SECED 2015 Conference: Earthquake Risk and Engineering towards a Resilient World
9-10 July 2015, Cambridge UK

DAMAGE AND VULNERABILITY ANALYSIS OF URM CHURCHES AFTER THE CANTERBURY EARTHQUAKE SEQUENCE 2010-2011

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Abstract: The Canterbury earthquake sequence, in 2010-2011, has highlighted once again the vulnerability of monumental structures, in particular churches, and the importance of reducing their risk from an economic, cultural and social point of view. Within this context, detailed analysis is reported of the earthquake-induced damage to a stock of 48 unreinforced masonry churches located in the Canterbury Region and the vulnerability analysis of a wider stock of 293 churches located all around New Zealand. New tools were developed for the assessment of New Zealand churches. The computation of a new damage grade is proposed, assessed as a proper combination of the damage level to each macroelement, as a step towards the definition of a New Zealand specific damage survey form. Several vulnerability indicators were selected, which are related to easily detectable structural details and geometric dimensions. The collection of such data for the larger set of churches (293) constitutes a useful basis for evaluating the potential impact of future seismic events.

Introduction

The 2010-2011 Canterbury earthquake sequence caused extreme 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; Lourenco et al., 2013). The consequences of the earthquake-induced damage to churches were severe; following the earthquakes 84% and 81% of the heritage unreinforced stone and clay brick masonry (URM) churches, respectively, were inaccessible to the local religion communities in the Canterbury region (Leite et al., 2013). Furthermore, after the Canterbury earthquakes significant issues have been raised on: the need to preserve New Zealand's cultural heritage; the high costs to strengthen churches as well as other heritage buildings; who should be responsible for covering the necessary costs; and which heritage buildings should have priority.

The issues described above emphasised the impelling need to define, for New Zealand (NZ), a systematic method to assess the seismic vulnerabilities of churches, applicable nationwide. The method should support, on the one hand, the detection of the structural and construction weakness of each church, towards the identification of more appropriate retrofitting techniques. On the other hand, the method should allow for the assessment of the level of

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damage expected to different churches in the event of an earthquake event, aiming to prioritise interventions and assess the benefit that a retrofitting campaign could bring.
To provide a prompt and effective answer to the aforementioned needs a specific research project “Vulnerability analysis of unreinforced masonry churches” was launched and funded by the New Zealand Earthquake Commission, EQC 2014 (EQC Project 14/660) within the EQC Biennial Contestable Grants Programme 2014. The on-going project is conceived as a multi-disciplinary, multi-agency and international effort, involving among others: 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.
Such a great collaboration and effort allowed parallel activities to proceed, resulting in timely and significant outputs. This paper presents some preliminary results, including detailed analysis of the seismic damage to a stock of 48 URM churches located in the Canterbury Region and the seismic vulnerability analysis of a wider stock of 309 URM churches located all around New Zealand. At the end, some preliminary conclusions are drawn.

Typological classification of New Zealand churches
Earthquake damage that has 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, 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). After the 1997 Umbria Marche earthquake one damage survey form was developed, which is made by 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 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 are rarely present in New Zealand. In fact New Zealand churches show typological and dimensional data different from Italian churches, 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 1), has been developed in order to group the structures that have a 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.

The histogram in Figure 1 shows the frequency of the typological classes for the Christchurch stock (48 URM churches), whereas at the end of the paper the statistics are extended to the entire stock of New Zealand URM churches. It is worth noticing 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 A class, but in the presence of the transept. The combined percentage of A and At types covers 80% of the analysed stock. 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 (Figure 2). 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 2.

