Using simplified indices to forecast the seismic vulnerability of New Zealand unreinforced masonry churches

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Abstract

Unreinforced masonry churches are particularly vulnerable to earthquakes because they are often deteriorated and damaged, they were built with comparatively low strength materials, they are heavy, and the connections between the various structural components are often insufficient to resist loads generated during earthquakes. A simplified method for seismic assessment of large span masonry churches is presented and data from 44 churches located in Italy, Portugal and Spain are used to provide lower bound limits for different simplified geometrical indexes. Subsequently, the proposed thresholds are validated with data from the 2010-2011 Canterbury earthquakes, including 48 clay brick and stone unreinforced masonry churches. Finally, data collected for 40 unreinforced masonry churches in Wellington and Dunedin are used to identify churches in these cities requiring priority detailed seismic evaluation.

Keywords: seismic, assessment, churches, index, simplified

INTRODUCTION

It is widely recognized that unreinforced masonry (URM) is one of the construction materials most frequently used in the built heritage, and that large monumental URM churches are both important heritage buildings within communities and frequently perform poorly in severe earthquakes. To address the seismic hazard posed by such buildings, simple and rapid screening tools are required so that they may be applied at territorial level to identify the most hazardous buildings meriting seismic intervention. Churches are of particular interest because of their intrinsic structural vulnerability due to open plan, large wall height to width ratio, the use of thrusting horizontal structural elements from vaulted ceilings and timber roofs, and because there is frequently ample geometric survey drawings and documentation available for this building class. Moreover, in earthquake prone countries, churches and other large monumental structures have often been previously subjected to earthquakes, and sometimes survived these events, meaning that they are historical testimonies and represent full-scale earthquake test data.

The features discussed above encourage the hypothesis that the geometries of churches, and most particularly ancient European churches, have been adjusted in response to local seismicity and observed prior failures. In response to this hypothesis, a simplified method of analysis for large span heritage buildings that was introduced by Lourenco and Roque (2006) is applied here to a database of 44 churches in Italy, Portugal and Spain, to provide lower bound formulas for different simplified geometrical indexes. Data collected following the 2010-2011 Canterbury earthquakes allowed validation of the proposed formulations with a real seismic input and observed damage. The technique was then blindly applied to all known URM churches in Wellington and Dunedin in an attempt to identify the most seismically vulnerable churches in these two cities. Although the technique has been developed to consider both in-plane and out-of-plane response, for brevity only in-plane response is reported here.

GEOMETRIC INDICES TO FORECAST EARTHQUAKE VULNERABILITY

The index method discussed here is intended to be a simple, rapid and low cost procedure, based on a simplified geometric approach for immediate screening of a large number of potentially earthquake-prone buildings. The objectives of the study are to compare simple geometrical data, taking into account local seismic hazard using Peak Ground Acceleration (PGA) as the governing parameter, and to evaluate the possibility of adopting simple indices (as numerical indicators deduced from observations and used as a forecast of performance) as a rapid screening technique to define priority buildings meriting further inspection with respect to seismic vulnerability. Subject to the adequate availability of surveyed building geometric information, the technique may be used without actually visiting the buildings and it is recognized that the technique therefore encompasses a low level of accuracy.

The use of simplified methods of analysis usually requires that the structure is regular and symmetric, that floors act as rigid diaphragms and that the dominant collapse mode is in-plane shear failure of the walls (Meli, 1998). In general, ancient URM structures do not satisfy these last two conditions, meaning that simplified methods should not be understood as a quantitative safety assessment but merely as a simple indicator of possible seismic performance of a building. The following simplified methods of analysis and corresponding indices are considered as in-plane indices (Index 1, In-plane area ratio; Index 2, Area to weight ratio, Index 3, Base shear ratio).

The simplest index to assess the safety of ancient URM buildings is the ratio between the total cross-sectional area of the earthquake resistant walls in each main direction (transversal x and longitudinal y, with respect to the church nave) and the total plan area of the building. According to Eurocode 8 (2004), walls should only be considered as earthquake resistant if their thickness is larger than 0.3 m, and the ratio between their height and thickness is smaller than 9. The first index $\gamma_{1,i}$ reads:

$$\gamma_{1,i} = A_{wi}/S \quad [-]$$ Equation 1

where A_{wi} is the sum of the cross-sectional areas of the earthquake resistant walls oriented in direction "i" and S is the total plan area of the building. The non-dimensional index $\gamma_{1,i}$ is the simplest one, being associated with the base shear strength. Special attention is required when using this index as it ignores the slenderness ratio of the walls and the mass of the building. Eurocode 8 recommends values up to 5-6% for regular structures with rigid floor diaphragms. In cases of high seismicity, a minimum value of 10% is recommended for historical masonry buildings (Meli, 1998). For simplicity, high seismicity cases can be assumed as those where the design ground acceleration for rock-like soils is larger than 0.20g.

Index 2 provides the ratio between the area of the earthquake resistant walls in each main direction (again, transversal x and longitudinal y) and the total weight of the building:

$$\gamma_{2,i} = A_{wi}/G \quad [L^2F^{-1}]$$ Equation 2

where A_{wi} is as defined for Equation 1 and G is the quasi-permanent vertical action. This index is associated with the horizontal cross-section of the building, per unit of weight. Therefore, the height (i.e. the mass) of the building is taken into account, but a major disadvantage is that the index is not non-dimensional, meaning that it must be analyzed for fixed units. In cases of high seismicity, a minimum value of 1.2 m^2/MN is recommended for historical masonry buildings (Meli, 1998), but on the basis of a more recent work (Lourenco and Roque, 2006), a minimum value of 2.5 m^2/MN is adopted for high seismicity zones.

