Seismic vulnerability assessment of churches at regional scale after the 2009 L'Aquila earthquake

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Abstract: The extension of damage on churches observed after strong earthquakes stresses the need to define suitable speedy methods for the assessment of the main sources of structural fragility for these constructions. This paper presents a methodology for seismic vulnerability assessment of churches based on a damage reconnaissance activity carried out after the 2009 L'Aquila earthquake on a population of 64 churches. Firstly, the post-earthquake evaluation of damage is described aiming at identifying recurrent damage mechanisms. It has been observed that the occurred damage scenario, shown through damage probability matrixes, can be represented by a binomial distribution, which depends only on mean damage level. Then, a literature predictive model is applied for outlining fragility curves, which represent a useful tool for prediction of likely damage scenarios. Finally, some ongoing applications of the proposed analysis methodology to churches of different territorial areas are described.

Keywords: seismic vulnerability; cultural heritage; old churches; structural damage; fragility curves.

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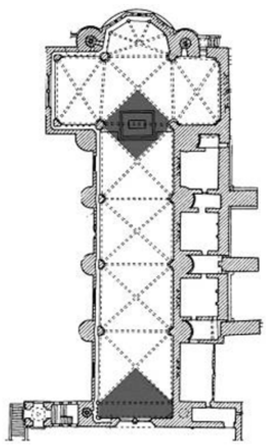
1 Introduction

Old masonry churches represent one of the most important assets of the Italian cultural heritage. The connection between seismic risk and conservation of such a type of structures is a topic of great importance in terms of both protection and losses prevention (Contestabile et al., 2016; Gesualdo et al., 2017).

Earthquakes occurred in the last 20 years in the Apennines (i.e., Umbria e Marche earthquake, 1997; L'Aquila earthquake, 2009; Emilia Romagna earthquake, 2012; Central Italy earthquake, 2016) evidenced the fragilities of old masonry churches and testified, once again, the importance of defining useful protection strategies to preserve their structural integrity, which often means historical identity of wide territories (Brandonisio et al., 2013; Criber et al., 2015). Indeed, the seismic protection of churches is not only a matter of cultural identity, but also a social and political issue, because, in an urban context, churches often represent the most important site of aggregation of people (Alessandri et al., 2012). Generally, awareness on modification of structures over the time is of utmost importance to obtain a reliable vulnerability assessment of historical buildings. In fact, these constructions very often have been altered by successive operations, whose structural influence has to be considered to define suitable restoration and retrofitting interventions (Bergamasco et al., 2017).

Figure 1 St. Francesco d'Assisi basilica



Note: Damages on the vault after the 1997 earthquake.

A meaningful example of how important is to protect churches from earthquake attacks is given by the partial collapses of the St. Francesco d'Assisi (PG) central vault (Umbria e Marche earthquake, 1997), shown in Figure 1, which caused not only human fatalities, but also losses of important and valuable frescoes.

The importance of protecting churches in order to preserve inestimable assets was also stressed by more recent earthquakes. The collapse of the transept of the basilica of Collemaggio [Figure 2(a)] in L'Aquila, which is a meaningful example of Romanesque architecture, represented the loss of an important part of the Abruzzi cultural heritage. Likewise, the recent seismic event of Centre of Italy (2016) irremediably struck one of the most significant medieval basilica of Umbria, the St. Benedetto church in Norcia: today, the façade and the apse are the only parts of the church that survived to the earthquake [Figure 2(b)].

Figure 2 (a) St. Maria di Collemaggio basilica (AQ) after L'Aquila earthquake (2009) and (b) St. Benedetto basilica in Norcia (PG) after the Centre of Italy earthquake (2016)

(a) (b)

On the other hand, it has to be recognised that the correct and precise evaluation of the structural behaviour of churches and more in general of monumental buildings, is very complex, due to specific issues related to the adopted constructional criteria (Calderoni et al., 2008). Due to the difficulty related to material modelling but also the geometrical complexity of the manufactures, the detailed specific analysis should be very elaborated and time consuming (Brando et al., 2015) or should be based on specific approximated methodologies, for instance the one proposed in (Ercolano, 1994; De Luca et al., 2004; Huerta, 2008; Addessi and Sacco, 2016), which are applicable in many but not all the situations.

All the above remarks emphasise the necessity to define suitable speditive vulnerability assessment methodologies at large-scale, which are able to predict potential likely damages scenarios. These methodologies have to account for the recurrent damage mechanisms observed on churches after earthquakes of the past, as well as for possible protection devices (i.e., iron ties, buttresses, connecting elements across the walls, etc.) that have been already installed for removing or mitigating some structural fragility sources. For instance, the possibility to use simplified methods is shown in Lourenço and Roque (2006), where a geometric approach is used to retrieve back simplified safety indexes, with the aim to define an immediate screening of a certain number of historical buildings and to priorities more detailed numerical analysis.

In this paper, the vulnerability assessment at large-scale of churches is dealt with. To this purpose, a methodology taken from existing literature and corroborated by post-earthquake observation carried out on a population of 64 three-nave churches after the 2009 L'Aquila earthquake in two of the most stricken dioceses of Abruzzi region is applied. In Section 2, the churches considered for the reconnaissance and the observed damage revealed after L'Aquila earthquake are described. Moreover, damage is classified in terms of severity and extension, in order to provide damage probability matrices (DPMs). These matrices provide a synthetic description of the occurred earthquake scenario corresponding to the occurred earthquake. In Section 3, the methodology for the vulnerability assessment is dealt with and used in order to provide fragility curves, which are able to predict damage scenarios for different earthquake intensity. In the following, the proposed methodology is referred to the population of 64 three nave churches identified in L'Aquila district. Finally, in Section 4, the ongoing research activity on churches belonging to a different territory is outlined, giving a first typological and structural description of identified buildings. It is worth noticing that issues provided in this paper has been presented by the authors also in previous studies, were the approach was mainly of observational type, i.e., aimed at evaluating by analytical procedure the damage scenario observed after the L'Aquila earthquake. Now, the intention of the author is to check the possibility to apply the proposed methodology also for preventive purposes, by defining a specific vulnerability index (i_v) to assess structural capacity of a large population of churches for predicting possible damage scenarios due to future earthquakes in different regions (De Matteis et al., 2016a).

