Seismic vulnerability of historical churches

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ABSTRACT: Ancient masonry structures are particularly vulnerable to dynamic actions, especially seismic actions. This paper presents a contribution to the safety assessment of historical masonry churches located in seismic areas. The approach proposed here aims at a simple, fast, and low cost procedure based on a simplified geometric approach for immediate screening of the large number of churches at risk. The objective is to evaluate the possibility of adopting simple indexes related to geometrical data as a first (and very fast) screening technique to define priority for further studies.

1 INTRODUCTION

Ancient masonry structures are particularly vulnerable to dynamic actions, especially seismic actions. Countries on the Mediterranean basin are particularly at risk due to the large number of ancient monuments and dwellings. Due to the ageing process, as well as to environmental factors, many cultural heritage buildings, as structures planned and constructed in the past, are vulnerable to dynamic loads, which may unpredictably induce a collapse of a portion of the building or drive the whole structure to a rapid failure. However, the high vulnerability of historical masonry buildings to seismic actions is mostly due to the absence of adequate connections between the various building parts (masonry walls, timber beams on the floors and timber beams on the roof). This characteristic leads to overturning collapse of the perimeter walls under seismic horizontal acceleration.

An analysis of the damage survey of historical masonry buildings for the Umbria-Marche earthquake (GNDT 1998, Lagomarsino 1998), which caused the most (damage) impact to monuments in the last years, shows that the problem is generalized and that structural typologies, as well as associated types and distribution of damage, are fairly recurring. Vulnerability may be reduced through retrofitting/protection to better resist the seismic demand. Anti-seismic action requires the knowledge of seismic site response, the definition of the seismic load (a rather challenging issue), and the knowledge of the characteristics of existing buildings. This is a gigantic task, requiring large funds and considerable investment of time, but efforts have been made to create damage scenarios and to prioritize retrofitting works (Barbat et al. 1996, Langa & Bachmanna 2004).

The approach proposed in this paper aims at a much more simple, fast, and low cost procedure based on a simplified geometric approach for immediate screening of the large number of buildings at risk. The objective is to evaluate the possibility of adopting simple indexes related to geometrical data as a first (very fast) screening technique to define priority for further studies with respect to seismic vulnerability. These fast techniques are to be used without actually visiting the buildings, being therefore not accurate. It is expected that the geometrical indexes could detect cases in serious risk and, thus, define priority for studies in countries/locations without recent earthquakes, as in Portugal.

The historical buildings considered at possible risk may deserve more detailed studies using advanced computer simulations, together with adequate material and structural characterization; see

Lourenço (2002) and ICOMOS (2001) for recommendations.

In the case of urban areas, and in spite of the diversity, a common matrix can usually be established for the seismic areas, more structural than technological. This consists of low building height (up to three stories), moderate spans (maximum of four or five meters), and large thickness of the walls (less than 1/7 of the height) (see Giuffrè 1995). However, this paper is focused on European churches, given:

- Their intrinsic greater structural vulnerability due to open plan, greater height to width ratio and, often, the presence of thrusting horizontal structures from vaulted ceilings and timber roofs.
- The ample geometry survey drawings and documentation available. Moreover, in earthquake prone countries, churches and monuments have already been subjected to earthquakes, and sometimes survived them, meaning that they are testimonies and represent full-scale testing data. This fact permits the discussion and, generally, the acceptance that these ancient structures have been adjusted to local seismicity.

Forty-four churches from Portugal, Spain, and Italy have been selected and analyzed considering three in-plane indexes and three out-of-plane indexes. The proposed geometrical indexes of monuments located in different seismic areas are compared with the respective seismic hazard, expressed by the peak ground acceleration (PGA), defined for a 10% probability of exceedance in 50 years for a rock-like soil, corresponding to a return period of 475 years. The recognition of the likely existence of a correlation between structural characteristics and seismic hazard is, therefore, sought.

2 SIMPLIFIED METHODS OF ANALYSIS

The analysis of historical masonry constructions is a highly complex task; namely, because (a) geometry data is missing; (b) information about the inner core of the structural elements is also missing; (c) characterization of the mechanical properties of the materials used is difficult and expensive; (d) mechanical properties exhibit large variability due to workmanship and use of natural materials; (e) core and constitution of structural elements present significant changes associated with long construction periods; (f) construction sequence is unknown; (g) existing damage in the structure is unknown; (h) regulations and codes are nonapplicable. Moreover, the behaviour of the connections between masonry elements (walls, lintels, arches and vaults) and masonry elements and timber elements (roofs and floors) is usually unknown. All these factors indicate that the quantitative results of structural analysis must be looked at with reservation, in the case of vertical loading and, even more carefully, in the case of seismic action. Therefore, more complex and accurate methods do not necessarily correspond to more reliable and better analyses.

