SIMPLIFIED PROCEDURES FOR SEISMIC VULNERABILITY ASSESSMENT OF MASONRY CHURCHES

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Abstract

The conservation of the huge building heritage in Italy is a very complex challenge considering the high structural vulnerability that characterizes historical buildings and the significant seismic hazard affecting the Italian territory. In order to adopt preventive policies aimed at preserving such a valuable heritage, in the last decades many simplified models calibrated on the evidences of the aftermath of strong seismic events and suitable for the damage prediction of homogenous class of buildings (e.g. residential buildings, schools, churches, etc.) have been proposed. The present study focuses on masonry churches, which revealed an exceptional seismic vulnerability after the meaningful seismic events that occurred in the Italian peninsula in the last decades. In particular, after the swarm event occurred in Central Italy in 2016, about four thousand masonry churches resulted damaged, they being collapsed or declared unsafe in the post-earthquake inspections. In the paper a state of art of predictive models for masonry churches present in literature is given. Then, a simplified empirical method for seismic vulnerability assessment of masonry churches is presented. The research is framed within a national project promoted by the agreement between the Italian consortium ReLUIS and the Department of Civil Protection (DPC), aimed at implementing national seismic risk maps for different structure typologies (i.e. residential buildings, schools, churches and bridges). The proposed empirical method, which considers only qualitative parameters available at a national scale, has been calibrated on the basis of the damage scenario observed in the aftermath of the L'Aquila (2009) and Central Italy (2016-17) earthquakes. The comparison with the results of the 1st Level methodology provided by the Italian code revealed a good correspondence in terms of vulnerability classes, showing the possibility that such a simplified method could be profitably used to implement national seismic risk maps for masonry churches.

Keywords: Cultural Heritage, Masonry Churches, Seismic Vulnerability Assessment, Predictive Models

1. Introduction

In large areas of Italy, but similarly to many other European countries, the high seismic risk is due not only to the seismic hazard of the territory but mainly to the excessive vulnerability of the existing buildings, especially the historical and the monumental ones. In this context, this paper considers simplified procedures for the seismic vulnerability assessment of masonry churches, which in past earthquakes showed exceptional inability to face the stress and displacement requirements arisen by earthquake occurrences. To give an idea of the scale of the problem, it is enough to mention that, according to a qualitative estimation, about 10000 masonry churches resulted damaged in Italy in the aftermath of recent seismic events (e.g. Umbria and Marche 1997, Molise 2002, L'Aquila 2009, Emilia 2012 and Central-Italy 2016-17). Therefore, the adoption of preventive strategies aimed at mitigating seismic risk is a noteworthy issue, which needs to be tackled with vigor and determination, but at the same time results complex to solve.

Many activities are being developed by the Italian research community in this field. In particular, the present study is framed within the national project MaRS, aimed at producing Italian seismic risk maps for different structural typologies (i.e. residential buildings, schools, bridges and indeed churches). Such a project is promoted by the agreement between the Italian consortium ReLUIS and the Department of Civil Protection (DPC), and tackles the problem following a territorial approach, which has been widely adopted in the past for similar issues.

In the past, many researchers focused their attention on large-scale methodologies aimed at assessing the vulnerability of existing buildings. In particular, Braga et al. [1] and Benedetti and Pertini [2] proposed vulnerability models and fragility curves for existing buildings, calibrated on the basis of the effects of the Irpinia earthquake (1980). Then, also thanks to the innovative studies carried out by Sandi and Floricel [3], in the early 2000 predictive models for large-scale vulnerability assessments of masonry churches were developed. In particular, based on the damage occurred after the 1997 Umbria and Marche seismic event, Lagomarsino and Podestà [4] proposed vulnerability curves for existing masonry churches. Therefore, based on the formulation of Eq. (1), it is possible to evaluate the expected average damage (μ_D) of a group of masonry churches according to the macro-seismic intensity in MCS scale (I) and the vulnerability index (i_v).

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+3.4375\cdot i_v-8.9125}{3}\right)\right] \tag{1}$$

After this study, in the last years and with reference to different seismic events, many research activities have been carried out with the aim to verify the reliability of these methodologies by comparing the observed damages with the predicted ones [5,6,7]. In particular, based on the damage on churches observed after the L'Aquila 2009 earthquake, the authors proposed a modification to the formulation of Eq. (1), according to Eq. (2) [8]. Moreover, in another recent work, they proposed also the use of an instrumental measure of the seismic intensity, namely the peak ground acceleration, rather than the common approach based on the macro-seismic intensity [9].

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+6.20\cdot i_v-11}{3}\right)\right] \tag{2}$$

Nevertheless, given the insufficiency of the information available for churches at national level, the application of these predictive models to large areas should require the definition of less detailed procedure, so to allow seismic vulnerability assessment on the basis of the few searchable data.