Finally, the base shear ratio provides an index value with respect to the shear safety of the building. The total base shear for seismic loading ($V_{Sd,base} = F_E$) can be estimated from an analysis with horizontal static loading equivalent to the seismic action ($F_E = \beta G$), where β is an equivalent seismic static coefficient related to the design ground acceleration. The shear strength of the structure ($V_{Rd,base} = F_{Rd}$) can be estimated from the contribution of all earthquake resistant walls $F_{Rd,i} = \sum A_{wi} f_{vk}$, where, according to Eurocode 6 (2006), $f_{vk} = f_{vk0} + 0.4\sigma_d$. Here, f_{vk0} is the cohesion, which can be assumed equal to a low value or zero in the absence of more information, σ_d is the design value of the normal stress and 0.4 represents the tangent of a constant friction angle, ϕ, equal to 22º. The new index γ_3 reads:

$$\gamma_{3,i} = F_{Rd,i}/F_E \quad [-]$$ Equation 3

If zero cohesion is assumed ($f_{vk0} = 0$), then $\gamma_{3,i}$ is independent from the building height, reading:

$$\gamma_{3,i} = V_{Rd,i}/V_{sd} = A_{wi}/A_w \times \tan\phi/\beta$$ Equation 4

but for a non-zero cohesion, which is most relevant for low height buildings, $\gamma_{3,i}$ reads:

$$\gamma_{3,i} = {}^{V_{Rd,i}}/_{V_{sd}} = {}^{A_{wi}}/_{A_w} \times [\tan\phi + f_{vk0}/(\gamma \times h)]/\beta \qquad \text{Equation 5}$$

where A_{wi} is the area of earthquake resistant walls in direction "i", A_w is the total area of earthquake resistant walls, h is the (average) height of the building, γ is the volumetric masonry weight, ϕ is the friction angle of masonry walls and β is an equivalent static seismic coefficient. In this study it was assumed that the normal stress in the walls is only due to wall self-weight, i.e. $\sigma_d = \gamma \times h$, which is conservative and is a reasonable approximation for historical URM building, usually made of thick walls.

Equation 5 must be used with care as the contribution of the cohesion can be large. Here, a cohesion value of 0.05 N/mm^2 (50 kPa) is assumed. This non-dimensional index considers the seismicity of the zone, taken into account via the parameter β. The building is forecasted to be more earthquake safe with an increasing ratio. For this type of buildings and design action, a minimum value of $\gamma_{3,i}$ equal to one is deemed acceptable.

For indices 1 and 2, the seismicity is taken into account by considering that the threshold value given above is valid for a PGA/g value of 0.25 and assuming a linear variation with PGA/g, as illustrated in Figure 1. Conversely, Index 3 should be constant in different seismic zones, as the effect of seismicity is incorporated. This index format is close to the traditional safety approach adopted for structural design, with a threshold value equal to 1 (see Figure 1).

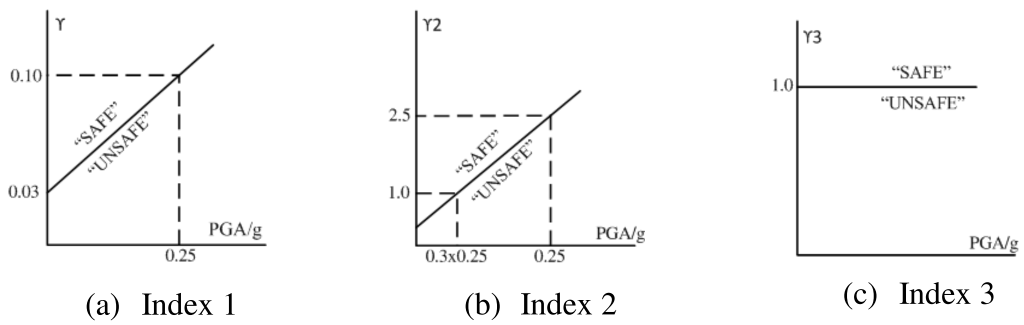
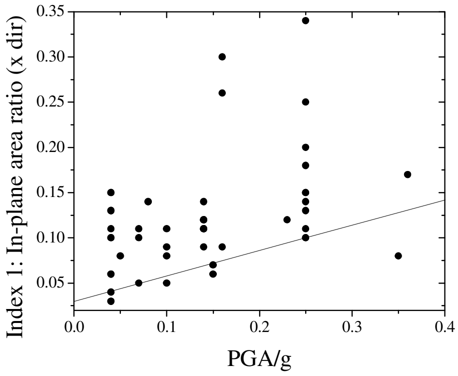


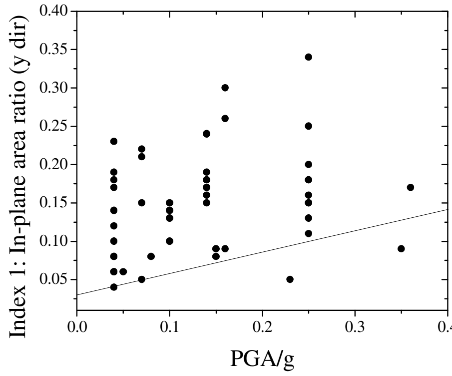
Figure 1. Assumed thresholds for indices 1, 2 and 3 as a function of PGA/g