The usage of simplified methods of analysis usually requires that the structure is regular and symmetric, that the floors act as rigid diaphragms, and that the dominant collapse mode is in-plane shear failure of the walls (Meli 1998). In general, these last two conditions are not verified by ancient masonry structures, meaning that simplified methods should not be understood as quantitative safety assessment but merely as a simple indicator of possible seismic performance of a building. The following simplified methods of analysis and corresponding indexes are considered. In-plane indexes:

- Index 1: In-plan area ratio
- Index 2: Area to weight ratio
- Index 3: Base shear ratio

Out-of-plane indexes:

- Index 4: Slenderness ratio of columns
- Index 5: Thickness to height ratio of columns
- Index 6: Thickness to height ratio of perimeter walls

These methods can be considered as an operator that manipulates the geometric values of the structural walls and columns and produces a scalar. As the methods measure different quantities, their application to a large sample of buildings contributes to further enlightening on their application. As aforementioned, a more rigorous assessment of the actual safety conditions of a building is necessary to have quantitative values and to define remedial measures, if necessary.

2.1 *In-plan area ratio*

The simplest index to assess the safety of ancient constructions is the ratio between the area of the earthquake resistant walls in each main direction (transversal x and longitudinal y, with respect to the church nave) and the total in-plan area of the building. According to Eurocode 8 (CEN-EC8 2003), walls should only be considered as earthquake resistant if the thickness is larger than

0.35 m, and the ratio between height and thickness is smaller than nine. The first index, $\gamma_{1,i}$, reads:

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

where A_{wi} is the in-plan area of earthquake resistant walls in direction "i" and S is the total in-plan area of the building. The nondimensional 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 construction.

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% seems to be recommended for historical masonry buildings (Meli 1998). For simplicity sake, high seismicity cases can be assumed as those where the peak ground acceleration for rock-like soils, established for a 475 y.r.p., is larger than 0.20 g.

2.2 *Area to weight ratio*

This index provides the ratio between the in-plan area of earthquake resistant walls in each main direction (again, transversal x and longitudinal y) and the total weight of the construction, reading:

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

where A_{wi} is the in-plan area of earthquake resistant walls in direction "i" 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; a major disadvantage is that the index is not nondimensional, meaning that it must be analyzed for fixed units. In cases of high seismicity, a minimum value of 1.2 m^2/MN seems to be recommended for historical masonry buildings (Meli 1998), but on the basis of a recent work (Lourenço & Roque 2004), a minimum value of 2.5 m^2/MN is adopted here for high seismicity zones.

2.3 *Base shear ratio*

Finally, the base shear ratio provides a safety value with respect to the shear safety of the construction. 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 peak ground acceleration. The shear strength of the structure ($V_{Rd,\,base} = F_{Rd}$) can be estimated from the contribution of all earthquake resistant walls $F_{Rd,i} = \Sigma A_{wi} f_{vk}$, where, according to Eurocode 6 (CEN-EC6 2003), $f_{vk} = f_{vk0} + 0.4\sigma_d$. 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 index, γ_3, reads:

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

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

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

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

$$\gamma_{3,i} = V_{Rd,i}/V_{Sd} = A_{wi}/A_w\times[\tan\phi+f_{vk0}/(\gamma\times h)]/\beta \tag{5}$$

where A_{wi} is the in-plan area of earthquake resistant walls in direction "i," A_w is the total in-plan 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. Here, it is assumed that the normal stress in the walls is only due to their self-weight, i.e. $\sigma_d = \gamma \times h$, which is on the safe side and is a very reasonable approximation for historical masonry buildings, usually made of very thick walls.

Equation (5) must be used rather carefully since the contribution of the cohesion can be very large. Within the scope of this work, a cohesion value of 0.05 N/mm^2 is assumed. This nondimensional index considers the seismicity of the zone, taken into account in β. The building will be safer with increasing ratio (earthquake resistant walls/weight), i.e. larger relation (A_{wi} / A_w) and lower heights. For this type of buildings and action, a minimum value of $\gamma_{3,i}$ equal to one seems to be acceptable.