2. Vulnerability assessment methodologies for masonry churches

2.1 Introduction

Many studies have been carried out with the aim to validate methodologies for the seismic vulnerability assessment of masonry churches [10, 11, 12, 13]. One of the most complete classification of the vulnerability assessment methodologies was proposed by Calvi et al. [14], according to which three typologies of vulnerability models can be distinguished in function of their approach and accuracy: i. empirical; ii. hybrid; iii. analytical. Since a large-scale approach is considered, an empirical vulnerability model could be considered the most suitable for the aim of the present study.

In Italy, the empirical 1st Level approach, based on the assumption given by the Italian Guidelines for the Cultural Heritage [15] and on the definition of a vulnerability index [2,16], is widely adopted for the aforementioned aims. Nevertheless, since specific inspections are necessary for the application of this model, it results to be unsuitable for a large and speed application at large scale.

2.2 The macro-element approach

According to the procedure proposed by the Italian Guidelines [15], the seismic damage and the seismic vulnerability assessment can be carried out through the macro-element approach, which allows to identify 28 possible damage mechanisms related to the main macro-elements detectable in a masonry church. The procedure exploits the definition of a vulnerability index (i_v) according to Eq. (3):

$$i_v = \frac{1}{6} \cdot \frac{\sum_{k=1}^{28} \rho_k \cdot (v_{k,i} - v_{k,p})}{\sum_{k=1}^{28} \rho_k} + \frac{1}{2} \tag{3}$$

where, ρ_k is the importance score factor assigned to each mechanism according to the influence that it has on the global behaviour of the structure, while $v_{k,i}$ and $v_{k,p}$ are the score related to the presence and the gravity of fragility indicators and the presence and the efficiency of anti-seismic devices related to the k^{th} mechanism, respectively. The damage mechanisms and the related ρ_k, defined according to previous studies present in literature [17, 18], are provided in Fig.1.

2.3 The MaChro form

Aiming at avoiding uncertainness and subjectivity of the judgment in the vulnerability assessment process, the MaChro form (Masonry CHurches Reconnaisance Operational Form) has been proposed by De Matteis et. al. [19]. By using such form, the compiler can identify only basic information about each studied church. All the data collected through the compilation are automatically processed by a spreadsheet, providing the value of the assessed vulnerability index (i_v), according to the aforementioned Eq. (3). The analysis of structural details is then performed throughout the methodology proposed by the Italian Guidelines [15], accounting both for the presence and the influence of the anti-seismic devices ($v_{k,p}$) and fragility indicators ($v_{k,i}$) detectable in each collapse mechanism.

2.4 Purposes and motivations of the study

The common methodology based on the macro-element approach could be adopted in case of accurate inspections of the considered buildings and therefore it is not suitable for the purposes of the present study. Indeed, in order to implement risk maps at a national scale, new methodologies aimed at assessing the vulnerability of existing masonry churches are necessary. The present paper provides a first attempt of a simpler and less detailed vulnerability model, calibrated on the basis of data (i.e. geometrical and typological information and damage analyses) collected after the two most destructive seismic events occurred in Italy in the last decades: the study focuses on 64 three-nave churches and 68 one-nave churches resulted hugely damaged after the L'Aquila earthquake (2009) and Central-Italy seismic sequence (2016-2017), respectively.