USE OF INDICES FOR EUROPEAN CHURCHES

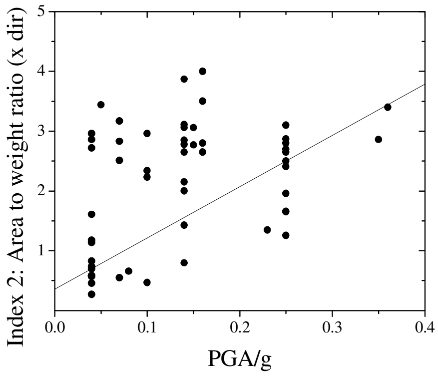
The simplified index method described above was applied to a sample of 44 Italian, Portuguese and Spanish URM churches (see Figure 2). These European churches were selected according to their seismic zonation and the availability of information, with the following objectives: (a) Validation of the hypothesis that ancient builders used empirical relations in design, potentially enabling an expeditious preliminary assessment of the seismic vulnerability of historical URM buildings; (b) Validation of the hypothesis of an empirical relation between the architectural-structural characteristics of historical URM buildings and seismicity; (c) Prioritizing further investigations and possible remedial measures for the selected sample; (d) Extrapolating, from the results of the sample, the seismic vulnerability of ancient unreinforced masonry buildings in the investigated countries.



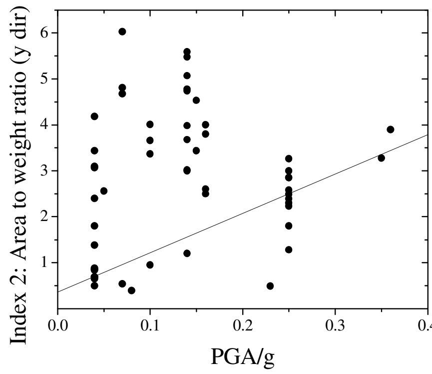
(a) Index 1, x direction



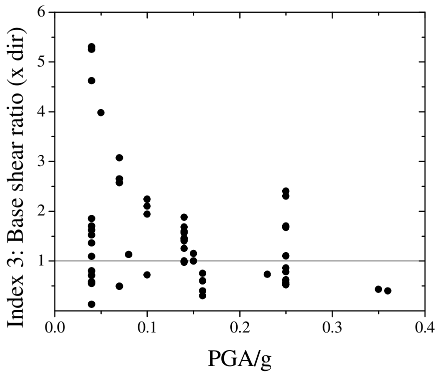
(b) Index 1, y direction



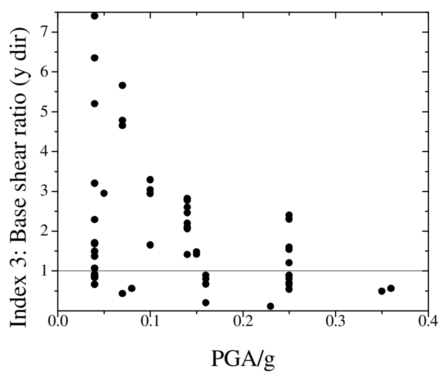
(c) Index 2, x direction



(d) Index 2, y direction



(e) Index 3, x direction



(f) Index 3, y direction

Figure 2. Relationship between in-plane indices and PGA/g for 44 European URM churches

From Figure 2 it is found that Index 1 average values are lower (less safe) in the transversal (x) direction of the church nave, which is expected due to church geometry, although Italian indices were found to be similar in both directions. Index 1 data do not exhibit a clear variation with seismicity, even if the Index value tends to grow roughly with increasing seismicity. It was found that 25% of the churches violated the proposed threshold in the x direction and that 9% violated the threshold in the y direction. This finding suggests that the cases that may merit further investigation are those churches demonstrating deficient earthquake resistance along the transversal direction of the church nave.

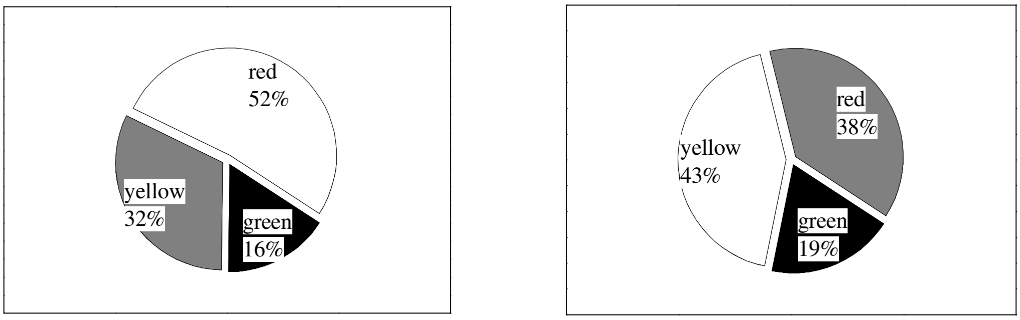
Index 2, although being inversely proportional to building height, presents a situation similar to Index 1. Again, the calculated values shown in Figure 2 do not exhibit a visible trend with respect to seismicity, although there is a tendency associated with an increase in Index 2 with increasing PGA. On average, Index 2 data present lower values in the x direction, again justified by typical church geometry. Consequently, this index is violated by 39% and 30% of the churches in x and y directions, respectively. This index is mainly violated by Spanish churches.