The adopted indexes measure rather different quantities and can hardly be compared. Index 2 is dimensional, which means that it should be used with particular care. Index 1 and index 2 are independent of the ground acceleration. Therefore, assuming that the buildings must have identical safety, these indexes should be larger with increasing seismicity. For indexes 1 and 2, the seismicity is taken into account by considering that the threshold value, defined above, is valid for a PGA value of 0.25 g and assuming its linear variation with PGA/g, as illustrated in Figure 1, see also Eurocode 8 (CEN-EC8 2003). On the other hand, index 3 should be constant in different seismic zones, as it intrinsically considers the effect of seismicity. This index format is close to the traditional safety approach adopted for structural design, being the threshold value equaled to 1.0, see Figure 1.

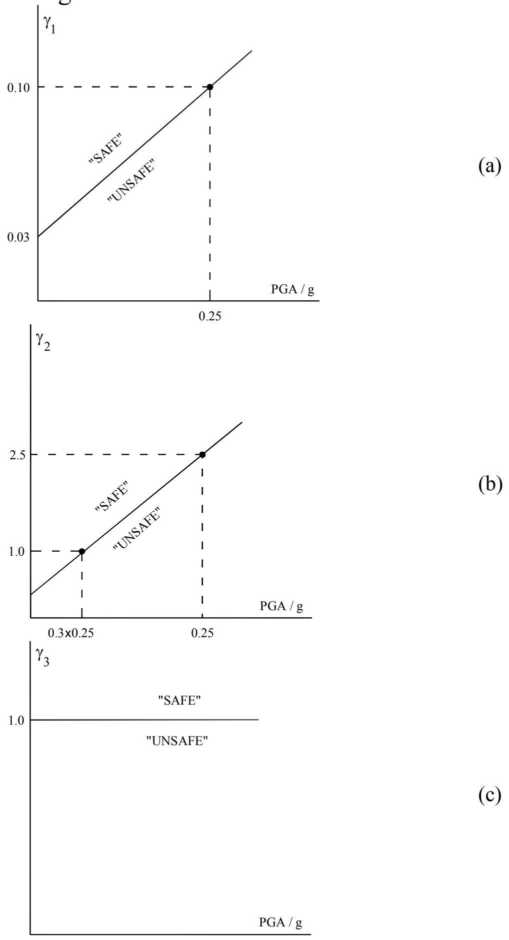

Figure 1. Assumed thresholds as functions of PGA/g: (a) index 1, (b) index 2 and (c) index 3.

2.4 *Out-of-plane indexes*

Besides the three indexes exposed above, other key indexes related to structural performance were computed for the monuments under analysis. In this study, three geometric ratios concerning the structural out-of-plane behaviour of columns and walls in main space were adopted, when applicable; slenderness ratio (γ_4), and thickness to height ratio of the columns (γ_5), as well as thickness to height ratio of the perimeter walls (γ_6), were analyzed, reading:

$$\gamma_4 = h_{col} / (I/A)^{1/2} \quad [-] \qquad (6)$$

$$\gamma_5 = d_{col} / h_{col} \quad [-] \qquad (7)$$

$$\gamma_6 = t_{wall} / h_{wall} \quad [-] \qquad (8)$$

where h_{col} is the free height of the columns, I and A are the inertia and the cross section area of the columns, respectively, d_{col} is the (equivalent) diameter of the columns, and t_{wall} and h_{wall} are the thickness and the (average) height of the perimeter walls, respectively. All of the out-of-plane indexes are dimensionless and do not consider the local seismicity. If identical safety factors for the monuments are assumed, these indexes should vary with increasing seismicity; namely, index 4 should decrease and indexes 5 and 6 should increase.

3 INVESTIGATION OF FORTY-FOUR EUROPEAN MONUMENTS

The investigation presented in this paper includes the application of the simplified methods previously described to a sample of forty-four monuments (19 from Portugal, 15 from Spain, and 10 from Italy), selected according to the seismic level and to the availability of information. This research pursues the following objectives:

- Validate the hypothesis of an empirical relation of the ancient builders, able to define and expedite preliminary assessment of seismic vulnerability of historical masonry buildings.
- Validate the hypothesis of an empirical relation between architectural-structural characteristics of historical masonry buildings and seismicity.
- Prioritize further investigations and possible remedial measures for the selected sample.
- Extrapolate, from the results on the sample, the seismic vulnerability of ancient masonry buildings in those countries.