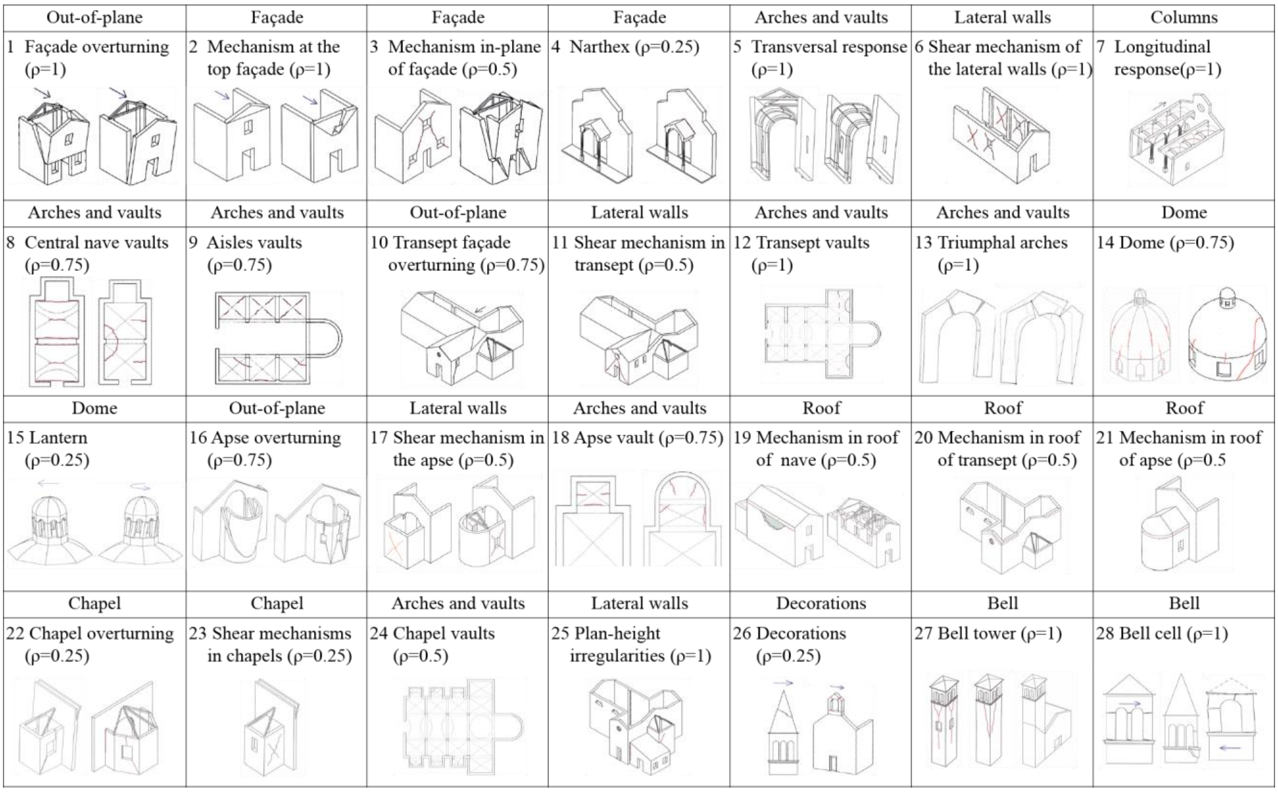

Fig. 1 – Classification of damage mechanisms for existing masonry churches [15]

3. The investigated churches

3.1 General

Within the inspective activities carried out in the aftermath of the L'Aquila (2009) and Central-Italy (2016-2017) seismic events, the authors acquired information for more than 100 churches. In the present section, a description of such churches is provided, together with some information on their damage state and the assessment of structural vulnerability.

3.2 Description of the sample

The considered sample is spread over a large area of the Central Italy and therefore could be considered strongly heterogeneous. The population is composed by 132 churches. Among these, 64 three-nave churches are located in the Abruzzi region, more specifically in the Sulmona-Valva and L'Aquila dioceses, and resulted damaged after the 2009 earthquake, while 68 one-nave churches experienced the 2016-17 seismic sequence and are located in Umbria, Lazio and Marche regions.

For the sake of brevity, qualitative information about the characteristics of the considered churches are provided in Fig.2. More details about the analysed population are given by the authors in previous works [8, 9]. In particular, the identified typological information has been selected for the implementation of the proposed vulnerability model, according to a preliminary sensitive analysis aimed at identifying the parameters that most influence the seismic behavior of a church [20]. The considered parameters are: i. century of primary erection (Fig.2a); ii. plan area (Fig.2b); iii. position of the church (e.g. isolated, in aggregate, in corner extremity or adjacent to short buildings, Fig.2c); iv. quality of masonry (Fig.2d); v. presence of plan-height irregularity (i.e. lateral chapels, transept and apse) and vault presence (Fig.2e).