2 The churches of L'Aquila and Sulmona-Valva dioceses

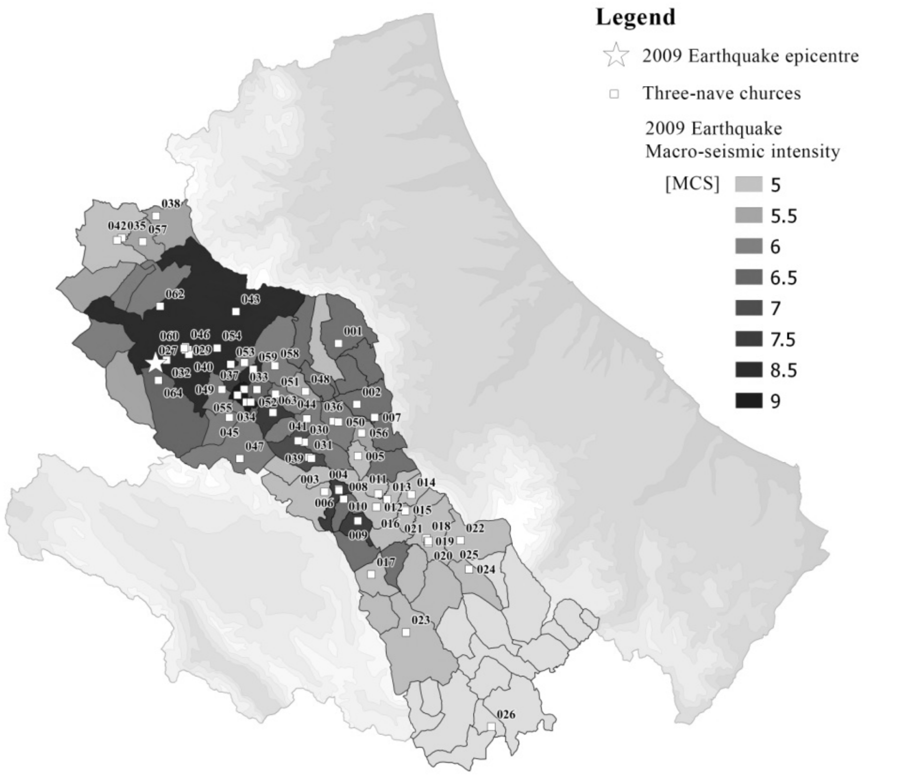
2.1 General

L'Aquila is the capital city of Abruzzi and is located in the inner part of the region. The district extends on almost half of the regional territory and covers three ecclesiastical areas. In particular, the dioceses of L'Aquila and Sulmona-Valva, which are shown in Figure 3, together with the acronyms used in the following parts of the paper, were the most affected by the 2009 seismic event and for this reason, they have been studied more in detail (Criber et al., 2015; Brando et al., 2015). In the investigated area, almost 640 churches, located in 77 municipalities, were identified. Among these, the 10% (64) are three nave churches: they were identified as belonging to the most representative typology and therefore, have been specifically considered for the reconnaissance activity; in fact, their structural complexity provides more interesting information in terms of vulnerability sources and collapse mechanisms.

2.2 Typological classification of churches under investigation

The observed group of churches was classified according to the foundation period, as well as to the structural construction techniques. However, this classification was not always clear because churches of inner Abruzzi are strongly marked by significant stratifications, due to the several reconstructions and restorations carried out in the past (Rovida et al., 2011), in particular after the earthquakes occurred in 1461 in L'Aquila (10 MCS), 1703 in the North of L'Aquila (10 MCS), 1706 near to Sulmona and 1915 in Avezzano (11 MCS).

Figure 3 The three naves churches in L'Aquila and Sulmona-Valva dioceses



001	**SME**	San Marco Evangelista	023	**SMV**	Santa Maria delle Valle	045	**MPF**	Chiesa di S.Maria e S.Pietro
002	**SMP**	Santa Maria della Pace	024	**SSL**	San Salvatore	046	**SGT**	Chiesa di San Giovanni Battista
003	**SMA**	San Martino	025	**SNB**	San Nicola di Bari	047	**SAS**	Chiesa di Santa Maria Assunta
004	**SFR**	San Francesco	026	**SMC**	Santa Maria del Carmelo	048	**SPS**	Chiesa di Santa Maria in Pant.
005	**SBA**	San Benedetto Abate	027	**SBR**	Chiesa di San Bernardino	049	**SSB**	Chiesa di San Sebastiano
006	**SGE**	San Giovanni Batt ed Ev.	028	**SBM**	Chiesa di San Biagio d'Amit.	050	**SMU**	Chiesa di Santa Maria in Cer.
007	**SPO**	San Pietro ad Oratorium	029	**SDM**	Chiesa di San Domenico	051	**SPF**	Chiesa di San Panfilo d'Ocre
008	**SMS**	Santa Maria Assunta	030	**CLM**	Basilica di S.Maria di Collem.	052	**SFM**	Chiesa di San Felice Martire
009	**SGM**	Santa Gemma	031	**SMG**	Chiesa dei Ss. Mass. e Giorgio	053	**SNC**	Chiesa di San Nicandro
010	**SMN**	Santa Maria Nova	032	**SSV**	Chiesa di San Silvestro	054	**SLU**	Chiesa di Santa Lucia
011	**SMB**	Santa Maria del Borgo	033	**SBB**	Chiesa di San Benedetto Abate	055	**SPI**	Chiesa di San Pietro
012	**SMM**	Santa Maria Maggiore	034	**SAN**	Chiesa di Santa Maria Assunta	056	**SDE**	Chiesa di San Demetrio
013	**SPE**	San Pelino	035	**SGI**	Chiesa di San Giustino	057	**SPT**	Chiesa di San Pietro Celestino
014	**SMI**	San Michele Arcangelo	036	**SNM**	Chiesa dei Ss. Nican. e Marc.	058	**SEU**	Chiesa di Sant'Eusanio Martire
015	**MDL**	Madonna della Libera	037	**SGO**	Chiesa di San Gregorio Magno	059	**SGV**	Chiesa di San Giovanni Evang.
016	**SPC**	San Pietro Celestino	038	**SLB**	Chiesa di San Lorenzo	060	**SGG**	Santi Giusta e Giorgio
017	**SGR**	Santa Maria delle Grazie	039	**SFB**	Chiesa di San Flaviano	061	**SRO**	Chiesa di Santa Maria della R.
018	**SSA**	Santissima Annunziata	040	**SMX**	Chiesa di S. Maria di Pic. E.M.	062	**SPN**	Chiesa di Santa Maria del Ponte
019	**SPA**	San Panfilo	041	**SLO**	Chiesa di Santa Maria del Loreto	063	**SAR**	Chiesa di San Michele Arcang.
020	**SDO**	San Domenico	042	**SFC**	Chiesa di San Flaviano	064	**SAG**	Chiesa di Sant'Agata
021	**SMT**	Santa Maria della Tomba	043	**SSS**	Chiesa di Santa Maria Assunta			
022	**SMR**	Santa Maria Maggiore	044	**SGL**	Chiesa di San Giovanni Battista			

Note: Localisation on the 2009 earthquake macro-seismic intensity map (MCS scale).