3.1 *In-plane indexes*

For the application of the simplified analysis methods, it was assumed that all the masonry materials were similar, the volumetric weight of masonry was 20 kN/m^3, and the weight of roofs was equal to 2.0 kN/m^2. The values computed for the three in-plane indexes, which can be found elsewhere (University of Minho 2005), are graphically represented in Figure 2 and Figure 3, for the entire sample and for each direction, as a function of the local parameter PGA/g.

In terms of average values, index γ_1 presents lower values in the transversal direction (x) of the church nave, which is expected due to churches' geometry, although Italian indexes are quite similar in both directions. Index γ_1 does not show a clear variation with seismicity, but Figure 2a and Figure 3a indicate that this index tends to grow roughly with increasing seismicity. When a comparison is made using the proposed threshold, 22.7% of the churches violate it in the x-direction and 6.8% in the y-direction, as expected, since the same criterion is used in both directions. This means that the cases that might require further investigation are due to a deficient earthquake resistance mainly along the transversal direction of the church nave.

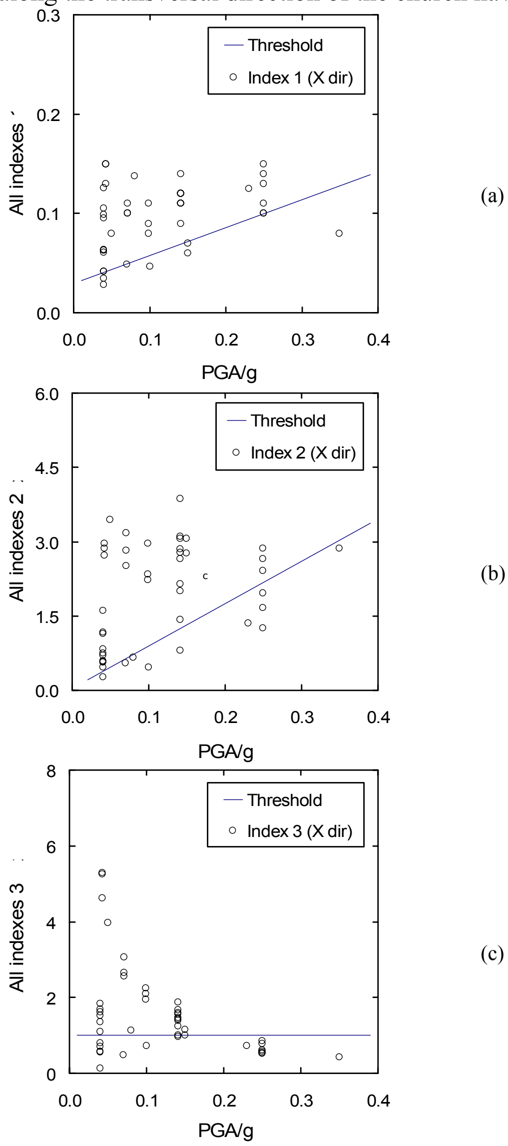

Figure 2. Relationship between in-plane indexes (direction x) and PGA/g, for the entire sample: (a) index 1, (b) index 2, (c) index 3.

Index $\gamma 2$, although being inversely proportional to the height of the buildings, presents a situation similar to index 1. Again, the calculated values do not show a visible trend with respect to seismicity; however, a slight tendency associates the increase of $\gamma 2$ with PGA increase (see Figure 2b and Figure 3b). On average terms, index $\gamma 2$ also presents lower values in the x-direction, which can be justified again by churches' geometry. As a result, this index is violated by 38.6% and 29.5% of the monuments in x- and y-directions, respectively. This index is mainly violated by Spanish churches.

