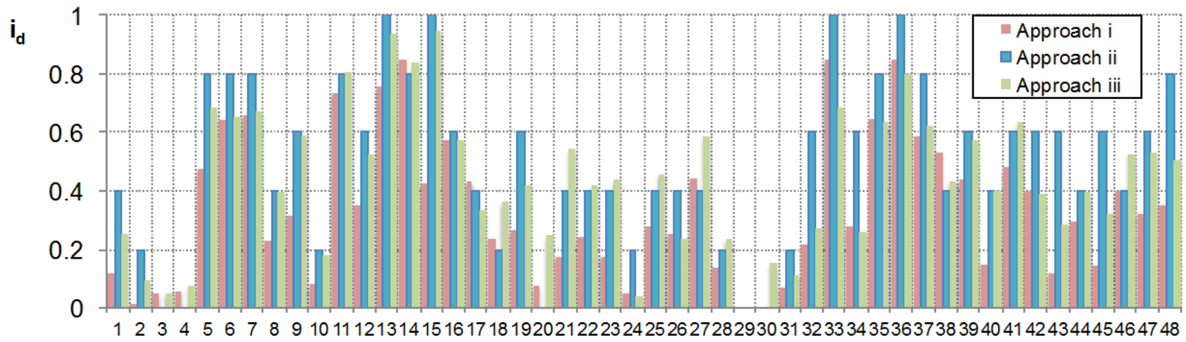


Figure 4.7 Comparison between the damage indices obtained from three different approaches applied on the 48 URM Christchurch churches.

Figure 4.8 summarizes the damage index of each church of the sample obtained from Approach (iii). In particular, Figure 4.8 illustrates the average damage index from the Approach (iii) method, for each macroelement in two conditions: a) the average index weighted only for the churches that have that macroelement; b) the average index weighted on the entire sample. From Figure 4.8a it is evident that the highest average damage value, (e.g., related to the dome, the lateral naves, the transept), but at the same time the most vulnerable macroelement, should be also widespread in the sample, as shown in Figure 4.8b).

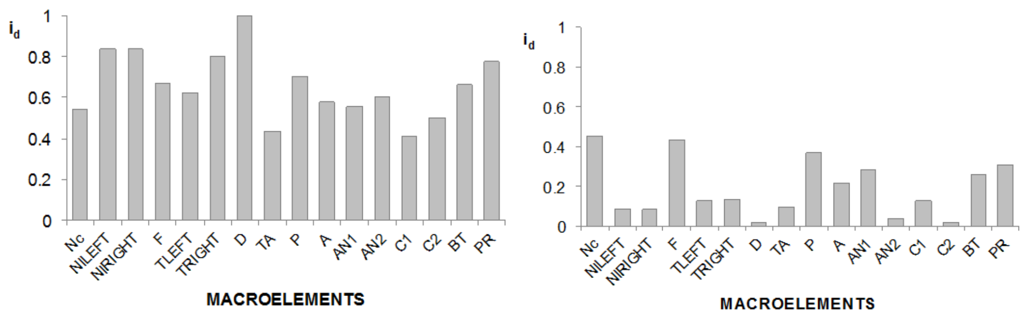


Figure 4.8 Frequency of the damage index not weighted (left) and weighted (right) on the sample.

4.4.1 A new method to assess the damage index for URM churches

The new proposed method (corresponding to Approach iii above) is based on these steps: 1) subdivision of the church into macroelements (considering those listed in Figure 4.2); 2) attribution of a weight to each identified macroelement, as a function of the geometrical importance within the church (i.e., plan and height dimensions); 3) check of any different activated collapse mechanisms for each identified macroelement.

Possible collapse mechanisms are listed in Table 4.1. For each macroelement, a level of damage D_k according to the European Macroseismic Scale EMS-98 damage scale (as in the Approach (ii) above) has to be ascribed to any activated mechanism. It is worth noting that the same type of mechanism can occur in different macroelements. Then, the damage grade of the macroelement is computed, according to different rules that consider peak and mean values of the different mechanisms, as well as their relative importance.

The weighted arithmetic average of damage grades in macroelements will provide the global damage index of the church. It is important to note that, over the ISF method, which considers only a fixed combination (28) of mechanisms and macroelements, a more clear definition of damage level in each macroelement is given. However, starting from data collected by the ISF, the new damage index can be evaluated a-posteriori, without an additional survey.

Table 4.1 List of the possible collapse mechanisms (Cattari et al., 2015a).

	Collapse mechanisms
1	Out-of-plane of masonry walls
2	Out-of-plane at the top of walls
3	In-plane response
4	Rocking of multi macro blocks kinematics
5	Flexural or shear damage in monodimensional hollow section structures
6	Vaults
7	Domes
8	Interaction between roof and walls
9	Damage due to interaction with other buildings
10	Rocking of single blocks

4.5 DERIVATION OF EMPIRICAL VULNERABILITY CURVES

The results of the damage survey, statistically elaborated, led to the formulation of a vulnerability index to each church and to the derivation of vulnerability curves, through a proper regression analysis. The curves enable verification of the correlation between the damage in the different macroelements and their geometric and construction typology, with particular reference to those structural details identified for the assessment of the intrinsic vulnerability. The identification of such factors represents a first critical step towards the development of a specific vulnerability model to be applied in New Zealand to support mitigation policies.

From the statistical analysis of the damage data a Damage Probability Matrix (DPM) was produced for churches, being a matrix in which for the different values of the macroseismic intensity, the probability histogram of the damage levels is listed (Whitman, 1973). Each church of the sample is associated with two different values of macroseismic intensity: a) one directly ascribed (Goded et al., 2014); b) one obtained from PGA data taken from shake maps, by using an Intensity-PGA correlation, calibrated in the study area through the data of the US Geological Survey (USGS 2011). Figure 4.9 shows PGA values (obtained from data and maps available from the US Geological Survey, 2011) and macroseismic intensity (Goded et al., 2014) associated with each church, together with correlation curves, derived from minimum and maximum values of PGA associated by USGS to each single value of intensity. The graph shows that in many churches low values of intensity were associated with high levels of PGA.

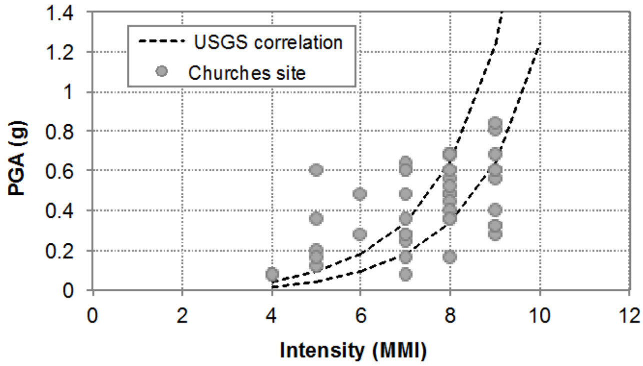


Figure 4.9 Correlation between Intensity and PGA.

Having defined the intensities, the churches of the sample were grouped according to shaking intensities that varied from Intensity 4 to 9 of the Mercalli Modified scale (MMI). For each intensity, the mean damage index and the variance were computed to identify the parameters of Beta distributions and so obtain the DPMs (Figure 4.10), by transformation of the beta distribution into discrete terms.

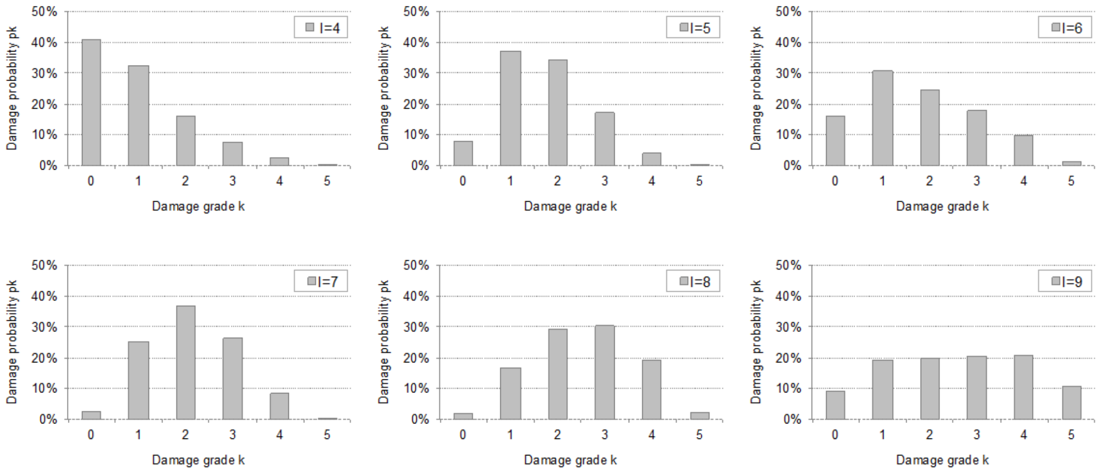


Figure 4.10 Beta discrete distribution for I from 4 to 9 MMI (damage grades from 0, no damage, to 5, collapse).

From the mean damage index and the values corresponding to the 16 and 84 percentiles, the empirical vulnerability curves of New Zealand churches were drawn, which correlate the intensity I to damage grade μ_d. These curves were compared with the curves calibrated for Italy, defined by the following expression and illustrated in Figure 4.11, adopting different values of Vulnerability Index (Vi) and Ductility Index Q equal to 3. This expression is proposed by Lagomarsino (2006) for churches, and it is calibrated on the basis of the observed damage in Lagomarsino and Podestà (2004b):

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right]$$ **Equation 1**

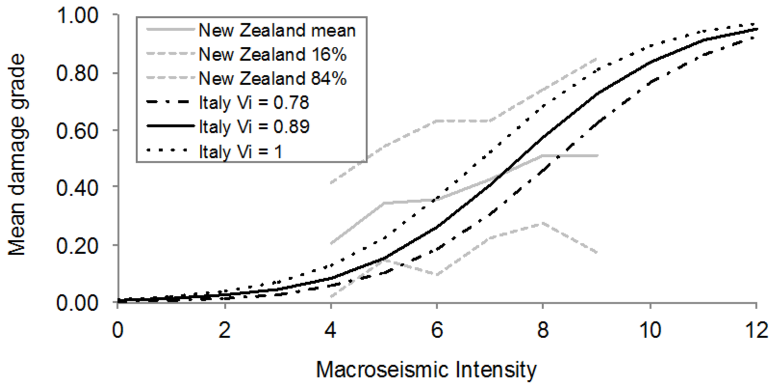


Figure 4.11 Vulnerability curves for New Zealand and Italian churches.

4.6 DAMAGE SURVEY FORM AND SPECIFIC VULNERABILITY FACTORS FOR NEW ZEALAND URM CHURCHES

4.6.1 Typological and vulnerability survey form

A variety of methods are available in literature to assess the seismic vulnerability of different types of buildings. Urban- and territorial-scale assessment methods have been developed since the early 1970's considering different approaches for the collection and interpretation of data. Procedures to assess the vulnerability of existing buildings are generally selected with respect to the dimension of the sample considered. Usually the larger the size of the sample the smaller the number of parameters to be collected, and vice versa.

Several of the methods referred to above have been reviewed in order to determine the most suitable method for application to New Zealand churches. Because the number of ecclesiastic buildings to be considered in the EQC project was relatively large (297), a qualitative tool was chosen, leading to the decision to use a Level 1 Macroseismic Vulnerability Methodology (Lagomarsino, 2006). This procedure is based on an on-site inspection of a number of parameters able to quantify the seismic performance. In addition to those parameters already included in the original form (typology, regularity, presence of vaults, masonry quality, transformations, state of preservation, damage level, position with respect to other buildings, topography), some others parameters were added to characterise more specifically the New Zealand churches (specialized typologies, masonry types, roof characteristics, more detailed description of damage).

The following list summarises the fields present in the survey form:

General information: not directly related to the vulnerability of the building but useful to its identification (denomination of the church, address, current use, …).

- Architectural features: referring to typological classification proposed above (Figure 4.1), taking the overall dimension and noting geometric irregularities in plan and elevation (e.g., presence of adjacent buildings and/or tower, interaction with buildings of different height).

- Structural characteristics: masonry type and quality (distinguishing between good and bad masonry and highlighting the masonry transversal section), type of roof (e.g., exerting or not thrust at support, mass size), connections between walls (e.g., interlocking, tie rods, …) and between walls and floors (e.g., ring beams, …), presence of buttresses, of large openings, of thrusting structures (e.g., arches, vaults, domes), of slender elements (e.g., pinnacles, parapet belfries, parapets).
- Architectural and structural transformations: alterations and additions that could affect seismic performance (e.g., extensions in plan, raising up, …) and recent retrofitting interventions (e.g., grout injections, insertion of tie rods, ring beams or cross-bracing system in the roof, …).
- State of preservation: decay of materials, rainwater percolation, humidity, …
- Damage level: due to earthquake (in the epicentral zone), soil settlements and weather actions.
- Site conditions: topography, soil settlement, liquefaction.

The complete typological and vulnerability survey form for New Zealand URM churches is listed in Appendix 4. Before that, Appendices 2 and 3 contain the new damage survey form developed for URM churches by the Genoa team, and its user's manual, respectively.

4.6.2 Vulnerability index factors and modifiers for New Zealand URM churches

The vulnerability of the 297 NZ URM churches can be defined through the Macroseismic method (Lagomarsino and Giovinazzi, 2006), based on the evaluation of the vulnerability curve, that provides the mean damage grade μ_D as a function of the macroseismic intensity MMI, only depending on two parameters: the vulnerability index V_i and the ductility index Q. The vulnerability index V_i is evaluated as the addition of: i) a typological vulnerability index V_0 (representing the average seismic behaviour of the URM NZ churches once the statistical analysis has been carried out) and ii) a behaviour modifier ΔV_m, which takes into account the presence of specific features of the single church such as the state of preservation, existence of narthex or buttresses, etc. (see Appendix 6).

$$V_i = V_0 + \Delta V_m$$ **Equation 2**

The behaviour modifier factor ΔV_m is evaluated according to Equation 3 as the sum of the scores $V_{m,k}$ (corresponding to the vulnerability index modifiers for each damage grade k) of the recognized behaviour modifiers:

$$\Delta V_m = \sum_k V_{m,k}$$ **Equation 3**

The typological vulnerability index V_0 and the values of each modifier factors are calibrated on past-earthquake damage observations of 48 unreinforced masonry churches located in the Canterbury Region. The calibration follows the knowledge and definition of the typological characteristic of the Canterbury and NZ samples, in order to determine if the Canterbury sample is representative of the entire New Zealand URM churches.

Macroseismic method is proposed to be used when the hazard is described in terms of macroseismic intensities, MMI. So for the calibration of the typological vulnerability index and the modifier factors, each church of the Canterbury sample is associated with a value of MMI.

In fact, each structure of the sample was correlated to a macroseismic intensity (Goded et al., 2014) and a value of PGA taken from USGS ShakeMaps (USGS, 2011). In Figure 4.12b the grey dots (MMI, PGA) represent the intensity measures at each church.

The USGS Shakemaps are also accompanied by the definition of an instrumental intensity MMI linked to a range of minimum and maximum values of PGA (Figure 4.12a) that allow to establish the MMI-PGA correlations, that are the dashed black curves in the Figure 4.12b. The graph shows that in many churches low values of intensity were associated with high levels of PGA.

From these curve and the dots it was possible to calibrate an *Intensity-PGA* correlation for the study area, based on the following equation and values.

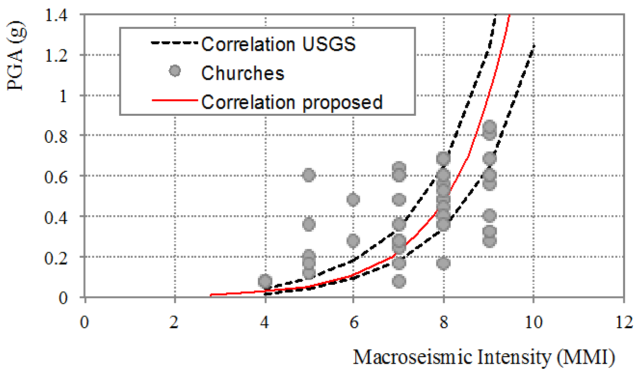
$$I = a_1 + a_2 \ln(PGA)$$ **Equation 4**

where: a_1=9, a_2=1.35 (PGA in g's).

This *I-PGA* law is the red line in Figure 4.12b. Although these types of correlations are far from precise, they can be very useful as represent an inevitable step to correlate and compare macroseismic observations with instrumental recordings.

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

a



b

Figure 4.12 Correlations between Intensity and PGA; a) USGS Shakemaps (USGS, 2011); b) This study (modified from Figure 4.9).

Both samples are described by a number of parameters able to quantify the seismic performance, like: masonry types, the plan and spatial features (according to the typological classification proposed in the project), regularity, presence of buttresses, presence of vaults, masonry quality, transformations, state of preservation, position with respect to other buildings, topography, roof characteristics, etc. They are established from on-site inspection (described in detail for the NZ churches in Marotta et al., 2015).

From these features, the modifier factors ΔV_m (see Equation 3 above) for the NZ URM churches have been obtained.

The following graphs illustrate the samples in terms of these parameters.

It is important to note that this description is essential to know if the sample of Christchurch, despite being limited, is representative of the NZ churches, in terms of the modifier factors.

CHRISTCHURCH SAMPLE **NEW ZEALAND SAMPLE**

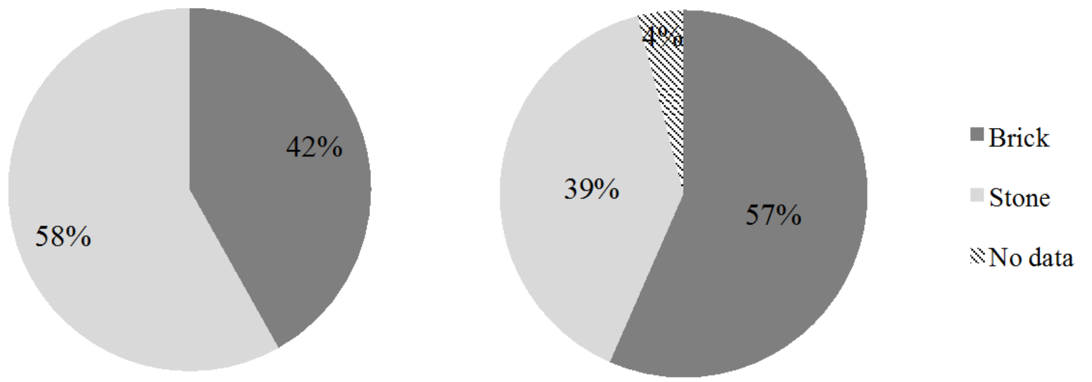


Figure 4.13 Masonry types

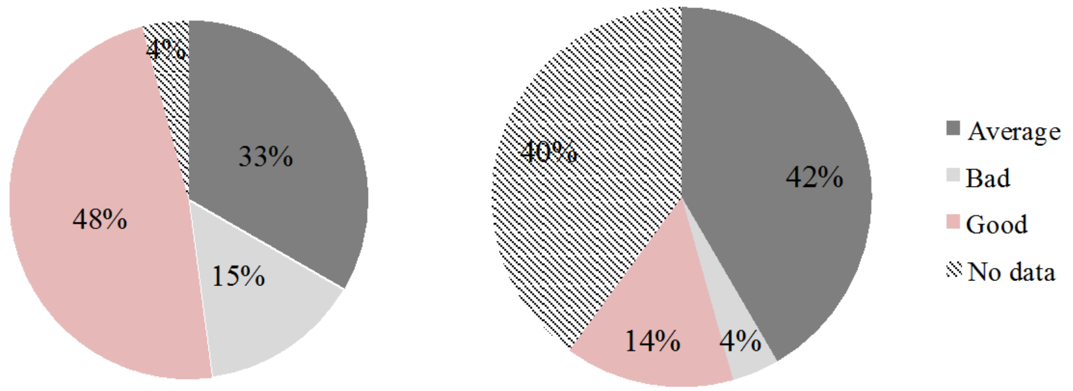


Figure 4.14 Quality of masonry

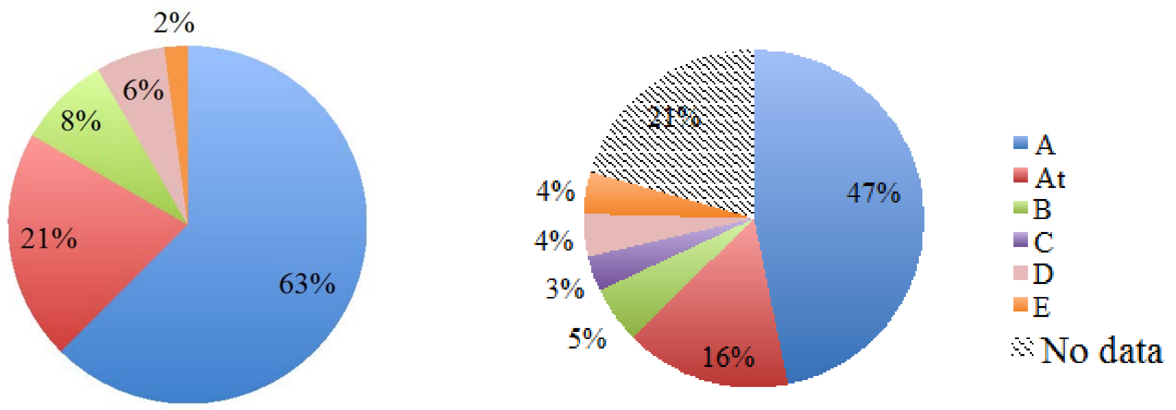


Figure 4.15 Plan configuration (according to Figure 4.1)

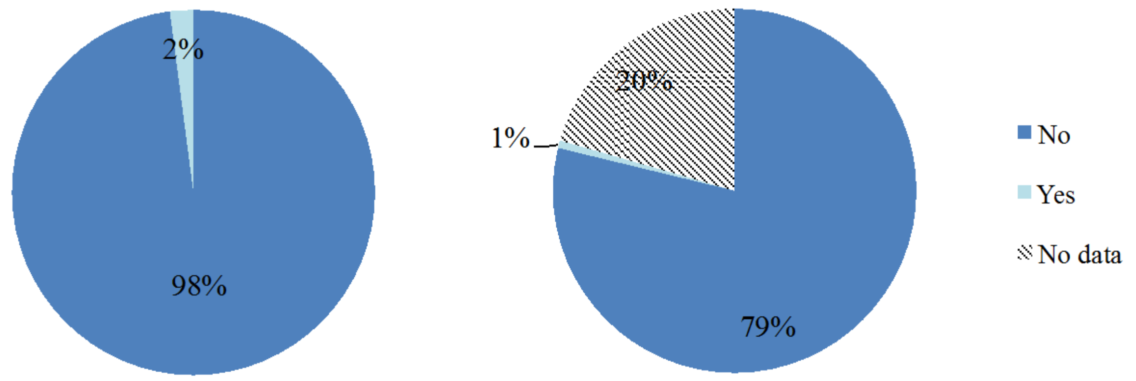


Figure 4.16 Presence of Dome

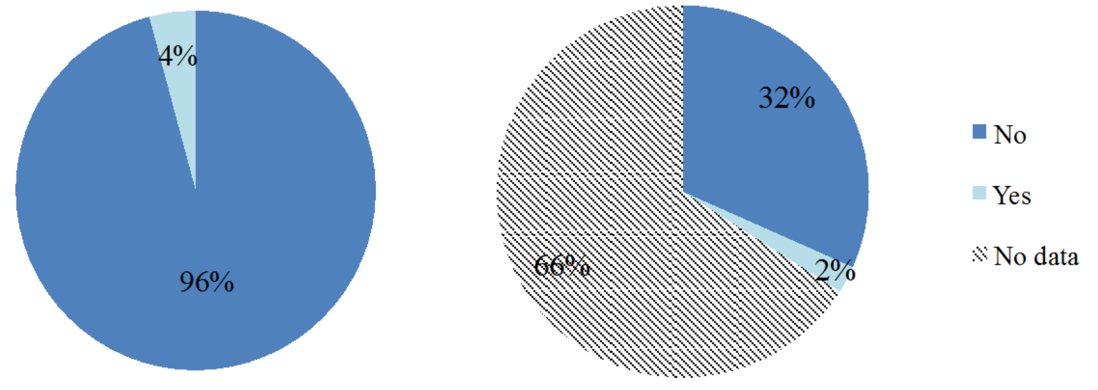


Figure 4.17 Presence of Vaults

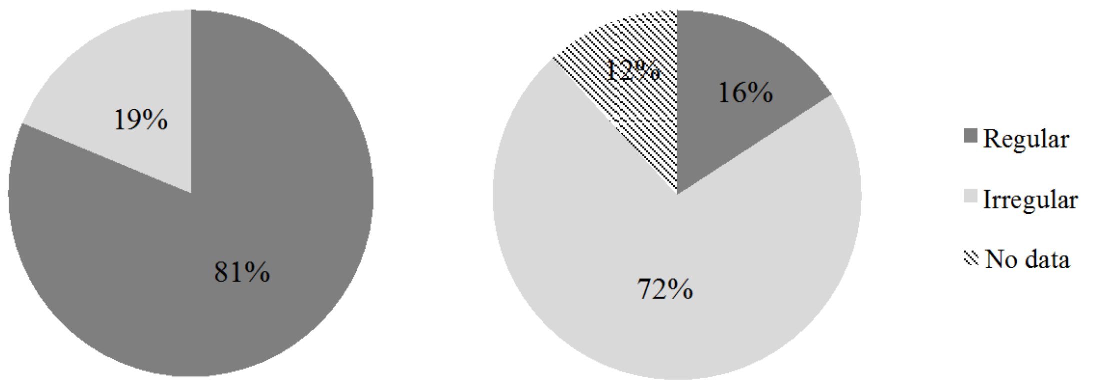


Figure 4.18 Regularity in plan

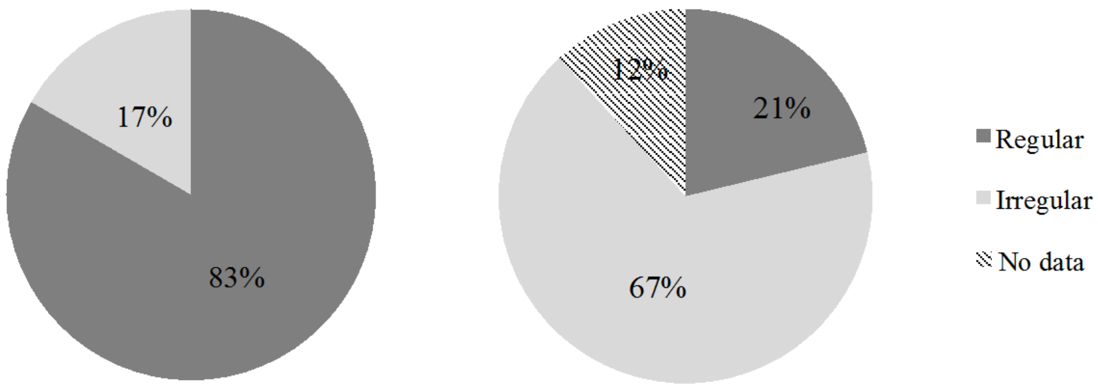


Figure 4.19 Regularity in elevation

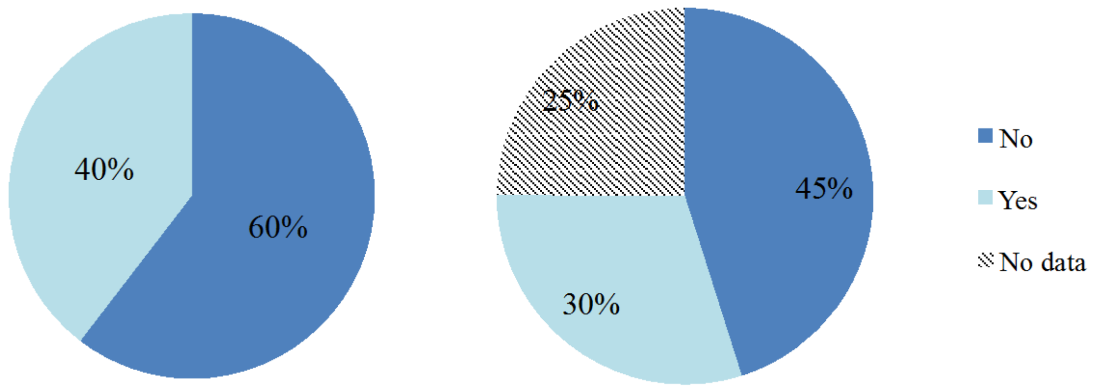


Figure 4.20 Presence of adjacent buildings

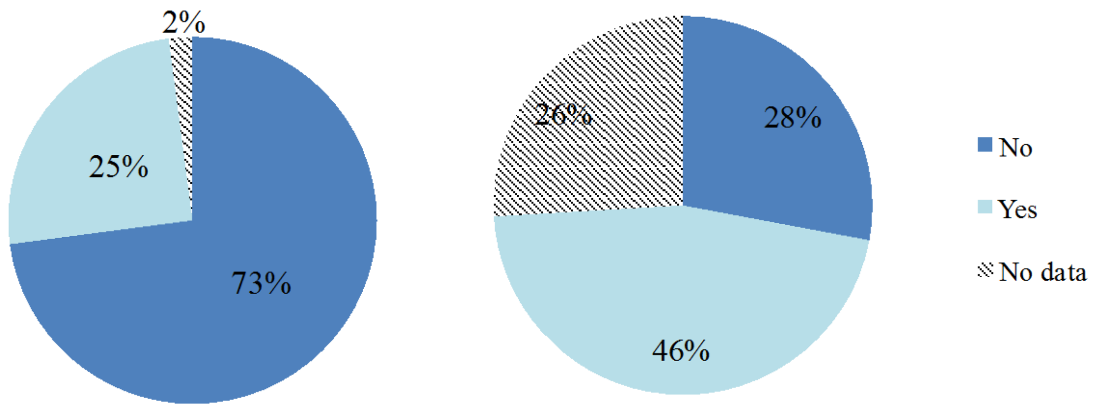


Figure 4.21 Presence of pinnacles

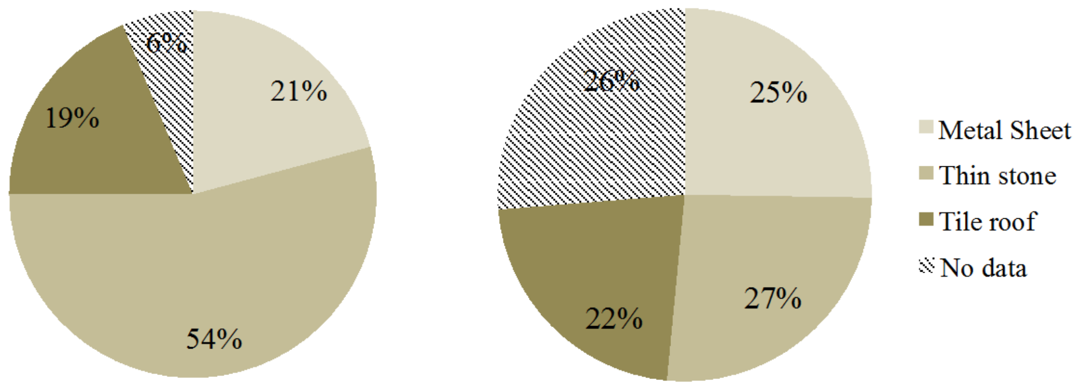


Figure 4.22 Covering roof

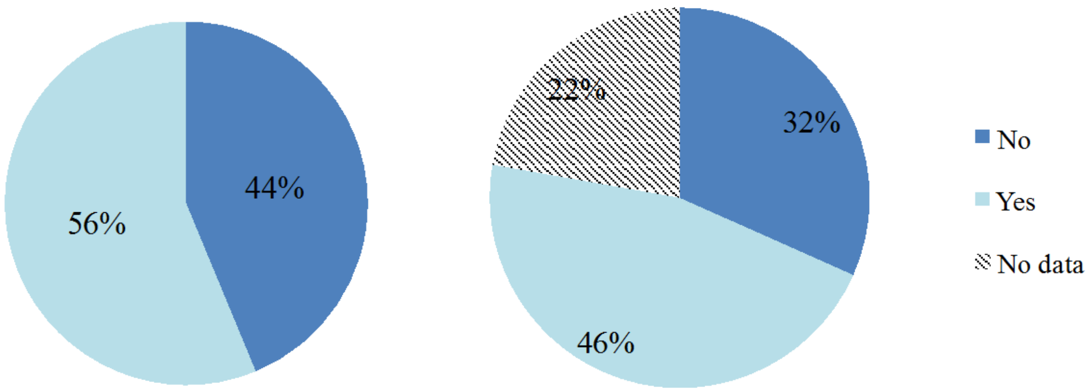


Figure 4.23 Presence of the rose/big windows

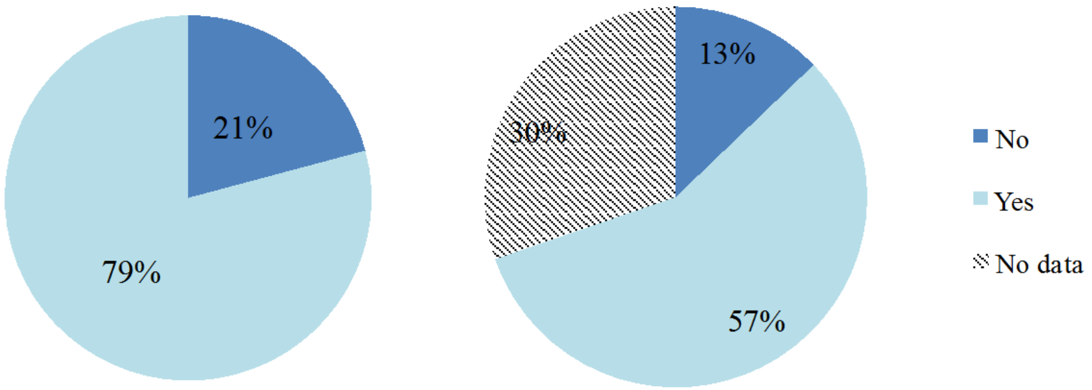


Figure 4.24 Presence of buttresses on the lateral walls

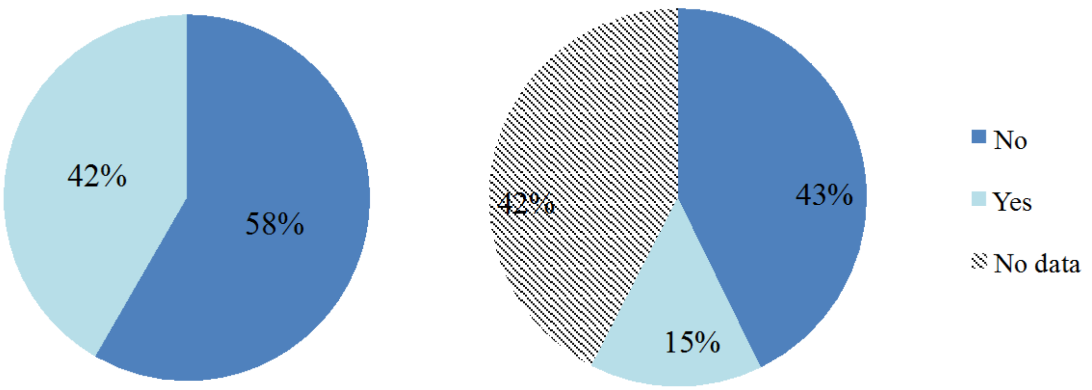


Figure 4.25 Presence of façade buttresses

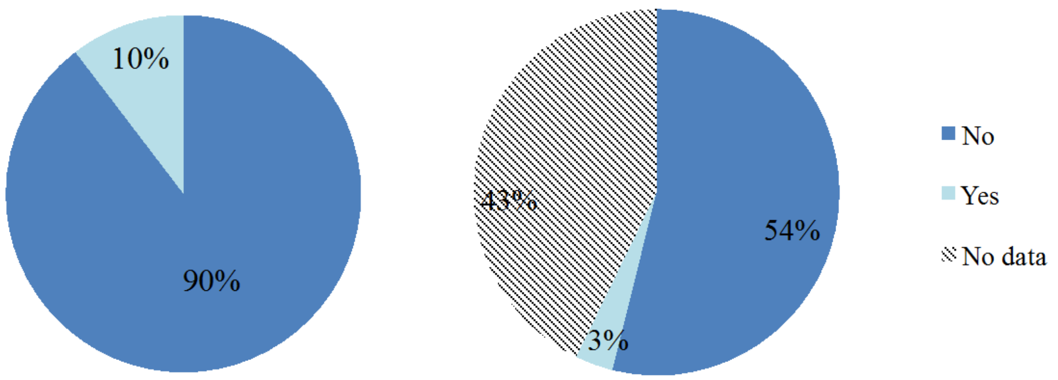


Figure 4.26 Presence of façade tie-rods

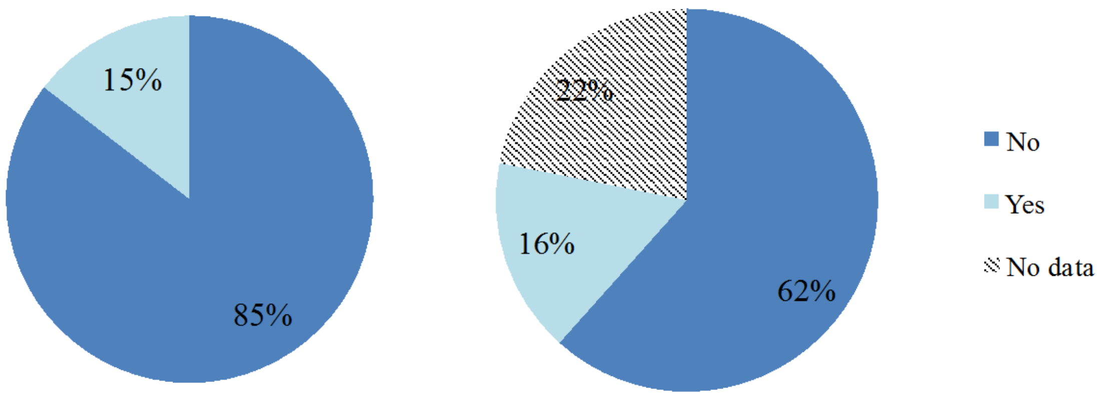


Figure 4.27 Presence of large openings on the lateral walls

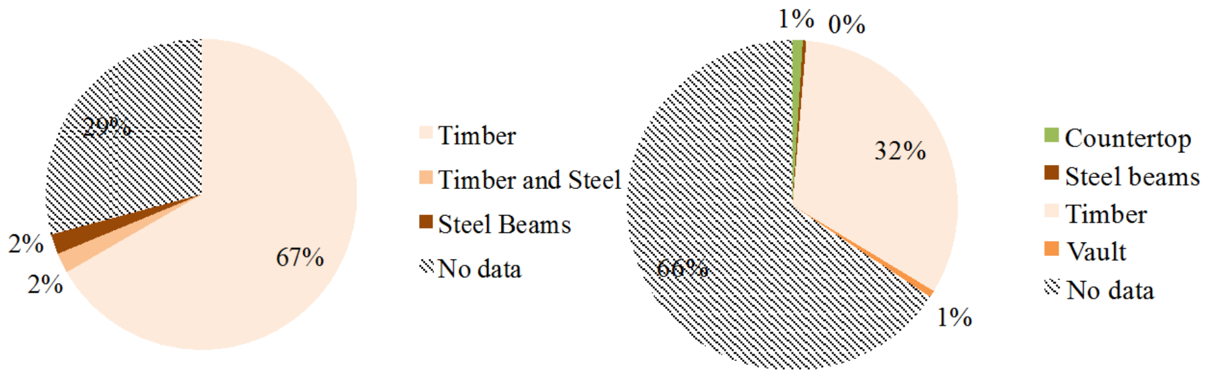


Figure 4.28 Type of roof

In the case of the New Zealand sample, also the type of transversal section has been investigated, as in Figure 4.29. It is very useful information but it was not observed at the scale of the Christchurch sample.