In particular, for the sake of simplicity, three main different types of churches were identified: *medieval*, *post-medieval* and *hybrid* churches.

The first group, including almost 20% of the whole population considered in the study, is composed by churches built from 11th to 14th century, generally characterised by poorness of decorations (a typical feature of the churches built in this period in the central part of Italy, see De Matteis and Mazzolani, 2010) and by a low seismic vulnerability. This is mainly due to the plan simplicity, the absence of transept and dome, the presence of a light wooden roof and a masonry of good quality. For instance, the church of San Pietro ad Oratorium (SPO) in Capestrano in the Diocese of L'Aquila [Figure 4(a)] is an important example of *mediaeval* church. Generally, the churches belonging to this group suffered low damage during the last L'Aquila earthquake.

The second group is composed by *post-medieval* churches (almost the 20% of the analysed stock), built between 15th and 17th centuries (Renaissance and Baroque period), which is characterised by a medium seismic vulnerability. These churches are generally characterised by a rectangular plan with three naves crossed by a transept and surmounted by a dome at the intersection, as observed in Madonna della Libera (MDL) church in Pratola Peligna (Diocese of L'Aquila), which is shown in Figure 4(b). In these cases, heavy vaults or mixed roofs are always present. The masonry is commonly made of rubble stones characterised by a chaotic texture.

The third group, namely the *hybrid* churches (almost the 60% of the whole analysed population), is composed by churches characterised by many stratifications and structural variations, often following the main seismic events occurred in the past in a specific territory (Giannantonio, 1988, 2000), implemented without effective structural design, leading sometimes to a worsening of the global structural response. The basilica di Santa Maria di Collemaggio (CLM) [Figure 4(c)] in L'Aquila represents one of the most important example of *hybrid* churches.

Figure 4 (a) SPO in Capestrano (AQ) (b) MDL in Pratola Peligna (AQ) (c) CLM basilica in L'Aquila (AQ)

(a) (b) (c)

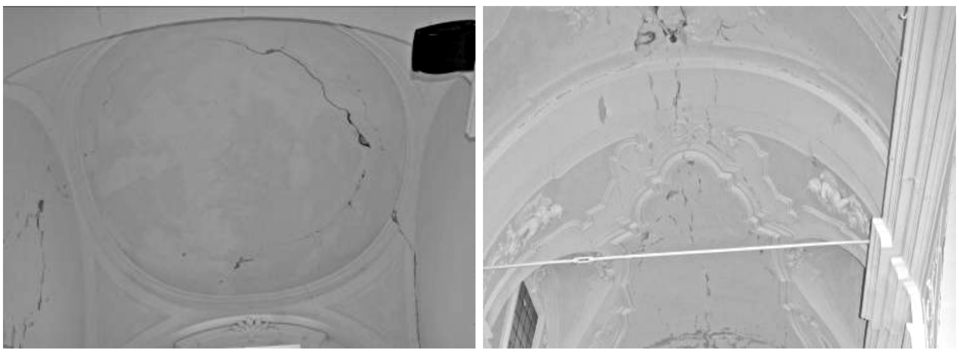
2.3 Survey of the main damage mechanisms

The most recurrent damage type is represented by cross diagonal cracks due to second mode mechanism type. This is associated to the in plane response of the wall, which is loaded by shear loads. Such type of mechanism has been frequently found on lateral walls, bell towers and domes, in particular when these elements were characterised by a poor masonry fabric (Figure 5). Vaults were characterised by significant damage, in particular for elliptical configurations, where fractures along both the diagonal directions and the circular spring-lines have been highlighted [Figure 6(a)]. Important damage has been observed also in barrel vaults, with longitudinal cracks generally localised along the key-stones [Figure 6(b)].

Figure 5 Diagonal cracks on wall after the 2009 seismic event, (a) bell tower of the St. Bernardino (SBR) church in L'Aquila (b) lateral walls in St. Eusanio (SEU) church in Sant' Eusanio Forconese (AQ) (c) apse in St. Massimo and Giorgio (SMG) church in L'Aquila

(a) (b) (c)

Figure 6 Observed damages on (a) elliptical vaults and (b) barrel vaults of St. Maria Nova (SMN) church in Goriano Sicoli after the 2009 seismic event



(a) (b)

In pillars, vertical cracks due to crushing phenomena have been sometimes relieved. These have been probably induced by the increasing compression stresses, due to the earthquake vertical component, which, even far from the epicentre, was often significant due to site effects (De Matteis et al., 2016b). The above failures are particularly evident on those columns made of rubble masonry (typical of *post-medieval* and *hybrid* churches), where cracks along the mortar have been observed (Figure 7).

Figure 7 Observed damages after the 2009 seismic event on rubble masonry pillars of St. Gemma (SGM) church in Goriano Sicoli (AQ)

Figure 8 Façade overturning in SGM church in Goriano Sicoli (AQ)

A heavy damage has been observed on churches where reinforced concrete roof or beams have been added in recent years without effective connection with the vertical walls. The presence of these elements is evident in those churches affected by horizontal sliding cracks at the ring beams at the top of the walls. Out-of-plane mechanisms have been identified when macro-elements resulted not correctly endowed with a proper number of well dimensioned ties. For the analysed churches, three main out-of-plane phenomena have been recognised: the rigid façade overturning, the façade top-corner overturning and the apse overturning. The first type of mechanism was evident, for example, in the SGM church in Goriano Sicoli (in the Sulmona-Valva Diocese). This church showed a fully developed mechanism, with a detachment between the façade and the lateral walls of about the thickness (Figure 8). The façade top-corner overturning has been detected when, even in presence of longitudinal ties that effectively constrained the rigid overturning of the whole façade, the corner connection was clearly inefficient due to the lack of restraining element [see Figure 9(a)]. Finally, the third type of overturning mechanism concerned the apse. It was generally due to a bad connection or to the presence of wide openings. A meaningful example is the case of St. Martino (SMA) church in Gagliano Aterno, where the diagonal cracks, typical of this mechanism, have been surveyed [see Figure 9(b)].