Index 3 data show an alarming decreasing variation with the PGA parameter. For moderate and high seismicity areas (PGA greater than 0.15g), Index 3 is violated by the majority of churches, in both directions. For low seismicity areas, Index 3 is also not entirely fulfilled. Individually, 41% and 32% of the churches in the x and y directions respectively violate the Index 3 threshold, which denotes a deficient earthquake resistance along both the transversal and longitudinal directions. This index is mainly violated by Italian churches.

In order to perform a preliminary screening and to prioritize deeper studies of historical URM churches in earthquake prone countries, a possible approach is to identify the buildings for which all in-plane indexes are violated, at least in one direction. An alternative identification criterion might be to consider the simultaneous violation of Index 3 and another of the two remaining indexes (1 or 2). Both criteria show that deficient resistance to earthquake loading is not only associated with high seismicity, such as for most of the Italian churches identified above, but that deficient earthquake strength can also be encountered in moderate seismicity areas, e.g. two Portuguese churches, or even in low seismicity areas, such as for the majority of the Spanish churches. Considering the first criterion, 18% of the sample requires remedial measures or, at least, more detailed evaluation. However, if the second criterion is used, almost half of the sample (43%) exhibits deficient earthquake resistance.

PERFORMANCE OF URM CHURCHES IN THE CANTERBURY EARTHQUAKES

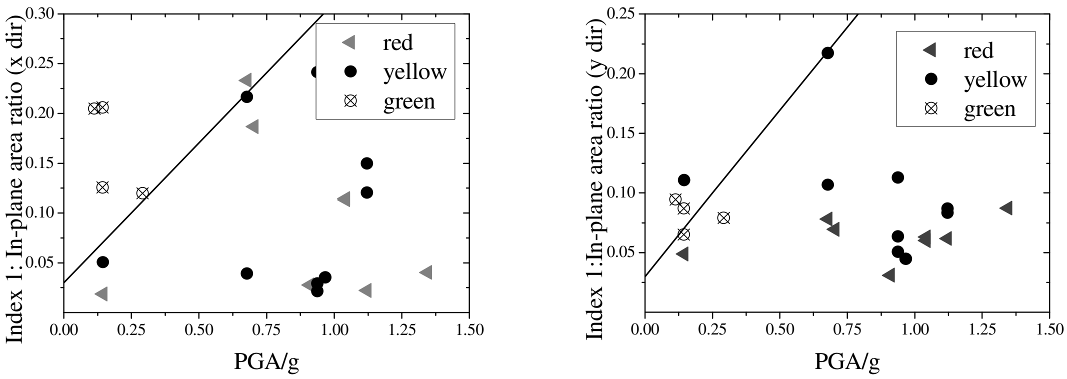
A comprehensive statistical analysis of the performance of churches in the Canterbury earthquakes is reported by Leite et al. (2012), including the in situ damage observed, the structural assessment classification assigned by the local authorities and a comparison with the structural classification used in Italy, where a specific survey form for churches is used. For stone URM churches, more than half of the churches (52%) were assigned a red placard and only 16% of the churches had a green placard assigned (see Figure 3(a)). Figure 3(b) shows that a red placard was assigned to 38% of the clay brick URM churches, while a yellow placard was assigned to 42% of those churches. The percentage of red placards assigned for the clay brick typology was smaller than the percentage assigned for the stone churches, but the sum of the red and yellow placards was similar for both masonry typologies and exceeded 80%.



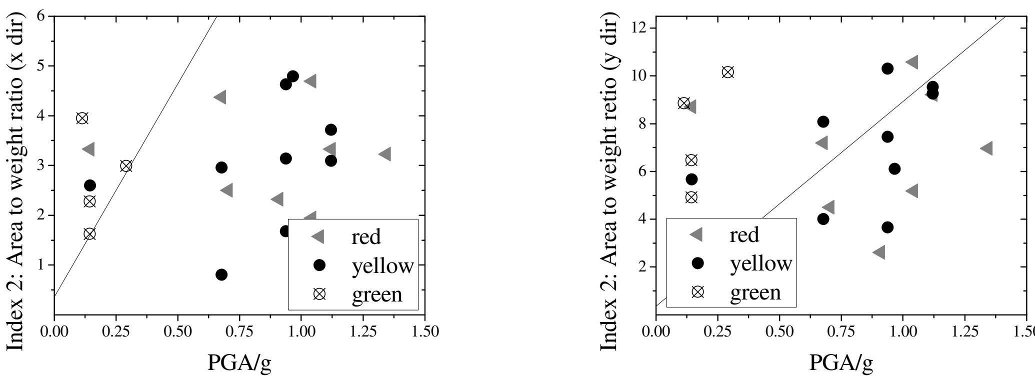
(a) stone churches (b) clay brick churches

Figure 3. Placard classification for assessed URM churches following the Canterbury earthquakes

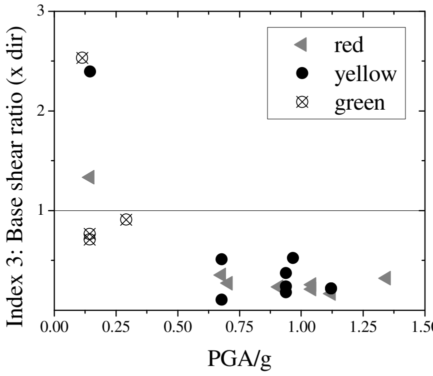
The indices related to the above mentioned simplified method of analysis were computed for all the stone and clay brick URM churches that were surveyed following the Canterbury earthquakes. Figure 4 presents the scatter plots of each index and the horizontal PGA of the 22 February 2011 event interpolated at each site for clay brick URM churches, as well as the proposed thresholds from Figure 1. The threshold for Index 1 is excellent, with all the green tagged churches falling above or near the line and one yellow and one red church incorrectly identified. The yellow tagged church had only minor cracking with the exception of a large shear crack on one longitudinal wall of the main nave. The red tagged church was also a particular case, as it had pinnacles overhanging from the transversal walls. The thresholds for Index 2 and Index 3 also have acceptable results. The x (transverse) direction provides better results for all three indices, and this is the critical direction. Index 3 exhibits the worse correlation if cohesion is taken into consideration, with better results obtained for zero cohesion.