New Zealand Sample

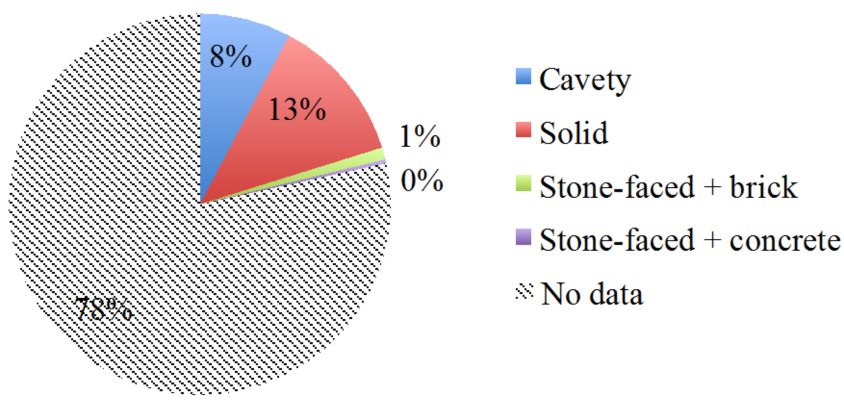


Figure 4.29 Type of masonry transversal section

These statistics show that the sample of Christchurch is quite representative of the NZ one, except for the case of the following parameters: the horizontal structures (dome, vaults and roof), the presence of pinnacles (widespread nationwide, but not in Christchurch), the role of the regularity in plan and elevation. Therefore, the statistical analysis of observed damage data after the Canterbury sequence will not give information about the role of these parameters and behaviour modifiers will be ascribed by expert judgment.

4.6.3 Results in terms of Vulnerability Curves for the New Zealand churches

In order to take into account all available information on the Intensity Measures, giving the unavoidable uncertainties at the scale of each single church, two independent values of the macroseismic intensity have been considered for each church: from Goded et al. (2014) and from the USGS Shakemaps (using the MMI-PGA correlation previously introduced, USGS, 2011). When the two sets of values were different, both have been considered; moreover, the information on the damage of a church for which the difference between the two values attributed to intensity is greater than one have been used to calculate intermediate values between the two, which have been used instead. In this way the data base was enriched, assigning a different weight which takes into account the reliability of each intensity assignment.

For each intensity, the mean damage index and the variance were computed to identify the parameters of Beta distributions and so obtain the DPMs (Cattari et al., 2015a), by transformation of the beta distribution into discrete terms.

The expression of the vulnerability curve (Equation 1 above) is proposed in Lagomarsino (2006) for churches and is calibrated on observed damage reported in Lagomarsino and Podestà (2004b).

The figures and tables with the Vulnerability Index modifiers obtained for New Zealand URM churches using this method are shown in Appendix 5.

4.7 Seismic scenarios for URM churches in Dunedin, Wellington and Auckland

Once the vulnerability index method was specifically developed for New Zealand URM churches (see Section 4.5 and Appendix 5), it was tested on churches in three cities, chosen for their different seismic activities: high (Wellington, 13 churches), intermediate (Dunedin, 27 churches) and low (Auckland, 41 churches). Seismic scenarios have been developed for all the URM churches in these 3 cities where data was collected (a total of 81 churches, Table 4.2). Most of the churches are made of brick (66) and only 15 churches are made of stone (Figure 4.30).

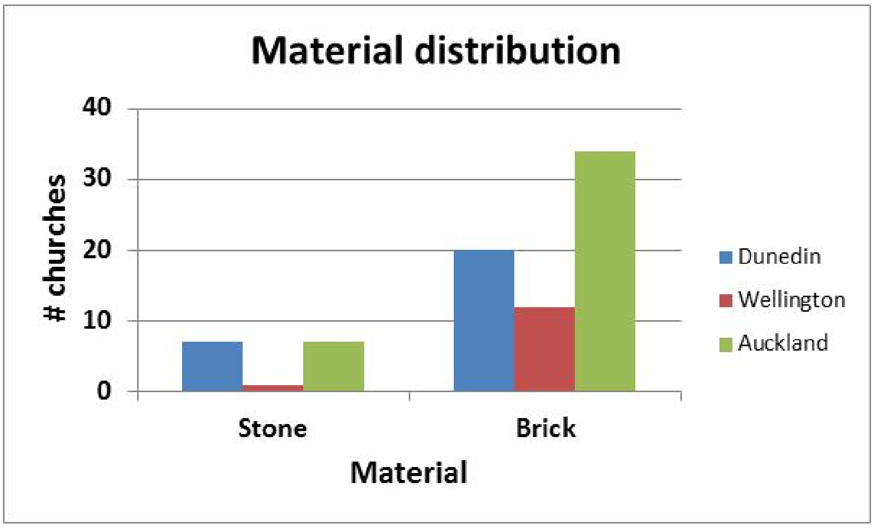


Figure 4.30 Material distribution for the URM churches in Dunedin, Wellington and Auckland.

First, for each of the three cities, the most characteristic seismic scenario was determined from the current National Seismic Hazard model. This was done by choosing the fault with the highest contribution to the seismic hazard for each of the three cities (Stirling et al., 2012; Mark Stirling, personal communication). Once the scenario has been chosen, the magnitude and distance to the town centre of the fault rupturing is used to calculate the Modified Mercalli intensity it corresponds to, using the intensity attenuation equation from Dowrick and Rhoades (2005). This way, the seismic scenario in terms of intensity is set up for each of the three cities. These seismic scenarios are:

Wellington: Wellington-Hutt valley fault, Mw=7.5, at 1km distance → MMI: medium=10.4 (Sigma = 0.43)

Auckland: Wairoa fault, Mw=6.7, 22 km → MMI: medium=8.3 (Sigma = 0.43)

Dunedin: Akatore fault, Mw=7.4, 13km → MMI: medium=9.8 (Sigma = 0.43)

It should be noted that with this method, the seismic scenarios for all the URM churches in each of the city will be developed as if all of them will experience the same intensity. However, it is likely that each church is located in a different geological setting and therefore there will be some intensity differences between them, known as site effects. The seismic scenarios have been developed using this first approach, that does not consider site effects. For site effects to be considered, more sophisticated analysis will need to be carried out, for example 1D site analysis that can calculate intensity amplifications at each location. This will need detailed data on the subsoil parameters under each of the churches, which is out of the scope of this project. An example of seismic scenarios developed using site effects for intensity amplifications can be found in Goded et al*.* (2012a, 2012b).

Once the seismic scenario is set for each church in terms of intensity, the damage grades are calculated, and the vulnerability curves are being derived. Once the vulnerability curve is obtained for each building, damage probabilities can be estimated, which represent the probability of suffering a specific damage level as a consequence of the action of an earthquake of a certain intensity. These probabilities are obtained based on the fact that the expected damage can be fitted to a binomial distribution defined by a unique parameter: the mean damage grade μ_d (Braga et al., 1982).The damage probabilities p_k associate to the damage grade k are obtained from Equation 5.

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

The complete set of Vulnerability Index modifiers, vulnerability curves, damage probabilities and damage histograms for the total 81 churches in Dunedin, Wellington and Auckland is shown in Appendix 6. It should be noted that this method is statistical, and thus should be considered with caution and in all cases in a global way and not in an individual case by case scenario. This means that, despite showing individual damage grade histograms and vulnerability curves (see Appendix 6), these should be considered in a general statistical way. For example, comparing results between churches and seeing the differences in vulnerability and the reasons why this is so is a very useful way of detecting vulnerable elements in the church. For example, a church without tie rods will be more vulnerable than one which has effective tie rods. A general overview of the behaviour of the churches in each of the three cities is presented below.

The medium (*) damage grade distribution for each of the 81 churches are shown in Table 4.2 and Figure 4.31. As it can be seen, the majority of the churches in Dunedin and shows damage grade 4 (heavy damage, see scale of damage grades in Section 4.3) in their respective characteristic scenarios, whereas the majority of the churches in Auckland will present damage grade 3 (moderate damage). This indicates that the lower seismic activity in Auckland with respect to Dunedin and Wellington is transformed in about one level less of damage grade in a characteristic scenario in each of the three cities.

To account for uncertainty, the vulnerability index modifier method also calculated the 16th and 84th percentiles, with which low and high damage grades can be estimated (see Appendix 5). However, these uncertainties should only be considered quantitatively if specific parameters for the church are missing. Given that for the Wellington, Dunedin and Auckland churches specific parameters are known, only the median values (using the 50th percentile) have been calculated and are shown. An exception are the individual vulnerability curves for each church in Appendix 6, that will include the lower and upper curves to visually account for uncertainty. However, these lower and upper curves should be treated with caution, and only the medium curves should be considered quantitatively.

(*) Note the so called “medium” values of damage grades, damage probabilities and the “medium” vulnerability curves correspond to median values (using the 50th percentile) as explained above, but will be referred to as “medium” in the text. The reason for this is to clarify that they are the intermediate values between the “low” (using the 16th percentile) and the “high” (using the 84th percentile) values.

Table 4.2 List of URM churches in Dunedin, Wellington and Auckland for which seismic scenarios have been developed. The macroseismic intensity (MMI) and medium damage grades obtained using the VI method are shown.

Ref.	Name	City	Brick/Stone	MMI	DG-med
1	St Davids Church	Dunedin	Brick	10	4.17
2	Glenaven Church	Dunedin	Brick	10	3.68
3	Catholic Church of the Sacred Heart of Jesus	Dunedin	Brick	10	3.98
4	Opoho Presbyterian Church	Dunedin	Brick	10	3.87
5	Dundas Street Methodist Church (Former)	Dunedin	Brick	10	4.01
6	All Saints' Church	Dunedin	Brick	10	3.87
7	Knox Church	Dunedin	Stone	10	4.46
8	Hanover Street Baptist Church	Dunedin	Brick	10	3.98
9	St Paul's Cathedral and Belfry	Dunedin	Stone (+RC)	10	4.68
10	Trinity Church (now Fortune Theatre)	Dunedin	Stone	10	4.46
11	Moray Place Congregational Church (Former)	Dunedin	Brick	10	4.17
12	Synagogue (*)	Dunedin	Brick	10	---
13	Cathedral Church of St Joseph	Dunedin	Stone	10	4.68
14	First Church of Otago	Dunedin	Brick	10	3.98
15	St Matthew's Church	Dunedin	Stone	10	4.63
16	St Andrew	Dunedin	Brick	10	3.80
17	Highgate Presbyterian Church	Dunedin	Brick	10	4.17
18	Kaikorai Presbyterian Church	Dunedin	Brick	10	3.98
19	Roslyn Presbyterian Church	Dunedin	Brick	10	4.17
20	Caversham Baptist Church	Dunedin	Brick	10	3.68
21	Caversham Church	Dunedin	Stone	10	4.46
22	St Peters Caversham	Dunedin	Brick	10	4.17
23	Wesley Church	Dunedin	Stone (+Brick)	10	4.50
24	St Patrick's Basilica	Dunedin	Brick (+Concrete)	10	3.76
25	St James (South Presbyterian)	Dunedin	Brick	10	3.87
26	Holy Cross	Dunedin	Brick	10	4.08
27	St Kilda Tongan Fellowship	Dunedin	Brick	10	3.76
28	Andersons Bay Presbyterian Church Deacons	Dunedin	Brick	10	3.87
29	North East Valley Baptist Church (*)	Dunedin	Brick	10	---
30	Halfway Bush Union Church (*)	Dunedin	Brick	10	---
31	St Clair (*)	Dunedin	Brick	10	---
32	All Saints Church – Abbot St	Wellington	Brick (+Timber)	10.5	4.14
33	St Luke's Parish	Wellington	Brick	10.5	4.25

Ref.	Name	City	Brick/Stone	MMI	DG-med
34	St Michael and All Angels	Wellington	Brick (+Timber)	10.5	4.04
35	Karori Crematorium Chapel	Wellington	Brick	10.5	4.04
36	Congregational Church	Wellington	Brick	10.5	4.37
37	Miramar Uniting Church	Wellington	Brick	10.5	4.30
38	Our Lady Star of the Sea Convent Chapel	Wellington	Brick	10.5	4.14
39	St Jude's	Wellington	Brick	10.5	4.25
40	St Hilda's (*)	Wellington	Brick	10.5	---
41	Sacred Heart Cathedral	Wellington	Brick (+RC)	10.5	4.14
42	All Saints Church – Hamilton St	Wellington	Brick	10.5	4.14
43	St Gerard's Church	Wellington	Brick	10.5	4.14
44	St Anne's Church (Former)	Wellington	Brick	10.5	4.04
45	Missions to Seamen Building (Former)	Wellington	Stone	10.5	4.46
46	St Patrick's Cathedral	Auckland	Brick	8.5	2.79
47	St Andrew's First Presbyterian Church	Auckland	Stone	8.5	3.38
48	St Matthew in the City	Auckland	Stone	8.5	4.22
49	Pitt street Methodist Church	Auckland	Brick	8.5	2.94
50	Congregational Church Of Jesus	Auckland	Brick	8.5	2.53
51	Baptist Tabernacle	Auckland	Brick	8.5	2.38
52	St Paul's Church	Auckland	Stone	8.5	3.98
53	Wesleyan Chapel	Auckland	Brick	8.5	2.53
54	St James' Church	Auckland	Stone	8.5	3.38
55	Church of the Melanesian Mission Building	Auckland	Stone	8.5	3.60
56	Dominion Road Methodist Church	Auckland	Brick	8.5	2.94
57	St Alban the Martyr	Auckland	Brick	8.5	2.79
58	St Barnabas	Auckland	Brick	8.5	2.79
59	Holy Trinity	Auckland	Brick	8.5	2.64
60	Holy Trinity	Auckland	Brick	8.5	3.09
61	St Augustine's Church	Auckland	Brick	8.5	3.09
62	St Francis de Sales, All Souls	Auckland	Brick	8.5	2.99
63	St Paul's Church – Presbyterian	Auckland	Brick	8.5	3.09
64	St Benedict's Church	Auckland	Brick	8.5	3.24
65	St Michael’s Church	Auckland	Brick	8.5	3.19
66	Church of Our Lady of the Assumption	Auckland	Brick	8.5	2.99
67	St Columba Church	Auckland	Brick	8.5	3.09
68	King's College Chapel	Auckland	Brick	8.5	3.09
69	St Paul's Church – Methodist	Auckland	Brick	8.5	3.09
70	St Saviour's Chapel	Auckland	Brick	8.5	2.64

Ref.	Name	City	Brick/Stone	MMI	DG-med
71	All Hallows	Auckland	Brick	8.5	2.64
72	Calvary Tamil Methodist Church	Auckland	Brick	8.5	3.24
73	St Vincent de Paul Church	Auckland	Brick	8.5	3.09
74	St Joseph and St Joachim	Auckland	Brick	8.5	3.09
75	St John's	Auckland	Stone	8.5	3.98
76	St Thomas	Auckland	Brick	8.5	2.53
77 (*)	Waikumete Cemetery Chapel	Auckland	Brick?	8.5	---
78	St David	Auckland	Brick	8.5	3.42
79	Neligan House Chapel	Auckland	Brick	8.5	2.64
80	St Andrews	Auckland	Brick	8.5	3.09
81	New Zealand Chinese Mission Church	Auckland	Brick (+Timber)	8.5	2.69
82	St Aidans	Auckland	Brick	8.5	3.09
83	Church 39 Margan Ave	Auckland	Brick	8.5	2.38
84	Church 40 Margan Ave	Auckland	Brick	8.5	2.64
85	Selwyn Chapel	Auckland	Stone	8.5	4.11
86	First Presbyterian Church Papakura	Auckland	Brick	8.5	3.09
87	St Johns	Auckland	Brick	8.5	2.99

(*) Churches not found during survey, therefore no data collected

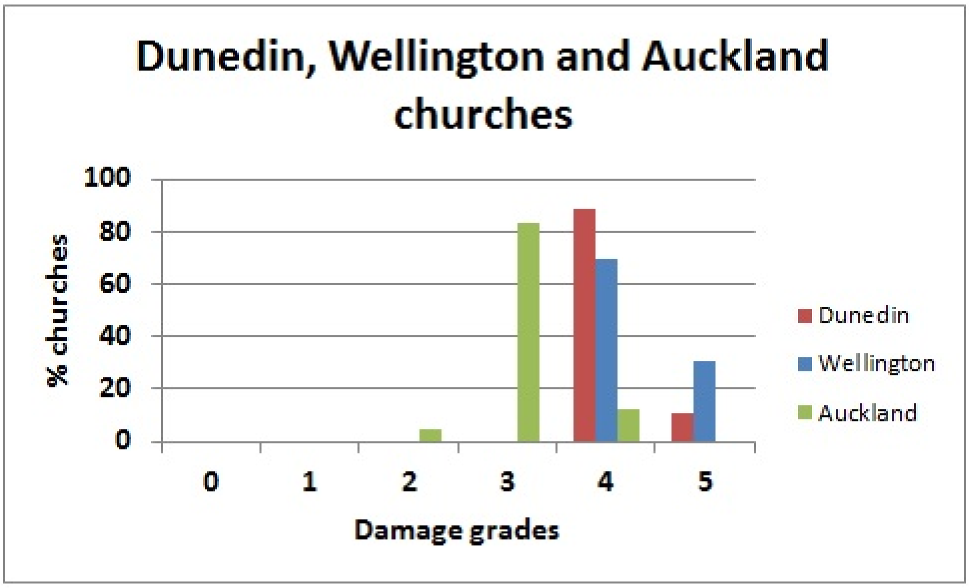


Figure 4.31 Medium damage grades distribution obtained for Dunedin, Wellington and Auckland URM churches.

Figure 4.32 show the medium damage probabilities distribution for the Dunedin, Wellington and Auckland URM churches. If the medium damage probabilities are considered, it can be seen that for Dunedin churches, 52% will have 20–30% probabilities of having moderate damage (grade 3), and the majority of them (88%) will have a 30–50% probability of having heavy damage (damage grade 4), and. About 25% of the Dunedin churches could have 50 to 80% probabilities of suffering total collapse (damage grade 5) if the Akatore fault should rupture.

For Wellington churches, there is a 10–20% probability of suffering moderate damage (grade 3), and a 30–50% probability of suffering heavy damage (damage grade 4) in the total amount of churches in the city. In addition, 38% of the churches could suffer total collapse with a 40–60% probability, in case there was a rupture from the Wellington-Hutt valley fault.

For the Auckland churches (Figure 4.32c), the probabilities of higher damage are lower than for the Dunedin and Wellington churches, being the highest probability of 30–40%, corresponding to moderate damage. About 50% of the churches might suffer heavy damage with a 20–30% probability. In addition, the probability of collapse is very low for the Auckland churches, with 75% of them showing a very low probability (less than 10%) of suffering collapse.

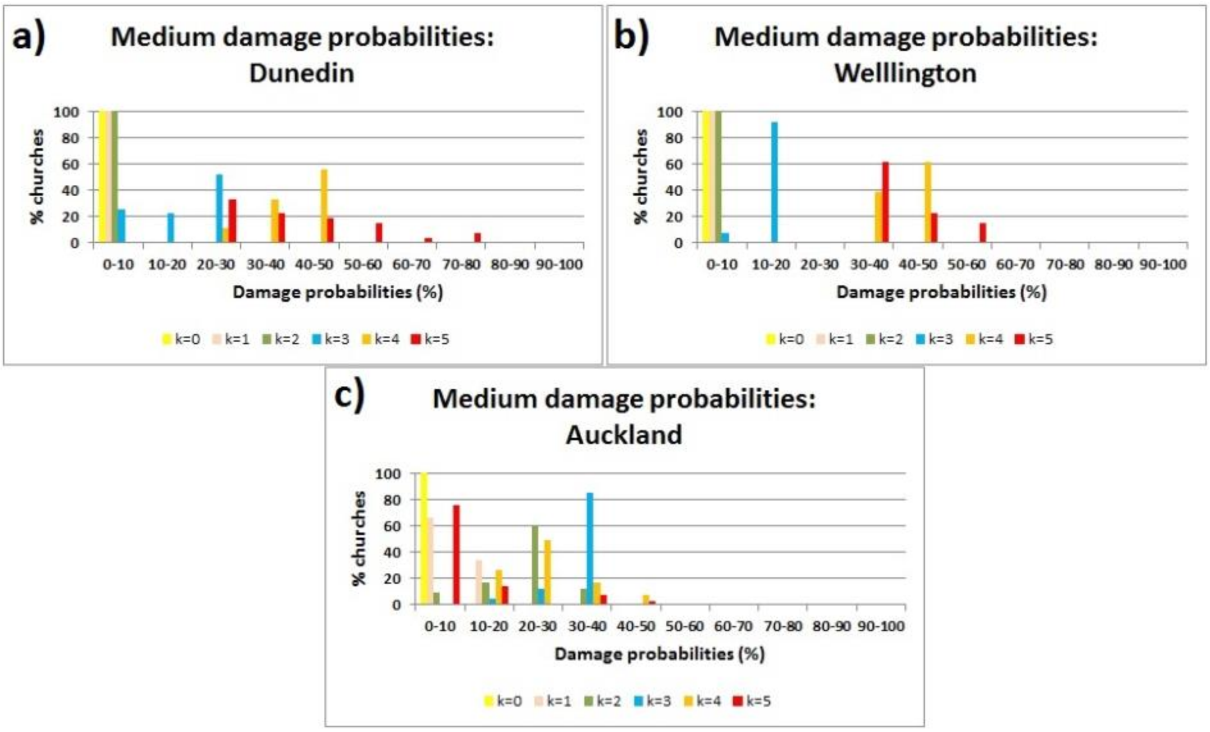


Figure 4.32 Distribution of medium damage probabilities obtained for Dunedin (a), Wellington (b) and Auckland (c) URM churches. Total number of URM churches in Dunedin = 27; Wellington = 13 and in Auckland = 41.

5.0 CONCLUSIONS AND FUTURE WORK

The heavy damage caused in the Canterbury URM churches following the Christchurch 2010–2011 earthquake sequence emphasised the impelling need to define, for New Zealand (NZ), a systematic method to assess the seismic vulnerability of churches, that can be applied nationwide. This project presents the first (to our knowledge) seismic vulnerability method created specifically for New Zealand URM churches. It is based on a macroseismic approach that uses seismic intensity as the damage parameter, and obtains damage grades using a single parameter, the vulnerability index. This index, and its modifiers, have been developed based on the damage caused to 48 URM churches in the Canterbury area during the 2010–2011 earthquake sequence. This report presents the main results and achievements of the project, including 1) a compiled database of 297 URM churches located all around New Zealand; 2) a specific typological classification for New Zealand URM churches; 3) a specific damage survey form drawn for URM churches; 4) a detailed analysis of the earthquake-induced damage to a stock of 48 URM churches located in the Canterbury Region; 5) a manual indicating the use of the proposed macroseismic method to obtain the seismic vulnerability of URM churches using vulnerability index; and 6) the development of seismic scenarios for the URM churches in Wellington, Auckland and Dunedin, using the new parameters developed within this project.

The results from the seismic scenarios show the differences in the seismic activity of the location. All these results indicate that the need to develop a vulnerability method for New Zealand URM churches was justified.

This project has produced several publications (two journal papers, one submitted, three conference proceedings, one Master thesis). In addition, within this project data has been collected for the whole set of New Zealand URM churches, instead of only for Christchurch, Dunedin, Wellington and Auckland as was promised in the application. It has become the first step in the development of a vulnerability method to be applied to New Zealand historical heritage.

The authors have identified following future research tasks to build on the work explained in this report and seek funding to carry out such future works when it becomes available.

- Development of seismic scenarios for the rest of the New Zealand URM churches (outside from Canterbury, Auckland, Dunedin and Wellington regions).
- Add site effects to the seismic scenarios, by considering the subsoil under each church location, undertaking 1D site response analysis.
- Development of a more sophisticated and detailed method to obtain the seismic vulnerability of URM churches, through a mechanical approach that takes into account the seismic behaviour of individual structural parts of the churches (macroelements).
- Data collection and development of a vulnerability method for other heritage buildings in the country (towers, palaces, etc.).

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APPENDICES

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A1.0 APPENDIX 1: UNREINFORCED MASONRY CHURCHES IN NEW ZEALAND

A complete list of URM churches in New Zealand, gathered during this project, is shown below. The classification has been made according to the different regions.

ANNEX 1 – UNREINFORCED MASONRY CHURCHES IN NORTHLAND

Name	Address	HNZ no.
PAIHIA		
Williams Memorial Church of St Paul	36 Marsden Rd	3824

ANNEX 2 – UNREINFORCED MASONRY CHURCHES IN AUCKLAND

Name	Address	HNZ no.
AUCKLAND		
St Patrick's Cathedral	1 St Patricks Square	97
St Andrew's First Presbyterian Church	Corner of Symonds St and Alten Rd	20
St Matthew in the City	Corner of Hobson St and Wellesley St	99
Pitt street Methodist Church	78 Pitt St	626
Congregational Church Of Jesus	3 East St	/
Baptist Tabernacle	429 Queen St	7357
St Paul's Church	28 Symonds St	650
Wesleyan Chapel	8A Pitt St	7752
St James' Church	39 Church Rd	689
Church of the Melanesian Mission Building	40-44 Tamaki Drive	111
Dominion Road Methodist Church	426 Dominion Rd	2607
St Alban the Martyr	443 Dominion Rd	511
St Barnabas	283 Mt Eden Rd	516
Holy Trinity	437 Parnell Rd	/
Holy Trinity	18 Mason Ave	2320
St Augustine's Church	95 Calliope Rd	4529
St Francis de Sales, All Souls	2A Albert Rd	/
St Paul's	Corner of Albert and Victoria Rds	/
St Benedict's Church	1 St Benedicts St	640
St Michaels Church	6 Beatrice Rd	118
Church of Our Lady of the Assumption	130 Church St	523
St Columba Church	100 Surrey Crescent	2644
King's College Chapel	41 Golf Ave	90
St Paul's Church	14 St Vincent Ave	651
St Saviour's Chapel	80 Wyllie Road	7169
All Hallows	218 Beach Road	/
Calvary Tamil Methodist Church	587 Manukau Road	/
St Vincent de Paul Church	Corner Fenwick Avenue and Shakespeare Rd,	/
St Joseph and St Joachim	118 Church St,	/
St John's	328 East Tamaki Rd	/
St Thomas	2 Islington Avenue	/

Name	Address	HNZ no.
Waikumete Cemetery Chapel	Glenview Rd	2605
St David	70 Khyber Pass Rd	/
Neligan House Chapel	12 St Stephens Ave	/
St Andrews	18 Station Rd	/
New Zealand Chinese Mission Church	161 Trafalgar St	/
St Aidans	90 Onewa Rd	/
?	39 Margan Ave	/
?	40 Margan Ave	/
Selwyn Chapel	105 Great South Rd	693
First Presbyterian Church Papakura	2 Coles Crescent	/
St Johns	120 Great South Rd	/
PUKEKOHE		
St Andrew's	37 Queen Street	/

ANNEX 3 – UNREINFORCED MASONRY CHURCHES IN WAIKATO

Name	Address	HNZ no.
GORDONTON		
St Mary's Church	974 Gordonton Rd	4303
HAMILTON		
St Mary's Convent Chapel	47 Clyde St	5460
St Andrews	Cnr River Rd and Te Aroha St	/
HUNTLY		
St Paul's Church	Corner of William St and Glasgow St	4165
HYDE		
?	9071 Eton St	/

Name	Address	HNZ no.
NGARUAWAHIA		
St Paul's Church	128 Thermal Explorer Highway	4246
RAGLAN		
Raglan District Union Church	3 Stewart St	/
TE AROHA		
St David's Union Church	8 Church St	4288
St Mark's Church	7 Kenrick St	4290
TE AWAMUTU		
Te Awamutu Church	261 Bank St	4295
TIRAU		
Tirau Co-Operating Church	67 Main Rd	/

ANNEX 4 – UNREINFORCED MASONRY CHURCHES IN BAY OF PLENTY

Name	Address	HNZ no.
OPOTIKI		
Former Methodist Church	?	/

ANNEX 5 – UNREINFORCED MASONRY CHURCHES IN GISBORNE

Name	Address	HNZ no.
GISBORNE		
Holy Trinity Church	79 Derby St	3526
St Andrew's Church	176 Cobden St	3525
WAIPIRO		
St Abraham's Memorial Church	12 Marae Rd	3490

ANNEX 6 – UNREINFORCED MASONRY CHURCHES IN HAWKE'S BAY

Name	Address	HNZ no.
PAKIPAKI		
Pakipaki War Memorial church	63 Old Main Rd	/

Name	Address	HNZ no.
WAIPUKURAU		
St Mary's	11 St Mary's Rd	/

ANNEX 7 – UNREINFORCED MASONRY CHURCHES IN TARANAKI

Name	Address	HNZ no.
HAWERA		
St Mary's Church	206 Princes St	861
INGLEWOOD		
St Andrew's Church	104 Rata Rd	875
NEW PLYMOUTH		
Taranaki Cathedral (St Mary's Church)	37 Vivian St	148

ANNEX 8 – UNREINFORCED MASONRY CHURCHES IN MANAWATU-WANGANUI

Name	Address	HNZ no.
CARTERTON		
St Mary	2 King St	/
DANNEVIRKE		
St John the Baptist	174 High St	4551
LEVIN		
St John's Church	90 Cambridge St	4091
MANAKAU		
Methodist Church (Former)	1104 State Highway 1	4051
MASTERTON		
St. Luke's Union Church	Cnr Worksop Rd and Queen St	/
MOAWHANGO		
Batley Memorial Chapel	32 Wherewhere Rd	3308
PALMERSTON NORTH		
Wesley Broadway	264 Broadway Ave	
All Saints' Church	338 Church St	191
WANGANUI		
Wanganui Collegiate School Chapel	128 Liverpool St	999

Name	Address	HNZ no.
WESTMERE		
St Oswald's Church	State highway 3	956
Westmere Memorial Church	110 State Highway 3	2738

ANNEX 9 – UNREINFORCED MASONRY CHURCHES IN WELLINGTON

Name	Address	HNZ no.
LOWER HUTT		
Epuni Baptist Church	304 Waiwhetu Rd	/
Methodist church	Laings Rd	/
WELLINGTON		
Erskine College Chapel	31 Avon Street	7795
All Saints Church	1 Abbot St	/
St Luke's Parish	34 Pitt St	/
St Michael and All Angels	Corner St Michael's Crescent and Upland Rd	/
Karori Crematorium Chapel	Old Karori Road	1399
Congregational Church	45 Cambridge Terrace	/
Miramar Uniting Church	56 Hobart St	/
Our Lady Star of the Sea Convent Chapel	16 Fettes Crescent	1413
St Jude's	68 Freyberg St	/
St Hilda's	311 The Parade	/
Sacred Heart Cathedral	40 Hill St	214
All Saints Church	94 Hamilton Rd	1331
St Gerard's Church	75 Hawker St	226
St Anne's Church (Former)	77 Northland Rd	3603
Missions to Seamen Building (Former)	7 Stout St	3611

ANNEX 10 – UNREINFORCED MASONRY CHURCHES IN TASMAN

Name	Address	HNZ no.
MOTUEKA		
St Peter Chanel (Former)	31 High St	1671
Former church	207 High St	/
TAKAKA		
Sacred Heart	94 Commercial St	/