Figure 9 (a) Top-corner overturning on St. Maria della Pace church in Capestrano and (b) apse overturning on SMA church in Gagliano Aterno

(a) (b)

2.4 *Damage classification*

Consistently with the Italian code *Guidelines for Cultural Heritage* (MiBACT, 2011), the classification of the observed damage has been carried out accounting for 28 mechanisms referred to the main macro-elements (i.e., the façade, the colonnade, the vaults, the apse, the transept, the dome and the bell tower). For each mechanism, a specific level of damage d_k ($0 \leq d_k \leq 5$), has been defined according to the criteria introduced by Grunthal for the European Macroseismic Scale EMS-1998 (Grunthal, 1998). In Figure 10, the Grunthal definition of damage levels, proposed for residential buildings, is related to churches, according to the criteria described in De Matteis et al. (2016b). Then, according to equation (1) proposed in guidelines, a global damage index (i_d), ranging from 0 (no damage) to 1 (full damage), has been calculated for each church belonging to the analysed stock. The results are given in Figure 11.

$$i_d = \frac{1}{5} \cdot \frac{\sum_{k=1}^{28} \rho_{k,i} \cdot d_{k,i}}{\sum_{k=1}^{28} \rho_{k,i}} \tag{1}$$

In equation (1), ρ_k is an importance factor that weights the damage of the mechanism k (ranging from 1 to 28) according to the importance that the mechanism itself has for the global stability of the church. The considered values are given in MiBACT (2011). Each damage index i_d has been therefore related to a damage score D_k (ranging from 0 to 5), accounting for the criteria provided by Lagomarsino et al. (2004). For each church, the obtained score D_k is shown in Figure 12. The statistical elaboration of the damage scores D_k for churches as a whole and for the single macro-elements (in this case, d_k coincides with D_k), allowed to determine the related DPMs, shown in Figure 13, which provide the frequency of occurrence of the different levels of damage D_k.

Figure 10 Damage classification for masonry churches according to the Grunthal approach

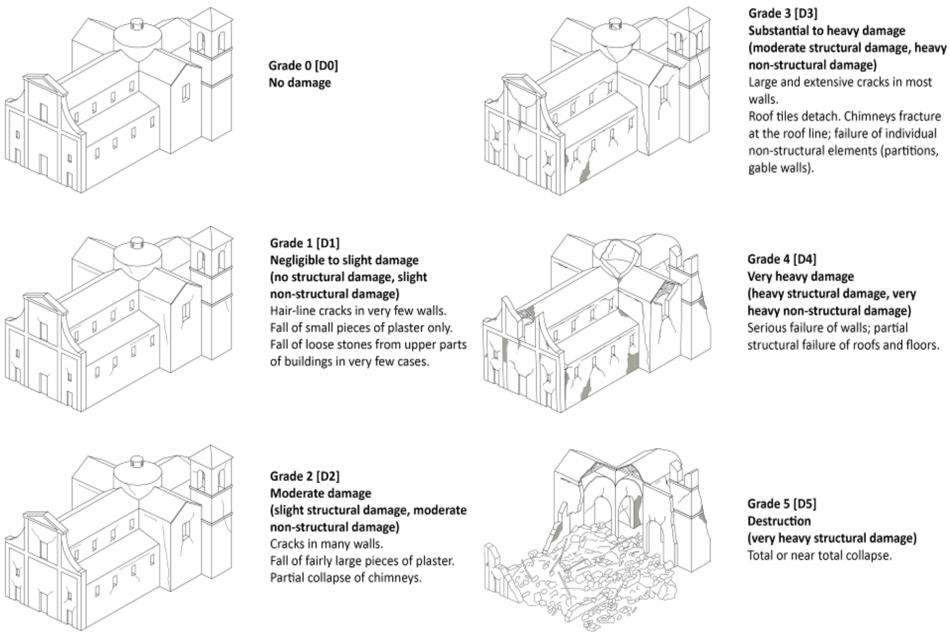
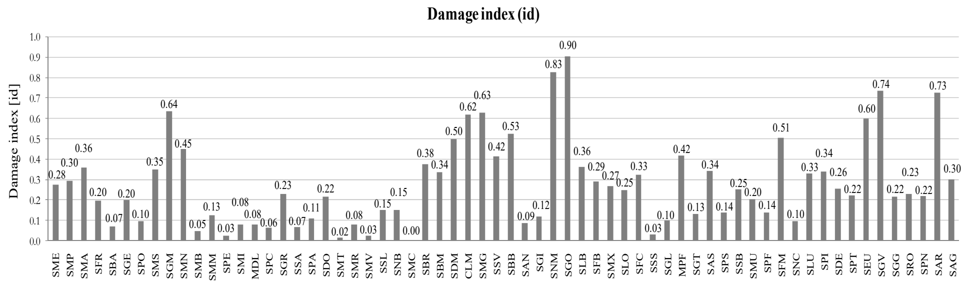


Figure 11 Damage index i_d for all the observed churches



Once the data on damage have been defined, it has been observed that a binomial probability distribution function (BPDF) fits suitably the related DPMs of both the whole churches and the single macro-elements, as shown in Figure 13. In particular, the adopted BPDF is given in equation (2), where p_k represents the probability to have a certain level of damage D_k, k ranges from 0 to 5 and represents the damage level, while μ_d is the mean damage level. The latter represents the mean value of the damage evaluated for the whole stock of observed churches; it could be referred to the damage related to either the whole church considered as a whole, in such a case it has been calculated according to equation (3) or to the damage related a specific macro-elements of the church, according to equation (4). In the case being, for the whole population of observed churches, while referring the damage to the whole church, the mean damage level μ_d, according to equation (3) resulted equal to 1.734.

$$p_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k \left(1-\frac{\mu_D}{5}\right)^{5-k} \tag{2}$$

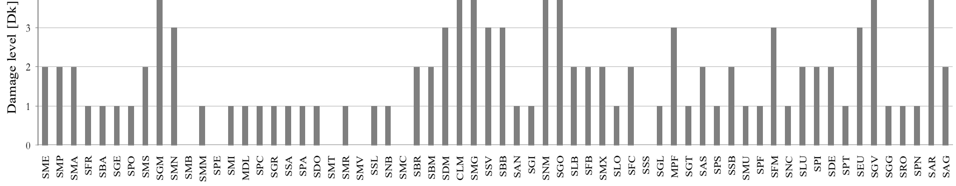
$$\mu_D = \frac{\sum_{i=1}^{n} D_{k,i}}{n} \tag{3}$$

$$\mu_D = \frac{\sum_{j=1}^{n}\left(\frac{\sum_{i=1}^{m} d_{k,i} \cdot \rho_i}{\sum_{i=1}^{m} \rho_i}\right)}{n} \tag{4}$$

In equations (2)–(4), n is the number of churches and m the number of potential relevant mechanisms. Equation (4) is a refinement of the equation used in De Matteis et al. (2016b), defined considering the weight of each mechanism in calculating the mean value of µd. Hence, the graphs shown in Figure 13 are quite different from those proposed in De Matteis et al. (2016b).