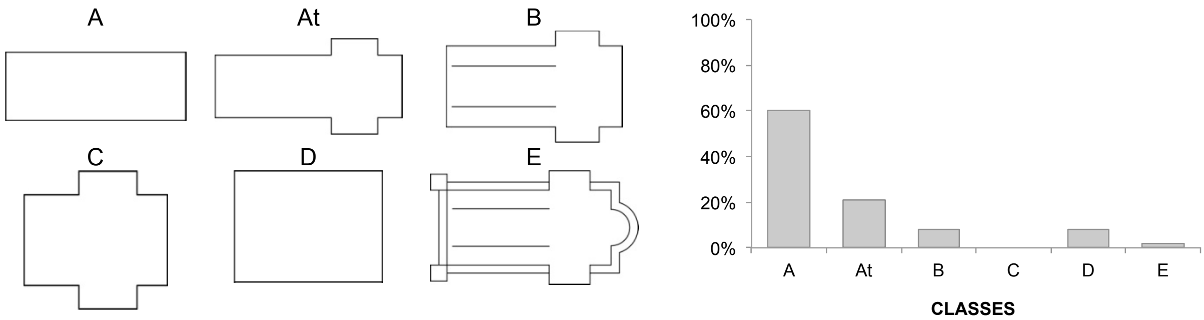


Figure 1. Classification of URM churches in New Zealand: a) recurring types; and b) their frequency within the stock of the 48 churches analyzed as part of the project.

Nc	CENTRAL NAVE
Nl_{LEFT}	LEFT LATERAL NAVES
Nl_{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

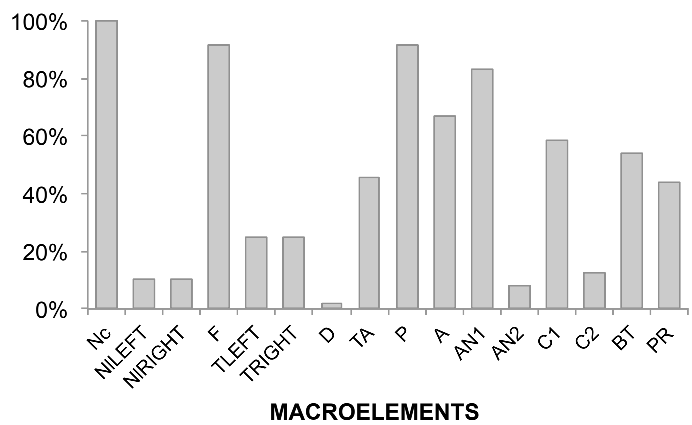


Figure 2. Frequency of the macroelements on the stock of 48 URM churches from Christchurch

Damage analysis of churches hit by the Canterbury earthquake sequence 2010-2011

Post-earthquake damage assessment represents a fundamental step to analyze 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) starting from the ISF, 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) by a new method based on the macroelement approach, according to the following three steps: 1) subdivision of the church into macroelements (considering those listed in Figure 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.

In particular the possible collapse mechanisms of the new method are listed in Table 1. For each macroelement, a level of damage D_k according to the EMS98 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. Afterwards, through the weighted arithmetic average of damage grades in macroelements, the global damage index of the church can be estimated. 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 1. List of the possible collapse mechanisms.

	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 kinematisms
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

Figure 3 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.

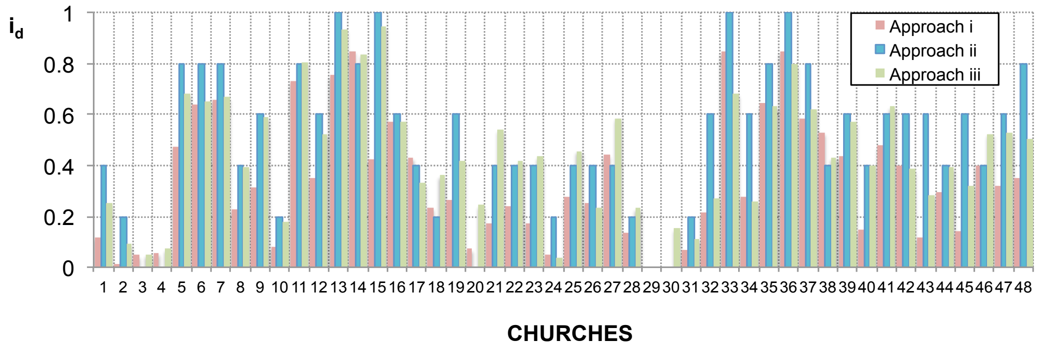


Figure 3. Comparison between the damage indices obtained from the different approaches

Errore. L'origine riferimento non è stata trovata. summarizes the damage index of each church of the sample obtained from approach (iii). In particular, **Errore. L'origine**

riferimento non è stata trovata. illustrates the average damage index from the latter 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 **Errore. L'origine riferimento non è stata trovata.**a 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 **Errore. L'origine riferimento non è stata trovata.**b).