ANNEX 11 – UNREINFORCED MASONRY CHURCHES IN NELSON

Name	Address	HNZ no.
NELSON		
Garin Memorial Chapel (Wakapuaka Cemetery)	272 Atawhai Drive	1637
All Saints	30 Vanguard St	/
Christ Church Cathedral	Trafalgar Square	/
STOKE		
St Barnabas’	523 Main Rd	3025

ANNEX 12 – UNREINFORCED MASONRY CHURCHES IN MARLBOROUGH

Name	Address	HNZ no.
BLENHEIM		
The Church of the Nativity	76 Alfred St	/
HAVELOCK		
St Peter's Church	30 Lawrence St	1496
Sacred Heart Church	15 Lawrence St	/
PICTON		
St Joseph’s	119 Wellington Rd	/
WARD		
St Peter’s Chanel	7298 SH1	/
WHARANUI		
St Oswald's Church	8817 State Highway 1	/

ANNEX 13 – UNREINFORCED MASONRY CHURCHES IN WEST COAST

Name	Address	HNZ no.
HOKITIKA		
St Mary’s	71 Sewell St	1705
St Andrew’s United Church	66 Hampden St	5013

ANNEX 14 – UNREINFORCED MASONRY CHURCHES IN CANTERBURY

Name	Address	HNZ no.
AKAROA PENINSULA		
St Paul's Church	850 Old Tai Tapu Rd	4395
St Kentigern	396 Kaituna Valley Rd	/
Church of St John the Evangelist	1131 Okains Bay Rd	1715
St Luke	1280 Chorlton Rd	7094
St Cuthbert's Church	8 Governors Bay Teddington Rd	281
ASHBURTON		
Church of the Holy Name	58 Sealy St	284
St Andrew's Presbyterian Church	130 Havelock St	1809
St Andrew's Presbyterian Church (Former)	130 Havelock St	1804
Ashburton Baptist Church	Corner Havelock St and Cass St	/
CAVE		
St Monica	6 Anne St	/
All Saint's Cave	30 Elizabeth St	/
St David's Memorial Church	Burnetts Rd	312
CHRISTCHURCH		
St Joseph's Parish	133 Main North Rd	/

Name	Address	HNZ no.
Christchurch North Methodist	61 Harewood Rd	/
Our Lady of Perpetual Help Church	58 Somme St	/
St John's Church	49 Bryndwr Rd	/
St Barnabas' Church	145 Fendalton Rd	3681
St Ninians' Church	9 Puriri St	/
St Peter's Church	24 Main South Rd	1792
St Brendan's Church	47 Kirk Rd	/
St John of God Chapel	12 Nash Rd	4393
Cashmere Hills Church	2 Macmillan Ave	1842
St Mark's Church	101 Opawa Rd	/
Opawa Community Church	158 Opawa Rd	/
Church of the All Saints	48 Wakefield Ave	/
St Mary's Parish	112 Lonsdale St	/
St Faith's	46 Hawke St	/
Synagogue	Gloucester St	/
The Rose Historic Chapel	866 Colombo St	7239
Trinity Congregational Church	124 Worcester St	306
Cathedral Church of Christ	100 Cathedral Square	46
Christ`s College Chapel	33 Rolleston Ave	3277
Nurses Memorial Chapel	2 Riccarton Ave	1851
Cathedral of the Blessed Sacrament	136 Barbadoes St	47
St James the Great Riccarton	69 Riccarton Rd	/
St John The Evangelist Church	Christchurch Akaroa Rd	5293
St Mark's Marshland	338 Prestons Rd	/

Name	Address	HNZ no.
St John The Evangelist Church	10 St Johns St	/
Prebbleton Community	641 Springs Rd	/
Nazareth House Chapel	220 Brougham St	/
Knox Church	28 Bealey Ave	/
St Columba	88 Petrie St	/
St Andrew's College	347 Papanui Rd	/
Shirley Church	Shirley Rd	/
Ex-St James	?	/
DUNTROON		
St Magnus Presbyterian Church	11 Rees St	3255
St Martin's Church	3487 Kurow - Duntroon Rd	2429
FAIRLIE		
St Patrick and All Saints	7 Gall St	/
GERALDINE		
St Andrew the Apostle	10 Cox St	/
Immaculate Conception	19 Hislop St	/
Church of the Holy Innocents	Rangitata Gorge Rd	1976
HORORATA		
St John's Hororata	224 Hororata Rd	/
KAIAPOI		
Methodist Church	52 Fuller St	3760
KUROW		
St Alban Chapel	5636 Kurow-Duntroon Rd	/
St Stephen	83 Provincial Highway	2435
LAKE TEKAPO		
Church of the Good Shepherd	Pioneer Drive	311
LEESTON		
St John's The Evangelist	158 High St	/

Name	Address	HNZ no.
MAKIKIHI		
St. Mary's Star of the Sea	1686 Waimate Highway	/
MAUNGATI		
St James' Maungati	143 Timaunga Rd	/
OTIPUA		
St Marks	High St	/
PLEASANT POINT		
St Mary's Church	29 Afghan St	7697
St Alban's Pleasant Point	20 Harris St	/
SAINT ANDREWS		
St Andrews	8 Thackeray St	/
SEFTON		
St Luke's	Upper Sefton Rd	/
SHEFFIELD		
St Ambrose Sheffield	46 Railway Tce East	/
SOUTHBRIDGE		
St James'	2 Hastings St	/
SOUTHBURN		
Southburn Church	994 Pareora River Rd	/
TEMUKA		
St Peter's Temuka	192 King St	/
St Josephs Catholic Church	28 Wilkin St	2033
Holy Trinity Arowhenua	3 Huirapa St	/
TIMARU		
St Paul	28 Seddon St	/
St Joseph's Church	42 Douglas St	/
Woodlands Road Methodist Church	Corner Woodlands Rd and North St	/
Bank Street Methodist Church	38 Bank St	3155
St Mary's Church	24 Church St	328
Chalmers Church	4 Elizabeth St	7107

Name	Address	HNZ no.
TOTARA VALLEY		
St Paul's Presbyterian Church (Former)	856 Cleland Rd	1995
WAIAU		
All Saints' Church	35 Parnassus St	3690
WAIHAO DOWNS		
St Michael's Church	1115 State Highway 82	/
WAIMATE		
St Pauls Waimate	11 Glasgow St	/
Knox Church	58 Shearman St	/
St Patrick's Church	2 Timaru Rd	7343
WAIPARA		
St Paul's Church	173 Church Rd	7111
WOODBURY		
St Thomas' Church	6 Church St	/
WOODEND		
Methodist Church	86 Main North Rd	3795

ANNEX 15 – UNREINFORCED MASONRY CHURCHES IN OTAGO

Name	Address	HNZ no.
ALEXANDRA		
St Enoch's church	12 Centennial Ave	/
St Aidan's	42 Shannon St	/
ARROWTOWN		
St John's Church	26 Berkshire St	2119
St Patrick's	7 Hertford St	2117
AWAMOKO		
Awamoko Presbyterian Church	1783 Georgetown - Pukeuri Rd	/
BANNOCKBURN		
Bannockburn Presbyterian Church	33 Hall Rd	2385

Name	Address	HNZ no.
CLYDE		
St Michael and All Angels Church	8 Matau St	2386
St Dunstan's Church	61 Sunderland St	2387
St Magnus'	60 Sunderland St	/
CROMWELL		
Goldfields Old Church	52 Erris St	/
Mary Immaculate and the Irish Martyrs	3 Sligo St	/
St John's Presbyterian Church	24 Inniscort St	2131
St Andrew's Anglican Church	41 Blyth St	2132
DUNEDIN		
St Davids Church	227 North Rd	4734
Glenaven Church	7 Chambers St	3371
Catholic Church of the Sacred Heart of Jesus	89 North Rd	2214
Opoho Presbyterian Church	50 Signal Hill Rd	/
Dundas Street Methodist Church (Former)	50 Dundas St	3367
All Saints' Church	786 Cumberland St	2136
Knox Church	463 George St	4372
Hanover Street Baptist Church	65 Hanover St	4792
St Paul's Cathedral and Belfry	36 The Octagon	376
Trinity Church (now Fortune Theatre)	231 Stuart St	3378
Moray Place Congregational Church (Former)	81 Moray Place	2218
Synagogue	29 Moray Place	9606
Cathedral Church of St Joseph	288 Rattray St	364

Name	Address	HNZ no.
First Church of Otago	410 Moray Place	60
St Matthew's Church	28 Hope St	2212
St Andrew	64 Melville St	3185
Highgate Presbyterian Church	580 Highgate	/
Kaikorai Presbyterian Church	127 Taieri Rd	/
Roslyn Presbyterian Church	21 Highgate	3377
Caversham Baptist Church	10 Surrey St	/
Caversham Church	61 Thorn St	7319
St Peters Caversham	57 Baker St	9545
Wesley Church	333 Hillside Rd	/
St Patrick's Basilica	32 Macandrew Rd	2213
St James (South Presbyterian)	400 King Edward St	/
Holy Cross	12 Richardson St	/
St Kilda Tongan Fellowship	56 Queens Drive	/
Andersons Bay Presbyterian Church Deacons	76 Silverton St	/
North East Valley Baptist Church	270 North Rd	/
Halfway Bush Union Church	28 Balmain St	/
St Clair	51 Albert St	/
ENFIELD		
Enfield Presbyterian Church	805 Weston-Ngapara Rd	2417
ESK VALLEY		
St Mary's Church	Church Hill Road	319
HAMPDEN		
Presbyterian Church	2 London St	3249

Name	Address	HNZ no.
HERBERT		
St John's Presbyterian Church	1 Ord St	2416
HERIOT		
Heriot Community Church	17 Roxburgh St	/
HYDE		
Catholic Church of the Sacred Heart of Jesus	9137 Eton St	2253
KOKONGA		
?	Kyeburn-Hyde Rd	/
KUROW		
Sacred Heart Roman Catholic church	5634 Kurow-Duntroon Rd	/
LAWRENCE		
Lawrence Presbyterian Church (Former)	7 Colonsay St	2243
St Patrick	12 Colonsay St	2243
Holy Trinity Anglican Church	9 Whitehaven St	2245
Lawrence Methodist Church	Corner of Whitehaven St and Colonsay St	/
LOVELLS FLAT		
?	Station Rd	/
MACRAES FLAT		
St Patrick's Catholic Church (Former)	7 Hyde St	2397
?	1726 Macraes Rd	/
MAHENO		
St Andrew’s	4 Short St	/
MIDDLEMARCH		
St John's Church	4 Aberafon St	/
MILTON		
St John	167 Union St	/
Tokomairiro Church	30 Union St	2250
Immaculate Conception	24 Dryden St	/

Name	Address	HNZ no.
MOSGIEL		
East Taieri Presbyterian Church	12A Cemetery Rd	2260
Gospel Hall	75 Gordon Rd	/
Mosgiel Presbyterian Church	11 Church St	/
NASEBY		
St George	46 Derwent St	/
NORTH TAIERI		
North Taieri Presbyterian Church	39 Wairongoa Rd	3234
OAMARU		
Rosary Chapel	70 Reed St	2301
St Patricks Basilica	64 Reed St	58
Reformed Church (Church of Christ)	6 Eden St	/
St Paul's Church	3 Coquet St	2300
St Luke's Anglican Church	2 Tees St	4365
Columba Presbyterian Church	33 Wansbeck St	7313
Wesley Church	22 Eden St	/
PALMERSTON		
St James' Church	80 Tiverton St	3247
St Mary's Church	8 Stromness St	2396
Blessed Sacrament	44 Ronaldsay St	/
PORT CHALMERS		
St Mary's Star of the Sea Church	34 Magnetic St	2328
Holy Trinity Church	1 Scotia St	2320
Iona Church	24 Mount St	7165
QUEENSTOWN		
St Peter's Church	6 Church St	2341
St Joseph's Church	41 Melbourne St	2340
RANFURLY		
Sacred Heart	4 Stuart Rd	/

Name	Address	HNZ no.
ROXBURGH		
Teviot Union Parish Church	75 Scotland St	/
St James' Church	12 Ferry Rd	2345
Our Lady of Peace	5 Liddle St	/
SAINT BATHANS		
St Patrick's Church	Cross St	3210

ANNEX 16 – UNREINFORCED MASONRY CHURCHES IN SOUTHLAND

Name	Address	HNZ no.
CENTRE BUSH		
St Andrew's Presbyterian Church (Former)	1785 Dipton-Winton Highway	7427
GORE		
Holy Trinity	15 Traford Street	/
?	4 Irk St	/
INVERCARGILL		
First Church	151 Tay St	387
St John's Anglican Church Complex	108 Tay St	391
Central Methodist Church	82 Jed St	2449
St Paul's Church	178 Dee St	2517
Windsor Community Church	19 Windsor St	/
All Saints Anglican Church and Parish Hall	509 Dee St	2440
St Stephen's Church	284 North Rd	2518
Sacred Heart	449 North Rd	/
St Patrick’s	33 Rimu St	/
St Mary’s	54 Eye St	/
MATAURA		
St Savious	127 Main Rd	/
Mataura Presbyterian	?	/
WYNDHAM		
St Kevin’s	45 Inkermann St	/

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A2.0 APPENDIX 2: DAMAGE SURVEY FORM FOR UNREINFORCED MASONRY CHURCHES IN NEW ZEALAND

Developed by the research group of University of Genova – Prof. Sergio Lagomarsino, Serena Cattari, Daria Ottonelli, Arianna Bazzurro, Matilde Pinna and Francesca Porta

This appendix should be read in conjunction with Appendix 3.

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DAMAGE SURVEY FORM FOR UNREINFORCED MASONRY CHURCHES

S. Lagormarsino, S. Cattari, D. Ottonelli, A. Bazzurro, M. Pinna, F. Porta

MACROELEMENT		***w***	***w'***	***w_A* (≥1)**	***w'_A***	***D_L***	***D_T***	***D***
N_C – CENTRAL NAVE	❑	1		…..		………	………	………
Nl_{LEFT} – LEFT LATERAL NAVES	❑	….. (0.5-1)		…..		………	………	………
Nl_{RIGHT} – RIGHT LATERAL NAVES	❑	….. (0.5-1)		…..		………	………	………
F – FAÇADE	❑	….. (0.6-1.2)		…..		………	………	………
T_{LEFT} – LEFT TRANSEPT	❑	….. (0.5-0.8)		…..		………	………	………
T_{RIGHT} – RIGHT TRANSEPT	❑	….. (0.5-0.8)		…..		………	………	………
D – DOME	❑	….. (0.5-1)		…..		………	………	………
TA – TRIUMPHAL ARCH	❑	….. (0.2-0.7)		…..			………	………
P – PRESBYTERY	❑	….. (0.2-0.6)		…..		………	………	………
A – APSE	❑	….. (0.4-0.8)		…..		………	………	………
AN_1 – ATRIUM/NARTHEX	❑	….. (0.2-0.8)		…..		………	………	………
AN_2 – ATRIUM/NARTHEX	❑	….. (0.2-0.8)		…..		………	………	………
C_1 – CHAPELS (1st group)	❑	….. (0.2-0.8)		…..		………	………	………
C_2 – CHAPELS (2nd group)	❑	….. (0.2-0.8)		…..		………	………	………
C_n – CHAPELS (nth group)	❑	….. (0.2-0.8)		…..		………	………	………
BT – BELL TOWER	❑	….. (0.5-1.2)		…..		………	………	………
PR_1 – PROJECTIONS (1st group)	❑	….. (0.2-0.7)		…..		………	………	………
PR_2 – PROJECTIONS (2nd group)	❑	….. (0.2-0.7)		…..		………	………	………
PR_n – PROJECTIONS (nth group)	❑	….. (0.2-0.7)		…..		………	………	………
						$D_{CHURCH,L}$ ……….	$D_{CHURCH,T}$ ……….	D_{CHURCH} ……….
								$D_{CHURCH,A}$ ……….

Nc – CENTRAL NAVE	❑	**w_{Nc} = 1**
Nc3(L) – cracks due to the in-plane response of side walls	6	❑ ❑ ❑ ❑ ❑
Nc4(L) – longitudinal response of the colonnade (in the case church with lateral naves)	7	❑ ❑ ❑ ❑ ❑
Nc4(T) – transversal response of the nave with overturning of the side walls	5	❑ ❑ ❑ ❑ ❑
Nc6 – damage in the vaults of the central nave	8	❑ ❑ ❑ ❑ ❑
Nc8 – damage at the connection between roof and side walls	19	❑ ❑ ❑ ❑ ❑
Nc9 – damage in the nave due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
NcH = max(Nc6,Nc8) = ...		
NcV_L = max(Nc3,$Nc4_L$) = ... if NcV_L = NcH → NcV_L = NcH+1	DNc_L = max(NcV_L,NcH) = ...	
NcV_T = $Nc4_T$ = ... if NcV_T = NcH → NcV_T = NcH+1	DNc_T = max(NcV_T,NcH) = ...	
NcV = max(NcV_L,NcV_T,Nc9) = ...	DNc = max(NcV,NcH) = ...	
Nl_{LEFT} – LEFT AISLE	❑	**$w_{Nl,left}$ = …..** (0.5-1)
Nl3(L) – cracks due to the in-plane response of side walls	6	❑ ❑ ❑ ❑ ❑
Nl4(L) – longitudinal response of the second colonnade (in the case of church with five naves)	7	❑ ❑ ❑ ❑ ❑
Nl4(T) – transversal response of the nave with overturning of the side walls	5	❑ ❑ ❑ ❑ ❑
Nl6 – damage in the vaults of the lateral nave	9	❑ ❑ ❑ ❑ ❑
Nl8 – damage at the connection between roof and side walls	19	❑ ❑ ❑ ❑ ❑
Nl9 – damage due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
Nl_LH = max(Nl6,Nl8) = ...		
Nl_LV_L = max(Nl3,$Nl4_L$)= ……… if Nl_LV_L = Nl_LH → Nl_LV_L = Nl_LH+1	$DNl_{left,L}$ = max(NlV_L,NlH) = ...	
Nl_LV_T = $Nl4_T$= ……… if Nl_LV_T=Nl_LH → Nl_LV_T=Nl_LH+1	$DNl_{left,T}$ = max(NlV_T,NlH) = ...	
Nl_LV=max(Nl_LV_L,Nl_LV_T,Nl9)= ………	DNl_{left} = max(NlV,NlH) = ...	
Nl_{RIGHT} – RIGHT AISLE	❑	**$w_{Nl,right}$ = …..** (0.5-1)
Nl3(L) – cracks due to the in-plane response of side walls	6	❑ ❑ ❑ ❑ ❑
Nl4(L) – longitudinal response of the colonnade of the church with five naves	7	❑ ❑ ❑ ❑ ❑
Nl4(T) – transversal response of the hall with overturning of the side walls	5	❑ ❑ ❑ ❑ ❑
Nl6 – damage in the vaults of the lateral nave	9	❑ ❑ ❑ ❑ ❑
Nl8 – damage at the connection between roof and side walls	19	❑ ❑ ❑ ❑ ❑
Nl9 – damage due to interaction	25	❑ ❑ ❑ ❑ ❑
Nl_RH = max(Nl6,Nl8)=		
Nl_RV_L = max(Nl3,$Nl4_L$)= ……… if Nl_RV_L = Nl_RH → Nl_RV_L = Nl_RH+1	$DNl_{right,L}$ = max(NlV_L,NlH) = ...	
Nl_RV_T = $Nl4_T$= ……… if NlV_T = NlH → NlV_T = NlH+1	$DNl_{right,T}$ = max(NlV_T,NlH) = ...	
Nl_RV = max(Nl_RV_L,Nl_RV_T,Nl9)= ………	DNl_{right} = max(NlV,NlH) = ...	

F – FAÇADE	❑	**w_F = …..** (0.6-1.2)
F1(L) – out-of-plane of the whole façade	1	❑ ❑ ❑ ❑ ❑
F2(L) – out-of-plane of the gable	2	❑ ❑ ❑ ❑ ❑
F3(T) – cracks due to the in-plane response of the façade	3	❑ ❑ ❑ ❑ ❑
F6 – damage in the vaults of the naves close to the façade	8-9	❑ ❑ ❑ ❑ ❑
F8 – damage at the connection between roof and façade	19	❑ ❑ ❑ ❑ ❑
F9 – damage due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
FH = max(F6,F8)-1 = ...		
FV_L = max($F1_L$,$F2_L$) = ...	DF_L = max(FV_L,FH) = ...	
FV_T = F3 = ...	DFT = max(FV_T,FH) = ...	
FV=max(FV_L, FV_T,F9) = ...	DF = max(FV,FH) = ...	
T_{LEFT} – LEFT TRANSEPT	❑	**$w_{T,left}$ = …..** (0.5-0.8)
T1(L) – out-of-plane of the side walls	-	❑ ❑ ❑ ❑ ❑
T3(L) – cracks due to the in-plane response of the end walls	11	❑ ❑ ❑ ❑ ❑
T1(T) – out-of-plane of the end wall	10	❑ ❑ ❑ ❑ ❑
T2(T) – out-of-plane of the gable of the end wall	-	❑ ❑ ❑ ❑ ❑
T3(T) – cracks due to the in-plane response of the side walls	11	❑ ❑ ❑ ❑ ❑
T6 – damage in the vaults of the transept	12	❑ ❑ ❑ ❑ ❑
T8 – damage at the connection between roof and transept	20	❑ ❑ ❑ ❑ ❑
T9 – damage due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
TH = max(T6,T8) = ...		
$T_L V_L$ = max($T1_L$,$T3_L$) = ... if $T_L V_L = T_L H \rightarrow T_L V_L = T_L H+1$	$DT_{left,L}$ = max($T_L V_L$,$T_L H$) = ...	
$T_L V_T$ = max($T1_T$,(T2-1),$T3_T$) = ... if $T_L V_T = T_L H \rightarrow T_L V_T = T_L H+1$	$DT_{left,T}$ = max($T_L V_T$,$T_L H$) = ...	
$T_L V$=max($T_L V_L$,$T_L V_T$,T9) = ...	DT_{left} = max($T_L V$,$T_L H$) = ...	
T_{RIGHT} – RIGHT TRANSEPT	❑	**$w_{T,right}$ = …..** (0.5-0.8)
T1(L) – out-of-plane of the side walls	-	❑ ❑ ❑ ❑ ❑
T3(L) – cracks due to the in-plane response of the end walls	11	❑ ❑ ❑ ❑ ❑
T1(T) – out-of-plane of the end wall	10	❑ ❑ ❑ ❑ ❑
T2(T) – out-of-plane of the gable of the end wall	-	❑ ❑ ❑ ❑ ❑
T3(T) – cracks due to the in-plane response of the side walls	11	❑ ❑ ❑ ❑ ❑
T6 – damage in the vaults of the transept	12	❑ ❑ ❑ ❑ ❑
T8 – damage at the connection between roof and transept	20	❑ ❑ ❑ ❑ ❑
T9 – Damage due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
$T_R H$ = max(T6,T8) = ...		
$T_R V_L$ = max($T1_L$,$T3_L$) = ... if $T_R V_L = T_R H \rightarrow T_R V_L = T_R H+1$	$DT_{right,L}$ = max($T_R V_L$,$T_R H$) = ...	
$T_R V_T$ = max($T1_T$,(T2-1),$T3_T$) = ... if $T_R V_T = T_R H \rightarrow T_R V_T = T_R H+1$	$DT_{right,t}$ = max($T_R V_T$,$T_R H$) = ...	
$T_R V$ = max($T_R V_L$,$T_R V_T$,T9) = ...	DT_{right} = max($T_R V$,$T_R H$) = ...	
D – DOME	❑	**w_D = …..** (0.5-1)
D4(L) – cracks in the longitudinal arches of the dome	13	❑ ❑ ❑ ❑ ❑
D4(T) – cracks in the transversal arches of the dome	13	❑ ❑ ❑ ❑ ❑

D7 – cracks in the dome	14	❑ ❑ ❑ ❑ ❑
D3 – cracks due to the in-plane response of the walls of the drum or the tiburium (dome cladding)	14	❑ ❑ ❑ ❑ ❑
D4 – lantern	15	❑ ❑ ❑ ❑ ❑
D8 – damage at the connection between roof and tiburium	-	❑ ❑ ❑ ❑ ❑
D_{top} = max($D4_{lantern}$,D8) = ... DH = max(D7,D3,D_{top}-1)		
$DV_L = D4_L$ If $D4_L$ = DH → $D4_L$=DH+1	DD_L =max(DV_L,DH) = ...	
$DV_T = D4_T$ If $D4_T$ = DH → $D4_T$=DH+1	DD_T max(DV_T,DH) = ...	
DDV = max(D4L,D4T) = ...	DD = max(DDV,DH) = ...	
TA – TRIUMPHAL ARCH	❑	**w_{TA} = ...** (0.2-0.7)
TA4(T) – cracks in the arch and rocking of piers	13	❑ ❑ ❑ ❑ ❑
TA6 – damage in the vaults of the nave and presbytery, close to triumphal arch	8-12	❑ ❑ ❑ ❑ ❑
TA8 – damage due to connection between roof and gable of the arch	-	❑ ❑ ❑ ❑ ❑
TAH=max(TA6,TA8)-1 = ...		
TAV = TAV_T = TA4 If TAV=TAH → TAV=TAH+1	DTA_T = max(TAV,TAH) = ...	
	DTA = DTA_T = ...	
P – PRESBYTERY	❑	**w_P = ...** (0.2-0.6)
P1(L) – out-of-plane of the end wall	16	❑ ❑ ❑ ❑ ❑
P2(L) – out-of-plane of the gable of the end wall	-	❑ ❑ ❑ ❑ ❑
P3(L) – cracks due to the in-plane response of the side walls	17	❑ ❑ ❑ ❑ ❑
P1(T) – out-of-plane of the lateral walls	-	❑ ❑ ❑ ❑ ❑
P3(T) – cracks due to the in-plane response of the end walls	17	❑ ❑ ❑ ❑ ❑
P6 – damage in the vaults of the presbytery	18	❑ ❑ ❑ ❑ ❑
P8 – damage due to connection between roof and walls	21	❑ ❑ ❑ ❑ ❑
P9 – damage due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
PH = max(P6,P8) = ...		
PV_L = max($P1_L$,P2,$P3_L$) = ... if PV_L=PH → PV_L=PH+1	DP_L = max(PV_L,PH) = ...	
PV_T = max($P1_T$,$P3_T$) = ... if PV_T=PH → PV_T=PH+1	DP_T = max(PV_T,PH) = ...	
PV = max(PV_L,PV_T,P9)	DP = max(PV,PH) = ...	
A – APSE	❑	**w_A = ...** (0.4-0.8)
A1(L) – out-of-plane of the walls	16	❑ ❑ ❑ ❑ ❑
A2(L) – out-of-plane of the gable of the end wall	-	❑ ❑ ❑ ❑ ❑
A3(L) – cracks due to the in-plane response of the walls	17	❑ ❑ ❑ ❑ ❑
A3(T) – cracks due to the in-plane response of the walls	17	❑ ❑ ❑ ❑ ❑
A6 – damage in the vaults of the apse	18	❑ ❑ ❑ ❑ ❑
A8 – damage due to connection between roof and apse walls	21	❑ ❑ ❑ ❑ ❑
A9 – damage due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
AH=max(A6,A8) = ...		
AV_L=max($A1_L$,$A2_L$,$A3_L$) = ... if AV_L=AH → AV_L=AH+1	DA_L = max(AV_L,AH) = ...	

$AV_T = A3_T$ = ……… If $AV_T = AH \rightarrow AV_T = AH+1$	$DA_T = \max(AV_T, AH)$ = ………	
$AV = \max(AV_L, AV_T, A9)$	$DA = \max(AV, AH)$ = ………	
AN_1 – ATRIUM/NARTHEX	❑	**w_{AN1} = …..** (0.2-0.8)
$AN_1 1(L)$ – out-of-plane of the end wall	4	❑ ❑ ❑ ❑ ❑
$AN_1 3(L)$ – cracks due to the in-plane response of walls	4	❑ ❑ ❑ ❑ ❑
$AN_1 4(L)$ – rocking of multiple block kinematisms of columns	4	❑ ❑ ❑ ❑ ❑
$AN_1 1(T)$ – out-of-plane of the end wall	4	❑ ❑ ❑ ❑ ❑
$AN_1 3(T)$ – cracks due to the in-plane response of walls	4	❑ ❑ ❑ ❑ ❑
$AN_1 4(T)$ – rocking of multiple block kinematisms of columns	4	❑ ❑ ❑ ❑ ❑
$AN_1 6$ – damage in the vaults of the atrium or narthex	4	❑ ❑ ❑ ❑ ❑
$AN_1 8$ – damage at connection between roof and atrium/narthex	-	❑ ❑ ❑ ❑ ❑
$AN_1H = \max(AN_1 6, AN_1 8)$= ……..		
$AN_1V_L = \max(AN_1 1_L, AN_1 3_L, AN_1 4_L)$= …….. if $AN_1V_L = AN_1H \rightarrow AN_1V_L = AN_1H+1$	$DAN_{1L} = \max(AN_1V_L, AN_1H)$ = ………	
$AN_1V_T = \max(AN_1 1_T, AN_1 3_T, AN_1 4_T)$ = …….. if $AN_1V_T = AN_1H \rightarrow AN_1V_T = AN_1H+1$	$DAN_{1T} = \max(AN_1V_T, AN_1H)$ = ………	
$AN_1V = \max(AN_1V_T, AN_1V_L)$	$DAN_1 = \max(AN_1V, AN_1H)$ = ………	
AN_2 – ATRIUM/NARTHEX (2nd group)	❑	**w_{AN2} = …..** (0.2-0.8)
$AN_2 1(L)$ – out-of-plane of the end wall	4	❑ ❑ ❑ ❑ ❑
$AN_2 3(L)$ – cracks due to the in-plane response of walls	4	❑ ❑ ❑ ❑ ❑
$AN_2 4(L)$ – rocking of multiple block kinematisms of columns	4	❑ ❑ ❑ ❑ ❑
$AN_2 1(T)$ – out-of-plane of the end wall	4	❑ ❑ ❑ ❑ ❑
$AN_2 3(T)$ – cracks due to the in-plane response of walls	4	❑ ❑ ❑ ❑ ❑
$AN_2 4(T)$ – rocking of multiple block kinematisms of columns	4	❑ ❑ ❑ ❑ ❑
$AN_2 6$ – damage in the vaults of the atrium or narthex	4	❑ ❑ ❑ ❑ ❑
$AN_2 8$ – damage at connection between roof and atrium/narthex	-	❑ ❑ ❑ ❑ ❑
$AN_2H = \max(AN_2 6, AN_2 8)$ = ……..		
$AN_2V_L = \max(AN_2 1_L, AN_2 3_L, AN_2 4_L)$ = …….. if $AN_2V_L = AN_2H \rightarrow AN_2V_L = AN_2H+1$	$DAN_{2L} = \max(AN_2V_L, AN_2H)$ = ……..	
$AN_2V_T = \max(AN_2 1_T, AN_2 3_T, AN_2 4_T)$ = …….. if $AN_2V_T = AN_2H \rightarrow AN_2V_T = AN_2H+1$	$DAN_{2T} = \max(AN_2V_T, AN_2H)$ = ……..	
$AN_2V = \max(AN_2V_T, AN_2V_L)$ = ……..	$DAN_2 = \max(AN_2V, AN_2H)$ = ……..	
C_1 – CHAPELS (1st group)	❑	**w_{C1} = …..** (0.2-0.8)
$C_1 3(L)$ – cracks due to the in-plane response of the end walls	23	❑ ❑ ❑ ❑ ❑
$C_1 1(T)$ – out-of-plane of the end wall	22	❑ ❑ ❑ ❑ ❑
$C_1 3(T)$ – cracks due to the in-plane response of the side walls	23	❑ ❑ ❑ ❑ ❑
$C_1 6$ – damage in the vaults of the chapels	24	❑ ❑ ❑ ❑ ❑
$C_1 8$ – damage due to connection between roof and chapels	-	❑ ❑ ❑ ❑ ❑
$C_1H = \max(C_1 6, C_1 8)$ = ……..		
$C_1V_L = C_1 3_L$ = …….. If $C_1V_L = C_1H \rightarrow C_1V_L = C_1H+1$	$DC_{1L} = \max(C_1V_L, C_1H)$ = ……..	
$C_1V_T = \max(C_1 1_T, C_1 3_T)$ = …….. if $C_1V_T = C_1H \rightarrow C_1V_T = C_1H+1$	$DC_{1T} = \max(C_1V_T, C_1H)$ = ……..	
$C_1V = \max(C_1V_T, C_1V_L)$ = ……..	$DC_1 = \max(C_1V, C_1H)$ = ……..	

C_n – CHAPELS (n^{th} group)	❑	**w_{Cn} = …..** (0.2-0.8)
$C_n3(L)$ – lesioni per azioni nel piano della parete di estremità	23	❑ ❑ ❑ ❑ ❑
$C_n1(T)$ – out-of-plane of the end wall	22	❑ ❑ ❑ ❑ ❑
$C_n3(T)$ – cracks due to the in-plane response of the side walls	23	❑ ❑ ❑ ❑ ❑
C_n6 – damage in the vaults of the chapels	24	❑ ❑ ❑ ❑ ❑
C_n8 – damage due to connection between roof and chapels	-	❑ ❑ ❑ ❑ ❑
$C_nH = \max(C_n6, C_n8)$ = ……..		
$C_nV_L = C_n3_L$ = …….. If $C_nV_L = C_nH \rightarrow C_nV_L=C_nH+1$	$DC_{nL} = \max(C_nV_L,C_nH)$ = ……..	
$C_nV_T = \max(C_n1_T,C_n3_T)$ = …….. if $C_nV_T = C_nH \rightarrow C_nV_T=C_nH+1$	$DC_{nT} = \max(C_nV_T,C_nH)$ = ……..	
$C_nV = \max(C_nV_T, C_nV_L)$ = ……..	$DC_n = \max(C_nV, C_nH)$ = ……..	
BT – BELL TOWER	❑	**w_{BT} = …..** (0.5-1.2)
BT5(L) – Flexural or shear damage in main body of the tower	27	❑ ❑ ❑ ❑ ❑
BT4(L) – Rocking of multiple block kinematisms of the belfry	28	❑ ❑ ❑ ❑ ❑
BT5(T) – Flexural or shear damage in main body of the tower	27	❑ ❑ ❑ ❑ ❑
BT4(T) – Rocking of multiple block kinematisms of the belfry	28	❑ ❑ ❑ ❑ ❑
BT8 – damage due to connection between roof and the walls of the tower	-	❑ ❑ ❑ ❑ ❑
BT9 – damage due to interaction with other buildings or the bell tower	25	❑ ❑ ❑ ❑ ❑
BT10 – spires	26	❑ ❑ ❑ ❑ ❑
$BTH=\max(BT8, (BT10-1))-1$= ……..		
$BTV_L=\max((BT4_L-1),BT5_L)$= …….. if $BTV_L=BTH \rightarrow BTV_L=BTH+1$	$DBT_L = \max(BTV_L,BTH)$ = ……..	
$BTV_T=\max((BT4_T-1),BT5_T)$= ……. if $BTV_T=BTH \rightarrow BTV_T=BTH+1$	$DBT_T = \max(BTV_T,BTH)$ = ……..	
$BTV= \max(BTV_T ,BTV_L,BT9)$= ……	$DBT = \max(BTV,BTH)$ = ……..	
PR_1 – PROJECTIONS (1^{st} group)	❑	**w_{PR1} = …..** (0.2-0.7)
$PR_14(L)$ – Rocking of multiple block kinematisms (plan belfry)	26	❑ ❑ ❑ ❑ ❑
$PR_110(L)$ – Rocking of single blocks	26	❑ ❑ ❑ ❑ ❑
$PR_14(T)$ – Rocking of multiple block kinematisms (plan belfry)	26	❑ ❑ ❑ ❑ ❑
$PR_110(T)$ – Rocking of single blocks	26	❑ ❑ ❑ ❑ ❑
$PR_{1L}= \max(PR_14_L,PR_110_L)$ = ……..	$DPR_{1,L} = PR1_L$ = ……..	
$PR_{1T}= \max(PR_14_T,PR_110_T)$ = ……..	$DPR_{1,T} = PR1_T$ = ……..	
	$DPR_1 = \max(DPR_{1,L}, DPR_{1,T})$ = ……..	
PR_n – PROJECTIONS (n^{th} group)	❑	**w_{PRn} = …..** (0.2-0.7)
$PR_n4(L)$ – Rocking of multiple block kinematisms (plan belfry)	26	❑ ❑ ❑ ❑ ❑
$PR_n10(L)$ – Rocking of single blocks	26	❑ ❑ ❑ ❑ ❑
$PR_n4(T)$ – Rocking of multiple block kinematisms (plan belfry)	26	❑ ❑ ❑ ❑ ❑
$PR_n10(T)$ – Rocking of single blocks	26	❑ ❑ ❑ ❑ ❑
$PR_{nL}= \max(PR_n4_L,PR_n10_L)$ = ……..	$DPR_{n,L} = PR_{n,L}$ = ……..	
$PR_{nT}= \max(PR_n4_T,PR_n10_T)$ = ……..	$DPR_{n,T} = PR_{n,T}$ = ……..	
	$DPR_n = \max(DPR_{n,L}, DPR_{n,T})$ = ……..	