It can be observed that the binomial distribution is particularly able to retrieve back the probability of having a certain level of damage for a given earthquake. This is a significant outcome, as the above distribution depends on one parameter only, namely the mean damage μ_d. The latter could be preventively assessed based on the structural fragility of the analysed churches, allowing the application of the above procedure as a predictive tool rather than as an observational analysis.

Figure 12 Damage level d_k for all the 64 observed churches



3 Seismic vulnerability assessment: definition and applications

In order to define predictive models for predicting possible damage scenarios, the expected mean damage μ_d should be preventively related to structural characteristics affecting the vulnerability of the churches of the analysed population. To this purpose, a procedure based on the definition of vulnerability index of the church i_v given by the *Italian Guidelines on Cultural Heritage* (MiBACT, 2011) has been applied after a suitable modification. Therefore, each church has been partitioned into macro-elements, accounting the 28 likely mechanisms defined in the previous section. Then, for each potential mechanism, fragility indicators and possible protection devices have been suitable defined and associated to a score ranging from 0 to 3. A score $v_{ki} = 0$ applied to structural fragilities means that the mechanism itself does not represent a source of vulnerability for the building, whereas a score of 3, means that it is characterised by the maximum fragility and therefore, it is prone to experience damage also for slight earthquakes. Similarly, a score $v_{k,pi} = 0$ applied to a protection device related to the mechanism i means that it is absent or completely un-effective for the elimination of that collapse mechanism. On the contrary, a score of 3 indicates the maximum effectiveness of the protection device for the collapse mechanism under consideration.

In this study, the evaluation of each score has been implemented by the definition of specific coefficients (i.e., z, w, f and η), which, for the sake of brevity are not fully provided in this paper, but are detailed in De Matteis et al. (2014) and are applied according to equations (5) and (6) for fragility indicators and anti-seismic devices scores, respectively:

$$v_{k,i} = \sum_{i=1}^{n} w \cdot z \cdot f \tag{5}$$

$$v_{k,p} = \sum_{i=1}^{n} w \cdot z \cdot \eta \tag{6}$$

In equations (5) and (6), z is a Boolean coefficient, which can be equal to 1 or 0, depending on the presence/absence of the fragility indicator and protection devices, for equations (5) and (6), respectively. The w coefficient is an importance factor ranging from 0 to 2. In equation (5), it represents the potentiality of the fragility indicator in determining the vulnerability of the mechanism, as well as, in equation (6), it is a measure of the capability of the applied protection device typology for inhibiting or limiting the mechanism development. For example, the vulnerability induced by irregularities has to be considered more important and influencing in those cases where there are irregularities both in elevation and in plan rather than in cases where only one irregularity is present. Similarly, constraining devices, as the buttresses or the ties, may have a different importance for out-of-plane mechanisms of a wall. The fragility coefficient f measures the effectiveness of the indicator and it ranges from 0 (in those cases for which the indicator does not influence the activation of the failure activation) to 1.5 (in case of fully vulnerability with respect to the onset of the failure). At the same manner, the efficiency coefficient η measures the effectiveness of the anti-seismic system that mitigated the possible failure. It also ranges from 0 to 1.5.

As an example, in the out of plane mechanism of the façade, the w coefficient for ties is set to 1, considering their effectiveness in overturning mechanism. If ties are actually present, the Boolean coefficient z is fixed equal to 1, whereas the efficiency coefficient η is set to 1.5 in case of totally effectiveness of devices. Similarly, the presence of opening at the corner has an important effect in the development of out of plane mechanism of façade. In this case, w is set to 1.5, z is fixed to 1 in case of presence, while the fragility coefficient f is set to 1.5 in case of large opening presence.

The scores described above have been used in order to obtain, for each building, the vulnerability index i_V given in equation (7), according to the definition proposed in MiBACT (2011), which is calibrated in order to retrieve back values ranging from 0 to 1.

$$i_v = \frac{1}{6} \cdot \frac{\sum_{k=1}^{28} \rho_{k,i}\left(v_{k,i} - v_{k,p}\right)}{\sum_{k=1}^{28} \rho_{k,i}} + \frac{1}{2} \tag{7}$$

In equation (7), ρ_k is the importance factor already provided in equation (1). As a matter of example, in Figure 14, the vulnerability indices of the churches of the two dioceses described in Section 2 are given.

Values ranging between i_V = 0.422 (St. Pelino and St. Pietro Celestino churches, in the Sulmona-Valva Diocese) and i_V = 0.705 (Ss. Nicandro and Marciano church, in the L'Aquila Diocese) have been founded, with a mean value of the obtained vulnerability indices equal to 0.568.

Figure 13 Damage probability matrix of the 64 observed churches vs. binomial distribution