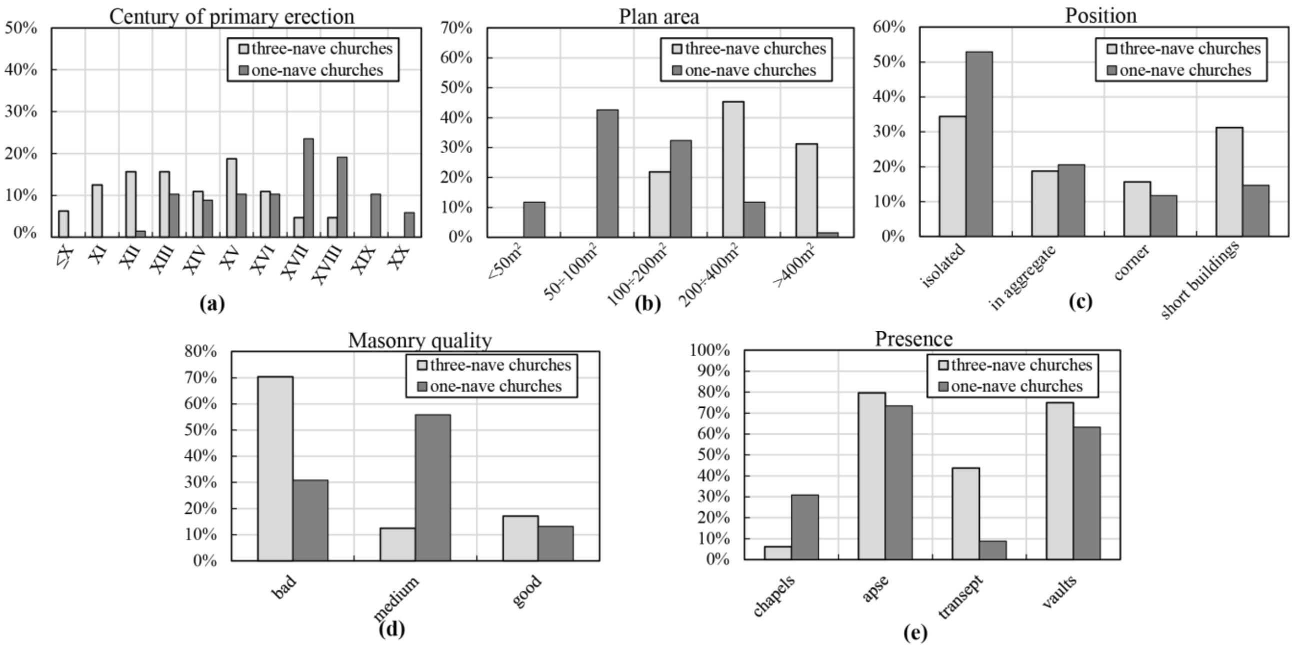

Fig. 2 – Typological characterization of the sample

The considered sample is rather heterogeneous and therefore it may result very suitable for the aims of this study. Anyway, some considerations could be made referring to the two groups of churches. In particular, the one-nave churches resulted generally more recent than the three-nave ones. Moreover, both groups mainly present typologies with apse and vaults, without transept and lateral chapels. Obviously, the surface extensions are strongly dependent on the plan of the church: the three-nave churches are generally characterized by a larger dimension. Lastly the position in urban context, as well as the quality of masonry, could not be related to the type of churches and the statistical analysis returned fairly distributed outcomes.

3.3 Vulnerability and damage assessment

Based on the large amount of data collected during the inspections conducted in the aftermath of the mentioned seismic events, the vulnerability of the considered churches has been assessed. In particular, by means of the MaChro form compilation, a vulnerability index has been estimated for each church according to Eq. (3). The obtained values are showed in Fig. 3a and Fig. 3b for the L'Aquila and Central-Italy groups, respectively.

It is possible to note that the vulnerability index calculated according to the Italian Guidelines provisions tends to be very close to a value equal to 0.5, despite the heterogeneity of the considered sample. In particular, the two groups revealed an average value of 0.57 and 0.48 for the three-nave and one-nave churches, respectively, which are highlighted in Fig. 3 by dotted lines.

In the context of the post-earthquake surveys, also a global damage index (i_d), varying in the range 0÷1, has been estimated, following the macro-element approach proposed by the Italian Guidelines [15]. To this purpose, Eq.(4) has been adopted, where d_k is the damage level assigned to the kth collapse mechanism according to EMCS-98 scale [21] and in the range 0÷5 (0 means no damage, while 5 means total collapse), and ρ_k is the importance factor previously defined.

$$i_d = \frac{1}{5} \cdot \frac{\sum_{k=1}^{28} \rho_k \cdot (d_k)}{\sum_{k=1}^{28} \rho_k} \tag{4}$$

The obtained i_d values are reported in Fig. 3 for the two groups of churches together with the vulnerability indexes. Moreover, the average values of the two samples, which resulted equal to 0.3 and 0.36 for the L'Aquila and Central-Italy churches, respectively, are highlighted with dotted lines.