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A3.0 APPENDIX 3: USER MANUAL OF THE DAMAGE SURVEY FORM FOR UNREINFORCED MASONRY CHURCHES IN NEW ZEALAND – *SEISMIC DAMAGE EVALUATION PROCEDURE FOR LOCAL ENGINEERS TO USE*

This appendix should be read in conjunction with Appendix 2.

The procedure is based on the definition of the macroelements (Table A3.1), present in the church (Figure A3.1, and the seismic responses (in-plane and out-of-plane) that can be potentially activated varying the morphology in different macroelements.

From the combination of the macroelements and the expected seismic responses, the collapse mechanisms are determined, including those defined in the ISF (Italian Survey Form). Specifically, ten different responses have been identified (Table A3.2) and graphically represented in Table A3.3 associated to some possible macroelements. The distinction between macroelements and the seismic responses makes the new form more versatile and flexible, overcoming the limit of a priori choice of the collapse mechanisms, as expected in the 28 collapse mechanisms defined in the Italian Survey Form.

The application of the proposed form is based on the following steps:

1. Identification of the macroelements presents ($i = 1... N$);

2. Recognition of the most important macroelement in the church, to which is associated a weight (w_i) equal to 1. Following, the weights less than 1 are assigned to the other macroelements as a function of the dimensions in plan and height of each one, compared to the overall size of the church and the most significant macroelement;

3. Definition of the collapse mechanisms that can be activated for the different macroelements, considering the directionality of the structural response according to the seismic action (if longitudinal and transversal, L and T, respectively, in the Table A3.2); Assignment of the damage level for each collapse mechanism established;

4. Computation of the damage level of the macroelement, according to combination rules that consider the peak and mean values of the different mechanisms as well as their importance. It also takes into account both the directionality and the distinction between the damage to the horizontal and vertical elements, allowing to evaluate for each macroelement three levels of damage: longitudinal (Di,L), transversal (Di,T) and global (Di);

5. Valuation of the damage level and index, mean and peak, of the church through respectively: a weighted mean of the damage of each macroelement and the maximum of these.

Hereinafter, the steps from 2 to 6 are briefly examined.

Defining the weights associated with each macroelement (step 2), the global damage level of the church results as a weighted average of the individual macroelements, which contribute to the global level based on their dimensional weight. A further factor allow to govern the weight of the macroelement, also with regard to its architectural and artistic importance (factors that may be relevant in the calculation of the associated losses, not only strictly economic). After the attribution of weights, the mechanisms related to the different macroelements are defined (step 3), paying attention to the direction of the response. In fact according to the direction of analysis, a macroelement can exhibit different seismic response. For example, for the central nave the “Rocking of multi macro blocks kinematisms” (number 4 of Table A3.2) longitudinally refers to response of the colonnade, in the case of a church with a nave and side aisles; while, transversely, concerns the overturning of the lateral walls.

Figure A3.1 Composition of the church in the macroelements.

Table A3.1 Identification of the macroelements.

ID.	Macroelements
NC	Central Nave
NL_{RIGHT}	Right Lateral Naves
NL_{LEFT}	Left Lateral Naves
F	Facade
T_{RIGHT}	Right Transept
T_{LEFT}	Left Transept
D	Dome
TA	Triumphal Arch
P	Presbytery
A	Apse
A-N	Atrium/Narthex
C	Chapels
BT	Bell Tower
PR	Projections

Table A3.2 Identification of the seismic responses.

ID	Direction	Seismic response
1	L,T	Out-of-plane of masonry walls
2	L,T	Out-of-plane at the top of walls
3	L,T	In-plane response
4	L,T	Rocking of multi macro blocks kinematisms
5	L,T	Flexural or shear damage in monodimensional hollow section structures
6		Damage in the vaults
7		Damage in the domes
8		Interaction between roof and walls
9		Damage due to interaction with other buildings
10		Rocking of single blocks

Defined, then, the collapse mechanisms for each macroelement is associated to them the level of damage (step 4) referring to the five levels (D_k=0…5) of the EMS98 (Grunthal 1998). The local damage index of the macroelement (step 5), is computed as the maximum of the damage occurred to the horizontal and vertical structural elements, considering the longitudinal and transversal direction. In particular, when the level of damage of the diaphragms is equal to that of the vertical structural elements, this is incremented by a unit to take into account that the loss of load-bearing capacity of the latter, it may be further affected by the loss or degradation of connection with the horizontal elements.

The next step is the calculation of the transversal ($D_{i,T}$) and longitudinal ($D_{i,L}$) damage indices, as maximum between the diaphragms and walls in the respective directions. In the end, the global index of the macroelement (D_i) is determined as maximum between the previous two, which appropriately weighed become:

$$\overline{D}_i = w_i D_i \qquad \textbf{Equation A3.1}$$

So, for each macroelement, three values of damage, the longitudinal, transversal and global are computed, which divided by 5 and appropriately weighed, determine the three indices of damage ($i_{di,L}$, $i_{di,T}$ and i_{di}).

As mentioned in step 6, starting from the above-mentioned damage levels, the global damage level of the church is evaluated as a weighted average of them (Equation A3.2). The weight of the individual macroelements assumes a primary role in this phase.

$$D_{CHURCH} = \frac{\sum_{i=1}^{N} \overline{D}_i}{\sum_{i=1}^{N} w_i} \qquad \textbf{Equation A3.2}$$

Vice versa, the longitudinal and transversal damage levels, are determined by the following relation:

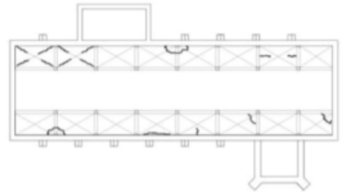
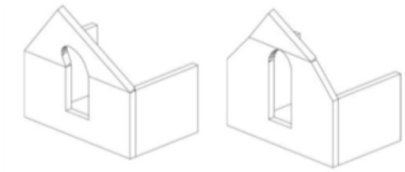
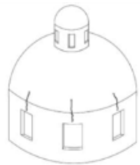
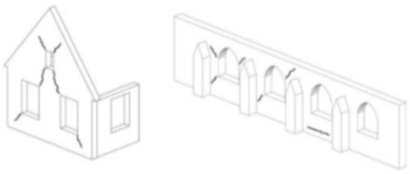
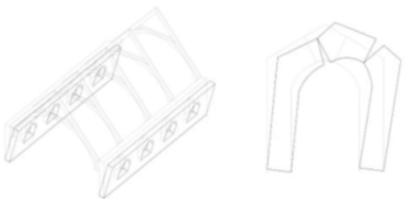
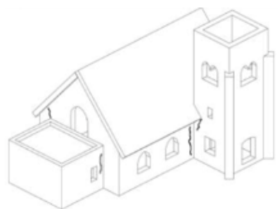
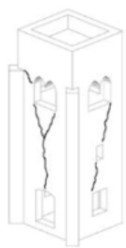
$$D_{CHURCH,L/T} = \sum_{i=1}^{N} \delta_{i,L/T} w_i D_{i,L/T} \qquad \textbf{Equation A3.3}$$

Where, the parameter $\delta_{i,L/T}$ is specified as:

$$\delta_{i,L/T} = \begin{cases} \textbf{0 if the macroelement does not admit mechanisms in direction L/T} \\ \textbf{1 if the macroelement admits mechanisms in direction L/T} \end{cases}$$ **Equation A3.4**

The parameter $\delta_{i,L/T}$ was introduced since some macroelements may not admit mechanisms in one direction: for example the triumphal arch (AT in Table A3.1, that does not present mode of damage that can be activated in the longitudinal direction.

Table A3.3 Abacus of the collapse mechanisms (ID corresponds to Table A3.2)

1		6	
2		7	
3		8	
4		9	
5		10	

Finally, from the damage levels of each macroelement the damage level of the church is evaluated as the maximum of the previous ones:

$$D_{CHURCH,Peak} = \max\left(\overline{D}_i\right) \qquad \textbf{Equation A3.5}$$

The damage levels are then normalized dividing by 5 thus leading to corresponding damage indices between 0 and 1.

It is important to note, that from the data collected with the new procedure, it is however also possible to fill the ISF form. Moreover the proposed method presents the possibility of double compilation:

- A quick one: which requires the assignment of the weight and the damage level referring to the five levels (D_k=0…5) of the EMS98 (Grunthal 1998) for each macroelement, without going through the more accurate analysis of the collapse mechanisms that can be activated;
- A complete one: which is based on the analysis of the response of each individual mechanism associated with the macro element and the application of analytical rules introduced above for the calculation of damage.

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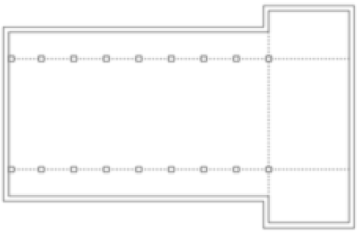
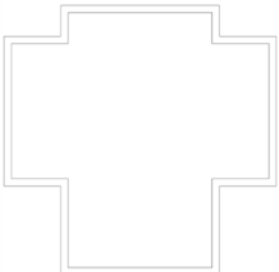
A4.0 APPENDIX 4: TYPOLOGICAL AND VULNERABILITY SURVEY FORM FOR UNREINFORCED MASONRY CHURCHES IN NEW ZEALAND

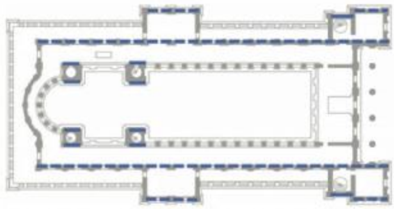
NZ-specific Vulnerability index (VI) method for churches

A4.1 PART 1. TYPOLOGICAL, GEOMETRICAL, STRUCTURAL FEATURES

A4.1.1 Plan configuration

Number of naves, the overall dimensions or the shape in plan. If the typology is different from the following, a simple sketch of the plan and a brief description could be useful.

Types of plan configuration (see Figure 4.1)	**Sketch and Photo**	
A - Longitudinal plan - One nave - No transept - Buttresses - Sloping roof		
At - Longitudinal plan - One nave - Transept - Buttresses - Sloping roof		
B - Longitudinal plan - Three naves - Transept - Apse (eventually) - Buttresses - Sloping roof		
C - Central Plan		

D - "Box-type" behaviour - Large hall without internal walls - Façade and perimetral walls as a building		
E - Catholic Basilica		
Other		

A4.1.2 Plan Regularity

- Asymmetry in plan
- Position and dimension in plan of the bell tower
- Etc. …

For each one of the options identified indicate whether it might affect the seismic vulnerability of the church and to what extent (i.e., Seismic Vulnerability Increase: N/A, Slight, Moderate, Significant).

A4.1.3 Presence of Domes and Vaults: percentage of extension in plan (based on judgement)

A4.1.4 Material type and quality

- Material type:
  - Brick (transversal connections)
  - Stone (Soft Stone; Hard Stone; Regular Cut; Uncut; Rubble; size of elements)
  - Mortar (Lime mortar; Cement mortar)
- Material Quality: good, average, bad

A4.1.5 Architectural transformations (indicate any structural transformation undertaken by the church):

- Extension in plan
- Raising up
- Etc……

For each one of the options identified indicate whether it might affect the seismic vulnerability of the church and to what extent (i.e., Seismic Vulnerability Increase: N/A, Slight, Moderate, Significant): Seismic Vulnerability Decrease: N/A, Slight, Moderate, Significant)).

A4.1.6 Recent structural interventions: (indicate which macroelement is involved, e.g., façade, transversal response of the nave, roof system,…):

- Modification of the roof
- Grout-injections
- Shotcrete
- Insertion of tie rods
- Insertion of ring beams
- Cross-bracing system in the roof

For each one of the options identified indicate whether it might affect the seismic vulnerability of the church and to what extent (i.e., Seismic Vulnerability Increase: N/A, Slight, Moderate, Significant): Seismic Vulnerability Decrease: N/A, Slight, Moderate, Significant)).

A4.1.7 State of maintenance (decay of materials and joints due to poor maintenance):

- Regular
- Bad

A4.2 PART 2. SEISMIC-INDUCED AND PRE-EXISTING DAMAGE

A4.2.1 Damage Location and Extension: (Additional to the data requested below a simple sketch of the damage pattern and a brief description could be useful).

- indicate the presence of cracks/damage in the different macroelement (façade, transversal response of nave, roof system, etc.) due to earthquakes or pre-existing;
- Specify the extension of the cracks/damage in the macroelement: 1–10%, 10–30%, 30–60% 60–100%.

For each one of the damaged macroelement identified indicate whether it might affect the seismic vulnerability of the church and to what extent (i.e., Seismic Vulnerability Increase: N/A, Slight, Moderate, Significant).

A4.2.2 Damage Level

Indicate the seismic-induced damage level sustained by the church, on a discrete damage level scale from D1 (light damage) to D5 (collapse), plus the absence of damage D0. (A specific abacus will be provided).

A4.3 PART 3. EXTERNAL FACTORS

A4.3.1 Site conditions, Topographic:

- The church is on the top of a hill
- The church is on the slope of a hill
- The foundation is at different levels (a part of the church has a basement storey)

A4.3.2 Site conditions, Soil Type and Liquefaction:

- The church is on soft soil
- The church is on rock
- The site has been affected by earthquake-induced liquefaction

A4.3.3 Regularity and Interaction

- Presence of adjacent buildings that might induce asymmetric conditions.
- Interaction with adjacent units of different height

For each one of the options identified indicate whether it might affect the seismic vulnerability of the church and to what extent (i.e., Seismic Vulnerability Increase: N/A, Slight, Moderate, Significant).

A4.4 PART 4. FURTHER SEISMIC BEHAVIOUR MODIFIERS SPECIFIC FOR NEW ZEALAND CHURCHES

- **Roof Type and Structures:**
  - Type: timber; other heavy structure
  - Thrust on lateral walls: none (good constructive system or added tie-rods), partial, high
  - Kind of support on masonry walls: on a corbel stone, below the top of the wall; on a timber beam on the top of the masonry
- **Roof Covering:**
  - Tile Roof
  - Thin Stone

A5.0 APPENDIX 5: NEW VULNERABILITY INDEX METHOD FOR UNREINFORCED MASONRY CHURCHES IN NEW ZEALAND

The following figure and tables show the curves and the vulnerability indexes (median and percentiles) for different sub-samples of Canterbury churches, in order to determine the typological vulnerability index V_0 (representing the seismic behaviour of the URM NZ churches) and ΔV_m contribution to take into account the presence of each seismic behaviour modifiers.

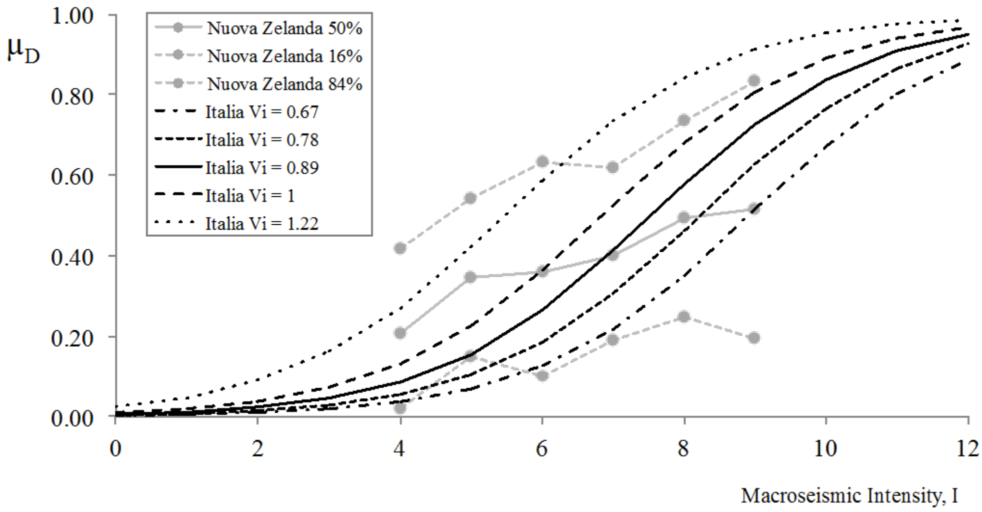
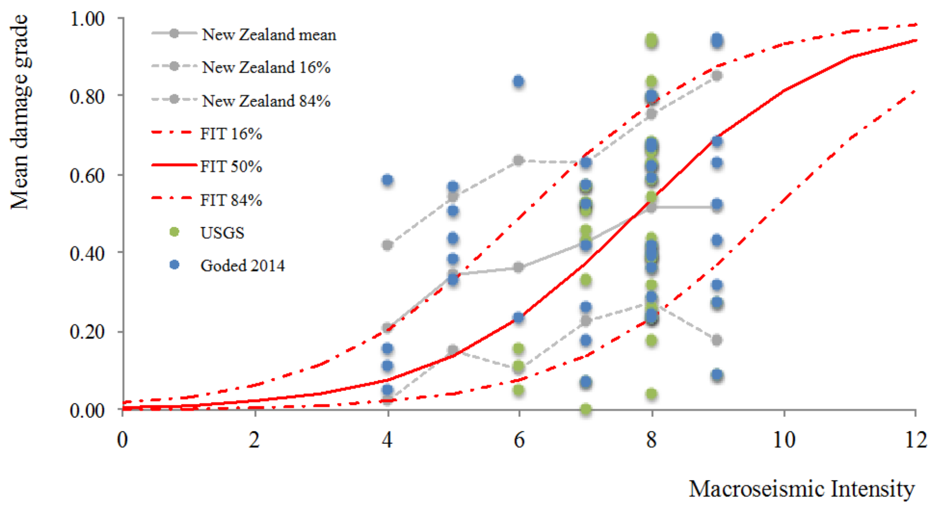


Figure A5.1 Vulnerability curves of the Italian data and New Zealand empirical data.

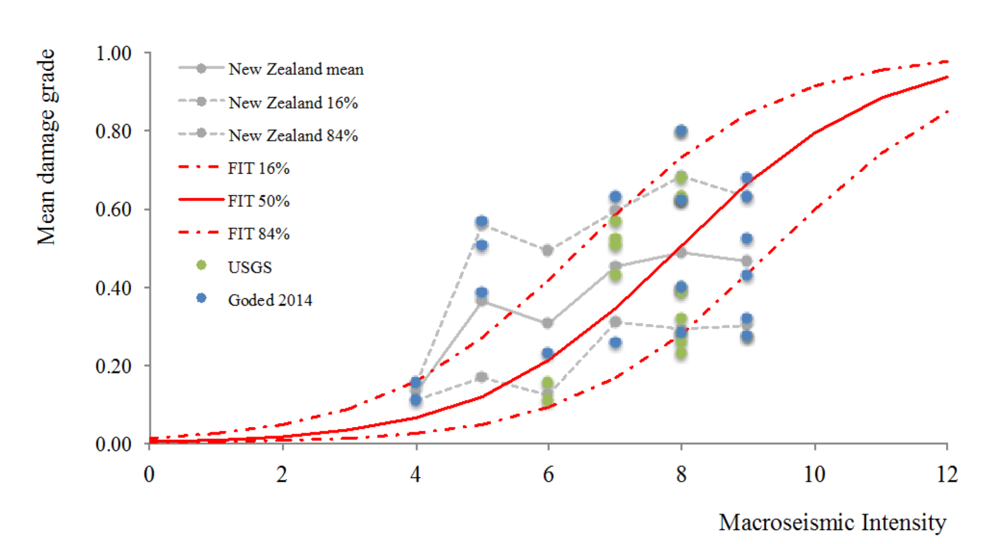
Vulnerability Curve for the Total Sample (without the r.c. churches)	
Number of churches: 40	
$V_{i,16\%}$	0.530
$V_{i,50\%}$	0.852
$V_{i,84\%}$	1.125



Vulnerability Curve for Brick Churches

Number of churches: 18

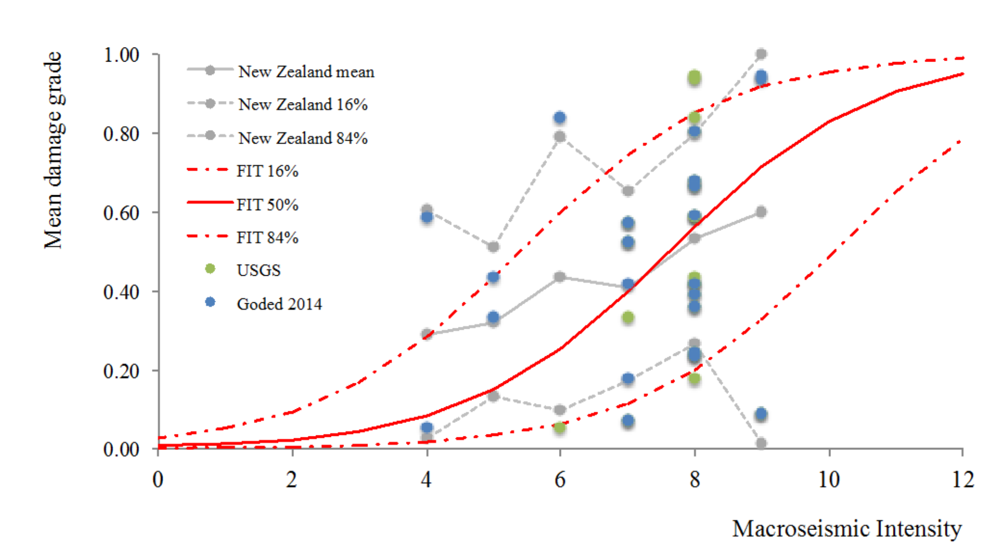
$V_{i,16\%}$	0.591
$V_{i,50\%}$	0.821
$V_{i,84\%}$	1.057

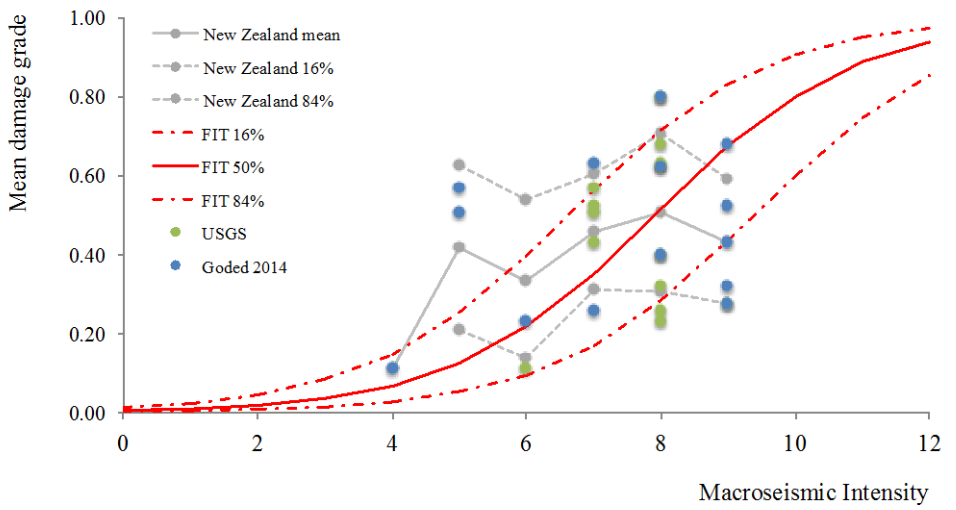


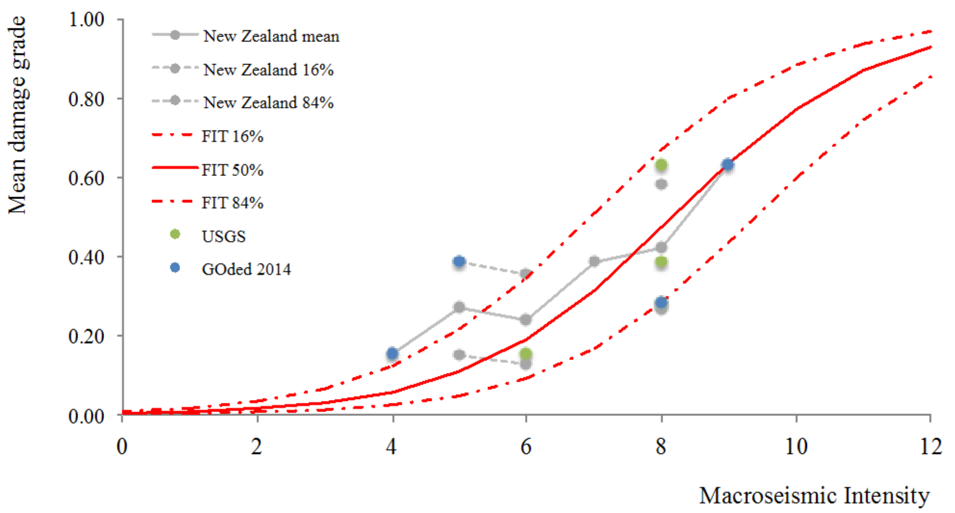
Vulnerability Curve for Stone Churches

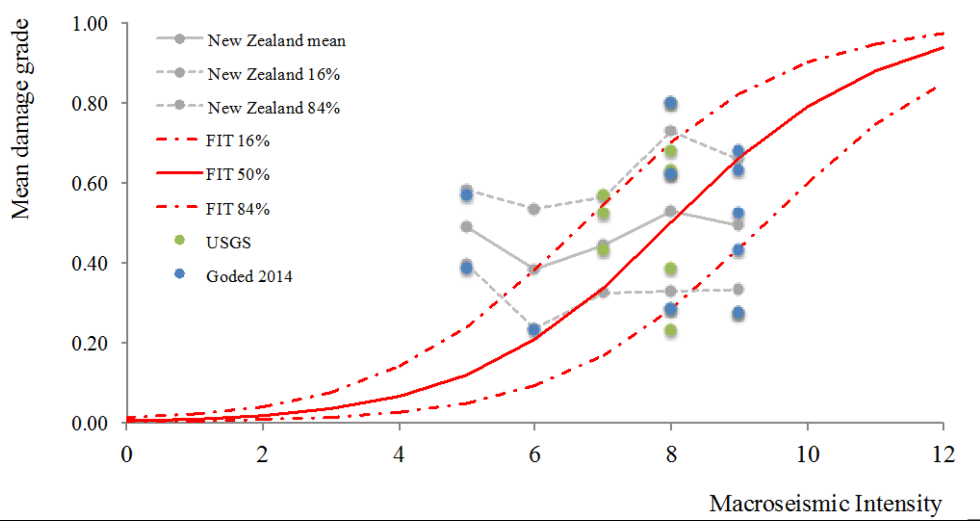
Number of churches: 22

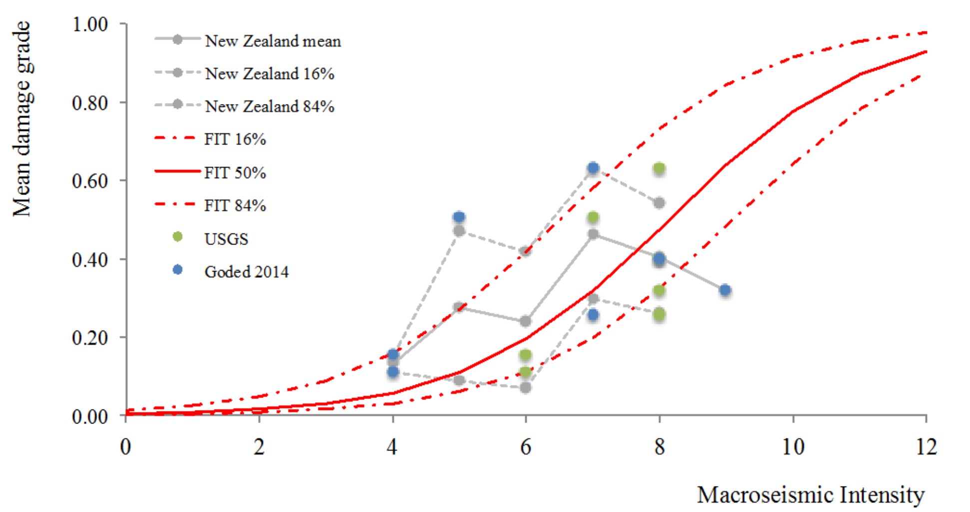
$V_{i,16\%}$	0.485
$V_{i,50\%}$	0.877
$V_{i,84\%}$	1.232



<table>
<tr><th colspan="3">Vulnerability Curve for Brick Churches with buttresses
Number of churches: 14</th></tr>
<tr><td>$V_{i,16\%}$</td><td>0.593</td><td rowspan="3">
</td></tr>
<tr><td>$V_{i,50\%}$</td><td>0.828</td></tr>
<tr><td>$V_{i,84\%}$</td><td>1.035</td></tr>
</table>

<table>
<tr><th colspan="3">Vulnerability Curve for Brick Churches without buttresses
Number of churches: 4</th></tr>
<tr><td>$V_{i,16\%}$</td><td>0.591</td><td rowspan="3">
</td></tr>
<tr><td>$V_{i,50\%}$</td><td>0.790</td></tr>
<tr><td>$V_{i,84\%}$</td><td>0.984</td></tr>
</table>

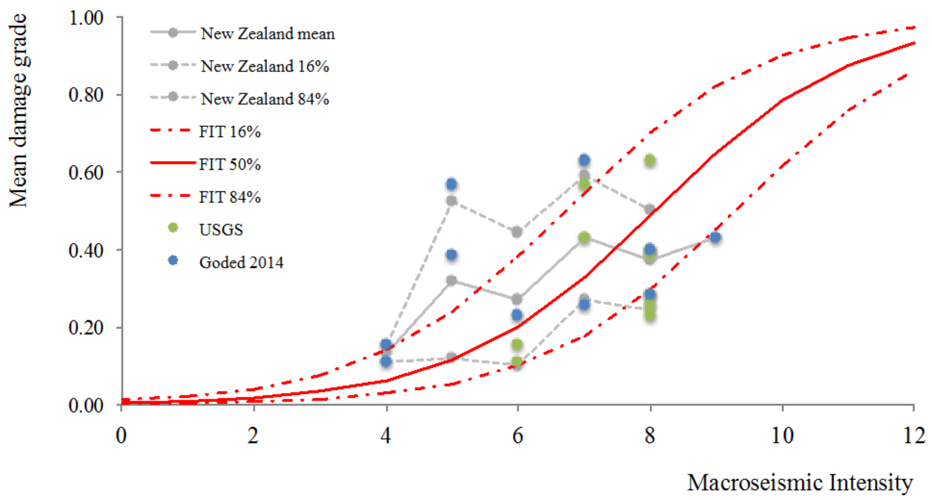
Vulnerability Curve for Brick Churches – Regularity in plan and elevation Number of churches: 11		
$V_{i,16\%}$	0.591	
$V_{i,50\%}$	0.815	
$V_{i,84\%}$	1.020	

Vulnerability Curve for Brick Churches – Irregularity in plan and elevation Number of churches: 7		
$V_{i,16\%}$	0.638	
$V_{i,50\%}$	0.792	
$V_{i,84\%}$	1.056	

Vulnerability Curve for Brick Churches – Quality of masonry: Good

Number of churches: 10

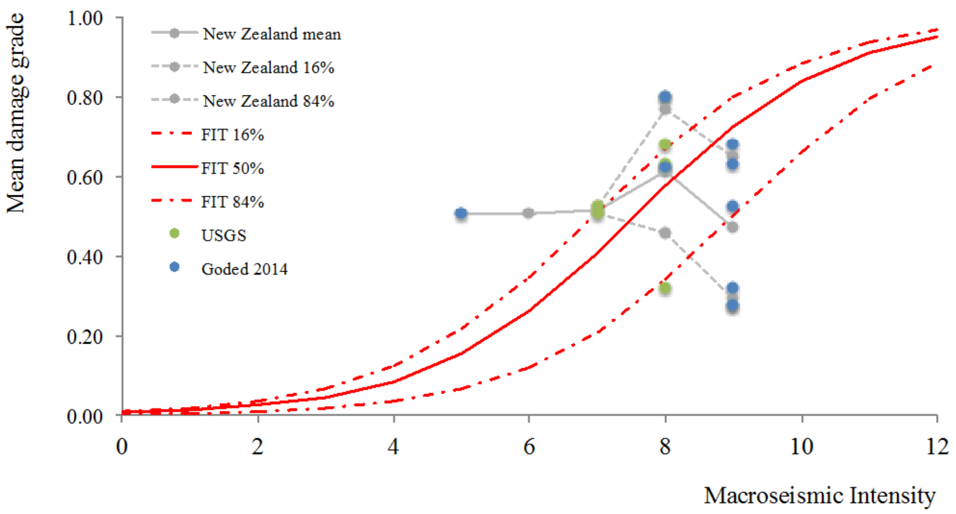
$V_{i,16\%}$	0.610
$V_{i,50\%}$	0.804
$V_{i,84\%}$	1.020



Vulnerability Curve for Brick Churches – Quality of masonry: Average/Bad

Number of churches: 8

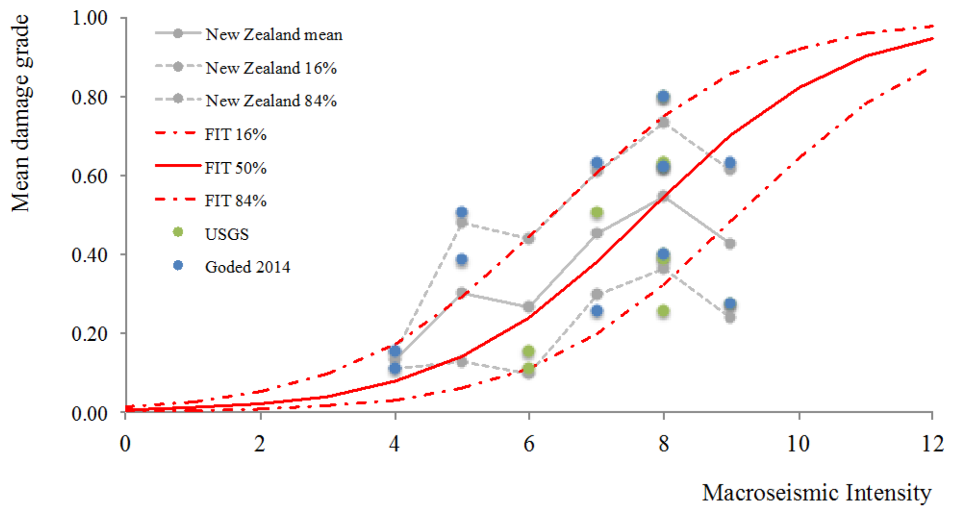
$V_{i,16\%}$	0.657
$V_{i,50\%}$	0.888
$V_{i,84\%}$	0.985