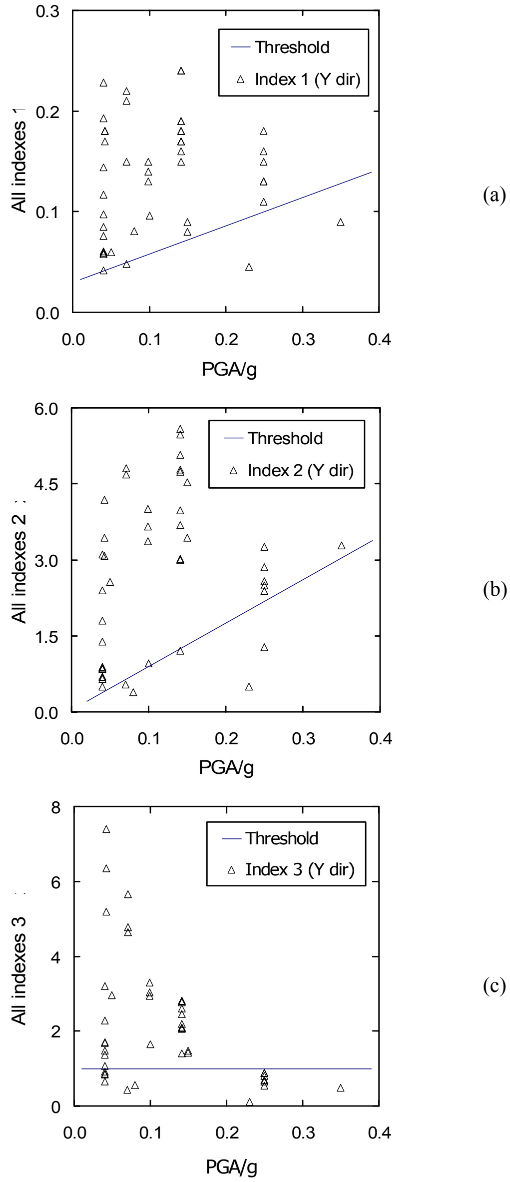

Figure 3. Relationship between in-plane indexes (direction y) and PGA/g, for the entire sample: (a) index 1, (b) index 2, (c) index 3.

Index γ_3 shows an unexpected and alarming decreasing variation with the PGA parameter (see Figure 2c and Figure 3c). For moderate and high seismicity areas (PGA greater than 0.15 g), index γ_3 is violated by all churches, in both directions. In spite of that, also for low seismicity areas, index γ_3 is not entirely fulfilled. As it happened with both previous indexes, index γ_3 presents lower values in the x-direction. Individually, 40.9% and 31.8% of the churches in x- and y-directions violate it, respectively, which denotes a deficient earthquake resistance along both the transversal and longitudinal directions. Unexpectedly, this index assumes minimum values slightly lower than 0.15, in both directions, which is most likely associated with highly vulnerable structures, probably unable to properly withstand an earthquake. This index is mainly violated by Italian churches.

In order to perform a preliminary screening and to prioritize deeper studies in historical masonry structures in earthquake prone countries, a possible approach is to identify the monuments for which all in-plane indexes are violated, at least in one direction. Following this approach, Table 1 presents the eight monuments of the sample that violate all in-plane indexes, at least in one direction.

Table 1. Monuments in which all in-plane indexes are violated, at least in one direction.

Monument	Direction / PGA
Church of the Castle of Penyafort, Spain	x / 0.04g
Oratorium of Sant Felip Neri de Gràcia, Spain	x / 0.04g
Church of Santa Eulàlia del Papiol, Spain	x / 0.04g
Church of Santa Maria de Ripoll, Spain	x / 0.10g
Cathedral of Granada, Spain	y / 0.23g
Cathedral of Sevilla, Spain	x, y / 0.07g
San Domenico Church, Noto, Italy	x / 0.25g
S. Maria Assunta Church, Montesanto, Italy	x, y / 0.35g

Alternatively, considering the simultaneous violation of index γ_3 and another one of the two remaining indexes, γ_1 or γ_2, eleven more monuments have to be considered (see Table 2).

Both criteria show that deficient resistance to earthquake loading is not only associated with high seismicity, like in most of the Italian churches identified above, but it can also happen in moderate seismicity areas, e.g. the two Portuguese churches, or even in low seismic areas, like in the majority of the Spanish churches referred to above. Considering the first criterion, 18.2% of the sample requires remedial measures or, at least, deeper investigations. However, if the second criterion is used instead, almost half of the sample (43.2%) exhibits deficient earthquake resistance.

Table 2. Monuments in which all in-plane indexes are violated, at least in one direction.

Monument	Direction / PGA
Ancient Jesus Monastery, Setúbal, Portugal	x / 0.14g
Church of Sta. Maria of Belém, Lisboa, Portugal	x / 0.14g
Cathedral of Mallorca, Spain	y / 0.04g
Cathedral of Girona, Spain	y / 0.08g
Church of Sant Miquel del Port, Spain	x / 0.04g
Monastery of Sant Cugat del Vallès, Spain	y / 0.04g
SS. Lucia and Vittore Church, Treviso, Italy	x / 0.25g
Santissima Annunziata Church, Ragusa, Italy	x, y / 0.25g
Santa Maria Gesù Church, Ragusa, Italy	x, y / 0.25g
S Gregorio Armeno Church, Naples, Italy	x, y / 0.25g
San Prosdocimo Church, Padova, Italy	x / 0.15g

3.2 *Out-of-plane indexes*

The values obtained for the three out-of-plane indexes are graphically represented in Figure 4, for the entire sample, as a function of the local seismicity.