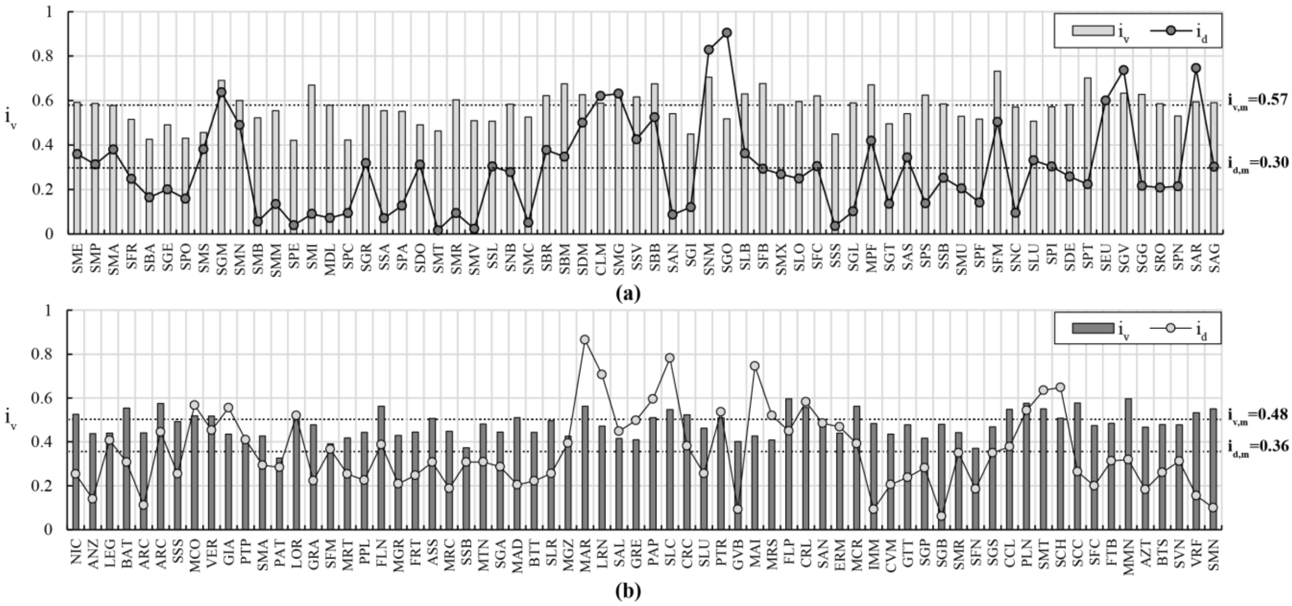

Fig. 3 – Vulnerability indexes for L'Aquila (a) and Central-Italy (b) churches

Since the considered churches have been subjected to a wide range of seismic intensities, a qualitative correspondence cannot be appreciated by the comparison between the damage and the vulnerability indexes. Therefore, in Fig.4 the observed damage indexes are provided in overlapping to the macro-seismic intensity maps (MCS scale) of the two relative seismic events (for the Central-Italy sequence, the Norcia event of 30th October 2016 has been considered). As can be noted, the damage levels exhibited by the considered churches qualitatively reflect the seismic intensity, since for the both samples the most damaged churches are very close to the seismic epicentres.

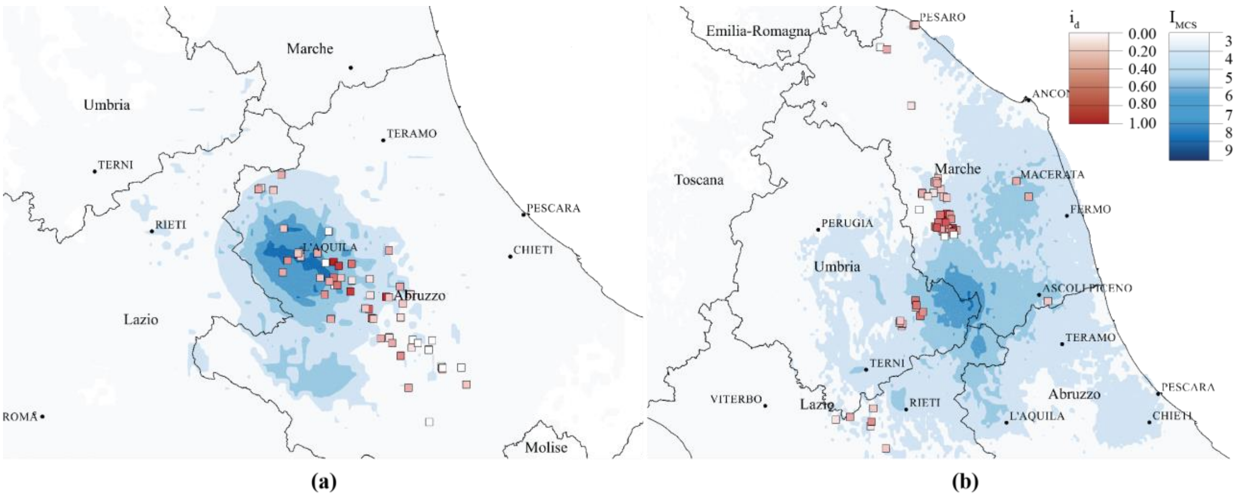

Fig. 4 – Damage index i_d for three-nave churches subjected to L'Aquila earthquake (2009) (a) and one-nave churches subjected to Central Italy earthquake (2016) (b) and overlapping with macro seismic intensity maps (MCS scale)

4. The proposed simplified vulnerability model

4.1 General

The proposed vulnerability model has been calibrated on the basis of the analyses proposed in this section in addition to the aforementioned sensitivity analysis results [20]. Based on this premise, the calibration procedure has been performed according to the following phases: i. subdivision of the total sample in homogeneous groups according to the earthquake I_{MCS} intensity experienced during the relevant seismic events; ii. evaluation of the influence of the parameters described in section 3.2 on the damage distribution observed in the subgroups of churches; iii. definition of the vulnerability model; iv. validation of the model by means of a comparison with the vulnerability index achieved with the Italian Guidelines approach.