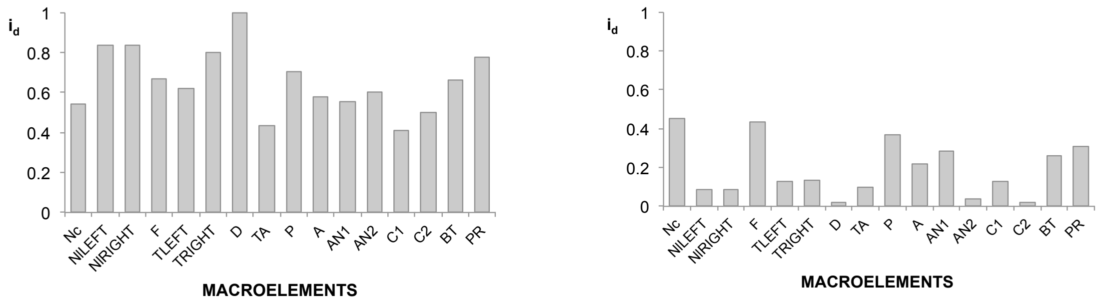


Figure 4. Frequency of the damage index not weighted (a) and weighted (b) on the sample

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 damage data the Damage Probability Matrix (DPM) for churches was produced, being a matrix in which for each macroseismic intensity the probability histogram of 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 5 shows PGA and macroseismic intensity values 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.

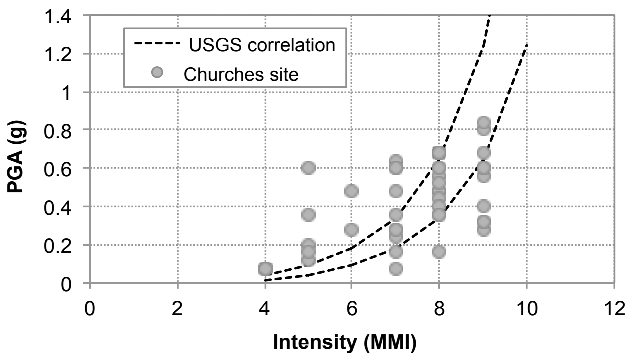


Figure 5. Correlations between Intensity and PGA.

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 6), by transformation of the beta distribution into discrete terms.

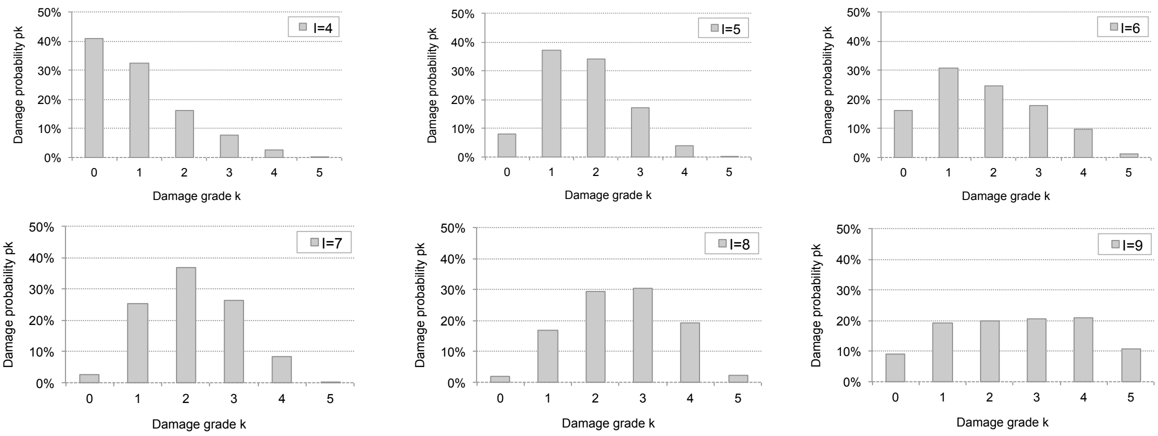


Figure 6. Beta discrete distribution for I from 4 to 9 MMI

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 to damage. These curves were compared with curves calibrated for Italy, defined by the following expression and illustrated in Figure 7, adopting different values of Vulnerability Index and Ductility Index Q equal to 3. The expression is proposed in Lagomarsino (2006) for churches and is calibrated on observed damage in Podestà and Lagomarsino (2004b):