As it happened with the in-plane indexes, the out-of-plane indexes do not show any clear relationship with seismicity (see Figure 4). However, a deeper analysis allows for the distinction of a slightly common variation of the three indexes with seismicity. In fact, for low and low-moderate seismicity areas (PGA up to 0.10g-0.15g), the indexes do not exhibit a dependency on seismicity, assuming a large range of values instead.

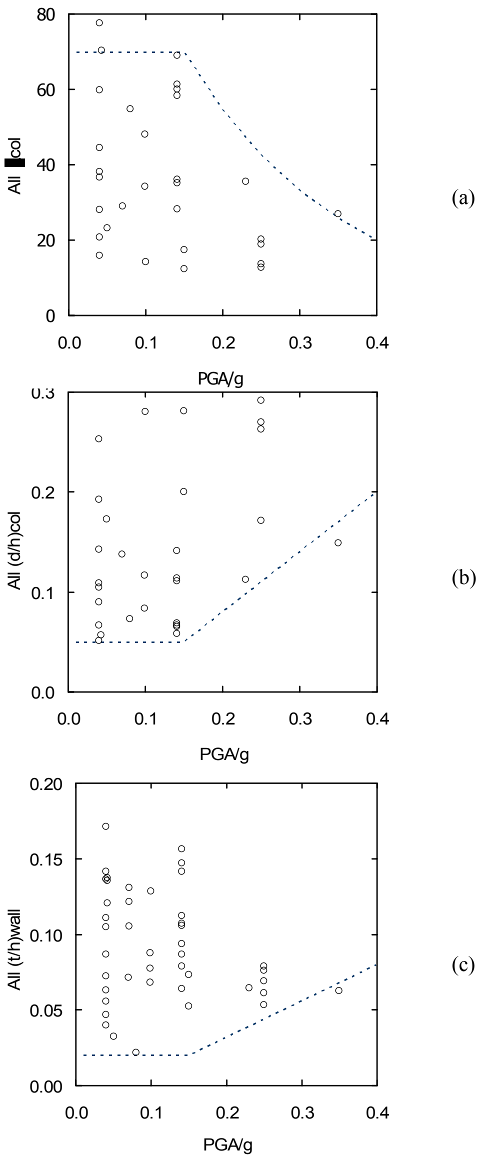

Figure 4. Relationship between out-of-plane indexes and PGA/g, for the entire sample: (a) index 4, (b) index 5, (c) index 6.

However, for a PGA greater than 0.15 g, a possible trend may be established. From Figure 4, it can be observed that maxima index 4 values (column's slenderness) tend to decrease with increasing seismicity and that both minima index 5 and index 6 values seem to increase continuously with seismicity. These trends are depicted in Figure 4 by dashed lines. Their general evolution with increasing seismicity was expected since, for the same safety level, index 4 should decrease and both index 5 and index 6 should increase. Therefore, the dashed lines can be seen as possible threshold proposals, to be comprehensively calibrated, that these indexes should observe.

4 CONCLUSIONS

This paper deals with an investigation regarding the possibility of using simplified methods of analysis and simple indexes as indicators for fast screening and decision to prioritize deeper studies in historical masonry buildings and to assess vulnerability to seismic loading. These indexes, both in-plane and out-of-plane, are established mostly on the in-plan dimensions and height of the buildings. In general, the longitudinal direction of the buildings (y) exhibits lower vulnerability than the transversal direction (x).

Indexes γ_1 and γ_2 do not present a clear trend with respect to seismicity; however, a slight tendency associates the increase of γ_1 and γ_2 with PGA growth.

For moderate and high seismicity zones, index γ_3 is violated by all churches, in both directions; also, for low seismicity zones, index γ_3 is not entirely fulfilled. This perception constitutes a major issue regarding seismic safety, thus requiring careful attention and deeper investigation of the churches at risk.

A proposal for the usage of simplified methods was made, taking into consideration the simultaneous violation of two or three of the in-plane indexes. The results show that the need for deeper investigations ranges between 18.2% and 43.2% of the sample (8 and 19 churches, respectively).

The analysis of the out-of-plane indexes shows that a logical common trend can be established. For low and moderate seismicity, indexes do not exhibit a dependency on seismicity. However, for increasing seismicity, they tend to vary in a logical pattern. Furthermore, the observed trend allowed the proposal of possible qualitative threshold criteria for each of the indexes.

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