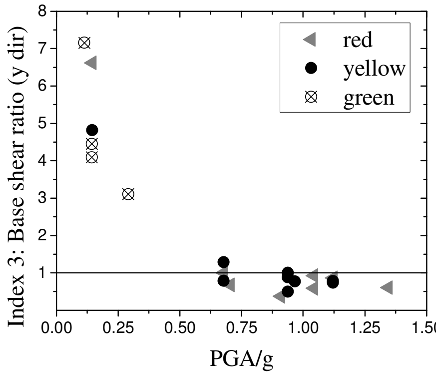
(a) Index 1, x direction (b) Index 1, y direction



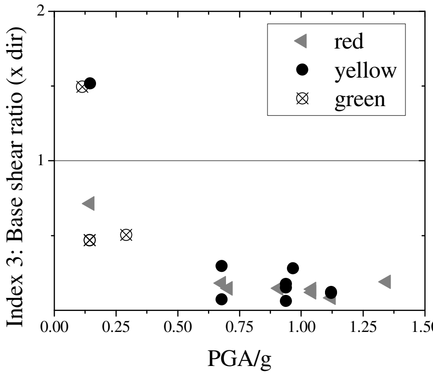
(c) Index 2, x direction (d) Index 2, y direction



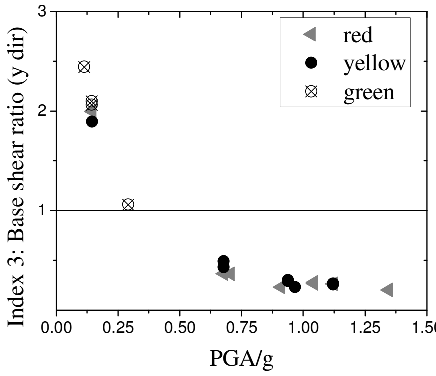
(e) Index 3, x direction



(f) Index 3, y direction



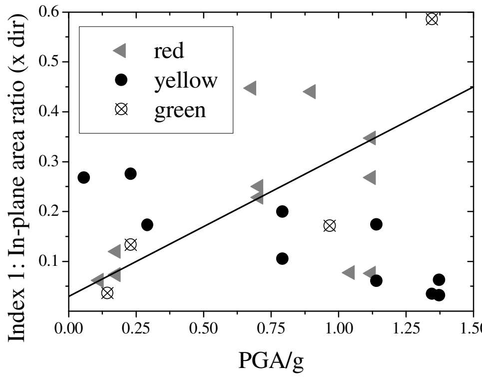
(g) Index 3, x direction (zero cohesion)



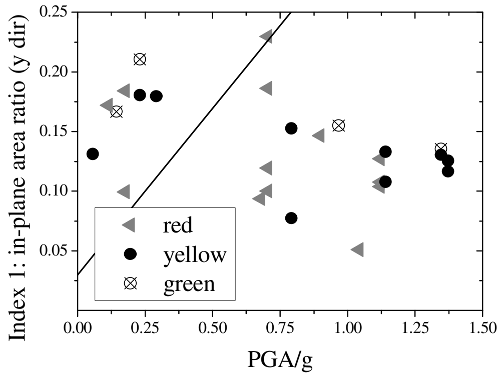
(h) Index 3, y direction (zero cohesion)

Figure 4. Indices for clay brick URM churches in the Canterbury earthquakes

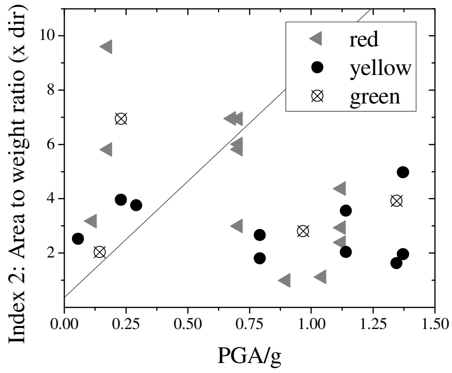
The thresholds for the stone URM churches are not as good as those for the clay brick URM churches (see Figure 5). For all indices in both directions, there are green tagged churches that lie under the threshold, and red tagged churches that lie above the threshold. The lack of homogeny of the stone URM churches justifies the lack of agreement with the thresholds, as the seismic behavior of these churches is rather different. Monumental good quality stone URM churches can present a seismic behavior similar to clay brick URM churches, while weak rubble stone URM masonry lacks interlocking and disaggregates, even for low PGA values, suggesting that it could be helpful to consider sub-sets of typologies for this class of church. Also, the data merits revisiting to establish if any of the stone URM churches had received prior seismic improvements. As for the clay brick URM churches, there is a better agreement with the threshold of Index 3 if cohesion is not taken into consideration.