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

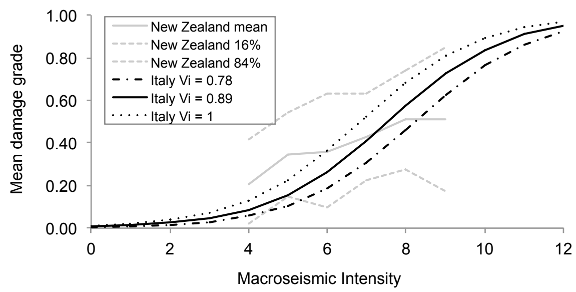


Figure 7. Vulnerability curves for the New Zealand and Italian churches

Specific vulnerability factors of New Zealand churches

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 smallest 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 (more than 300), a qualitative tool was chosen, leading to the decision to use the Level 1 Macroseismic Vulnerability Methodology (Lagomarsino 2006). This procedure is based on an accurate on-site inspection of a number of parameters able to qualify 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 characterize

more specifically the New Zealand churches (specialized typologies, masonry types, roof characteristics, more detailed description of damage).
The following list summarizes 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 8), 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 - Figure 9).
- 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, Figure 10), 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.

Given the aim of EQC project, it was necessary to apply the survey form to a large set of New Zealand churches. No list of churches was available at the beginning of the research. Consequently an inventory was compiled, listing location, age, general information and architectural characteristics of the building. Such general information were collected starting from the records available within the New Zealand Heritage List (HNZ 2014, formerly the Register), online inventories of the dioceses, archive researches, architectural books and preliminary observations in Google Street View. This literature survey has delivered information about the architectural (construction phases, designer, commissioner, ...), structural (site of origin of the materials, …), and seismic history of the buildings.


(a) St Mary Star of the Sea, Makikihi (class A)


(b) Knox Church, Waimate (class At)


(c) Wesley Church, Dunedin (class D)


(d) St. Andrew's, Maheno (class A)


(e) St Patrick's, Oamaru (class E)


(f) Baptist Tabernacle, Auckland (class D)

Figure 8. Examples of New Zealand plan configuration, according to Figure 1

(a) Church of St Thomas, Auckland

(b) Wesley Broadway Methodist Church, Palmerston North

Figure 9. Geometric irregularities in plan and elevation and position with respect to other buildings

(a) St Augustine, Auckland

(b) St Peter's, Queenstown

Figure 10. Common typology of thrusting roof in New Zealand churches

The inventory data collection has led to a preliminary determination of approximately 350 URM churches nationwide, 45 of those being in the city of Christchurch. A large number of these churches are included in HNZ (2014), emphasizing the significant historical and cultural value of the ecclesiastic heritage.

The month-long field trip performed in 2014 was about 10,000 km long (Figure 11). During the field trip some of the churches included in the first version of the database were excluded after discovering that they had been demolished, or that they were not load-bearing masonry structures. Vice versa, some others, discovered on the road, were included in an updated version of the list. During the on-site surveys the fields of the form were filled. In addition, some basic geometric characteristics (e.g., thickness and height of walls, church gross area, etc.), were collected. Most of these parameters have been obtainable during a quick inspection, sometimes just from the outside of collapse-prone buildings.

The histograms in Figure 12 show the frequency of the typological classes on: (a) the entire sample of churches; and (b) most recurring macro-elements. A correspondence with the analogous graphs referring to the Christchurch sample is clearly evident (Figure 1 and Figure 2). It was once again confirmed (Figure 12a) that class A is the most widespread typology for New Zealand churches (60% of the whole sample), with the percentage rising to 80% when considering the presence of transept (class At). This result corroborates the already highlighted simplicity of the architecture of New Zealand churches. Consequently, the most recurring macro-elements, listed in Figure 12b, are the central nave and the façade, in almost 100% of the churches. A considerable number of macro-elements are present in about 50% of the surveyed churches, mostly related to: the presbytery, the atrium, the bell tower and the projections.