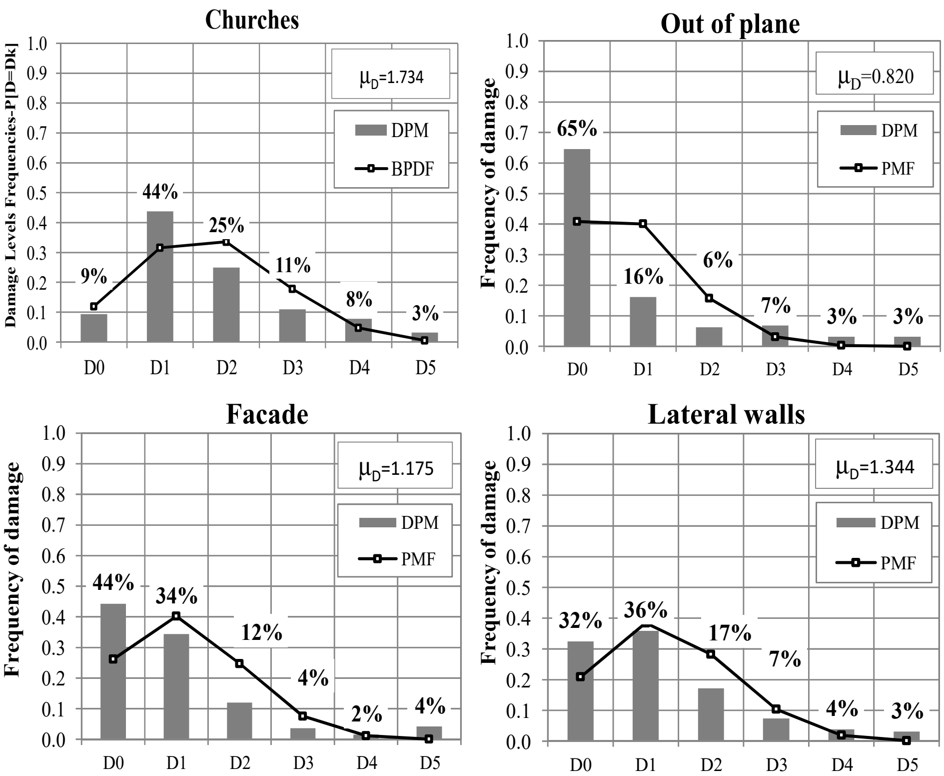
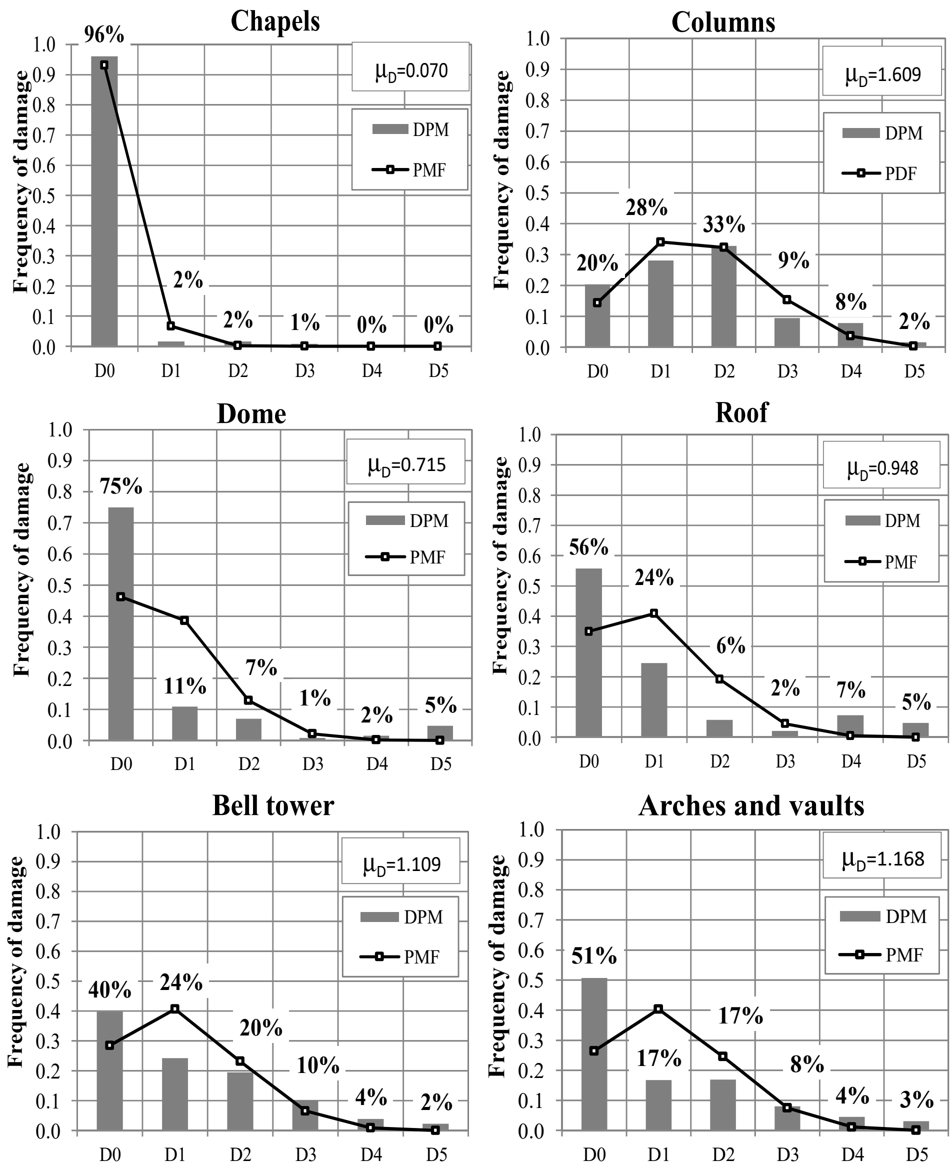


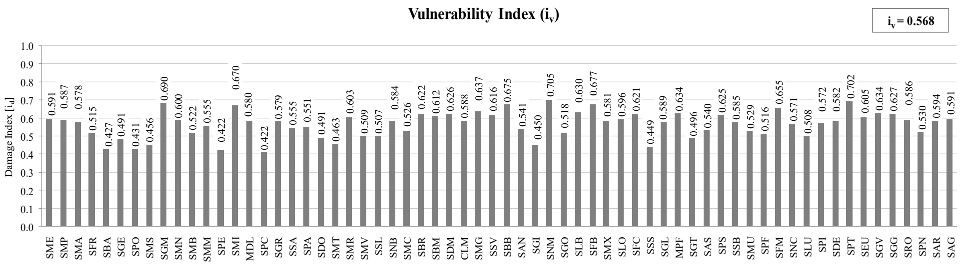
Figure 13 Damage probability matrix of the 64 observed churches vs. binomial distribution (continued)



The above mean value can be used for determining the expected mean damage for several earthquakes of macro-seismic intensity *I*, according to equation (8) already used in other studies, such as the ones described in Lagomarsino and Podestà (2004) and Lagomarsino and Giovinazzi (2006).