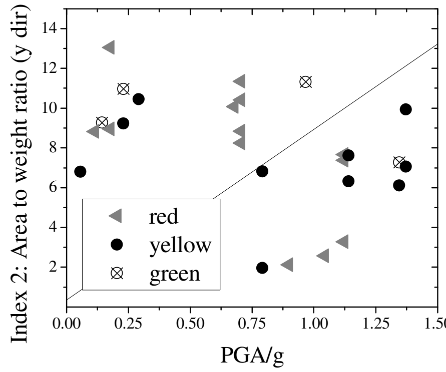
(a) Index 1, x direction



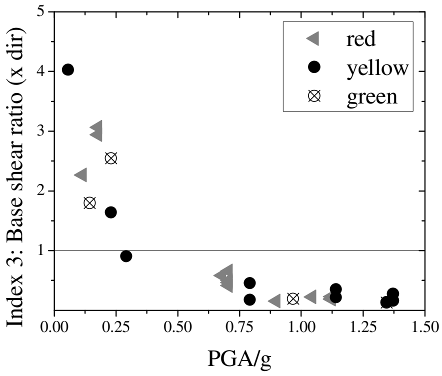
(b) Index 1, y direction



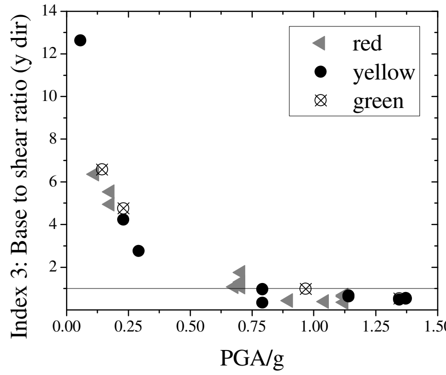
(c) Index 2, x direction



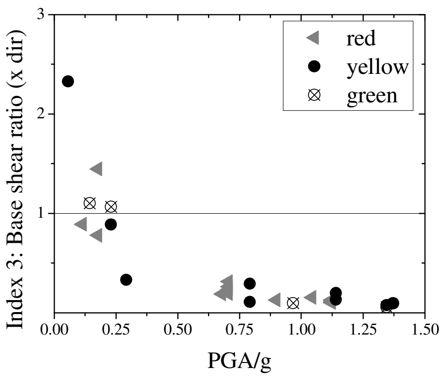
(d) Index 2, y direction



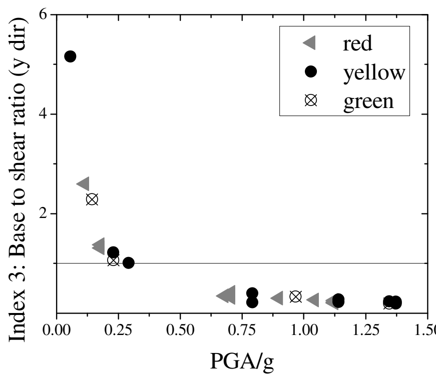
(e) Index 3, x direction



(f) Index 3, y direction



(g) Index 3, x direction (zero cohesion)



(h) Index 3, y direction (zero cohesion)

Figure 5. Indices for stone URM churches in the Canterbury earthquakes

URM CHURCHES IN WELLINGTON AND DUNEDIN

In an attempt to apply the knowledge acquired in the Canterbury earthquakes regarding the seismic performance of New Zealand URM churches, the study was extended to consider URM churches in two other New Zealand cities. Wellington was selected because it is New Zealand's capital city and is a region of high seismicity. However, it is acknowledged that because of the long history of seismic activity in Wellington, many of the city's churches are constructed of timber. 11 URM churches were identified in Wellington, and because archived records of geometric details were poor, all churches were field inspected to collect the necessary survey data. The study concluded by considering URM churches in Dunedin, with a field inspection again undertaken. Dunedin was selected because the history of development of the city was somewhat comparable to that of Christchurch, with an expectation that the stock of URM churches in Dunedin was analogous to that of Christchurch. 29 URM churches were inspected in Dunedin. Christophersen et al. (2011) report that for a 500 year return period, the 2010 New Zealand National Seismic Hazard Model (2010 NSHM) results in values of PGA/g of 0.540 for Wellington and of 0.192 for Dunedin. The PGA data is also shown in Figure 6.

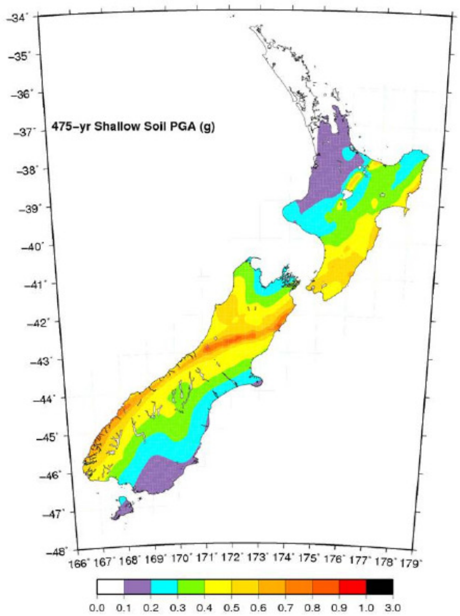
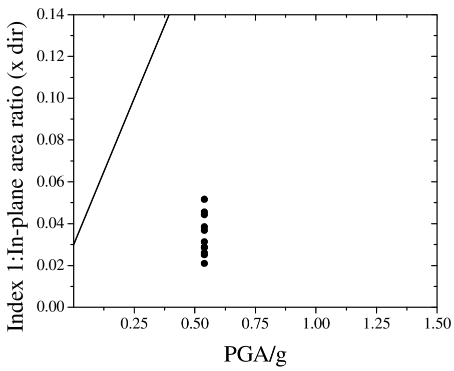
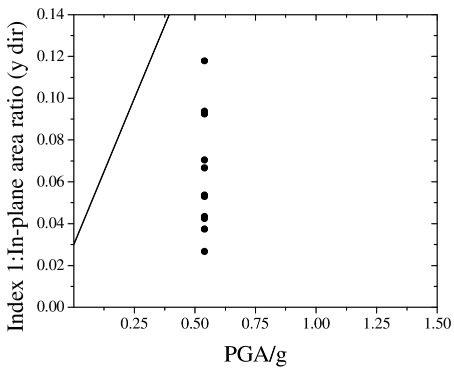