4.2 Calibration procedure

The total sample of churches has been divided in subgroups on the basis of the I_{MCS} assigned for each site in the post-earthquake assessments [22, 23]. In particular, the defined macro-seismic intensities referred to the site of the considered churches were in the range of I_{MCS}=4÷9. Therefore, in order to investigate the influence that each parameter has on the global damage exhibited by the structures, as well as to have equally distributed sub-samples, the following groups have been defined: i. Group I: $I_{MCS} \leq 5$ (34 churches); ii. Group II: $5 < I_{MCS} < 6$ (37 churches); iii. Group III: $6 \leq I_{MCS} \leq 7$ (23 churches); iv. Group IV: $I_{MCS} > 7$ (38 churches).

Then, the calibration procedure has been carried out based on the simplified assumption that for the same earthquake intensity a church with a certain vulnerability should exhibit the same damage (as confirmed by the reliable predictive models of Eq. (1) and Eq. (2)). Hence, for each subgroup the determined damage has been graphically related to each investigated parameter. The outcomes of the above calibration procedure are shown in Fig. 5 for each selected parameter and for each subgroup of churches. In particular, each graph provides the specific characterizations of the investigated parameters on the x-axis and the values of the damage indexes on the y-axis. The dotted lines represent the tendency lines obtained by connecting the average values of the damage indexes related to each specific typological parameter.

By examining the obtained results, the following qualitative considerations can be stated.

– Churches realized before the XIII century or after the XVIII century on average exhibited a less damage level than churches built in the intermediate periods (Fig. 5a).

– Fig. 5b shows that, in case of churches belonging to Group IV, the damage level appears to be more serious for churches having smaller and larger plan area. This outcome could be ascribed, on the one hand, to the typological and structural complexity of the three-nave churches and, on the other hand, to the general poorer constructive quality of the very small one-nave churches. The outcomes arising from other sub-groups (i.e. I, II and III) could be considered less significant, since the considered range of surface extension do not result equally distributed.

– With regard to the position in the urban context, it could be asserted that when a church is isolated or surrounded by short buildings, it results more vulnerable due to the absence of effective lateral retaining elements, as can be particularly appreciate in the trend exhibited by Group I and II (Fig5c). The isolated churches are those that revealed the higher damage also in Group III and in Group IV, despite a different trend of the damage indexes has been obtained in these sub-groups of churches.

– As it could be expected, the quality of masonry plays an important role; indeed, structures realized with a good masonry pattern normally exhibited a lower damage level (Fig 5d).

– As far as plan geometric irregularity is concerned, the presence of additional elements in the church generally implies an increment of structural complexity and, as a consequence, of the seismic vulnerability, although by the obtained results this is not ever clearly appreciable (Fig 5e, 5f and 5g).

– The presence of vaults, which are generally one of the most damaged structural elements in a church in case of seismic event [24], represents a clear vulnerability indicator, as shown in Fig 5h.