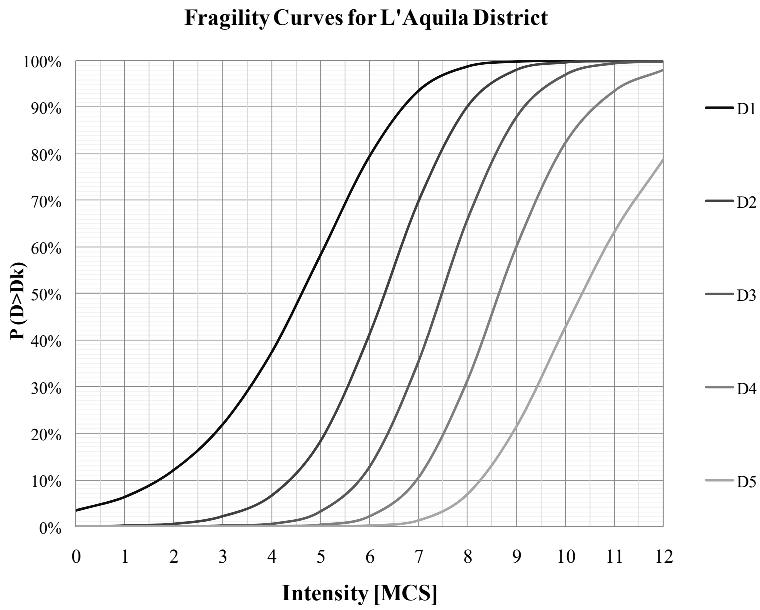
$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+3.4375\cdot\bar{i}_v-8.9125}{3}\right)\right] \tag{8}$$

Figure 14 Vulnerability indexes for the 64 churches observed in the Sulmona-Valva and L'Aquila dioceses



It is worth of being noticed that most of the 64 churches considered in this paper experienced a macro-seismic intensity *I* of about 6 (the average is 6.3, indeed). The mean damage that can be obtained for this earthquake intensity is equal to 1.75, which is almost equal to the mean value obtained downstream the damage reconnaissance activity (1.73), this meaning that the proposed methodology is quite reliable in reproducing the damage observed after L'Aquila earthquake. Obviously, this is a rough conclusion because a more precise evaluation of the reliability of equation (8) should consider separate stocks of buildings for different earthquake intensity levels. The methodology described above has been used in order to outline damage scenarios for several earthquake intensities, by getting out, for each damage level D_k, the related fragility curves. Through the use of BPBDF, previously introduced and given in equation (2). The outcome results allow to give back the probability of exceeding of a certain level of damage [$P(D \geq D_k) = \sum p_j$; with $1 \leq D_k \leq 5$], as a function of the macro-seismic intensity, considering the value of expected mean damage given by equation (8).

Figure 15 Fragility curves for three nave churches in the Sulmona-Valva and L'Aquila dioceses



The obtained fragility curves are shown in Figure 15. It is clear that the proposed fragility curves may represent a powerful tool to be used for outlining possible mitigation policies based on costs-benefits analyses and on the definition of acceptable risk for different levels of expected hazard. In addition, the proposed methodology allows to appreciate the reduction of seismic risk that can be pursued by applied strategically some retrofitting interventions on a stock of churches that can lead to a reduction of the vulnerability indices and, therefore, of the damage that they could undergo for a given earthquake intensity.

4 Extension of the study: perspectives

It has been clearly proved that the above presented methodology, which is based on an approach similar to the one illustrated also in MiBACT (2011), Lagomarsino and Podestà (2004) and Lagomarsino and Giovinazzi (2006), may be applied also for preventive purposes, through the use of equation (2) and equations (5)–(8), rather than for assessing the damage scenarios observed after a specific earthquake by using equations (1)–(4). For this reason, additional studies are in progress regarding different geographical areas. In particular, two additional dioceses of Abruzzi have been identified, namely the Chieti-Vasto and the Lanciano-Ortona dioceses (Figure 16).

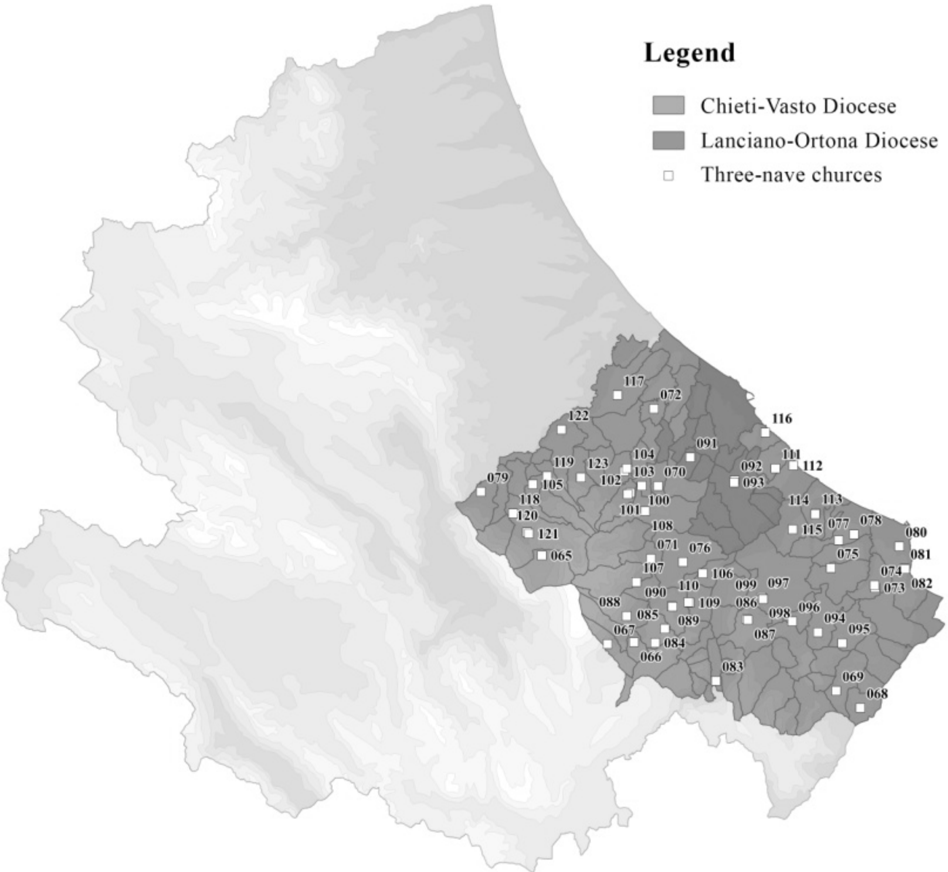
In such dioceses, 59 three nave churches have been identified as shown in Figure 16. They represent the 18% of the whole religious heritage of the investigated area. These churches are quite different by the ones belonging to the inner Abruzzi discussed in the paper. In fact, the coastal part of Abruzzi is characterised by a low seismicity, and therefore, by churches with less significant stratifications, but also with less important anti-seismic systems. On the other hand, also the type of masonry is different with respect to the churches studied in this paper. In fact, fired clay bricks are widely used due to the presence of furnaces in the territory.