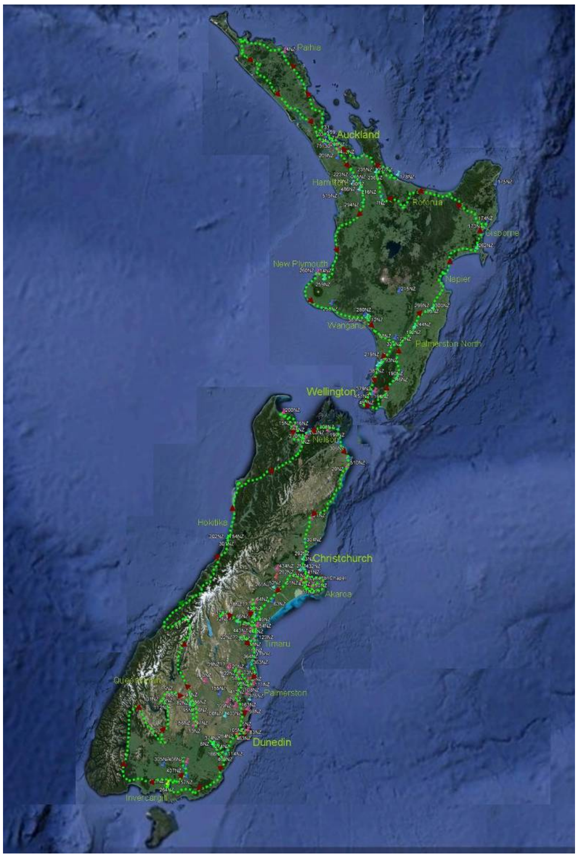
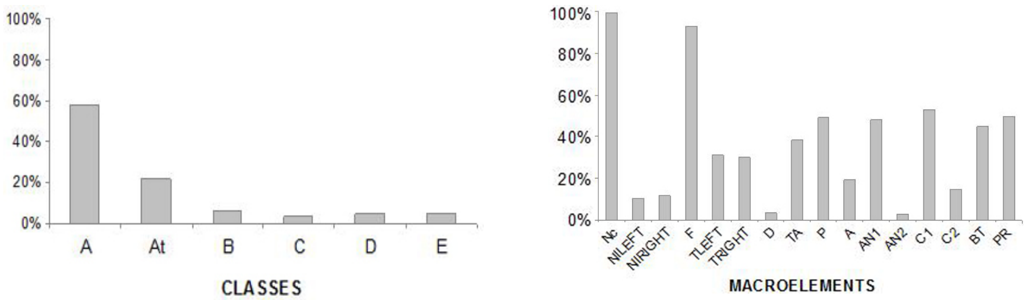


Figure 11. Field trip route



(a) (b)

Figure 12. Classification of the recurring types of URM churches in New Zealand (a) and frequency of the macro-elements on the entire sample of churches.

Concluding remarks

The identification of the macro-elements that mostly characterize the NZ URM church typology represents a first critical step towards the development of a specific vulnerability model to be applied countrywide to support mitigation policies. To advance this aim, the support provided by the interpretation of the damage that occurred in churches hit by the 2010-2011 Canterbury earthquake constitutes another essential tool. In the reported study different methods to assess the damage index, either already available in literature or originally developed starting from the analysis of such stock of churches, are discussed and compared. Finally, the collection of vulnerability data for a larger set of churches provides an overview of structural features of this class in New Zealand and constitutes a useful basis for evaluating the potential impact of future seismic events.

REFERENCES

Anagnostopoulou M, Bruneau M, Gavin HP (2010) Performance of Churches During the Darfield Earthquake of September 4, 2010, *Bulletin of the New Zealand Society for Earthquake Engineering*, 43 (4), 374-381.