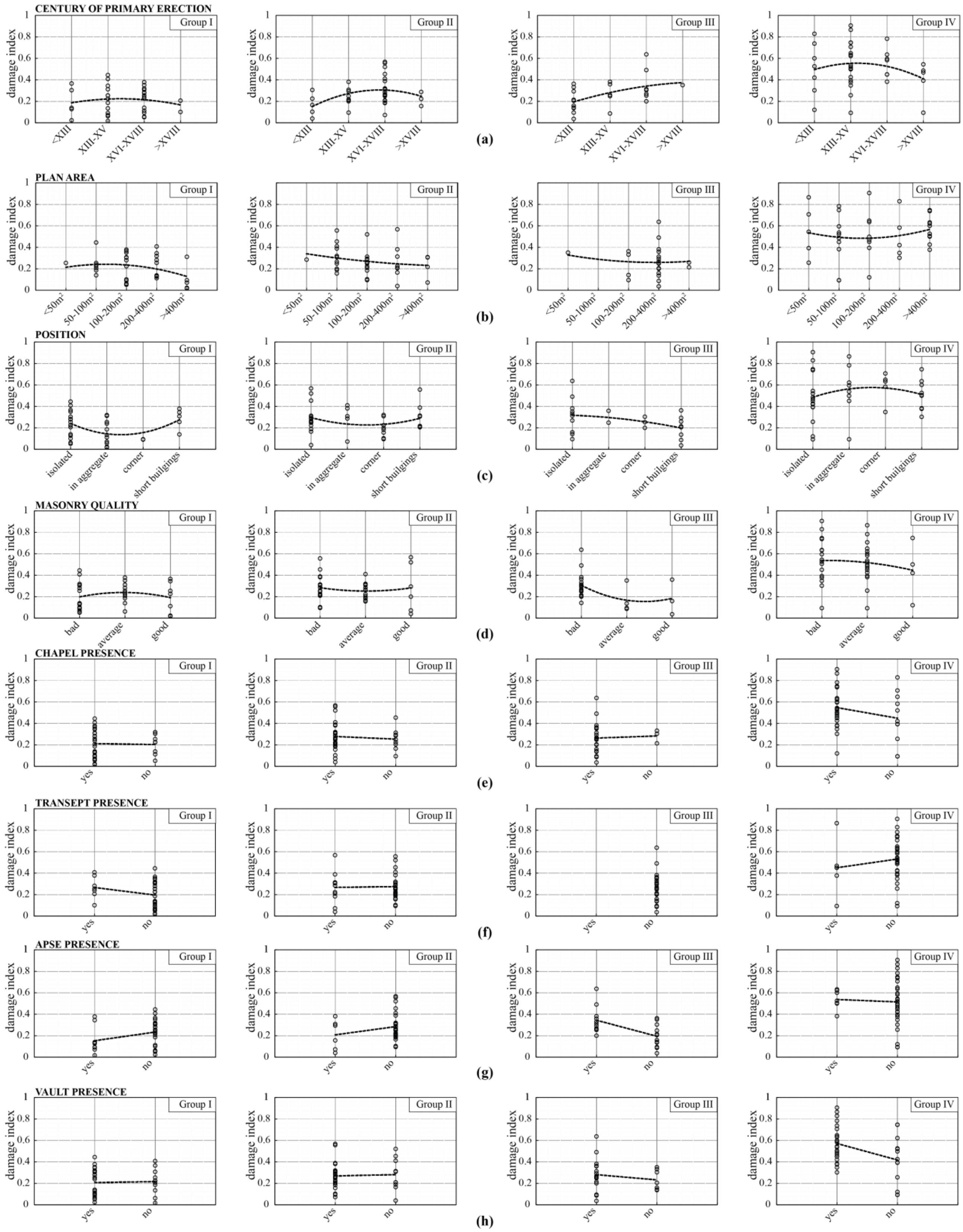

Fig. 5 – Calibration of the vulnerability model: century of primary erection (a), plan area (b), position (c), masonry quality (d), chapel presence (e), transept presence (f), apse presence(g) and vault presence (h).

4.3 Proposed interpretative model

Based on the above calibration procedure, a simplified vulnerability model has been implemented. In particular, the formulation proposed for the assessment of the vulnerability index of an existing church is reported in Eq. (5):

$$i_v = \frac{1}{6} \cdot \frac{\sum_{k=1}^{9} \rho_k \cdot v_k}{\sum_{k=1}^{9} \rho_k} + \frac{1}{2} \tag{5}$$

where v_k is the score assigned for each condition of the considered parameter, while ρ_k is the importance factor. The values to be assumed for v_k and ρ_k are reported in Table 1.

In order to check the reliability of the proposed model, a comparison between the obtained outcomes and those arisen from the application of the MaChro form has been carried out in both qualitative and quantitative terms. Three different vulnerability classes have been preliminary defined: low vulnerability class (LV, i_v<0.4), medium vulnerability class (MV, 0.4≤i_v≤0.6) and high vulnerability class (HV, i_v>0.6). Hence, the comparison in terms of vulnerability index has been carried out considering separately the L'Aquila and the Central-Italy samples of churches, as well as the entire stock of churches. The obtained outcomes are shown in Fig. 6, where the percentages of occurrence of the vulnerability index of the considered churches into the three vulnerability classes and evaluated according to the two different methods are reported.

It is possible to observe that the proposed model provides an acceptable correspondence with the more refined method, for the both church samples (Fig. 6a and 6b) as well as for the total stock of churches (Fig. 6c). In particular, it is worth noticing that by applying such a simplified method, in more than 80% of analyzed cases the obtained vulnerability class agrees with those arisen from the more refined MaChro form application based on the Italian Guidelines provisions.

In order to further corroborate the reliability of the proposed model, an additional comparison has been carried out between the values of the vulnerability index obtained with the proposed vulnerability model and the existing one for each considered church. The obtained results are showed in Fig. 7, where the percentage error Δ% between the vulnerability index determined by the MaChro form approach ($i_{v,MC}$) and that evaluated according to the proposed methodology ($i_{v,p}$) is provided according to Eq. (6).

$$\Delta\% = 1 - \frac{i_{v,MC}}{i_{v,p}} \tag{6}$$

Also in this case, the outcomes show a good correspondence, with difference percentage values less than 10% for most of the cases. Therefore, in the whole, the proposed model results seem to be suitable, providing an acceptable accuracy for vulnerability prediction, despite it is based on few qualitative information.