Vulnerability Curve for Brick Churches – Presence of rose windows

Number of churches: 8

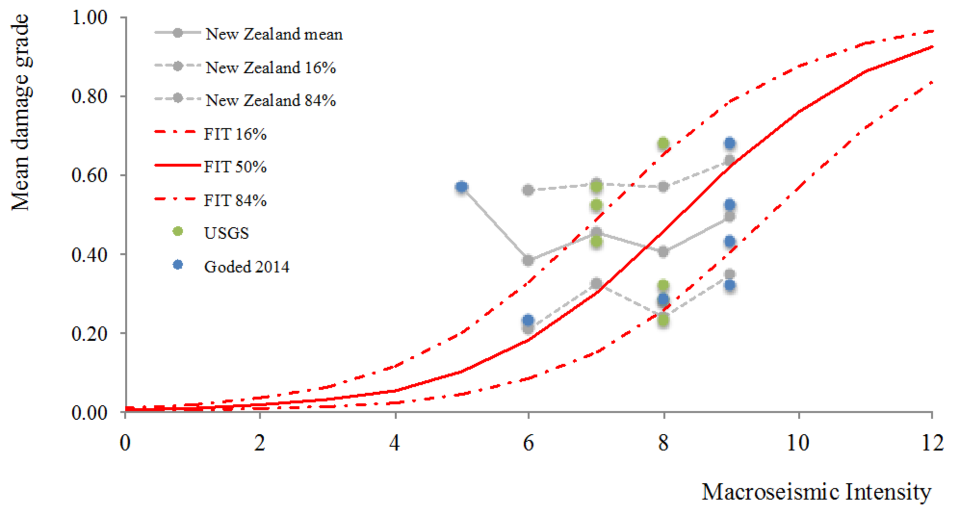
$V_{i,16\%}$	0.639
$V_{i,50\%}$	0.861
$V_{i,84\%}$	1.081



Vulnerability Curve for Brick Churches – Absence of rose windows

Number of churches:

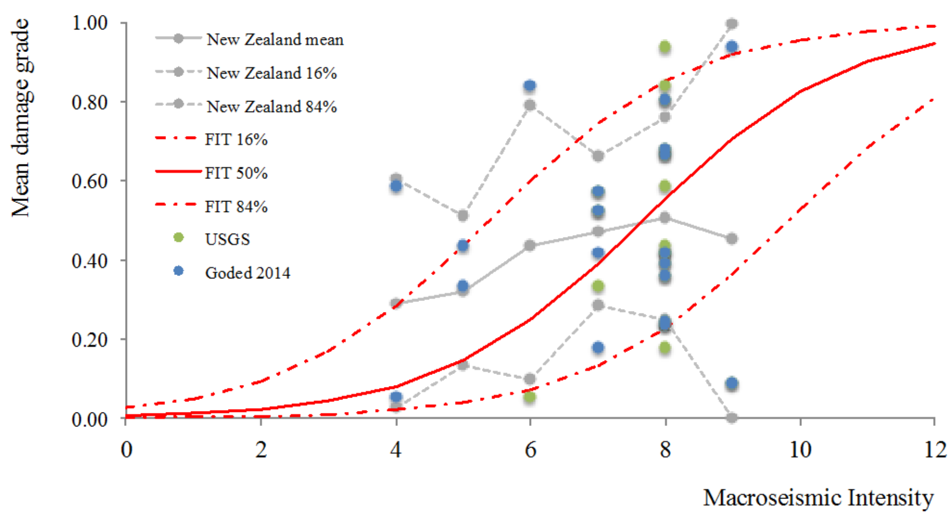
$V_{i,16\%}$	0.563
$V_{i,50\%}$	0.772
$V_{i,84\%}$	0.965



Vulnerability Curve for Stone Churches with buttresses

Number of churches: 19

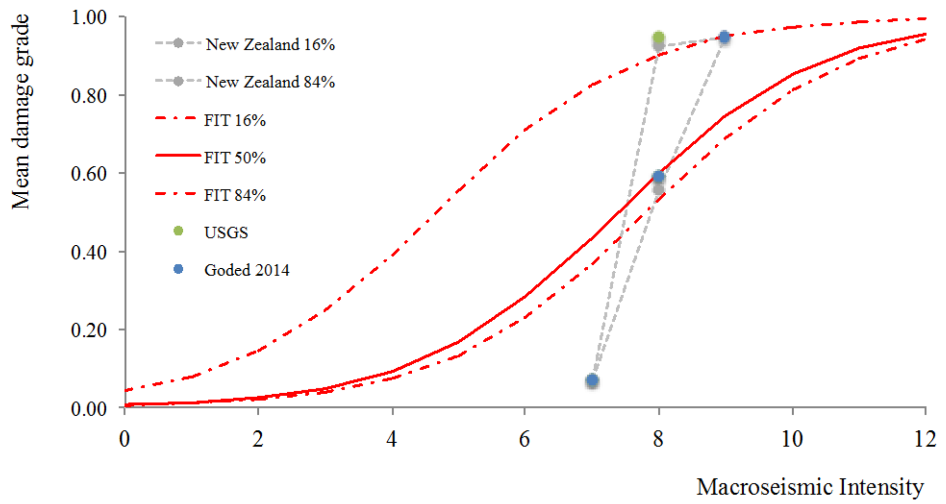
$V_{i,16\%}$	0.521
$V_{i,50\%}$	0.868
$V_{i,84\%}$	1.231



Vulnerability Curve for Stone Churches without buttresses

Number of churches: 3

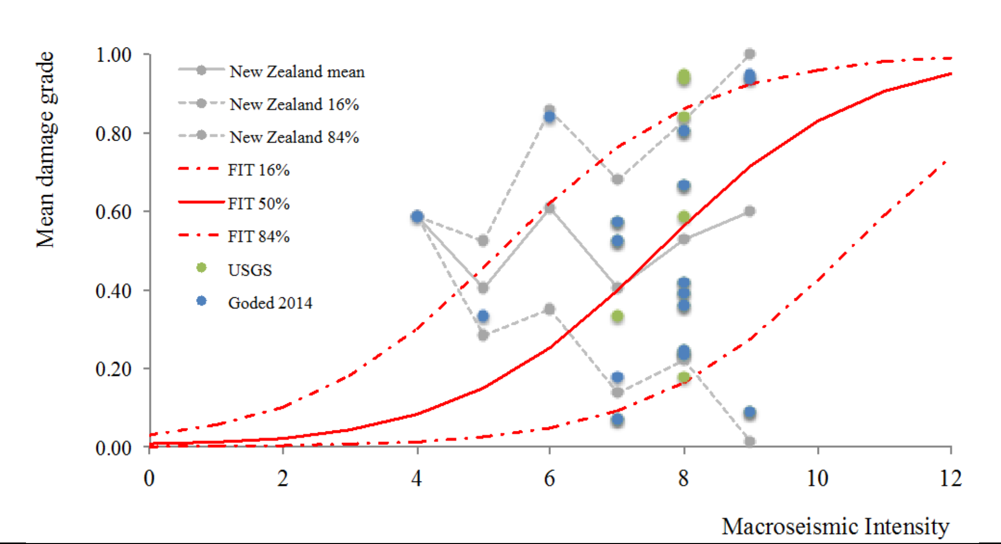
$V_{i,16\%}$	0.846
$V_{i,50\%}$	0.912
$V_{i,84\%}$	0.912



Vulnerability Curve for Stone Churches – Regularity in plan and elevation

Number of churches: 17

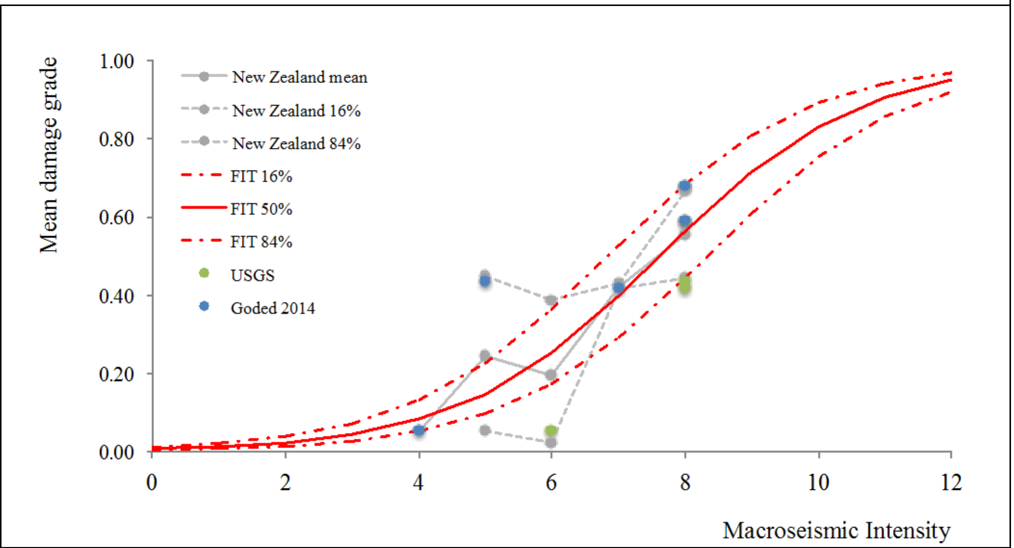
$V_{i,16\%}$	0.424
$V_{i,50\%}$	0.877
$V_{i,84\%}$	1.254



Vulnerability Curve for Stone Churches – Irregularity in plan or elevation

Number of churches: 5

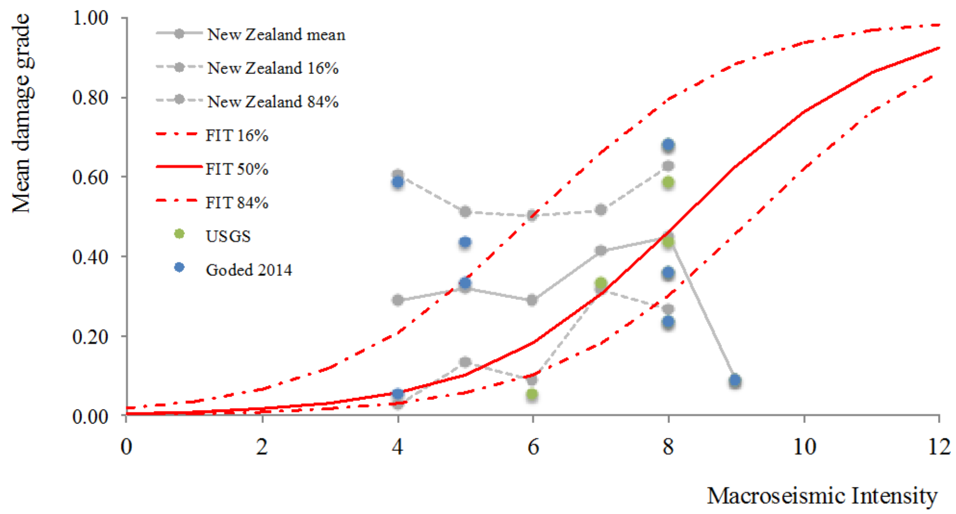
$V_{i,16\%}$	0.763
$V_{i,50\%}$	0.875
$V_{i,84\%}$	1.000



Vulnerability Curve for Stone Churches – Quality of masonry: Good

Number of churches: 8

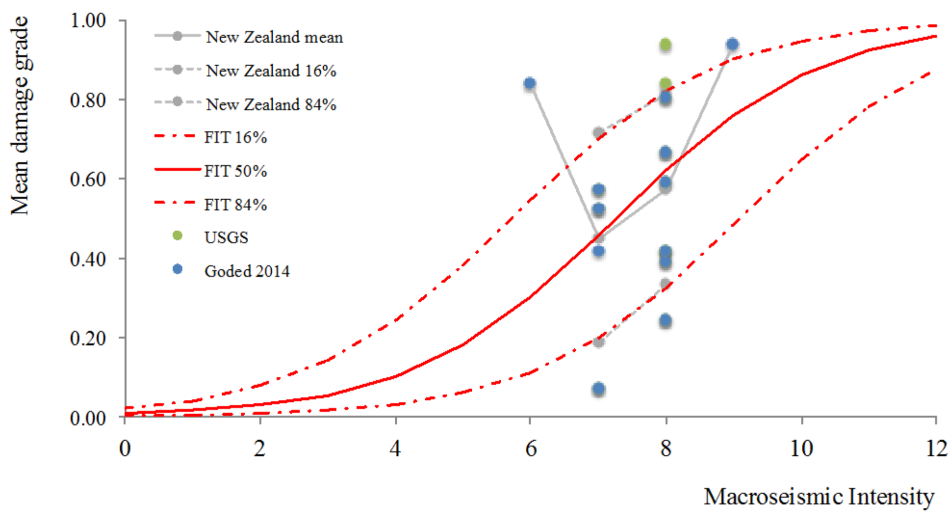
$V_{i,16\%}$	0.614
$V_{i,50\%}$	0.777
$V_{i,84\%}$	1.138



Vulnerability Curve for Stone Churches – Quality of masonry: Average and Bad

Number of churches: 12

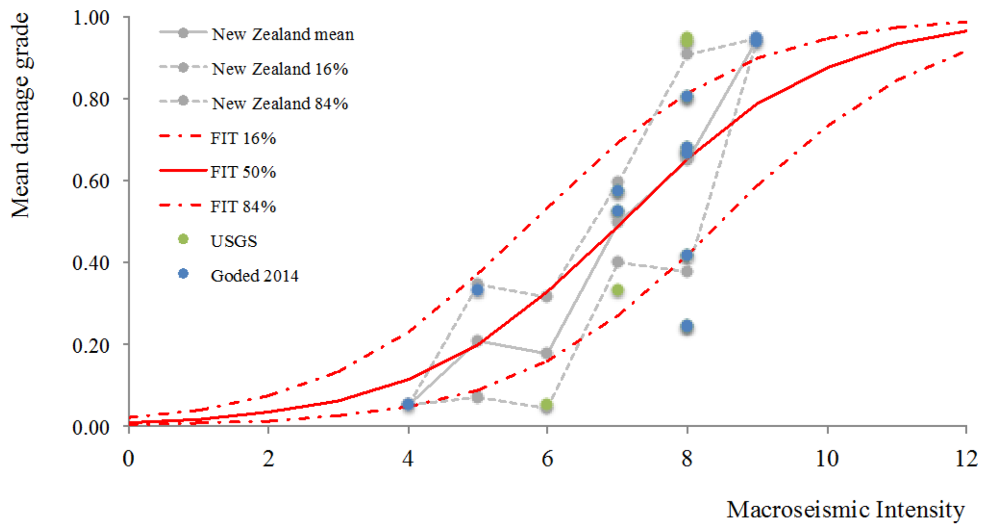
$V_{i,16\%}$	0.640
$V_{i,50\%}$	0.932
$V_{i,84\%}$	1.181



Vulnerability Curve for Stone Churches – Quality of masonry: Presence of Rose windows

Number of churches: 11

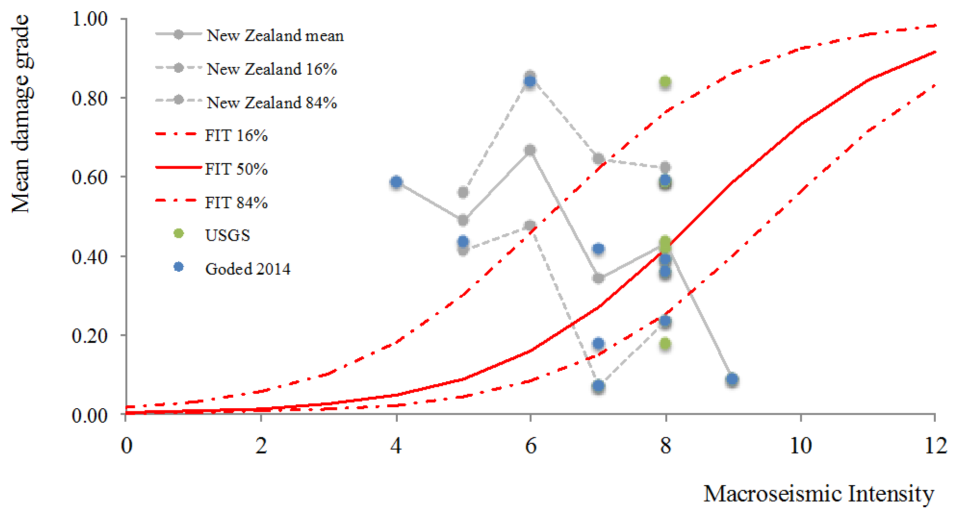
$V_{i,16\%}$	0.737
$V_{i,50\%}$	0.965
$V_{i,84\%}$	1.168



Vulnerability Curve for Stone Churches – Quality of masonry: Absence of Rose windows

Number of churches: 11

$V_{i,16\%}$	0.737
$V_{i,50\%}$	0.737
$V_{i,84\%}$	1.095



Modifier factors for NEW ZEALAND URM churches

The seismic behaviour of a structure does not only depend on its structural system (in the examined case URM), but it is affected by many other factors as introduced in Section 4.5.

The behaviour modifiers identification has been made following two approaches:

i. on the basis of damage index and typological data collected after the Canterbury earthquake sequence, in 2010–2011: in this case, the $V_{m,k}$ is defined starting from the vulnerability index of each sample characterized by the different modifier;

ii. on the basis of the observation of general and typical damage pattern and by a previous proposal (Lagormarsino, 2006): in this case, the scores $V_{m,k}$ are attributed on the basis of expert judgment.

From the statistical analysis of observed damage, the following modifier factors are identified:

- **Masonry types**: the vulnerability of stone masonry churches is higher than that of brick masonry churches; moreover, the vulnerability curves of these latter are less scattered: this is due to the fact that brick masonry is more standardized;
- **The quality of the masonry;**
- **The presence of the buttresses,** only for the stone churches;
- The presence of rose windows.

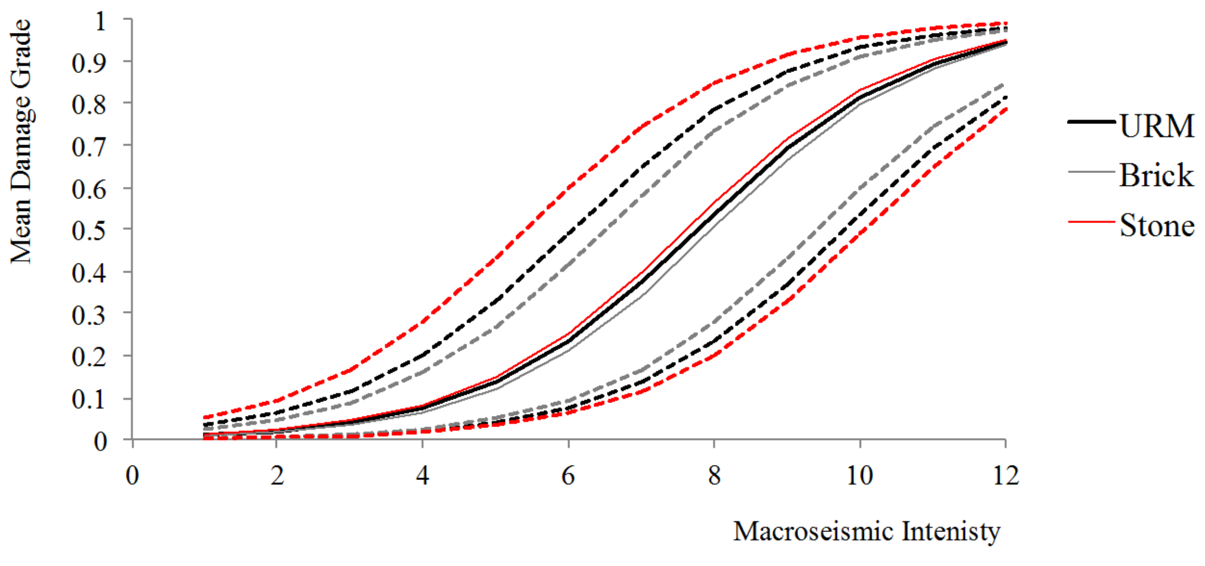


Figure A5.2 Median and percentiles vulnerability curves according to the masonry types.

In addition, the following modifier factors are proposed by expert judgment:

- **The presence of cavity walls only for the brick churches;**
- **The presence of narthex / atrium;**
- **The presence of tie rods;**
- **The presence of vaults;**
- **The characteristics of the roof.**

The proposed values are mainly derived from observed data, with some slight adjustments due to the lack of data and the limited statistical reliability.

The Vulnerability Index Modifiers obtained in this method for New Zealand URM churches are shown in the following tables.

Table A5.1 Vulnerability Index for New Zealand URM churches.

Vulnerability Index	**Description**	V_{mk}
URM churches	Low	0.530
	Medium	0.852
	High	1.125

Table A5.2 Main Vulnerability Index Modifiers: Masonry typology.

Main behaviour Modifier	**Description**	V_{mk}
Masonry typology	Brick	-0.03
	Stone	+0.03

Table A5.3 Vulnerability Index Modifiers for stone churches.

Behaviour Modifiers for stone churches	**Description**	V_{mk}
Buttresses on the lateral wall	Presence	-0.01
	Absence	+0.04
State of preservation of masonry	Good	-0.10
	Bad and Average	+0.06
Rose windows (big)	Presence	+0.09
	Absence	-0.10
Narthex / Atrium	Presence	+0.01
	Absence	-0.02
Tie-rods	Present and effective	-0.06
	Absence or ineffective	+0.04
Vaults and/or dome	Absence	0.00
	Extended presence	+0.04
	Presence of a big dome	+0.08
Characteristics of the roof	Metal sheet	-0.02
	Thin stones or tile roof	+0.02
	Heavy roof	+0.06

Table A5.4 Vulnerability Index Modifiers for brick churches.

Behaviour Modifiers for brick churches	**Description**	V_{mk}
State of preservation of masonry	Good and Average	-0.02
	Bad and/or Cavity walls	+0.07
Rose windows	Presence	+0.04
	Absence	-0.05
Narthex / Atrium	Presence	+0.01
	Absence	-0.02
Tie-rods	Present and effective	-0.04
	Absence or ineffective	+0.02
Vaults and/or dome	Absence	0.00
	Extended presence	+0.02
	Presence of a big dome	+0.05
Characteristics of the roof	Metal sheet	-0.01
	Thin stones or tile roof	+0.01
	Heavy roof	+0.04

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A6.0 APPENDIX 6: SEISMIC SCENARIOS FOR UNREINFORCED MASONRY CHURCHES IN WELLINGTON, AUCKLAND AND DUNEDIN

According to the new Vulnerability Index method for New Zealand URM churches described in Section 4.5 and Appendix 5, this section shows the results of applying this method to the URM churches in Wellington, Auckland and Dunedin. These cities were selected as representing different seismic regions, from a low seismicity city (Auckland) to a high seismicity city (Wellington) being Dunedin a city of medium seismicity levels. For each of the churches, the Vulnerability Index modifiers, Vulnerability Curves, damage probabilities and damage histograms are shown in the following sections. These have been obtained following the new method explained in Section 4.5 and Appendix 2.

The vulnerability curves shown below will include the lower and upper curves, to account for uncertainty. These curves have been obtained using the statistical analysis shown in Appendix 5, for the 16% and 84% percentiles, respectively. They are designed for churches which do not have specific parameters to calculate individual vulnerability index modifiers. Given that for the Wellington, Dunedin and Auckland churches specific parameters are known and modifiers have been calculated, only the medium values should be considered quantitatively. Vulnerability curves and damage probability histograms in sections b) and d) will include the lower and upper values, but section c) will only contain the values for medium damage probabilities.

A6.1 VULNERABILITY INDEX VALUES

The Vulnerability Index modifiers and final results for the lower, medium and upper results are shown in the following tables, both in text and in numerical values. References correspond to Table 4.2. Numbers in brackets after the title have been added when more than one table was needed to show all the churches for each city.

A6.2 VULNERABILITY CURVES

The Vulnerability curves for each of the churches are shown in this section, together with the expected damage grade (marked with a black triangle on the medium vulnerability curve, from 0, no damage, to 5, collapse) in the most characteristic seismic scenario for each of the three cities (see details in Section 4.6).

Table A6.1 Vulnerability index (V_i) modifiers (text): Dunedin stone churches.

Parameters	Reference	7	9	10	13	15	21	23
V_i Modifiers	**Brick / Stone**	Stone	Stone	Stone	Stone	Stone	Stone	Stone
	Buttresses on the lateral wall (STONE ONLY)	Presence	Presence	Presence	Presence	Presence	Presence	Presence
	State of preservation of masonry	Bad	Bad	Average	Bad	Average	Bad	Average
	Rose windows	Presence	Presence	Presence	Presence	Presence	Presence	Presence
	Narthex / Atrium	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Tie-rods	Present and effective	Absence or ineffective	Present and effective	Absence or ineffective	Absence or ineffective	Present and effective	Absence or ineffective
	Vaults and/or dome	Absence	Extended presence	Absence	Extended presence	Absence	Absence	Absence
	Characteristics of the roof	Heavy roof	Heavy roof	Heavy roof	Heavy roof	Heavy roof	Heavy roof	Metal sheet

Table A6.2 Vulnerability index (V_i) modifiers (text): Dunedin brick churches (1).

Parameters	Reference	1	2	3	4	5	6	8	11
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	----	----	----	----	----	----	----	----
	State of preservation of masonry	Average	Average	Average	Average	Average	Average	Average	Average
	Rose windows	Presence	Absence	Presence	Presence	Presence	Presence	Presence	Presence
	Narthex / Atrium	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Tie-rods	Absence or ineffective	Absence or ineffective	Present and effective	Present and effective	Absence or ineffective	Present and effective	Present and effective	Absence or ineffective
	Vaults and/or dome	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Characteristics of the roof	Heavy roof	Metal sheet	Heavy roof	Thin stones or tile roof	Metal sheet	Thin stones or tile roof	Heavy roof	Heavy roof

Table A6.3 Vulnerability index (V_i) modifiers (text): Dunedin brick churches (2).

Parameters	Reference	12 (*)	14	16	17	18	19	20	22
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	----	----	----	----	----	----	----	----
	State of preservation of masonry	----	Average	Average	Average	Average	Average	Average	Average
	Rose windows	----	Presence	Presence	Presence	Presence	Presence	Absence	Presence
	Narthex / Atrium	----	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Tie-rods	----	Present and effective	Present and effective	Absence or ineffective	Present and effective	Absence or ineffective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	----	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Characteristics of the roof	----	Heavy roof	Metal sheet	Heavy roof	Heavy roof	Heavy roof	Metal sheet	Heavy roof

Table A6.4 Vulnerability index (V_i) modifiers (text): Dunedin brick churches (3).

Parameters	Reference	24	25	26	27	28	29 (*)	30 (*)	31 (*)
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	----	----	----	----	----	----	----	----
	State of preservation of masonry	Average	Average	Average	Average	Average	----	----	----
	Rose windows	Absence	Presence	Presence	Absence	Absence	----	----	----
	Narthex / Atrium	Absence	Absence	Absence	Presence	Absence	----	----	----
	Tie-rods	Absence or ineffective	Present and effective	Absence or ineffective	Present and effective	Absence or ineffective	----	----	----
	Vaults and/or dome	Extended presence	Absence	Absence	Absence	Absence	----	----	----
	Characteristics of the roof	Metal sheet	Thin stones or tile roof	Thin stones or tile roof	Heavy roof	Heavy roof	----	----	----

Table A6.5 Vulnerability index (V_i) modifiers (text): Wellington stone churches.

Parameters	Reference	45
V_i Modifiers	**Brick / Stone**	Stone
	Buttresses on the lateral wall (STONE ONLY)	Absence
	State of preservation of masonry	Average
	Rose windows	Absence
	Narthex / Atrium	Absence
	Tie-rods	Absence or ineffective
	Vaults and/or dome	Absence
	Characteristics of the roof	Thin stones or tile roof

Table A6.6 Vulnerability index (V_i) modifiers (text): Wellington brick churches (1).

Parameters	Reference	32	33	34	35	36	37	38	39
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	Average	Average	Average	Average	Average	Average	Average	Average
	Rose windows	Absence	Presence	Absence	Absence	Presence	Presence	Absence	Presence
	Narthex / Atrium	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Tie-rods	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Characteristics of the roof	Heavy roof	Metal sheet	Thin stones or tile roof	Thin stones or tile roof	Heavy roof	Thin stones or tile roof	Heavy roof	Metal sheet

Table A6.7 Vulnerability index (V_i) modifiers (text): Wellington brick churches (2).

Parameters	Reference	40 (*)	41	42	43	44
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	Average	---	---	---
	State of preservation of masonry	---	Absence	Average	Average	Average
	Rose windows	---	Presence	Absence	Absence	Absence
	Narthex / Atrium	---	Absence or ineffective	Absence	Absence	Absence
	Tie-rods	---	Absence	Absence or ineffective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	---	Thin stones or tile roof	Absence	Absence	Absence
	Characteristics of the roof	---	Average	Heavy roof	Heavy roof	Thin stones or tile roof

Table A6.8 Vulnerability index (V_i) modifiers (text): Auckland stone churches.

Parameters	Reference	47	48	52	54	55	75	85
V_i Modifiers	**Brick / Stone**	Stone	Stone	Stone	Stone	Stone	Stone	Stone
	Buttresses on the lateral wall (STONE ONLY)	Absence	Presence	Presence	Presence	Absence	Presence	Presence
	State of preservation of masonry	Average	Average	Average	Average	Average	Average	Average
	Rose windows	Absence	Presence	Presence	Absence	Absence	Presence	Presence
	Narthex / Atrium	Presence	Absence	Absence	Absence	Absence	Absence	Absence
	Tie-rods	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	Absence	Extended presence	Absence	Absence	Absence	Absence	Absence
	Characteristics of the roof	Metal sheet	Heavy roof	Thin stones or tile roof	Heavy roof	Heavy roof	Thin stones or tile roof	Heavy roof

Table A6.9 Vulnerability index (V_i) modifiers (text): Auckland brick churches (1).

Parameters	Reference	46	49	50	51	53	56	57	58
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	Average	Average	Average	Average	Average	Average	Average	Average
	Rose windows	Absence	Presence	Absence	Absence	Absence	Presence	Absence	Absence
	Narthex / Atrium	Absence	Absence	Absence	Presence	Absence	Absence	Absence	Absence
	Tie-rods	Absence or ineffective	Present and effective	Absence or ineffective	Present and effective	Absence or ineffective	Present and effective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Characteristics of the roof	Heavy roof	Heavy roof	Metal sheet	Metal sheet	Metal sheet	Heavy roof	Heavy roof	Heavy roof

Table A6.10 Vulnerability index (V_i) modifiers (text): Auckland brick churches (2).

Parameters	Reference	59	60	61	62	63	64	65	66
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	Average	Average	Average	Average	Average	Average	Average	Average
	Rose windows	Absence	Presence	Presence	Presence	Presence	Presence	Presence	Presence
	Narthex / Atrium	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Tie-rods	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	Extended presence	Absence	Absence	Absence	Absence	Absence	Extended presence	Absence
	Characteristics of the roof	Metal sheet	Thin stones or tile roof	Thin stones or tile roof	Metal sheet	Thin stones or tile roof	Heavy roof	Thin stones or tile roof	Metal sheet

Table A6.11 Vulnerability index (V_i) modifiers (text): Auckland brick churches (3).

Parameters	Reference	67	68	69	70	71	72	73	74
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	Average	Average	Average	Average	Average	Average	Average	Average
	Rose windows	Presence	Presence	Presence	Absence	Absence	Presence	Presence	Presence
	Narthex / Atrium	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Tie-rods	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	Absence	Absence	Absence	Absence	Absence	Absence	Absence	Absence
	Characteristics of the roof	Thin stones or tile roof	Thin stones or tile roof	Thin stones or tile roof	Thin stones or tile roof	Thin stones or tile roof	Heavy roof	Thin stones or tile roof	Thin stones or tile roof

Table A6.12 Vulnerability index (V_i) modifiers (text): Auckland brick churches (4).

Parameters	Reference	76	77 (*)	78	79	80	81	82	83
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	Average	---	Bad and/or cavity walls	Average	Average	Average	Average	Average
	Rose windows	Absence	---	Presence	Absence	Presence	Presence	Presence	Absence
	Narthex / Atrium	Absence	---	Absence	Absence	Absence	Absence	Absence	Presence
	Tie-rods	Absence or ineffective	---	Absence or ineffective	Absence or ineffective	Absence or ineffective	Present and effective	Absence or ineffective	Present and effective
	Vaults and/or dome	Absence	---	Absence	Absence	Absence	Absence	Absence	Absence
	Characteristics of the roof	Metal sheet	---	Metal sheet	Thin stones or tile roof	Thin stones or tile roof	Metal sheet	Thin stones or tile roof	Metal sheet

Table A6.13 Vulnerability index (V_i) modifiers (text): Auckland brick churches (5).

Parameters	Reference	84	86	87
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---
	State of preservation of masonry	Average	Average	Average
	Rose windows	Absence	Presence	Presence
	Narthex / Atrium	Absence	Absence	Absence
	Tie-rods	Absence or ineffective	Absence or ineffective	Absence or ineffective
	Vaults and/or dome	Absence	Absence	Absence
	Characteristics of the roof	Thin stones or tile roof	Thin stones or tile roof	Metal sheet

Table A6.14 Vulnerability index (V_i) modifiers (values): Dunedin stone churches.

Parameters	Reference	7	9	10	13	15	21	23
V_i Modifiers	**Brick / Stone**	Stone	Stone	Stone	Stone	Stone	Stone	Stone
	Buttresses on the lateral wall (STONE ONLY)	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
	State of preservation of masonry	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	Rose windows	0.09	0.09	0.09	0.09	0.09	0.09	0.09
	Narthex / Atrium	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Tie-rods	-0.06	0.04	-0.06	0.04	0.04	-0.06	0.04
	Vaults and/or dome	0	0.04	0	0.04	0	0	0
	Characteristics of the roof	0.06	0.06	0.06	0.06	0.06	0.06	-0.02
	V_i modifier brick/stone	0.03	0.03	0.03	0.03	0.03	0.03	0.17
	Total V_i modifier	0.15	0.29	0.15	0.29	0.25	0.15	0.700
	Final V_i low	0.680	0.820	0.680	0.820	0.780	0.680	1.022
	Final V_i medium	1.002	1.142	1.002	1.142	1.102	1.002	1.265
	Final V_i high	1.245	1.385	1.245	1.385	1.345	1.245	0.17

Table A6.15 Vulnerability index (V_i) modifiers (values): Dunedin brick churches (1).

Parameters	Reference	1	2	3	4	5	6	8	11
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	0	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	State of preservation of masonry	-0.02	-0.05	0.04	0.04	0.04	0.04	0.04	0.04
	Rose windows	0.04	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Narthex / Atrium	-0.02	0.02	-0.04	-0.04	0.02	-0.04	-0.04	0.02
	Tie-rods	0.02	0	0	0	0	0	0	0
	Vaults and/or dome	0	-0.01	0.04	0.01	-0.01	0.01	0.04	0.04
	Characteristics of the roof	0.04	-0.02	0.07	-0.02	-0.02	0.07	-0.02	0.07
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	0.03	-0.11	-0.03	-0.06	-0.02	-0.06	-0.03	0.03
	Final V_i low	0.560	0.420	0.500	0.470	0.510	0.470	0.500	0.560
	Final V_i medium	0.882	0.742	0.822	0.792	0.832	0.792	0.822	0.882
	Final V_i high	1.185	1.045	1.125	1.095	1.135	1.095	1.125	1.185

Table A6.16 Vulnerability index (V_i) modifiers (values): Dunedin brick churches (2).