Doglioni F, Moretti A, Petrini V, Angeletti P (1994) *Le Chiese e il Terremoti: Dalla Vulnerabilità Constatata nel Terremoto del Friuli al Miglioramento Antisismico nel Restauro, Verso una Politica di Prevenzione*, Edizioni Lint, Trieste, Italy

G.U. no.55, 7/03/2006. Approval of forms for the seismic damage assessment of cultural heritage buildings, Decree of the Prime Minister, Rome 23/02/2006 (in Italian)

Goded T, Cousins WJ, Fenaughty KF (2014) *Analysis of the Severe-Damage Online Felt Reports for the Canterbury (New Zealand) 2011 Aftershocks on 22 February Mw 6.2, 13 June Mw 6.0, and 23 December Mw 6.0. Seismological Research Letters*, 85(3), doi: 10.1785/0220130198

Grünthal G (editor) (1998) *European Macroseismic Scale 1998 (EMS-98). Cahiers du Centre Européen de Géodynamique et de Séismologie 15,* Luxembourg, 99 pp

HNZ - Heritage New Zealand (2014) "The List - Rārangi Kōrero". Accessed during December 2013 and January 2014. Available from http://www.heritage.org.nz/the-list

Ingham JM, Lourenco PB, Leite J, Castelino S, Colaco E (2012) *Using simplified indices to forecast the seismic vulnerability of New Zealand unreinforced masonry churches*, Proceedings of the Australian Earthquake Engineering Society 2012 Conference, Gold Coast, Australia, 13 pp

Lagomarsino S., Giovinazzi S., Podestà S., Resemini S. (2003). RISK-UE. An advanced approach to earthquake risk scenarios with applications to different European towns. WP5: Vulnerability assessment of historical and monumental buildings. DISEG, University of Genoa, Italy, 90 ps.

Lagomarsino S, Podestà S (2004a) Seismic Vulnerability of Ancient Churches: I. Damage Assessment and Emergency Planning, *Earthquake Spectra,* 20(2): 377–394

Lagomarsino S, Podestà S (2004b) Seismic Vulnerability of Ancient Churches: II. Statistical Analysis of Surveyed Data and Methods for Risk Analysis, *Earthquake Spectra,* 20(2): 395–412

Lagomarsino S., Podestà S. (2004c). Damage and Vulnerability Assessment of Churches after the 2002 Molise, Italy, Earthquake. *Earthquake Spectra*, 20(S1), pages S271–S283

Lagomarsino S, Podestà S, Cifani G, Lemme A (2004) *The 31st October 2002 Earthquake in Molise (Italy): a New Methodology for the Damage and Seismic Vulnerability Survey of Churches,* Proc. of 13th World Conference on Earthquake Engineering, Vancouver, Canada, August 1-6, Paper 1366

Lagomarsino S (2006). On the vulnerability assessment of monumental buildings. *Bulletin of Earthquake Engineering*, 4: 445-463.

Lagomasino S. (2012). Damage assessment of churches after L'Aquila earthquake (2009). *Bulletin of Earthquake Engineering*, 10: 73–92

Leite J, Lourenco PB and Ingham JM (2013) Statistical assessment of damage to churches affected by the 2010-2011 Canterbury (New Zealand) earthquake sequence, *Journal of Earthquake Engineering*, 17 73-97

Liberatore D., Martino D., D'Orsi L. (2009*) Valutazione della vulnerabilità e stima del danno atteso di edifici ecclesiastici della Basilicata*. XIII Convegno dell'Associazione Nazionale Italiana di Ingegneria Sismica (ANIDIS) L'Ingegneria Sismica in Italia, Bologna, 28 Giugno – 2 Luglio 2009, ref. S14.19

Lourenco PB, Oliveira DV, Leite JC, Ingham JM, Modena C, da Porto F (2013) Simplified indexes for the seismic assessment of masonry buildings: international database and validation, *Engineering Failure Analysis*, http://dx.doi.org/10.1016/j.engfailanal.2013.02.014

Novelli VI, D'Ayala D, Makhloufi N, Benouar D, Zekagh A (2015) A procedure for the identification of the seismic vulnerability at territorial scale. Application to the Casbah of Algiers, *Bulletin of Earthquake Engineering*, 13:177-202

Sorrentino L, Liberatore L, Decanini LD and Liberatore D (2014) The performance of churches in the 2012 Emilia earthquakes, *Bulletin of Earthquake Engineering*, 12: 2299–2331

USGS (2011) US Geological Survey ShakeMap: South Island of New Zealand February 22nd, 2011, http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/b0001igm/

Whitman RV, Reed JW, Hong ST (1973) *Earthquake Damage Probability Matrices*, Proceeding of the 5th European Conference on Earthquake Engineering, Rome, pp: 2531.