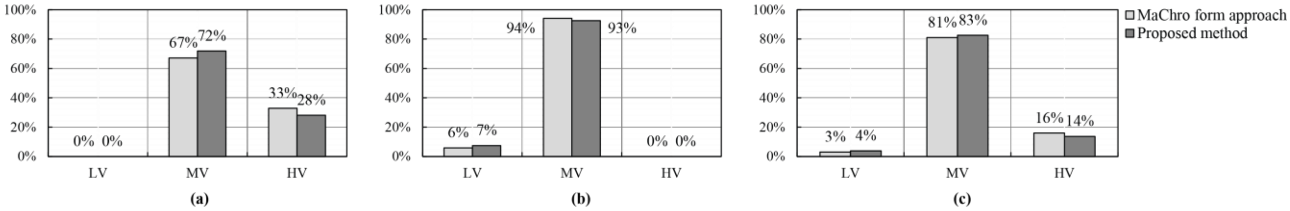

Fig. 6 - Comparison between the proposed model and the Italian Guidelines approach: three-nave churches (a), one-nave churches (b) and total stock (c)

Table 1 – Vulnerability model proposal: scores of the v_k and ρ_k parameters

Parameter	ρ_k	**condition**	v_k
Century of first erection	1/7	<XIII century	-1
		XIII-XV century	+1
		XVI-XVIII century	+1
		>XVIII century	-1
Plan area	1/7	< 50m^2	+1
		50-100 m^2	-1
		100-200 m^2	-1
		200-400 m^2	+1
Position in the urban context	1/7	isolated	+1
		in aggregate	-1
		corner	-1
		short buildings	+1
Masonry quality	1/7	bad	+1
		average	0
		good	-1
Plan-height irregularity	1/21	Chapels present	+1
		Chapels absent	-1
	1/21	Apse presents	+1
		Apse absents	-1
	1/21	Transept presents	+1
		Transept absents	-1
Vault presence	1/7	Vaults present	+1
		Vaults absent	-1
Plan typology	1/7	Three-nave	+1
		One-nave	-1
		Other	0

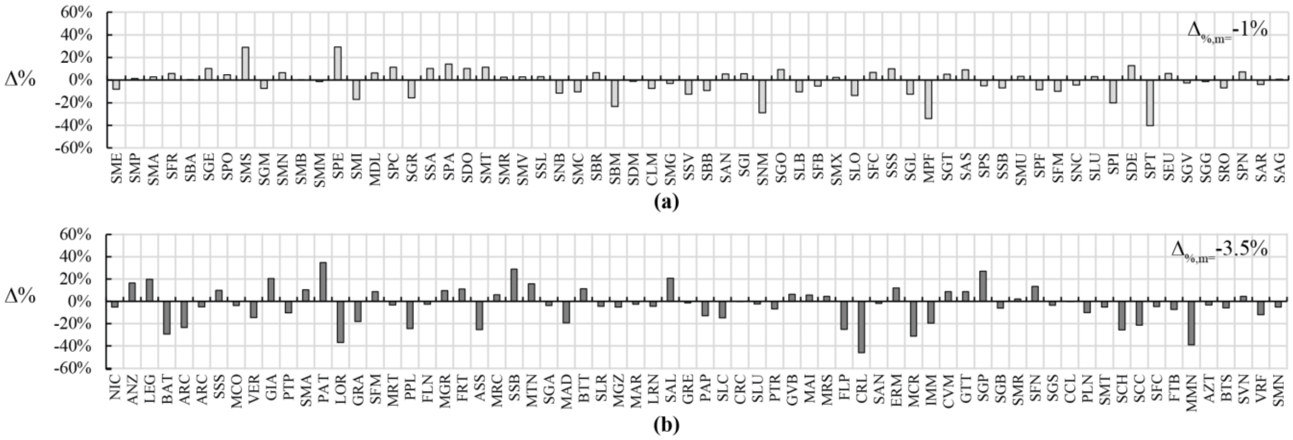

Fig. 7 – Comparison in terms of vulnerability index between the proposed model and the Italian Guidelines approach: percentage errors for three-nave churches (a) and one-nave churches (b)

5. Conclusion and further developments

The existing masonry churches may have a very high seismic vulnerability, as it was proven by many the recent earthquakes. Considering the large amount of churches present in many countries, as for instance in the Italian territory, as well as their architectonical, artistic and also social value, it is clear that the problem of preserving such a heritage must be faced by adopting adequate preventive strategies. In this context, in the present study a simplified procedure for the seismic vulnerability assessment of existing masonry churches is proposed with the aim to define a toll which could be used to develop national seismic risk maps. The proposed typological model, which has been calibrated on the basis of the data collected in the aftermaths of the seismic events of L'Aquila (2009) and Central-Italy (2016-17), could provide vulnerability classes of churches according to few typological parameters which could be available at a national scale. Despite its simplicity, the proposed model has shown a very good correspondence in both qualitative and quantitative terms with the results obtained by applying more refined vulnerability models which are already available in literature. Therefore, it appears to be suitable to assess the seismic vulnerability of a large stock of churches by considering a territorial scale approach, based on few and simple typological information. Nevertheless, the proposed method has to be considered as a first attempt and it should be furtherly checked and verified based on additional and larger comparative analyses.

6. Acknowledgements

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