Parameters	Reference	12 (*)	14	16	17	18	19	20	22
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	---	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Rose windows	---	0.04	0.04	0.04	0.04	0.04	-0.05	0.04
	Narthex / Atrium	---	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Tie-rods	---	-0.04	-0.04	0.02	-0.04	0.02	0.02	0.02
	Vaults and/or dome	---	0	0	0	0	0	0	0
	Characteristics of the roof	---	0.04	-0.01	0.04	0.04	0.04	-0.01	0.04
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	---	-0.03	-0.08	0.03	-0.03	0.03	-0.11	0.03
	Final V_i low	---	0.500	0.450	0.560	0.500	0.560	0.420	0.560
	Final V_i medium	---	0.822	0.772	0.882	0.822	0.882	0.742	0.882
	Final V_i high	---	1.125	1.075	1.185	1.125	1.185	1.045	1.185

Table A6.17 Vulnerability index (V_i) modifiers (values): Dunedin brick churches (3).

Parameters	Reference	24	25	26	27	28	29 (*)	30 (*)	31 (*)
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	-0.02	-0.02	-0.02	-0.02	-0.02	---	---	---
	Rose windows	-0.05	0.04	0.04	-0.05	-0.05	---	---	---
	Narthex / Atrium	-0.02	-0.02	-0.02	0.01	-0.02	---	---	---
	Tie-rods	0.02	-0.04	0.02	-0.04	0.02	---	---	---
	Vaults and/or dome	0.02	0	0	0	0	---	---	---
	Characteristics of the roof	-0.01	0.01	0.01	0.04	0.04	---	---	---
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	-0.09	-0.06	0	-0.09	-0.06	---	---	---
	Final V_i low	0.440	0.470	0.530	0.440	0.470	---	---	---
	Final V_i medium	0.762	0.792	0.852	0.762	0.792	---	---	---
	Final V_i high	1.065	1.095	1.155	1.065	1.095	---	---	---

Table A6.18 Vulnerability index (V_i) modifiers (values): Wellington stone churches.

Parameters	Reference	45
V_i Modifiers	Brick / Stone	Stone
	Buttresses on the lateral wall (STONE ONLY)	0.04
	State of preservation of masonry	0.06
	Rose windows	-0.1
	Narthex / Atrium	-0.02
	Tie-rods	0.04
	Vaults and/or dome	0
	Characteristics of the roof	0.02
	V_i modifier brick/stone	0.03
	Total V_i modifier	0.07
	Final V_i low	0.600
	Final V_i medium	0.922
	Final V_i high	1.165

Table A6.19 Vulnerability index (V_i) modifiers (values): Wellington brick churches (1).

Parameters	Reference	32	33	34	35	36	37	38	39
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Rose windows	-0.05	0.04	-0.05	-0.05	0.04	0.04	-0.05	0.04
	Narthex / Atrium	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Tie-rods	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Vaults and/or dome	0	0	0	0	0	0	0	0
	Characteristics of the roof	0.04	-0.01	0.01	0.01	0.04	0.01	0.04	-0.01
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	-0.06	-0.02	-0.09	-0.09	0.03	0.00	-0.06	-0.02
	Final V_i low	0.470	0.510	0.440	0.440	0.560	0.530	0.470	0.510
	Final V_i medium	0.792	0.832	0.762	0.762	0.882	0.852	0.792	0.832
	Final V_i high	1.095	1.135	1.065	1.065	1.185	1.155	1.095	1.135

Table A6.20 Vulnerability index (V_i) modifiers (values): Wellington brick churches (2).

Parameters	Reference	40 (*)	41	42	43	44
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---
	State of preservation of masonry	---	-0.02	-0.02	-0.02	-0.02
	Rose windows	---	-0.05	-0.05	-0.05	-0.05
	Narthex / Atrium	---	0.01	-0.02	-0.02	-0.02
	Tie-rods	---	0.02	0.02	0.02	0.02
	Vaults and/or dome	---	0	0	0	0
	Characteristics of the roof	---	0.01	0.04	0.04	0.01
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	---	-0.06	-0.06	-0.06	-0.09
	Final V_i low	---	0.470	0.470	0.470	0.440
	Final V_i medium	---	0.792	0.792	0.792	0.762
	Final V_i high	---	1.095	1.095	1.095	1.065

Table A6.21 Vulnerability index (V_i) modifiers (values): Auckland stone churches.

Parameters	Reference	47	48	52	54	55	75	85
V_i Modifiers	**Brick / Stone**	Stone	Stone	Stone	Stone	Stone	Stone	Stone
	Buttresses on the lateral wall (STONE ONLY)	0.04	-0.01	-0.01	-0.01	0.04	-0.01	-0.01
	State of preservation of masonry	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	Rose windows	-0.1	0.09	0.09	-0.1	-0.1	0.09	0.09
	Narthex / Atrium	0.01	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Tie-rods	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	Vaults and/or dome	0	0.04	0	0	0	0	0
	Characteristics of the roof	-0.02	0.06	0.02	0.06	0.06	0.02	0.06
	V_i modifier brick/stone	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	Total V_i modifier	0.06	0.29	0.21	0.06	0.11	0.21	0.25
	Final V_i low	0.590	0.820	0.740	0.590	0.640	0.740	0.780
	Final V_i medium	0.912	1.142	1.062	0.912	0.962	1.062	1.102
	Final V_i high	1.155	1.385	1.305	1.155	1.205	1.305	1.345

Table A6.22 Vulnerability index (V_i) modifiers (values): Auckland brick churches (1).

Parameters	Reference	46	49	50	51	53	56	57	58
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Rose windows	-0.05	0.04	-0.05	-0.05	-0.05	0.04	-0.05	-0.05
	Narthex / Atrium	-0.02	-0.02	-0.02	0.01	-0.02	-0.02	-0.02	-0.02
	Tie-rods	0.02	-0.04	0.02	-0.04	0.02	-0.04	0.02	0.02
	Vaults and/or dome	0	0	0	0	0	0	0	0
	Characteristics of the roof	0.04	0.04	-0.01	-0.01	-0.01	0.04	0.04	0.04
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	-0.06	-0.03	-0.11	-0.14	-0.11	-0.03	-0.06	-0.06
	Final V_i low	0.470	0.500	0.420	0.390	0.420	0.500	0.470	0.470
	Final V_i medium	0.792	0.822	0.742	0.712	0.742	0.822	0.792	0.792
	Final V_i high	1.095	1.125	1.045	1.015	1.045	1.125	1.095	1.095

Table A6.23 Vulnerability index (V_i) modifiers (values): Auckland brick churches (2).

Parameters	Reference	59	60	61	62	63	64	65	66
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Rose windows	-0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	Narthex / Atrium	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Tie-rods	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Vaults and/or dome	0.02	0	0	0	0	0	0.02	0
	Characteristics of the roof	-0.01	0.01	0.01	-0.01	0.01	0.04	0.01	-0.01
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	-0.09	0	0	-0.02	0	0.03	0.02	-0.02
	Final V_i low	0.440	0.530	0.530	0.510	0.530	0.560	0.550	0.510
	Final V_i medium	0.762	0.852	0.852	0.832	0.852	0.882	0.872	0.832
	Final V_i high	1.065	1.155	1.155	1.135	1.155	1.185	1.175	1.135

Table A6.24 Vulnerability index (V_i) modifiers (values): Auckland brick churches (3).

Parameters	Reference	67	68	69	70	71	72	73	74
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Rose windows	0.04	0.04	0.04	-0.05	-0.05	0.04	0.04	0.04
	Narthex / Atrium	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Tie-rods	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	Vaults and/or dome	0	0	0	0	0	0	0	0
	Characteristics of the roof	0.01	0.01	0.01	0.01	0.01	0.04	0.01	0.01
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	0	0	0	-0.09	-0.09	0.03	0	0
	Final V_i low	0.530	0.530	0.530	0.440	0.440	0.560	0.530	0.530
	Final V_i medium	0.852	0.852	0.852	0.762	0.762	0.882	0.852	0.852
	Final V_i high	1.155	1.155	1.155	1.065	1.065	1.185	1.155	1.155

Table A6.25 Vulnerability index (V_i) modifiers (values): Auckland brick churches (4).

Parameters	Reference	76	77 (*)	78	79	80	81	82	83
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick	Brick	Brick	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---	---	---	---	---	---
	State of preservation of masonry	-0.02	---	0.07	-0.02	-0.02	-0.02	-0.02	-0.02
	Rose windows	-0.05	---	0.04	-0.05	0.04	0.04	0.04	-0.05
	Narthex / Atrium	-0.02	---	-0.02	-0.02	-0.02	-0.02	-0.02	0.01
	Tie-rods	0.02	---	0.02	0.02	0.02	-0.04	0.02	-0.04
	Vaults and/or dome	0	---	0	0	0	0	0	0
	Characteristics of the roof	-0.01	---	-0.01	0.01	0.01	-0.01	0.01	-0.01
	V_i modifier brick/stone	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total V_i modifier	-0.11	---	0.07	-0.09	0	-0.08	0	-0.14
	Final V_i low	0.420	---	0.600	0.440	0.530	0.450	0.530	0.390
	Final V_i medium	0.742	---	0.922	0.762	0.852	0.772	0.852	0.712
	Final V_i high	1.045	---	1.225	1.065	1.155	1.075	1.155	1.015

Table A6.26 Vulnerability index (V_i) modifiers (values): Auckland brick churches (5).

Parameters	Reference	84	86	87
V_i Modifiers	**Brick / Stone**	Brick	Brick	Brick
	Buttresses on the lateral wall (STONE ONLY)	---	---	---
	State of preservation of masonry	-0.02	-0.02	-0.02
	Rose windows	-0.05	0.04	0.04
	Narthex / Atrium	-0.02	-0.02	-0.02
	Tie-rods	0.02	0.02	0.02
	Vaults and/or dome	0	0	0
	Characteristics of the roof	0.01	0.01	-0.01
	V_i modifier brick/stone	-0.03	-0.03	-0.03
	Total V_i modifier	-0.09	0	-0.02
	Final V_i low	0.440	0.530	0.510
	Final V_i medium	0.762	0.852	0.832
	Final V_i high	1.065	1.155	1.135

(*) Churches not found during survey, therefore, no data collected.

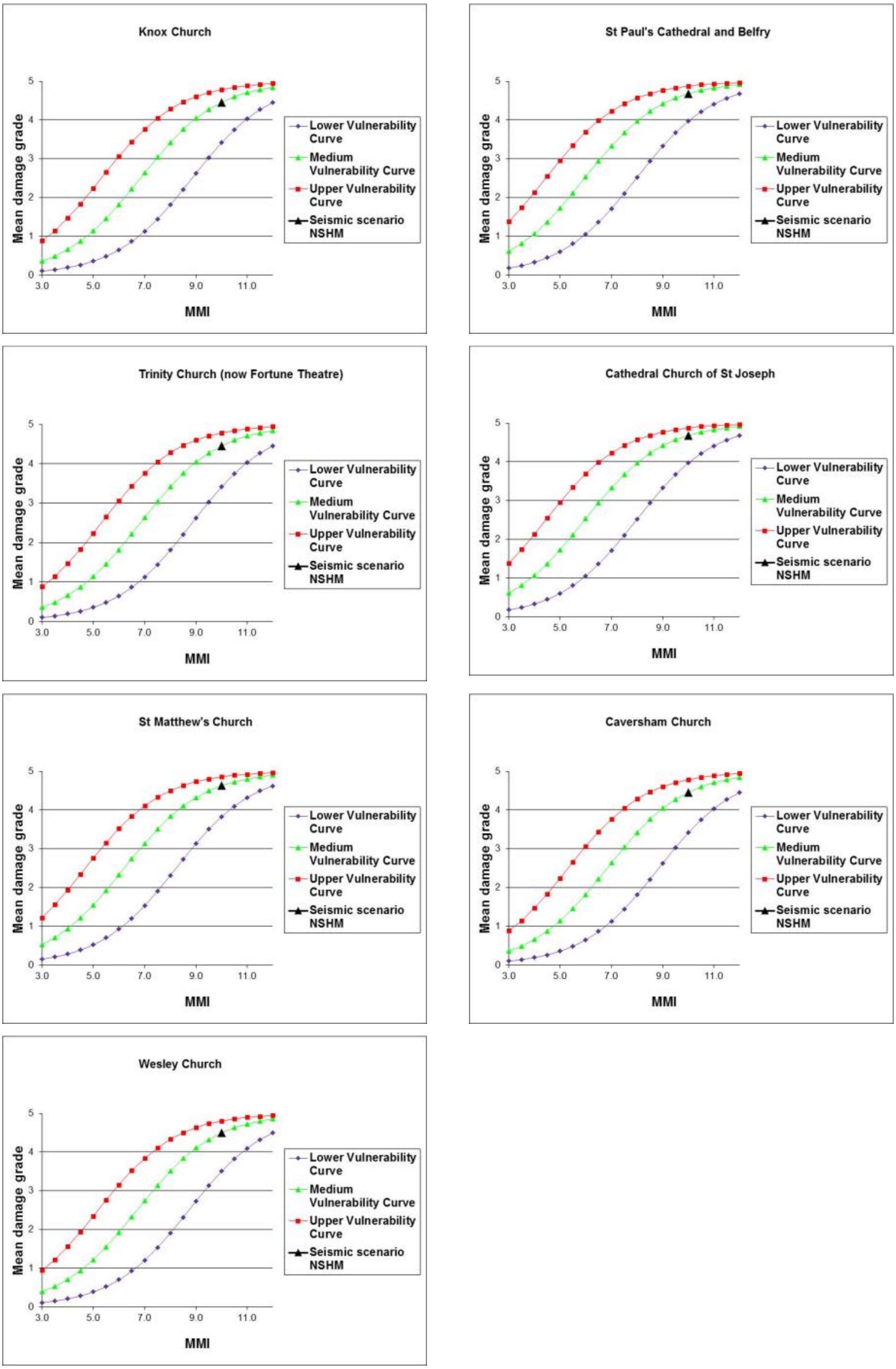


Figure A6.1 Vulnerability curves: Dunedin stone churches.

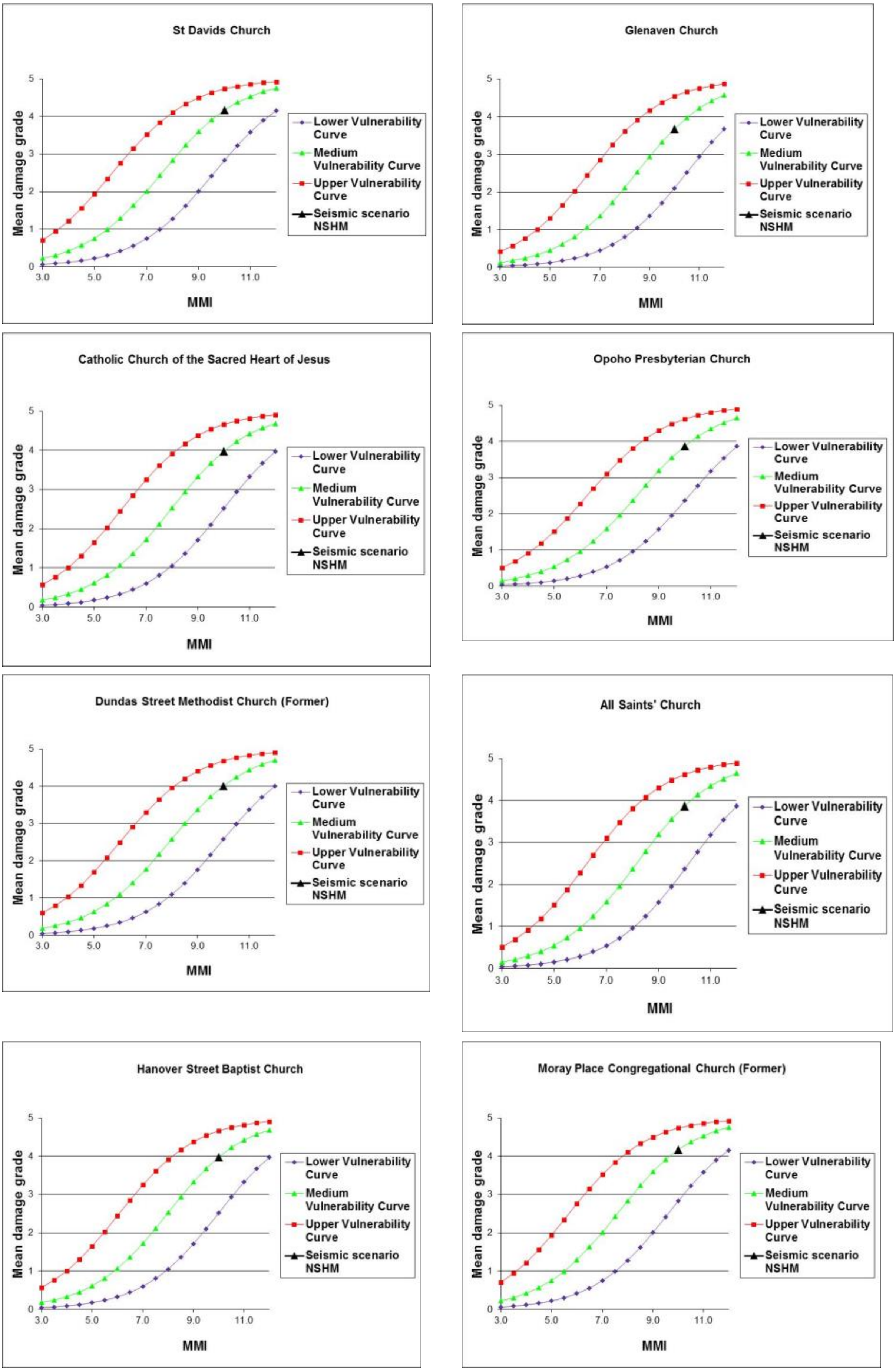


Figure A6.2 Vulnerability curves: Dunedin brick churches.

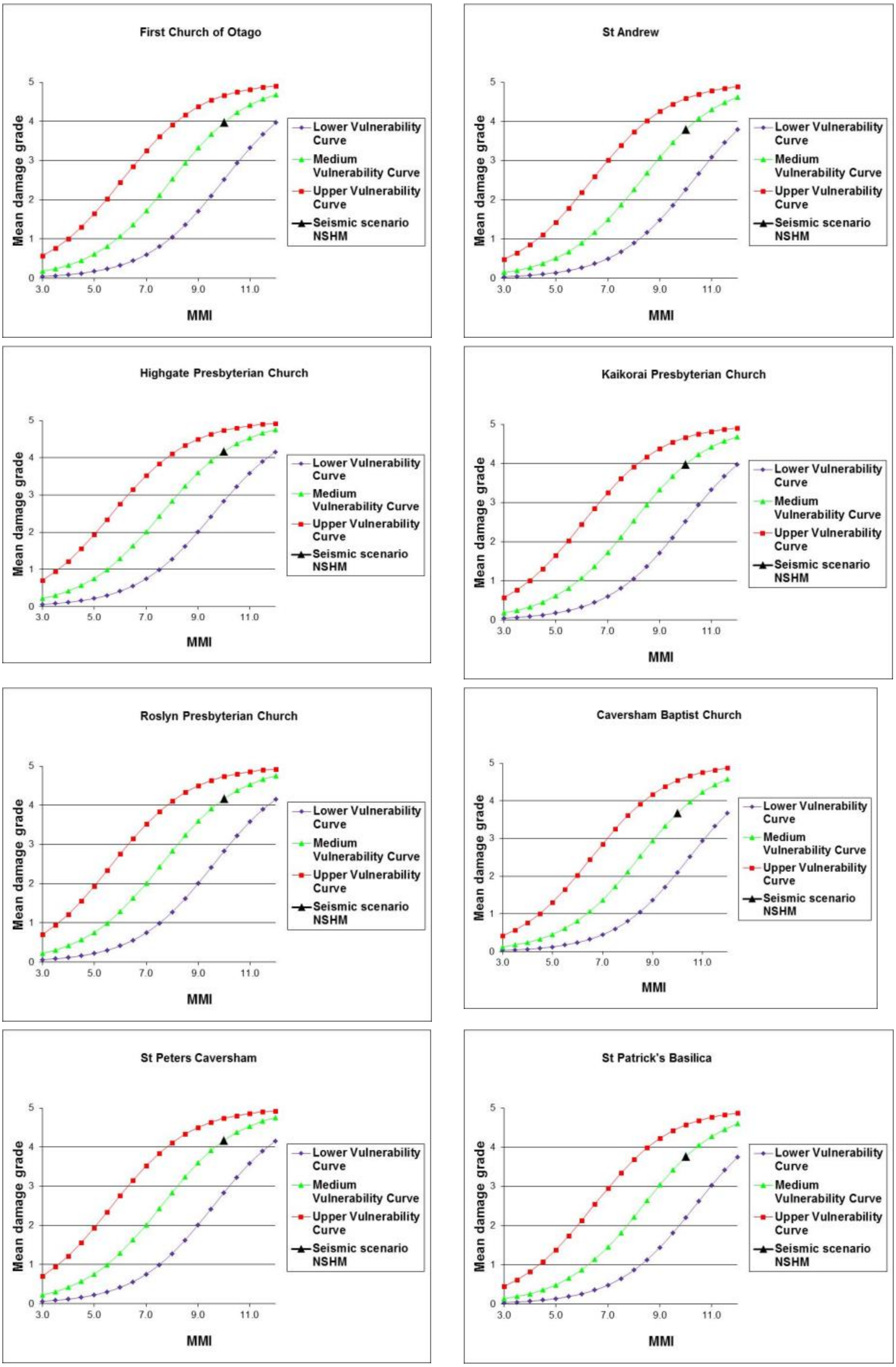


Figure A6.3 Vulnerability curves: Dunedin brick churches (cont.).

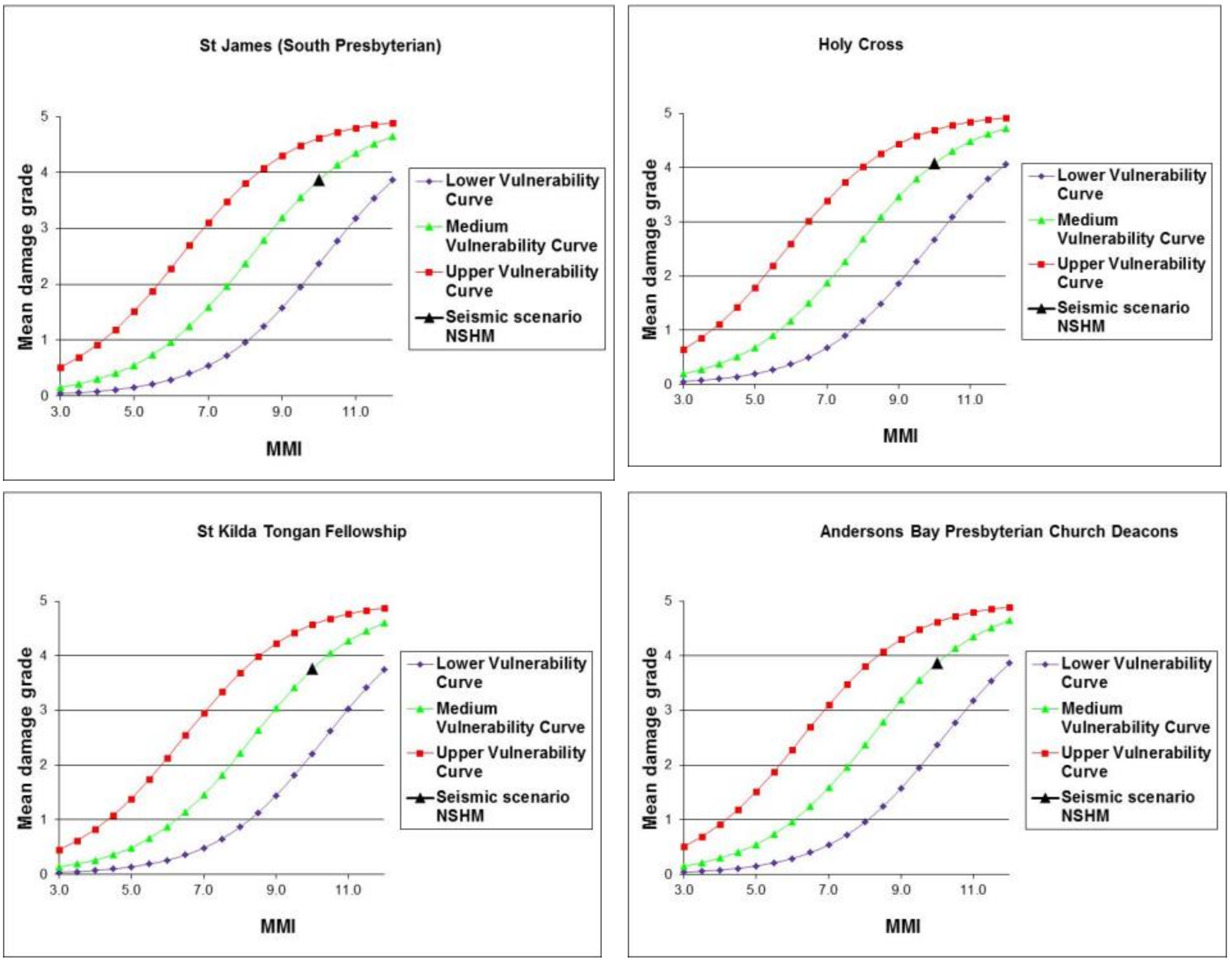


Figure A6.4 Vulnerability curves: Dunedin brick churches (cont.2).

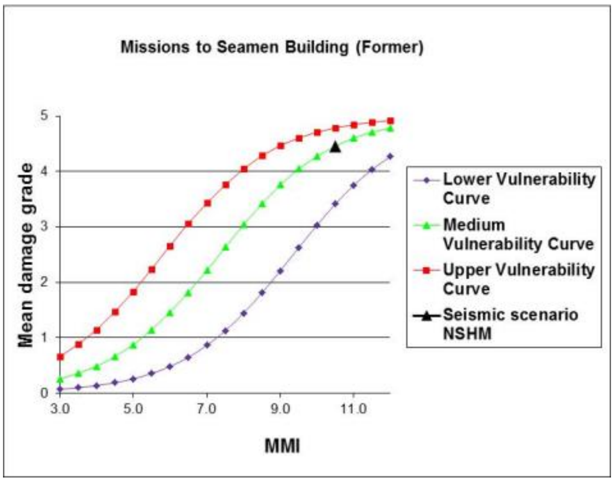


Figure A6.5 Vulnerability curves: Wellington stone churches.

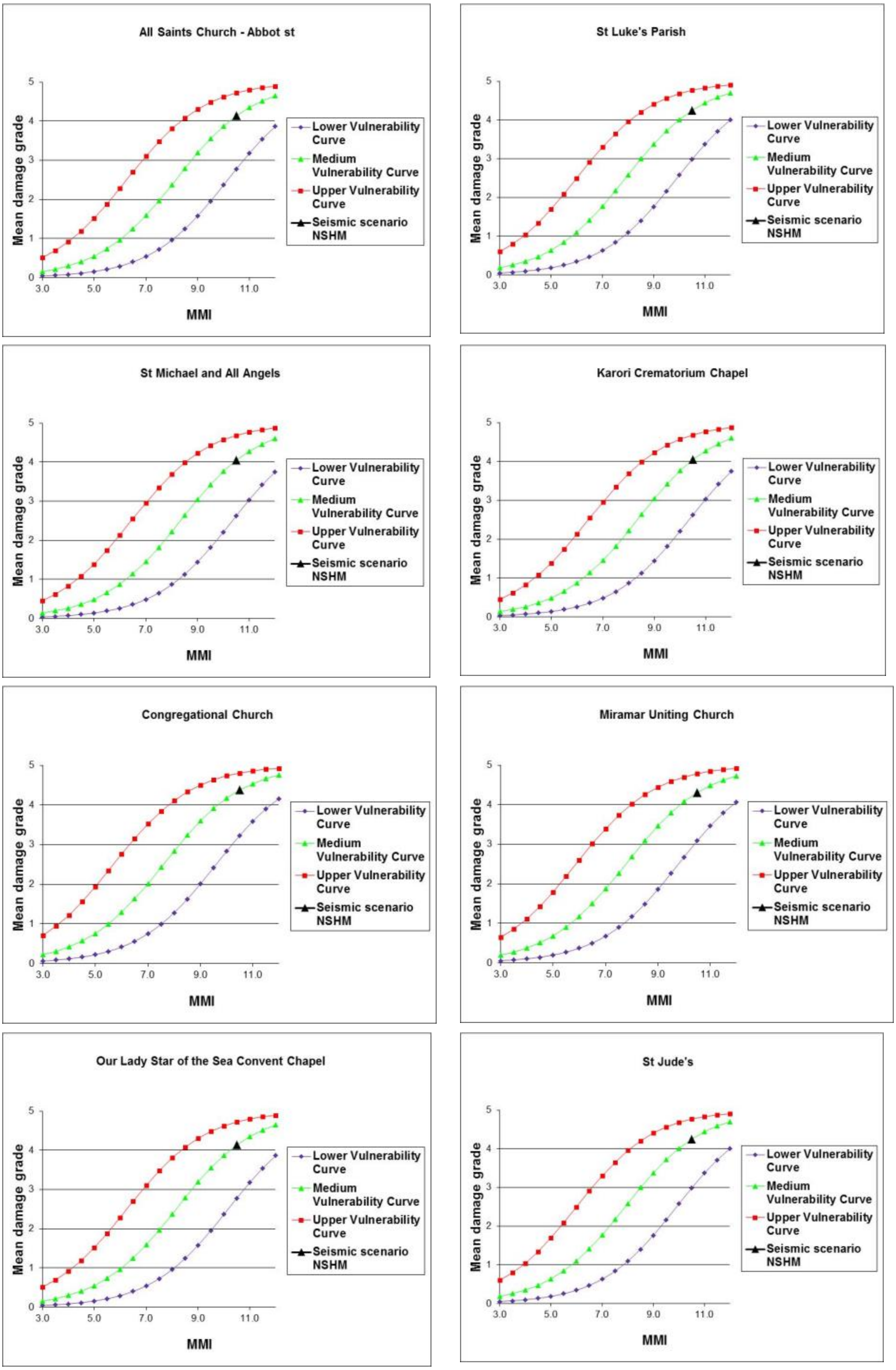


Figure A6.6 Vulnerability curves: Wellington brick churches.

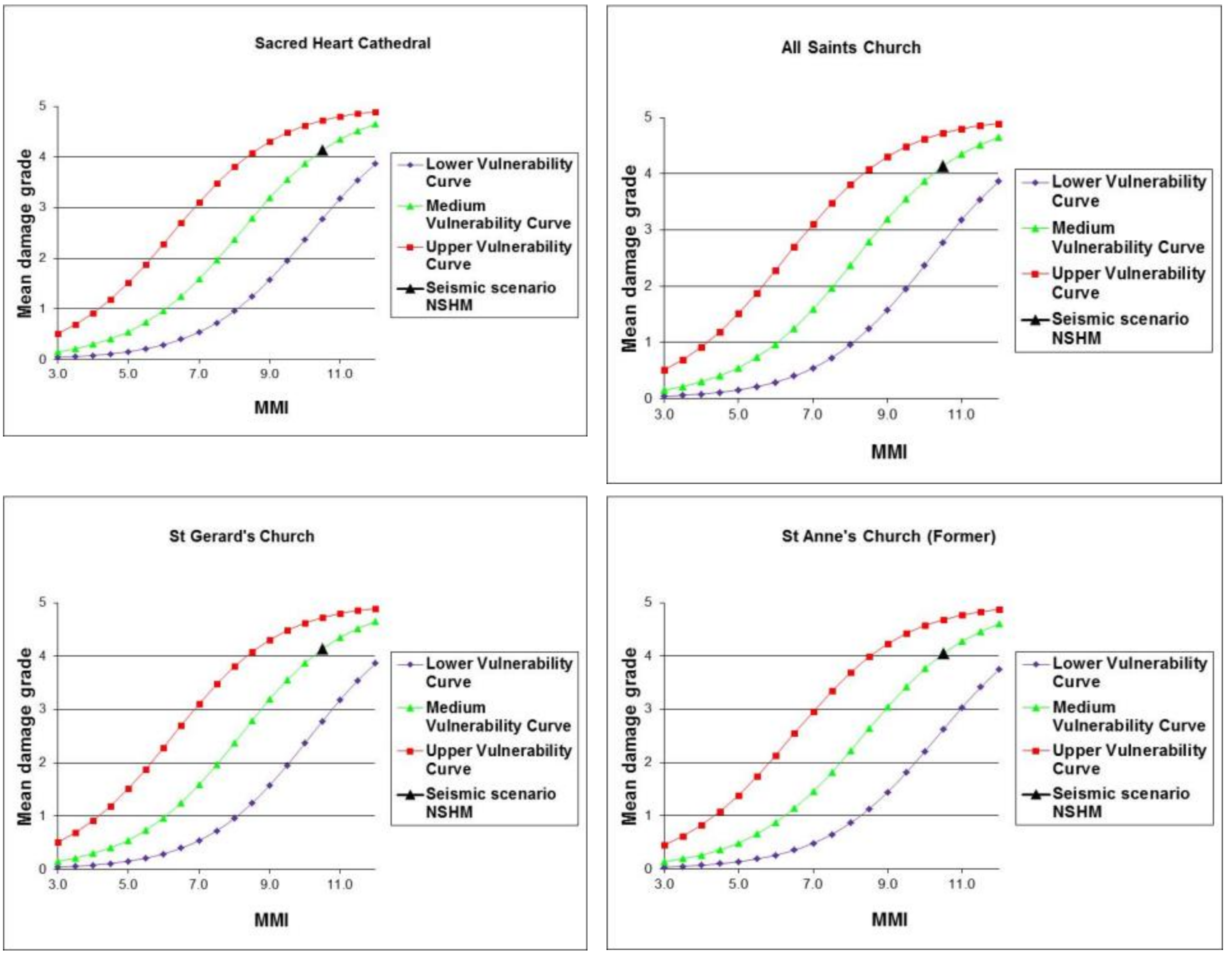


Figure A6.7 Vulnerability curves: Wellington brick churches (cont.).