Figure 6. PGA/g values for a 500 year return period earthquake (from Stirling et al. (2012))

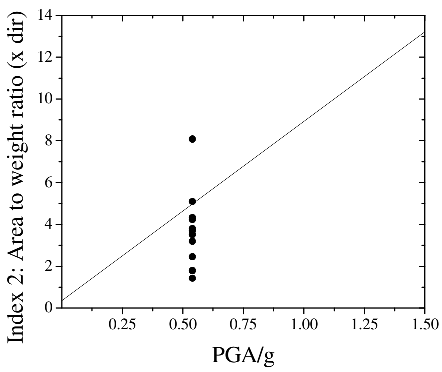
From Figure 7 it may be established that all URM churches in Wellington failed Index 1, for both loading directions. This outcome is largely a result of the high PGA for the region. For Index 2 82% (9 of 11) of Wellington URM churches failed in the x (transversal) direction and 45% (5 of 11) failed in the y (longitudinal direction). For Index 3 100% and 73% (8 of 11) failed in the x and y directions respectively. From this data it is evident that most Wellington URM churches can be expected to perform poorly in a design level earthquake. Recognising that Wellington is a region of high seismicity, this finding is in general agreement with the damage reported to Christchurch URM churches as shown in Figure 3.



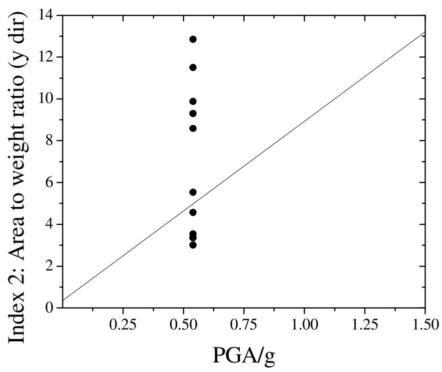
(a) Index 1, x direction



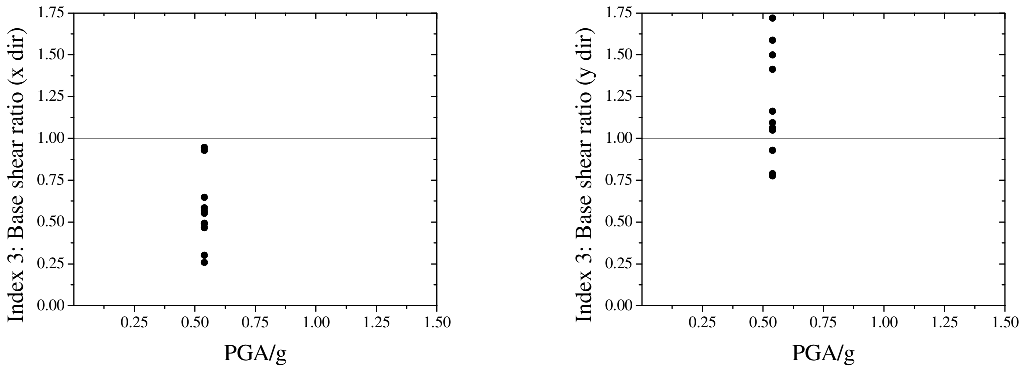
(b) Index 1, y direction



(c) Index 2, x direction



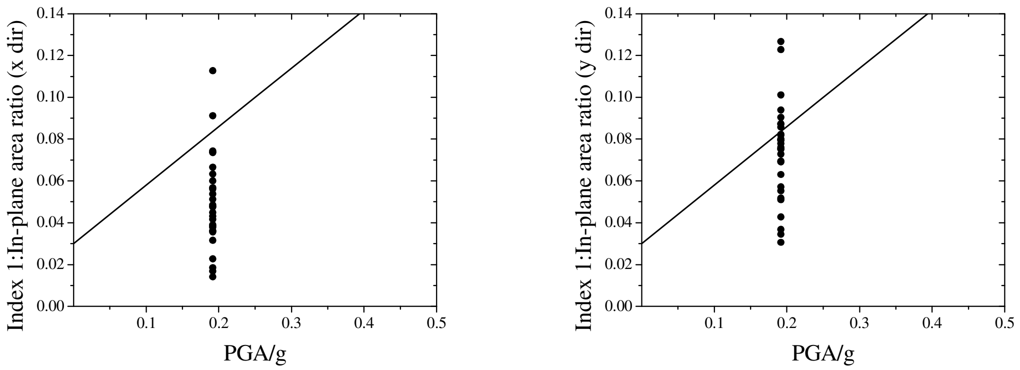
(d) Index 2, y direction



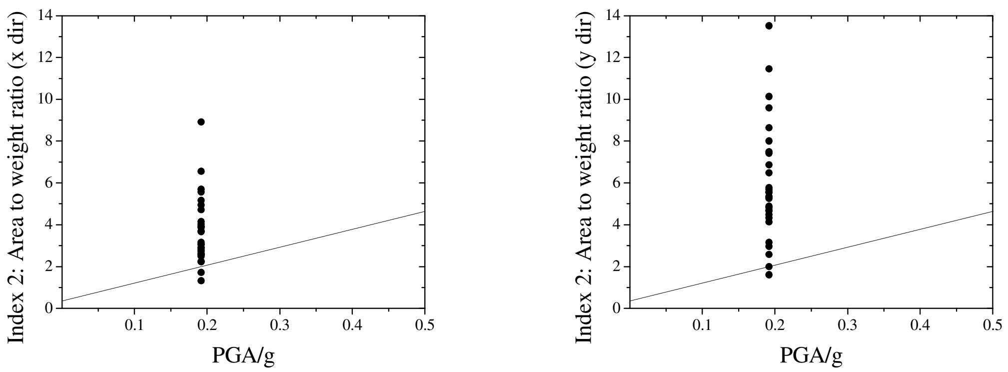
(e) Index 3, x direction (f) Index 3, y direction

Figure 7. Indices for URM churches in Wellington

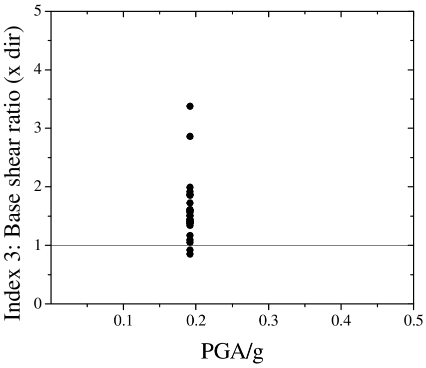
From Figure 8 it is evident that 93% (27 of 29) of Dunedin URM churches fail Index 1 in the x direction and 72% (21 of 29) fail Index 1 in the y direction. However, this finding is in contrast with Index 2 where only 7% (2 of 29) fail in each of the two directions. For Index 3 only 7% (2 of 29) of Dunedin URM churches fail for each orientation. Overall the results from the Dunedin study are an excellent endorsement of the simplified index method, as the procedure has resulted in the identification of a small subset of URM churches that specifically merit priority attention for seismic improvement in a region that by New Zealand standards is of moderate/low seismicity. Images of the three churches that were identified using the simplified index method as most seismically vulnerable are shown in Figure 9.



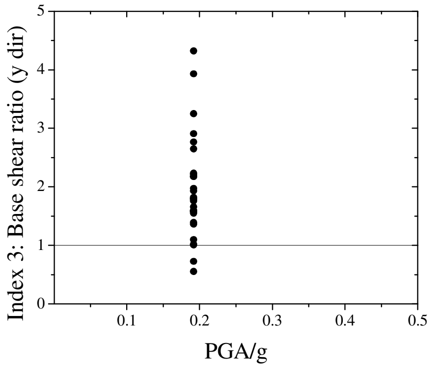
(a) Index 1, x direction (b) Index 1, y direction



(c) Index 2, x direction (d) Index 2, y direction



(e) Index 3, x direction



(f) Index 3, y direction

Figure 8. Indices for URM churches in Dunedin

(a) St Paul's Cathedral

(b) Knox Church

(c) St Joseph's Basilica