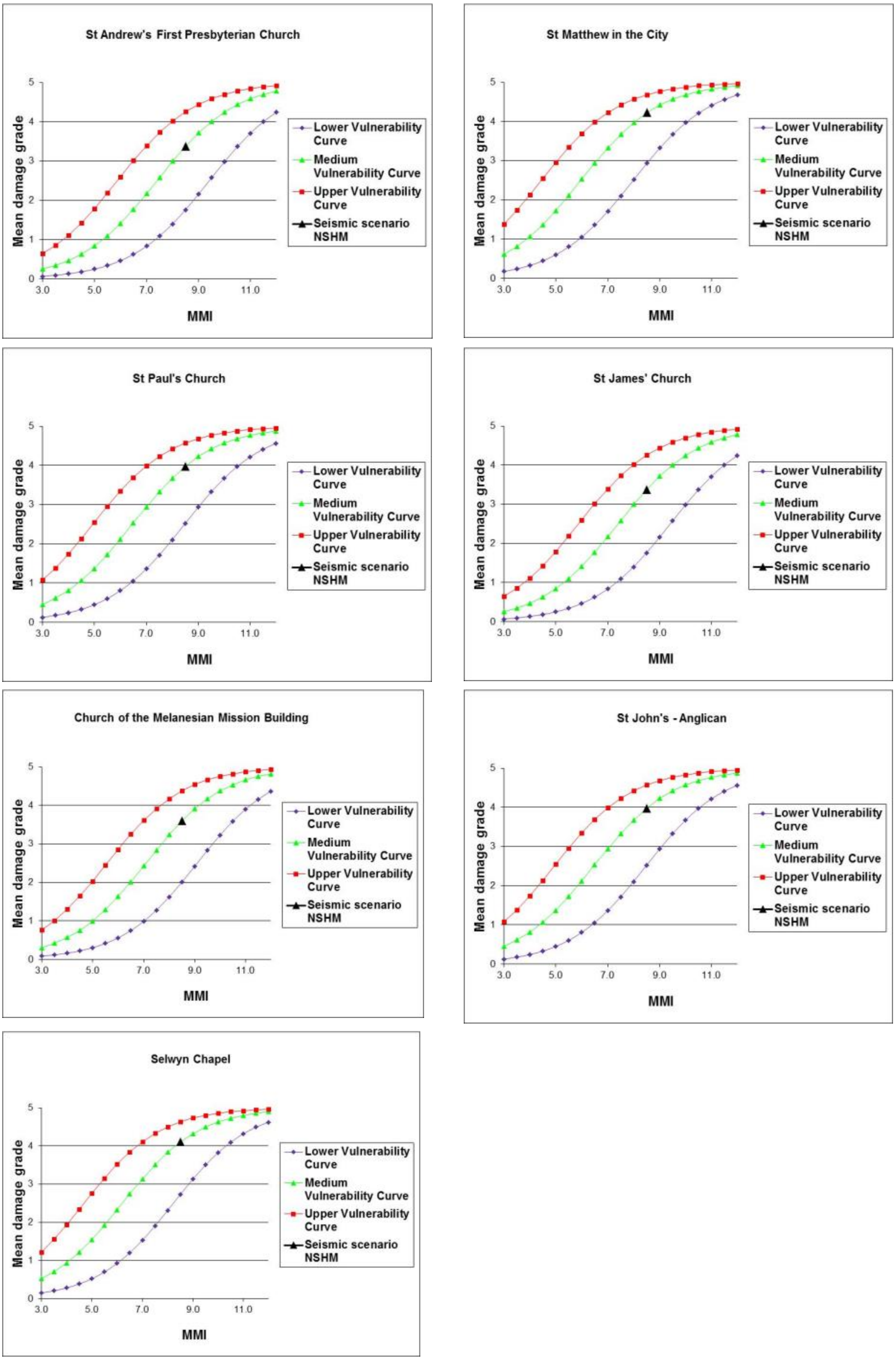


Figure A6.8 Vulnerability curves: Auckland stone churches.

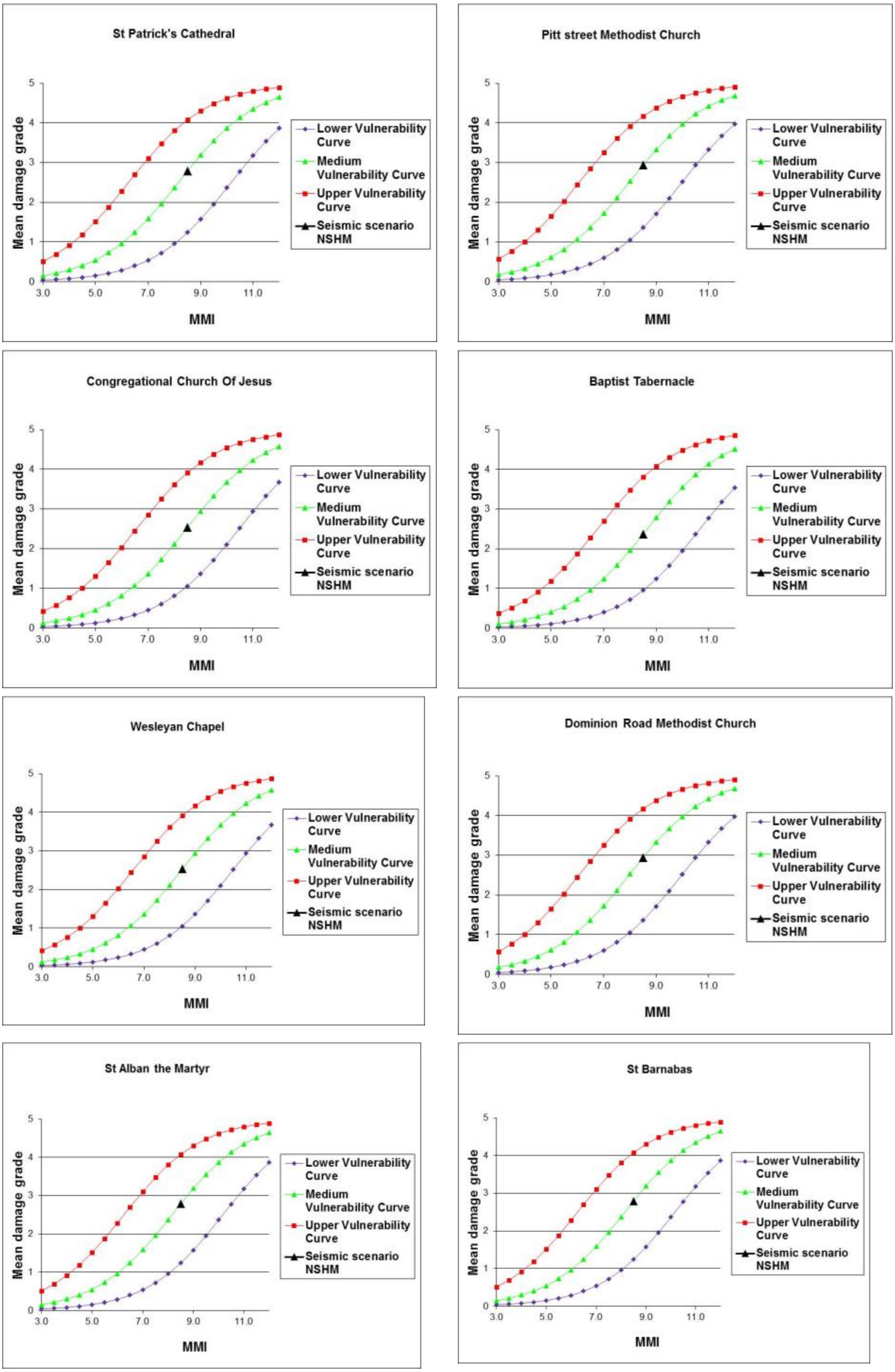


Figure A6.9 Vulnerability curves: Auckland brick churches.

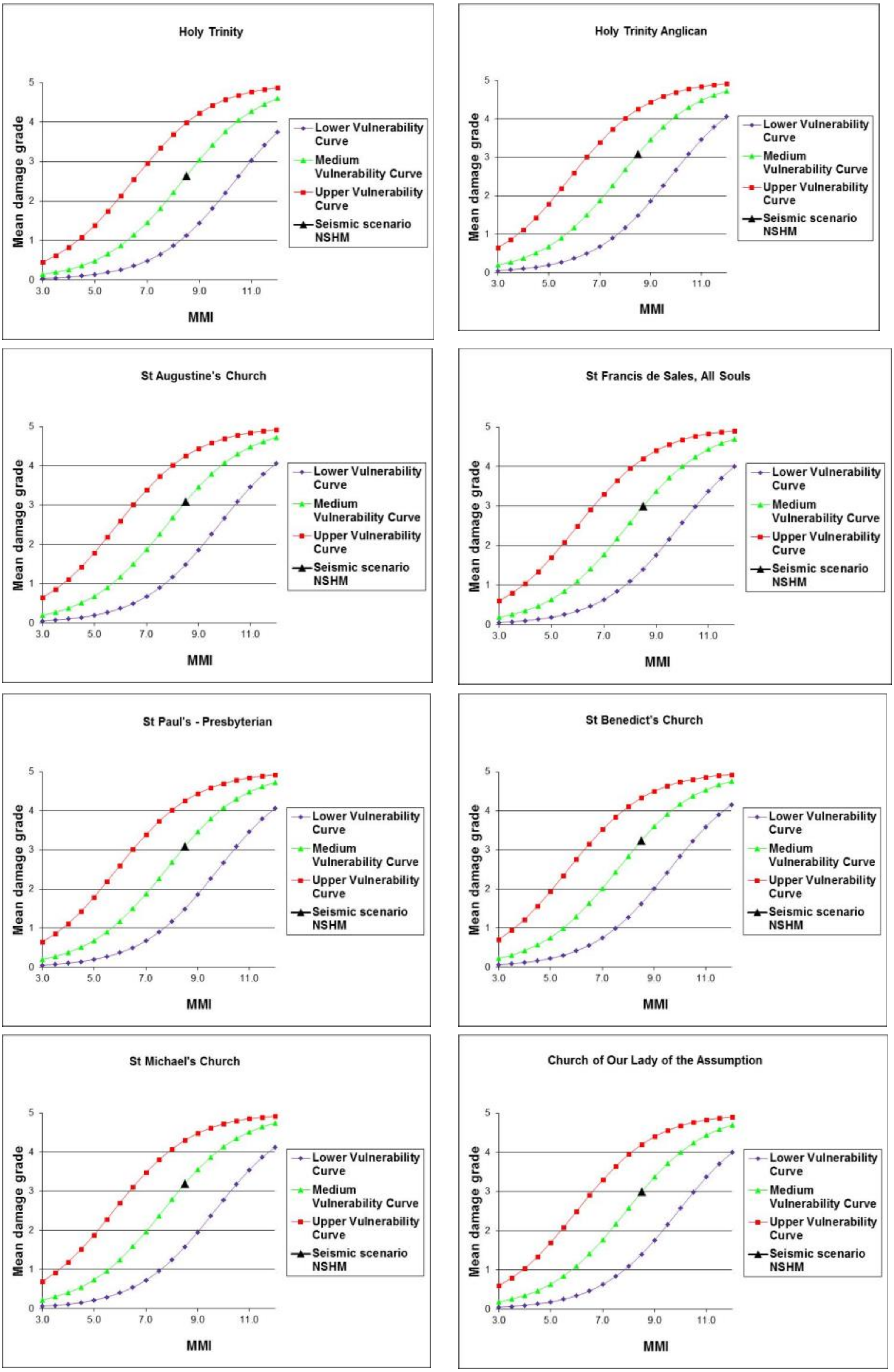


Figure A6.10 Vulnerability curves: Auckland brick churches (cont.).

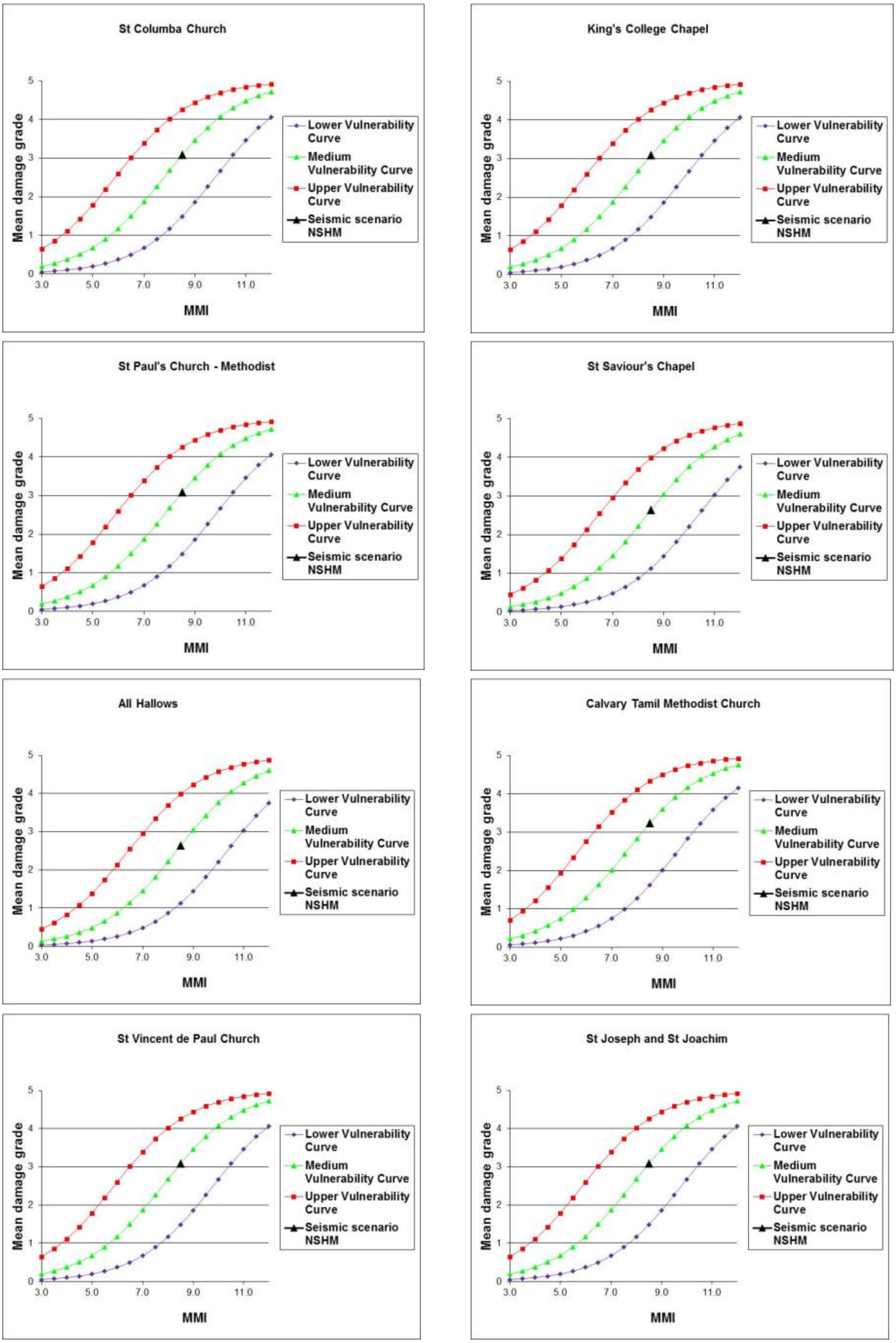


Figure A6.11 Vulnerability curves: Auckland brick churches (cont.2).

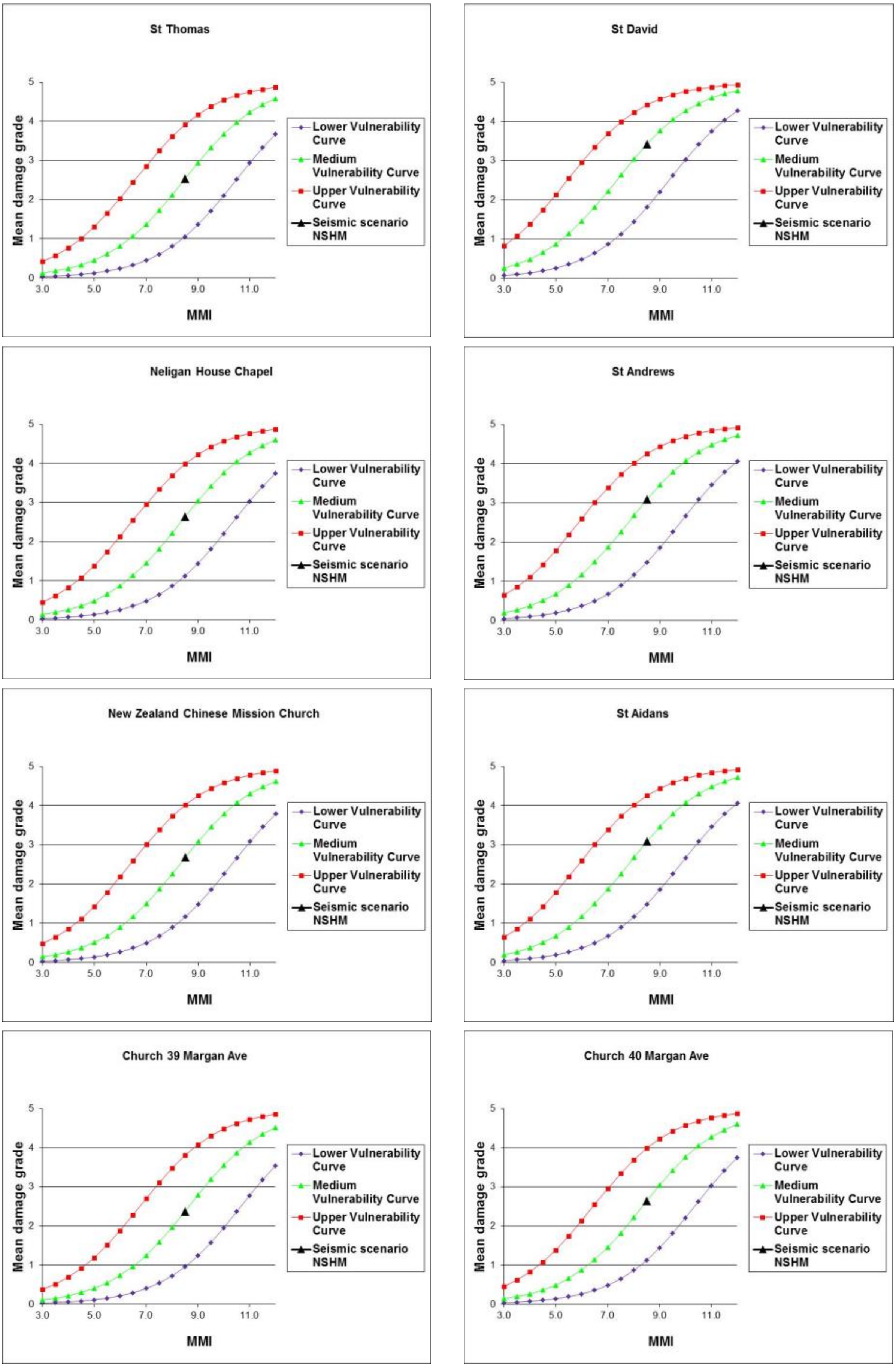


Figure A6.12 Vulnerability curves: Auckland brick churches (cont.3).

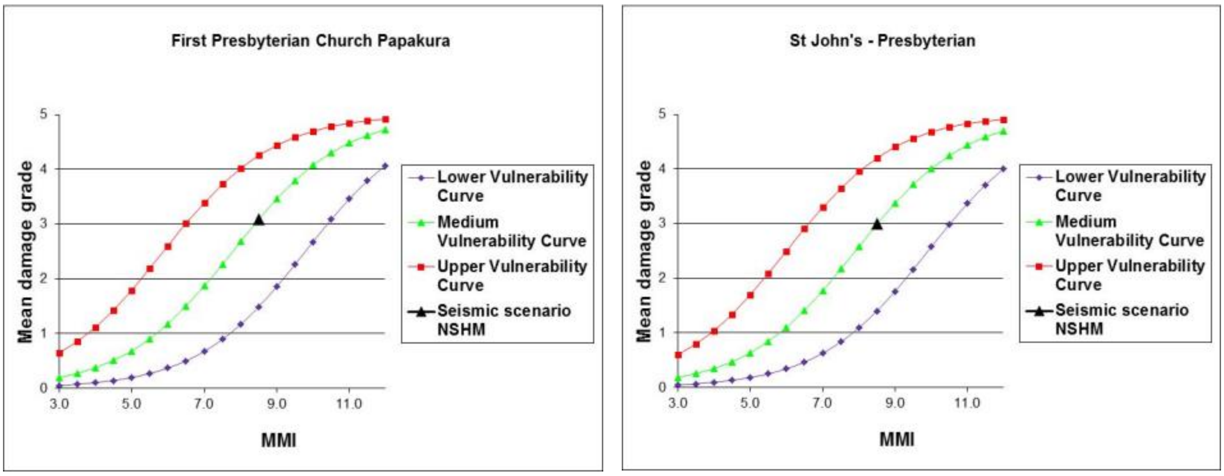


Figure A6.13 Vulnerability curves: Auckland brick churches (cont.4).

A6.3 DAMAGE PROBABILITIES

This section shows the table with the medium damage probability values for the six damage levels (k=0, no damage, to k=5, total destruction) for the URM churches in Wellington, Auckland and Dunedin, calculated using Equation 5.

Table A6.27 Damage probabilities from the medium vulnerability index value (references correspond to Table 4.2).

Damage grade (k) / Church ref.	0 (no damage)	1 (negligible damage)	2 (slight damage)	3 (moderate damage)	4 (heavy damage)	5 (collapse)
1	0.000	0.003	0.032	0.161	0.402	0.402
2	0.001	0.018	0.100	0.278	0.387	0.216
3	0.000	0.007	0.054	0.211	0.409	0.319
4	0.001	0.010	0.069	0.236	0.406	0.279
5	0.000	0.006	0.050	0.202	0.410	0.332
6	0.001	0.010	0.069	0.236	0.406	0.279
7	0.000	0.001	0.010	0.083	0.342	0.564
8	0.000	0.007	0.054	0.211	0.409	0.319
9	0.000	0.000	0.002	0.033	0.244	0.720
10	0.000	0.001	0.010	0.083	0.342	0.564
11	0.000	0.003	0.032	0.161	0.402	0.402
12 (*)	---	---	---	---	---	---
13	0.000	0.000	0.002	0.033	0.244	0.720
14	0.000	0.007	0.054	0.211	0.409	0.319
15	0.000	0.000	0.003	0.044	0.272	0.680
16	0.001	0.013	0.080	0.253	0.400	0.253
17	0.000	0.003	0.032	0.161	0.402	0.402
18	0.000	0.007	0.054	0.211	0.409	0.319
19	0.000	0.003	0.032	0.161	0.402	0.402

Church ref. \ Damage grade (k)	0 (no damage)	1 (negligible damage)	2 (slight damage)	3 (moderate damage)	4 (heavy damage)	5 (collapse)
20	0.001	0.018	0.100	0.278	0.387	0.216
21	0.000	0.001	0.010	0.083	0.342	0.564
22	0.000	0.003	0.032	0.161	0.402	0.402
23	0.000	0.000	0.008	0.074	0.329	0.589
24	0.001	0.014	0.086	0.262	0.396	0.240
25	0.001	0.010	0.069	0.236	0.406	0.279
26	0.000	0.005	0.042	0.185	0.408	0.360
27	0.001	0.014	0.086	0.262	0.396	0.240
28	0.001	0.010	0.069	0.236	0.406	0.279
29 (*)	---	---	---	---	---	---
30 (*)	---	---	---	---	---	---
31 (*)	---	---	---	---	---	---
32	0.000	0.004	0.035	0.169	0.404	0.388
33	0.000	0.002	0.024	0.138	0.392	0.443
34	0.000	0.005	0.046	0.194	0.409	0.346
35	0.000	0.005	0.046	0.194	0.409	0.346
36	0.000	0.001	0.015	0.105	0.367	0.512
37	0.000	0.002	0.020	0.124	0.383	0.471
38	0.000	0.004	0.035	0.169	0.404	0.388
39	0.000	0.002	0.024	0.138	0.392	0.443
40 (*)	---	---	---	---	---	---
41	0.000	0.004	0.035	0.169	0.404	0.388
42	0.000	0.004	0.035	0.169	0.404	0.388
43	0.000	0.004	0.035	0.169	0.404	0.388
44	0.000	0.005	0.046	0.194	0.409	0.346
45	0.000	0.001	0.010	0.083	0.342	0.564
46	0.017	0.106	0.269	0.339	0.214	0.054
47	0.004	0.037	0.156	0.325	0.338	0.141
48	0.000	0.002	0.027	0.146	0.395	0.429
49	0.012	0.084	0.241	0.345	0.247	0.071
50	0.029	0.150	0.308	0.316	0.162	0.033
51	0.040	0.180	0.326	0.295	0.134	0.024
52	0.000	0.007	0.054	0.211	0.409	0.319
53	0.029	0.150	0.308	0.316	0.162	0.033
54	0.004	0.037	0.156	0.325	0.338	0.141
55	0.002	0.022	0.114	0.297	0.376	0.193
56	0.012	0.084	0.241	0.345	0.247	0.071
57	0.017	0.106	0.269	0.339	0.214	0.054
58	0.017	0.106	0.269	0.339	0.214	0.054
59	0.024	0.132	0.294	0.327	0.182	0.041

Damage grade (k) / Church ref.	0 (no damage)	1 (negligible damage)	2 (slight damage)	3 (moderate damage)	4 (heavy damage)	5 (collapse)
60	0.008	0.065	0.212	0.344	0.279	0.091
61	0.008	0.065	0.212	0.344	0.279	0.091
62	0.010	0.078	0.232	0.346	0.258	0.077
63	0.008	0.065	0.212	0.344	0.279	0.091
64	0.005	0.050	0.184	0.337	0.310	0.114
65	0.006	0.055	0.193	0.340	0.300	0.106
66	0.010	0.078	0.232	0.346	0.258	0.077
67	0.008	0.065	0.212	0.344	0.279	0.091
68	0.008	0.065	0.212	0.344	0.279	0.091
69	0.008	0.065	0.212	0.344	0.279	0.091
70	0.024	0.132	0.294	0.327	0.182	0.041
71	0.024	0.132	0.294	0.327	0.182	0.041
72	0.005	0.050	0.184	0.337	0.310	0.114
73	0.008	0.065	0.212	0.344	0.279	0.091
74	0.008	0.065	0.212	0.344	0.279	0.091
75	0.000	0.007	0.054	0.211	0.409	0.319
76	0.029	0.150	0.308	0.316	0.162	0.033
77 (*)	---	---	---	---	---	---
78	0.003	0.034	0.147	0.319	0.346	0.150
79	0.024	0.132	0.294	0.327	0.182	0.041
80	0.008	0.065	0.212	0.344	0.279	0.091
81	0.021	0.123	0.286	0.332	0.193	0.045
82	0.008	0.065	0.212	0.344	0.279	0.091
83	0.040	0.180	0.326	0.295	0.134	0.024
84	0.024	0.132	0.294	0.327	0.182	0.041
85	0.000	0.004	0.039	0.177	0.407	0.374
86	0.008	0.065	0.212	0.344	0.279	0.091
87	0.010	0.078	0.232	0.346	0.258	0.077

(*) Churches not found during survey, therefore no data collected

A6.4 DAMAGE HISTOGRAMS

The histograms with the lower medium (values shown in Table A6.27) and upper damage probabilities for the six damage levels (k=0, no damage, to k=5, total destruction) are shown here for the URM churches in Wellington, Auckland and Dunedin.

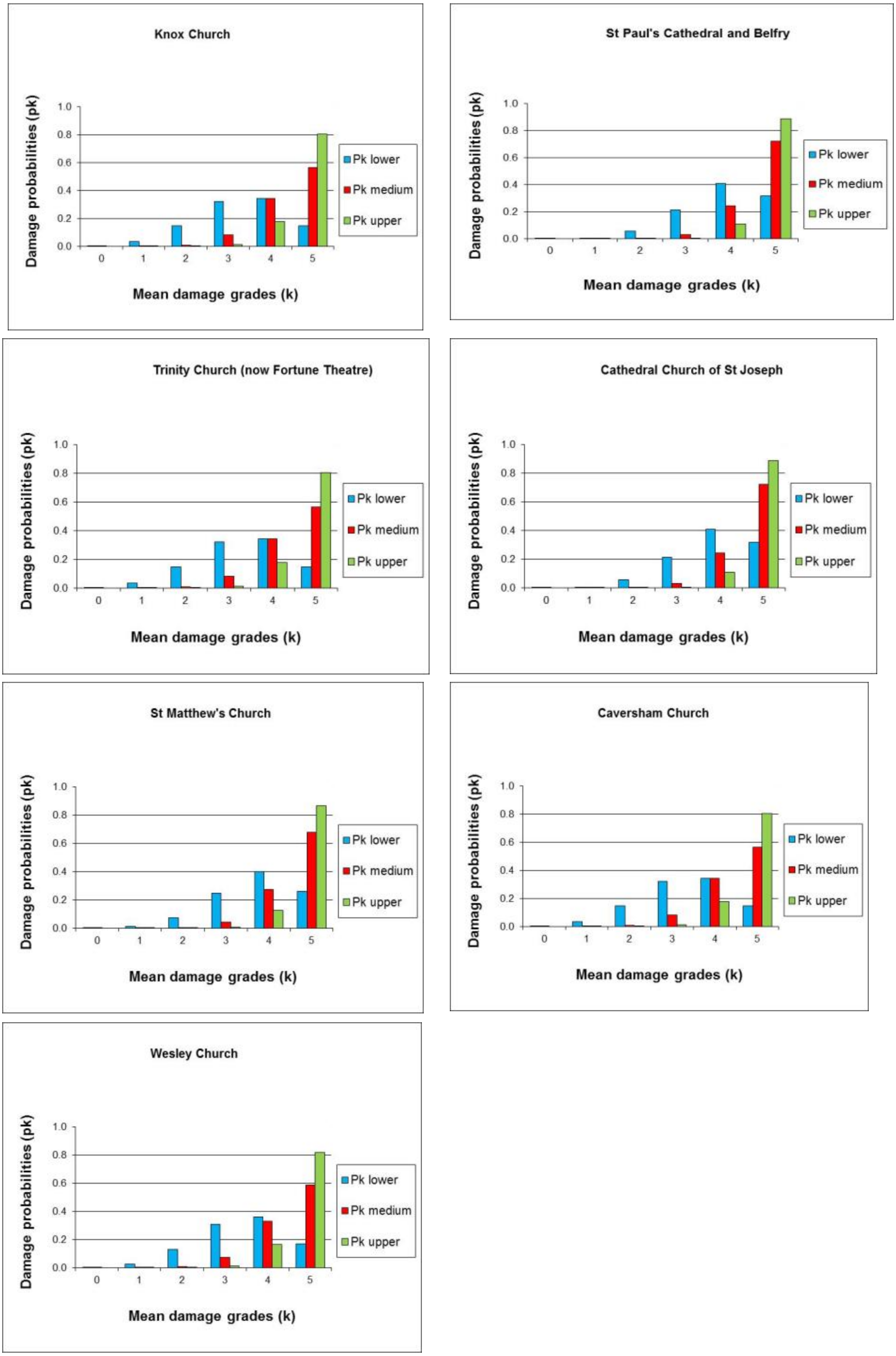


Figure A6.14 Histograms of damage probabilities: Dunedin stone churches.

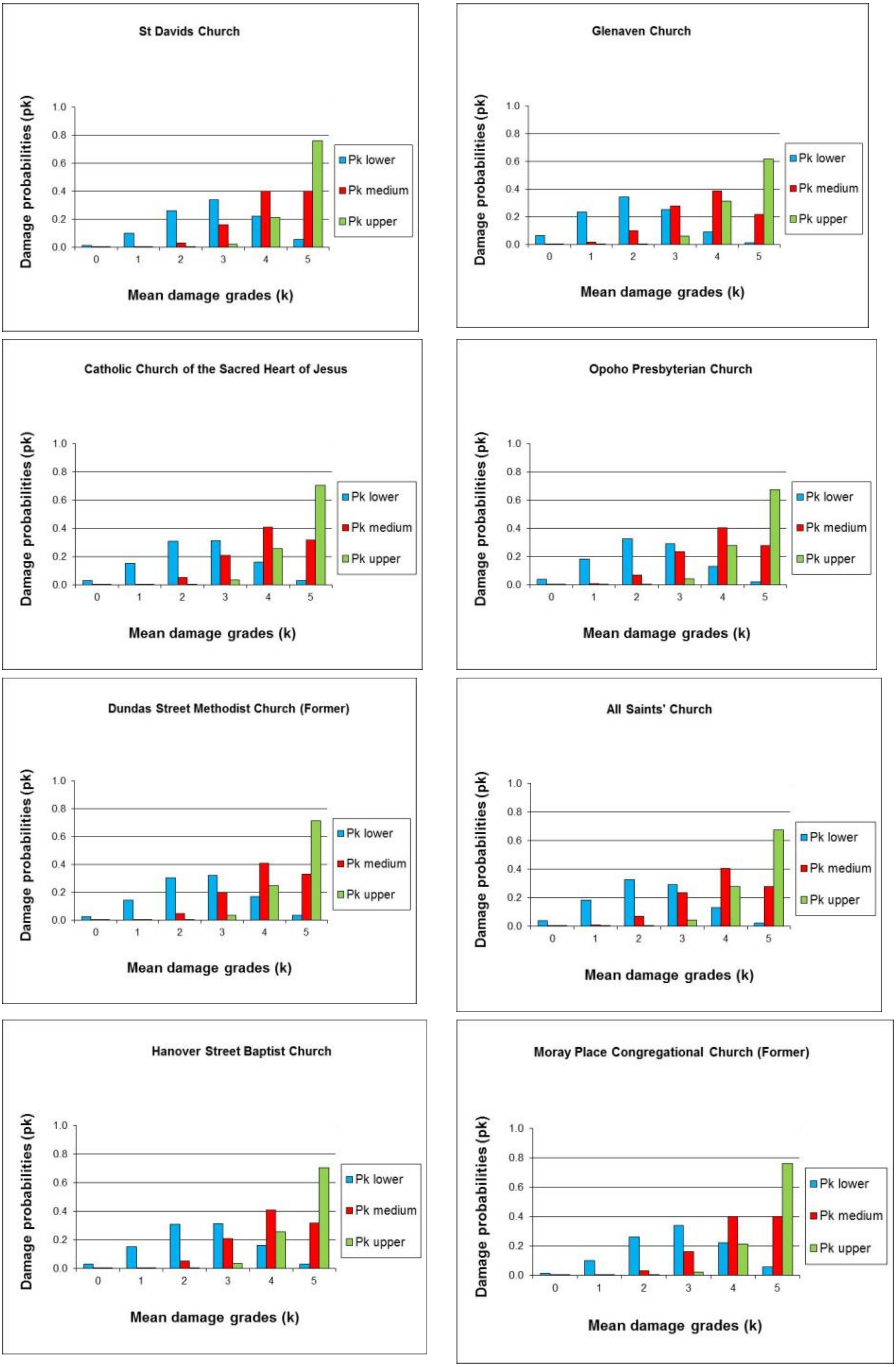


Figure A6.15 Histograms of damage probabilities: Dunedin brick churches.

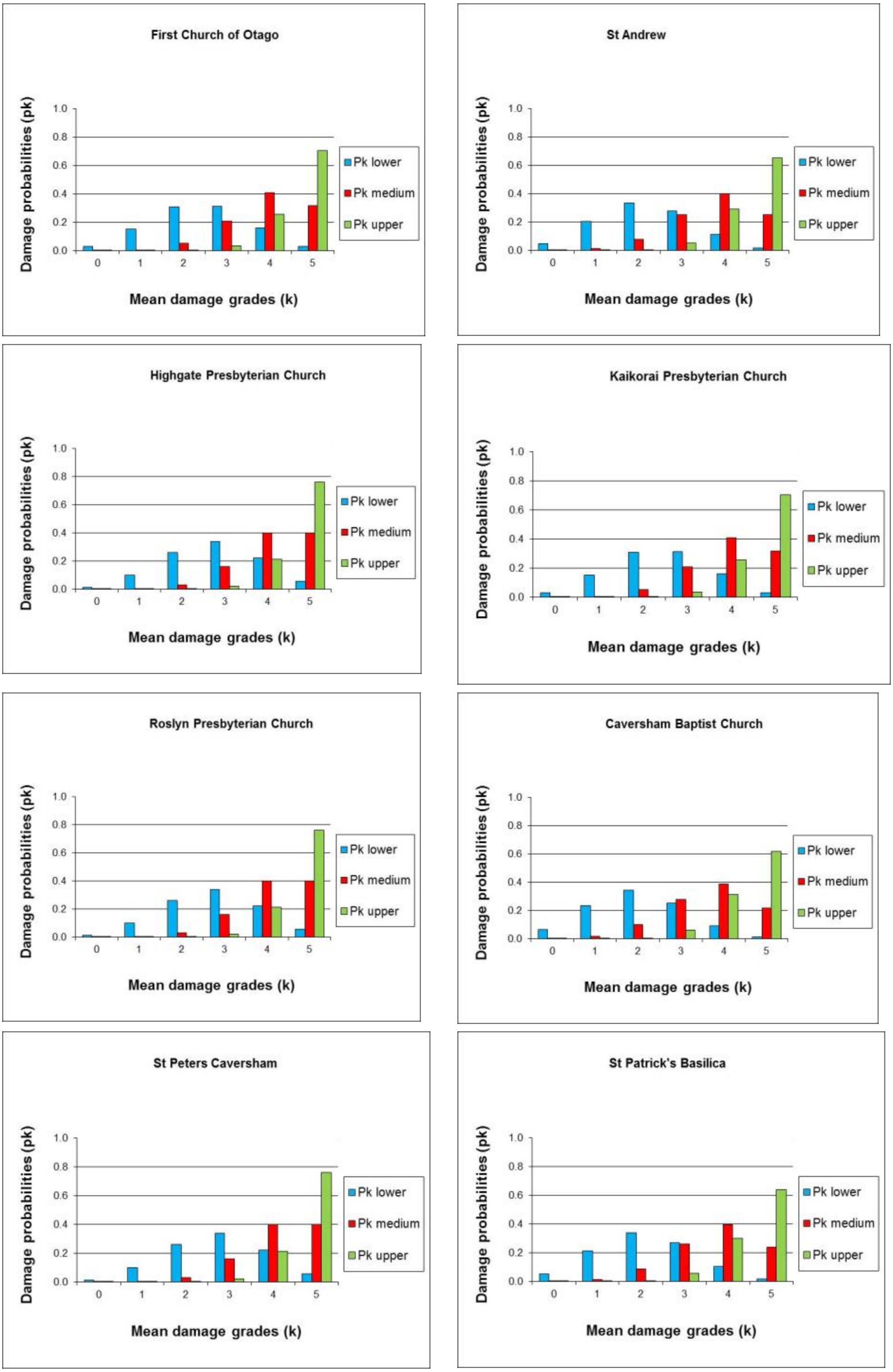


Figure A6.16 Histograms of damage probabilities: Dunedin brick churches (cont.).

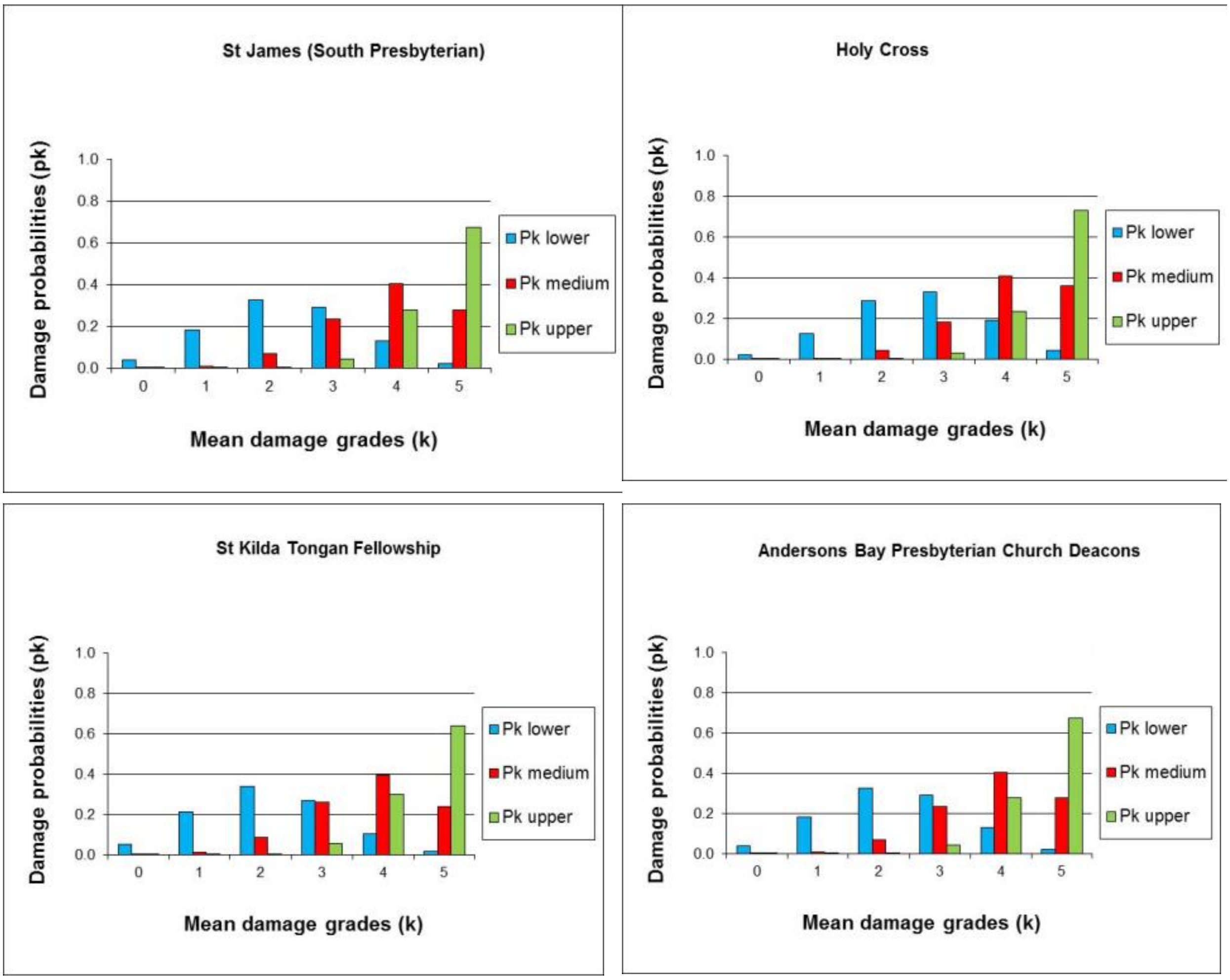


Figure A6.17 Histograms of damage probabilities: Dunedin brick churches (cont.2).

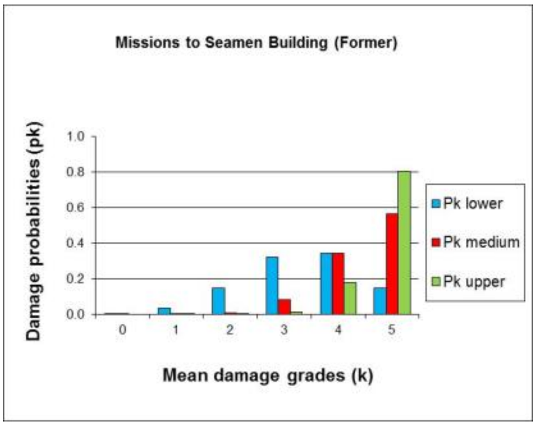


Figure A6.18 Histograms of damage probabilities: Wellington stone churches.

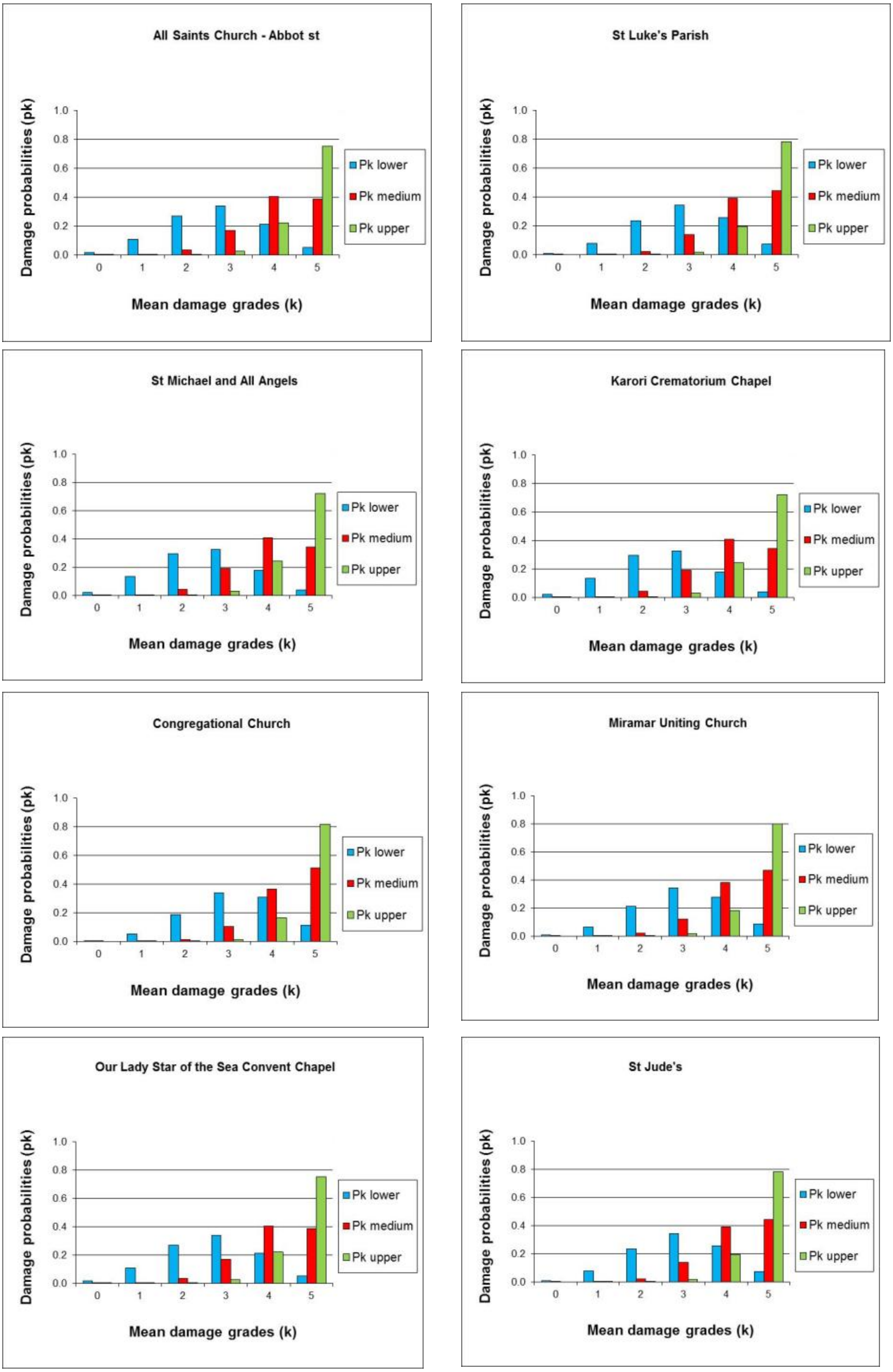


Figure A6.19 Histograms of damage probabilities: Wellington brick churches.

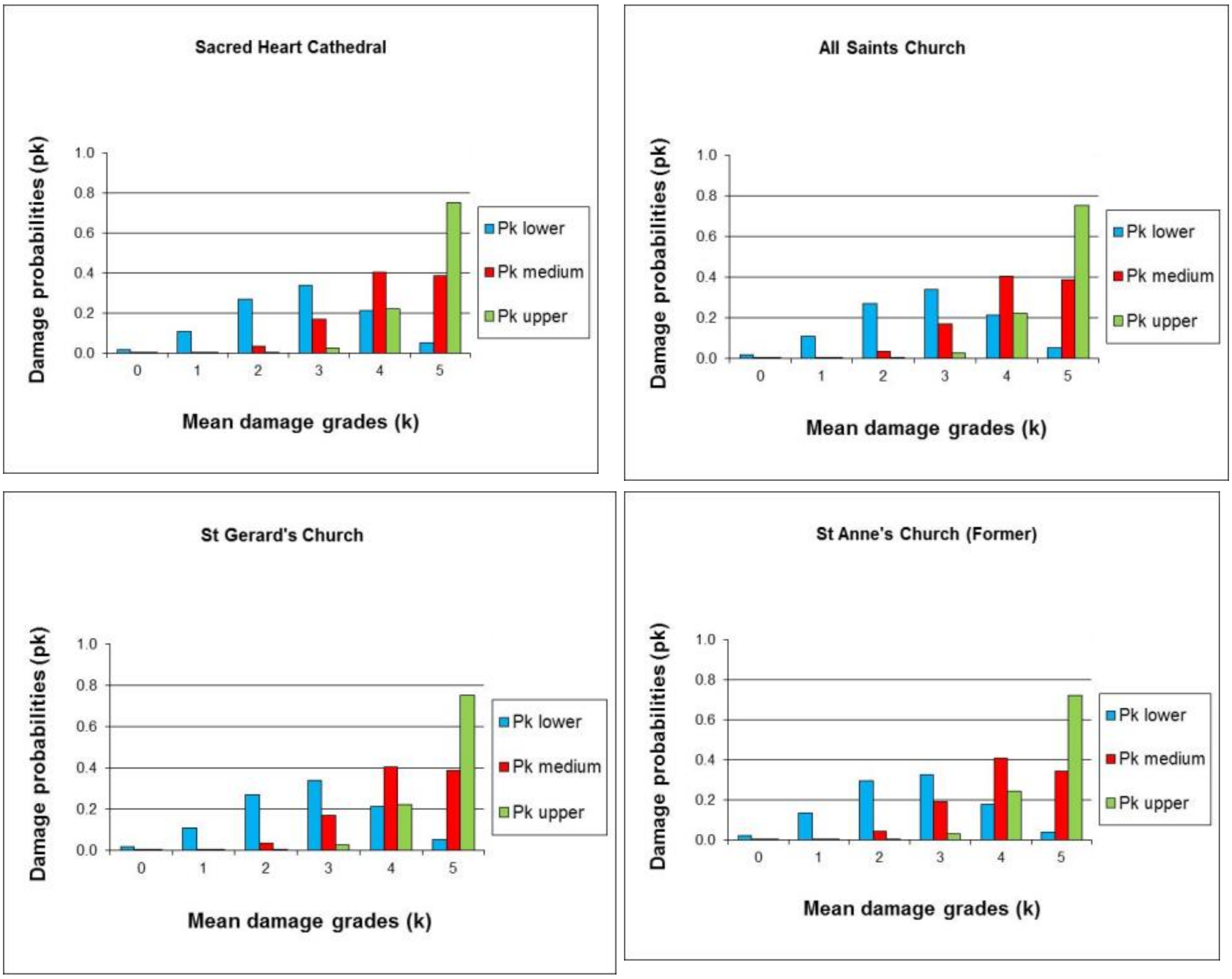


Figure A6.20 Histograms of damage probabilities: Wellington brick churches (cont.).

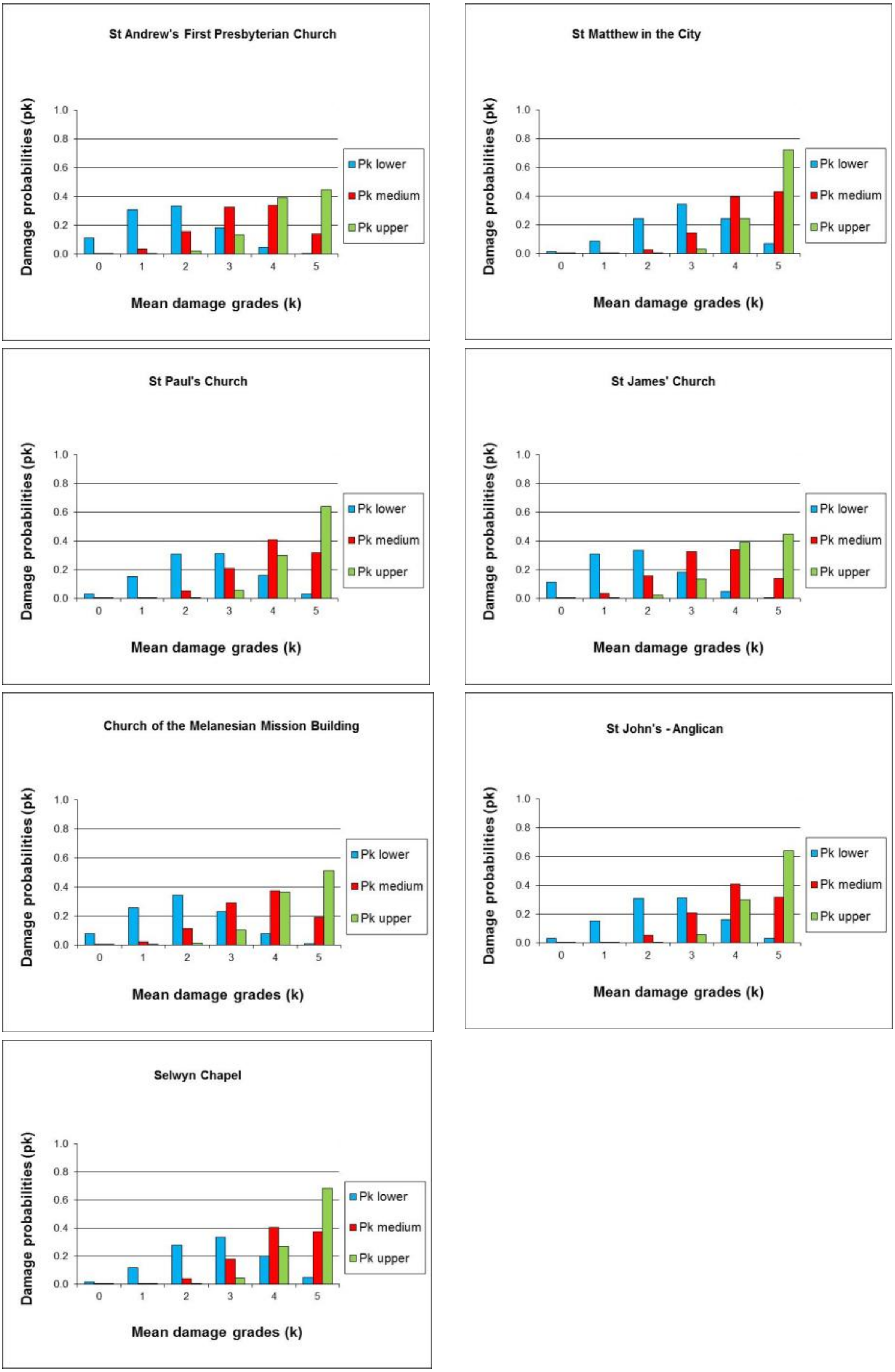


Figure A6.21 Histograms of damage probabilities: Auckland stone churches.

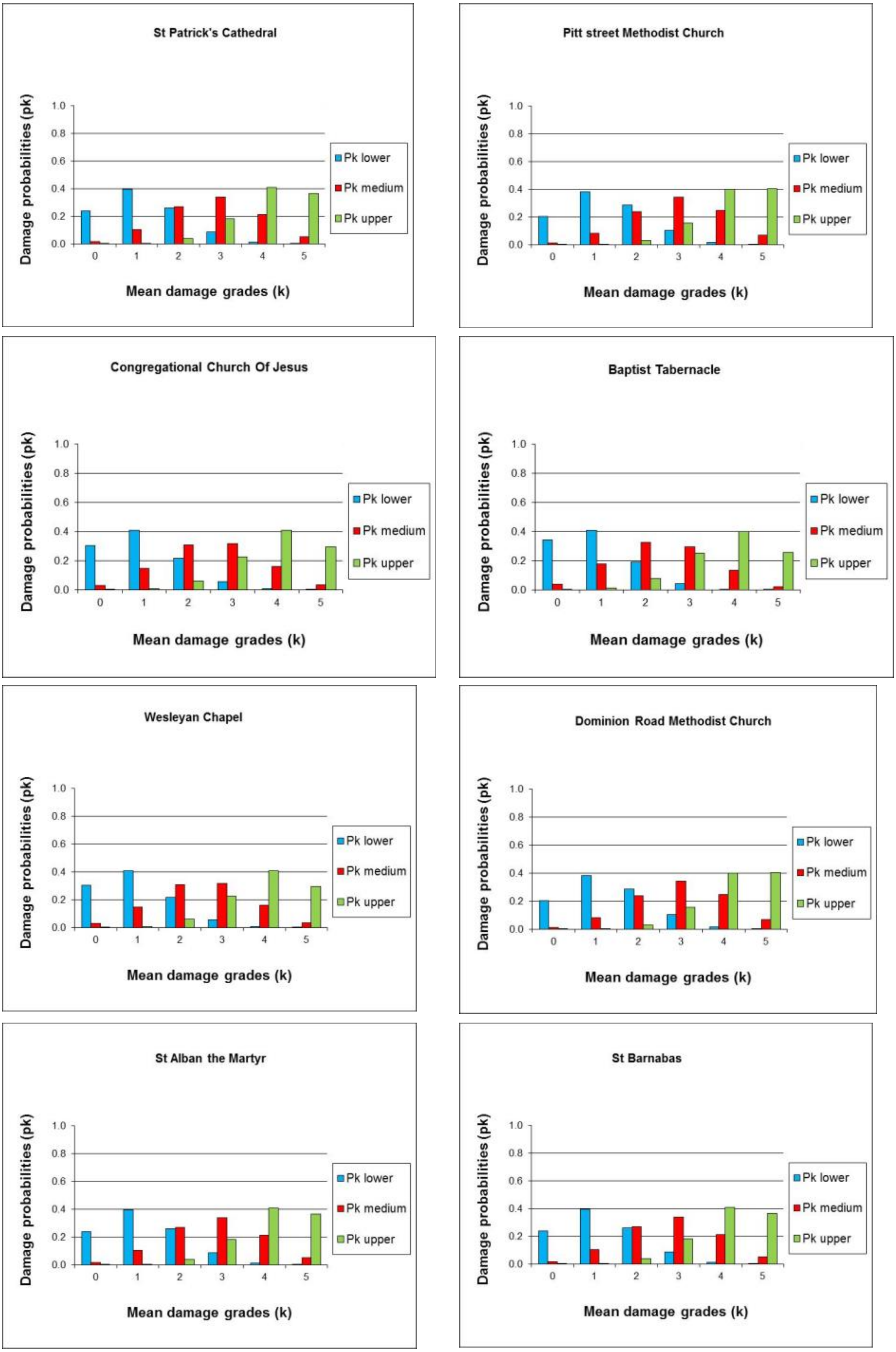


Figure A6.22 Histograms of damage probabilities: Auckland brick churches.

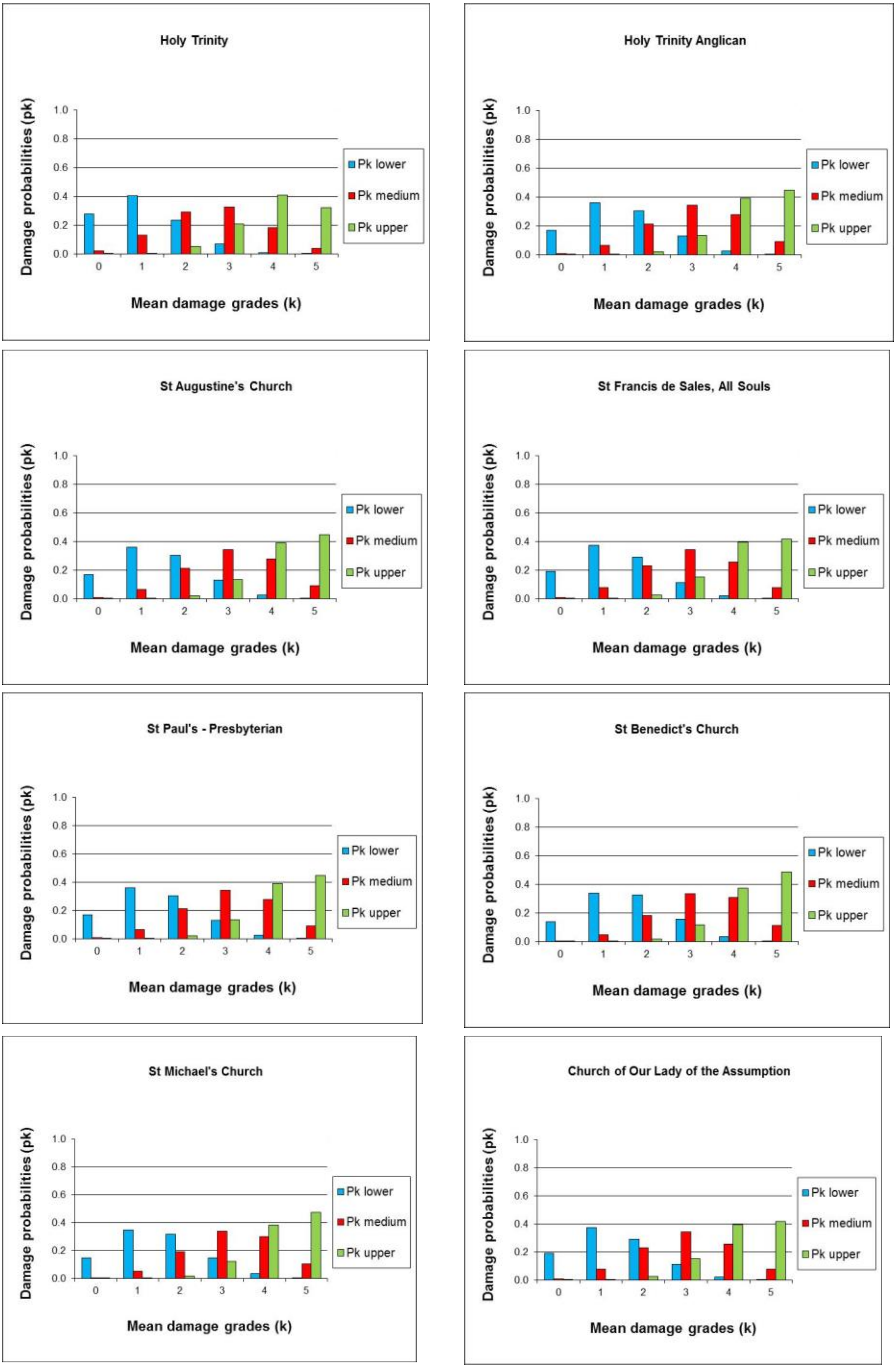


Figure A6.23 Histograms of damage probabilities: Auckland brick churches (cont.).

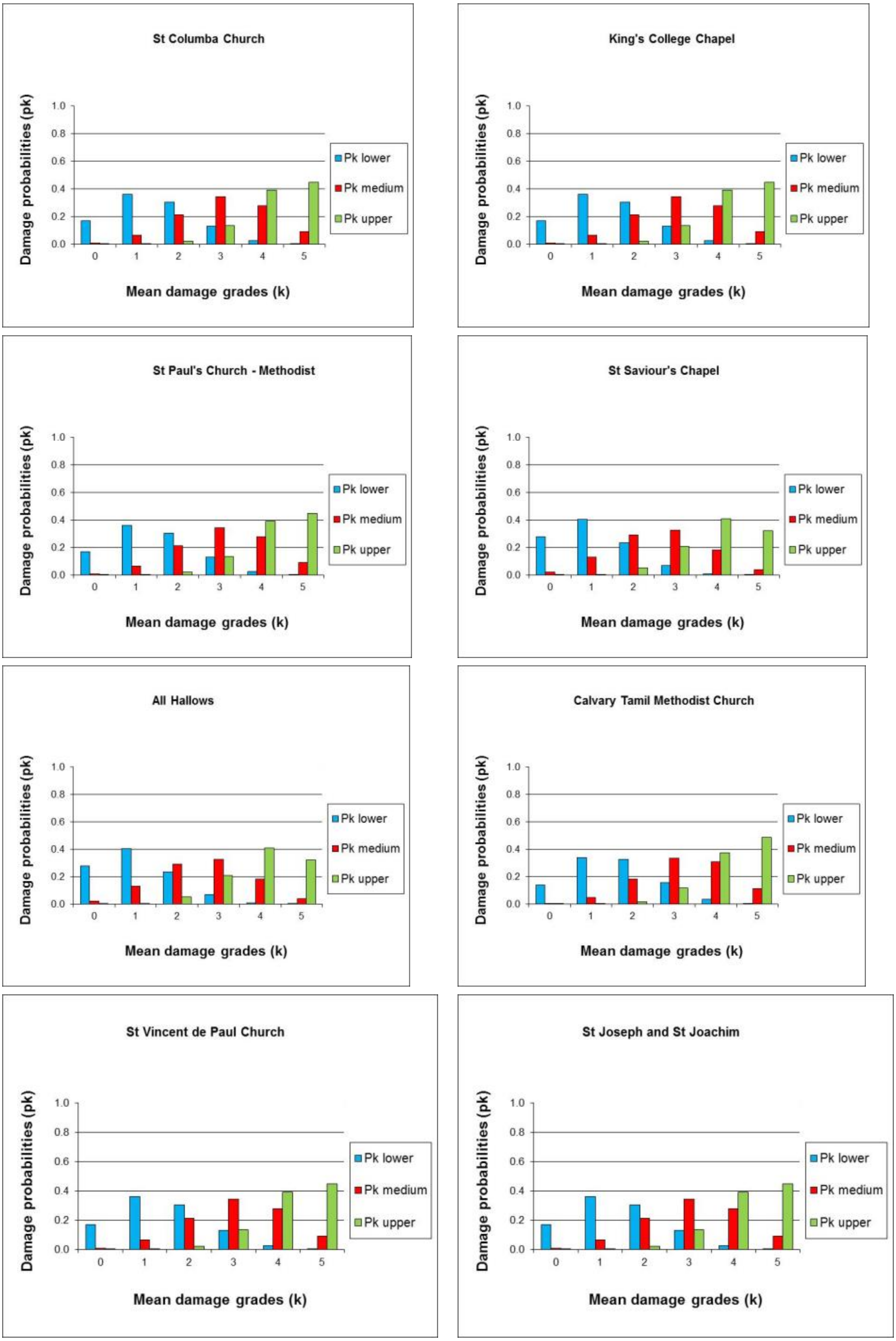


Figure A6.24 Histograms of damage probabilities: Auckland brick churches (cont.2).

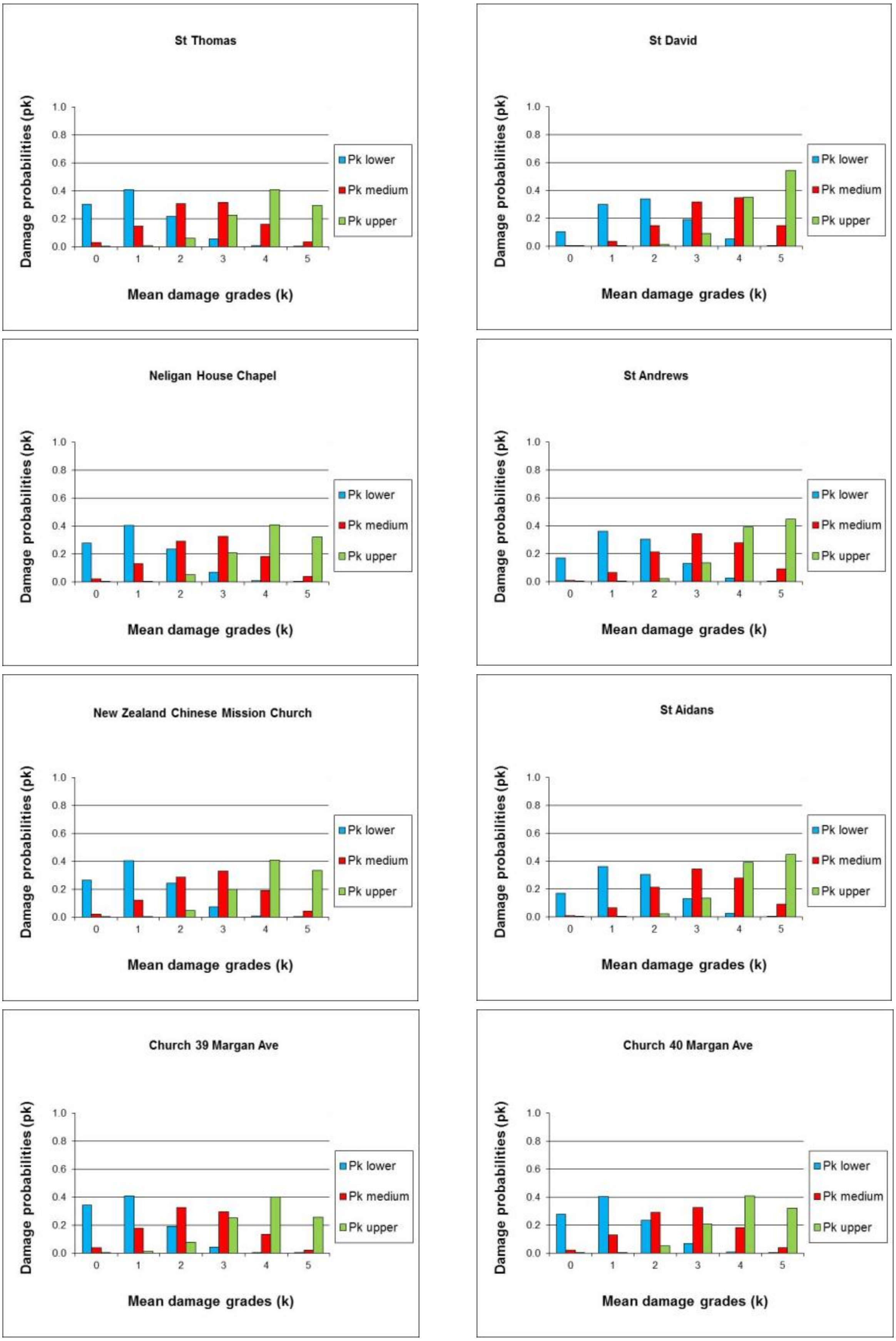
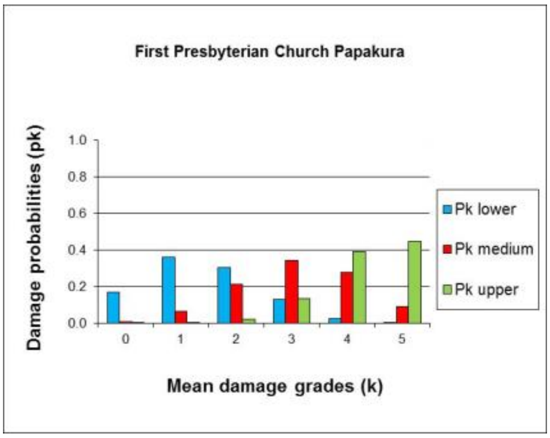


Figure A6.25 Histograms of damage probabilities: Auckland brick churches (cont.3).



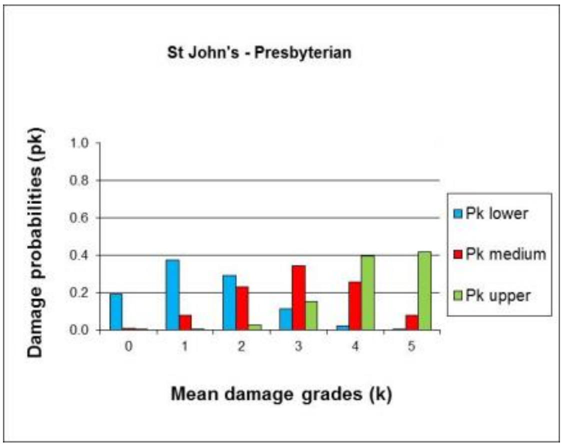


Figure A6.26 Histograms of damage probabilities: Auckland brick churches (cont.4).

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