Figure 9. Three Dunedin URM churches that score poorly on all indices

CONCLUSIONS

A simplified index method has been presented and its use demonstrated with application to European monumental churches in Italy, Portugal and Spain. The method was then applied to the data collected in the Canterbury earthquakes, with an overall good correlation, such that URM churches that performed well in the Canterbury earthquakes were mostly forecasted by the simplified index method to do so, and similarly churches that performed poorly in the Canterbury earthquakes were forecasted by the simplified index method to be unsafe.

Whilst a cohesion of 50 kPa was assumed when applying the simplified index method to European churches, it was found that for URM churches impacted by the Canterbury earthquakes the best correlation was obtained when zero cohesion was assumed. It is theorised that this finding was influenced by the facts that (i) the 22 Feb 2011 Christchurch earthquake was preceded by the 4 Sept 2010 Darfield earthquake, such that many URM churches would have had some cracking (and hence loss of cohesion) prior to the Christchurch earthquake; and (ii) vertical accelerations during the 22 Feb 2011 Christchurch earthquake were amongst the highest ever recorded. Despite the superior correlation when assuming zero cohesion, it was assumed that the above earthquake attributes are not typical, and the assessment of URM churches in Wellington and Dunedin again adopted a cohesion value of 50 kPa.

When applying the simplified index method to the Wellington URM church stock it was found that most churches would be expected to perform poorly. This outcome is sensible, as Wellington is located in a high seismic zone. Finally the method was applied to URM churches in Dunedin, a region of moderate/low seismicity, and a small number of churches were identified as being unsafe when using the simplified index method. The purpose of the method was therefore realised.

More generally, it is anticipated that the current work will form the beginning of a comprehensive study on the seismic vulnerability of URM churches throughout New Zealand, with a range of tools being used in the investigation. Hence it is emphasised that the current work is both intentionally simple, and of an introductory or preliminary nature.

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