Also, the Campania region is characterised by very high seismic hazard, and above all, a considerable exposition factor. In fact, due to the geographical configuration and the cultural evolution of the region, the population density is about four times larger than in Abruzzi. Moreover, both the high presence and the different concentration of churches, due to the ancient history of the Campania region, reveal a potential very high seismic fragility of such area. For such a reason this territory represents an area of interest for the application of the above presented methodology.

In the whole, the Campania region is formed by 550 municipalities, five political districts and 24 ecclesiastical administrative boundaries, (i.e., the dioceses). In the Caserta district, there are seven dioceses and several hundred parish churches have been identified (Figure 17). In such area, churches are characterised by heterogeneous features in terms of geometric proportions and architectonic style and also structural typology.

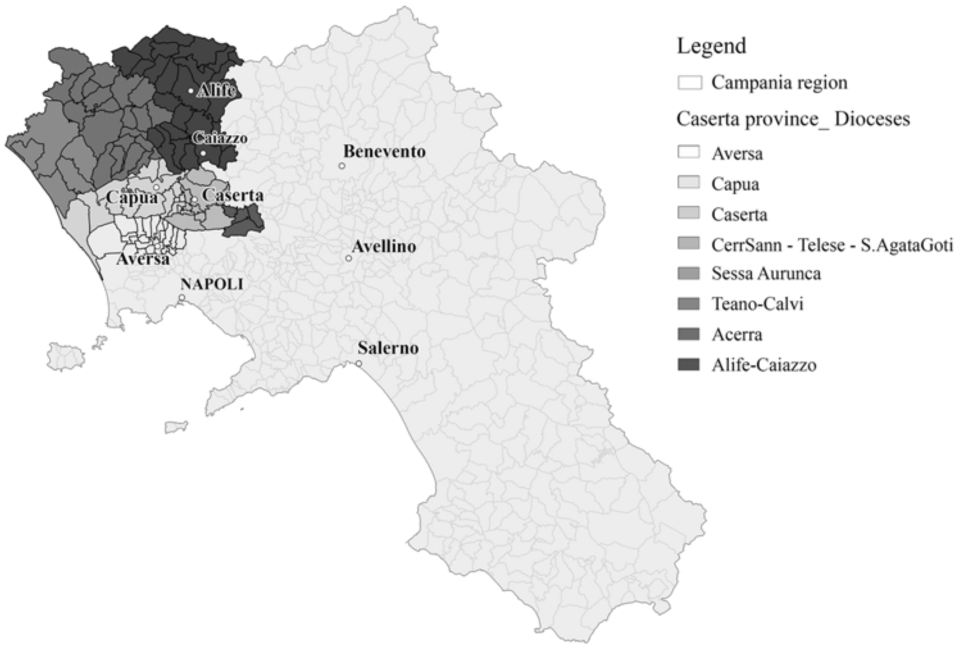
In Figure 18, the relation between the location of some churches in Caserta (including both the main dioceses of the district, namely Caserta, Capua and Aversa and the Alife-Caiazzo diocese, the latter nestled beneath the Matese massif) with population density in the area [Figure 18(a)] and the seismic hazard [Figure 18(b)] is shown. Despite the lower population density, the diocese of Alife-Caiazzo appears to be the most interesting one for the higher seismic hazard.

Figure 16 The three naves churches in Chieti-Vasto and Lanciano-Ortona dioceses



065	**SLM**	San Liberatore a Majella	087	**MDC**	Madonna di Carpineto	109	**SEU**	Sant'Eustachio
066	**SMA**	Santa Maria Arabona	088	**SCZ**	San Cristinziano	110	**MDM**	Madonna dei Miracoli
067	**SMM**	Santa Maria Maggiore	089	**SDM**	San Domenico	111	**SSL**	San Salvatore
068	**SNB**	San Nicola di Bari	090	**MDC**	Madonna della Cintura	112	**SSM**	Santa Maria Maggiore
069	**SNB**	San Nicola di Bari	091	**SCR**	Santa Croce	113	**SPN**	San Panfilo
070	**STM**	Chiesa di San Tommaso	092	**SMM**	Santa Maria Maddalena	114	**SGB**	San Giovanni Battista
071	**SGT**	Chiesa di San Giustino	093	**SSV**	San Sabino Vescovo	115	**MDG**	Madonna delle Grazie
072	**CIM**	Chiesa dell'Immacolata C.	094	**SMA**	Santa Maria assunta	116	**SMM**	Santa Maria Maggiore
073	**MAC**	Santa Maria Assunta in Cielo	095	**SMM**	Santa Maria Maggiore	117	**SMS**	Santa Maria della Serra
074	**MDL**	Chiesa Madonna di Loreto	096	**SNC**	San Nicola	118	**SML**	Santa Maria della Libera
075	**SLV**	Chiesa di San Salvatore	097	**SMA**	San Michele Arcangelo	119	**SMG**	Santa maria delle Grazie
076	**SGV**	San Giovanni in Venere	098	**MDR**	Santa Maria dei Raccomandati	120	**SGS**	Santa Giusta
077	**SMT**	San Matteo	099	**SMM**	Santa Maria Maggiore	121	**SNB**	San Nicola di Bari
078	**SPT**	San Pietro	100	**SNC**	Santi Nicola e Clemente	122	**SMM**	Santa Maria in Monteplanizio
079	**CED**	SS Cosma e Damiano	101	**MDC**	Madonna del Carmine	123	**SBT**	San Bartolomeo
080	**SSV**	San Silvestro	102	**SVT**	Santa Vittoria			
081	**RMG**	San Remigio	103	**SGM**	San Giacomo			
082	**SMP**	Santa Maria del Popolo	104	**SNC**	San Nicola			
083	**MEL**	Madonna dell'Elcina	105	**MIB**	Madonna in Basilica			
084	**SLV**	San Salvatore	106	**SMM**	Santa Maria Maggiore			
085	**MDP**	Madonna del Ponte	107	**SSA**	Santissimia Addolorata			
086	**SGV**	San Giovanni	108	**SMI**	Maria Santissima Incoronata			

Figure 17 Dioceses localisation of the Caserta political district

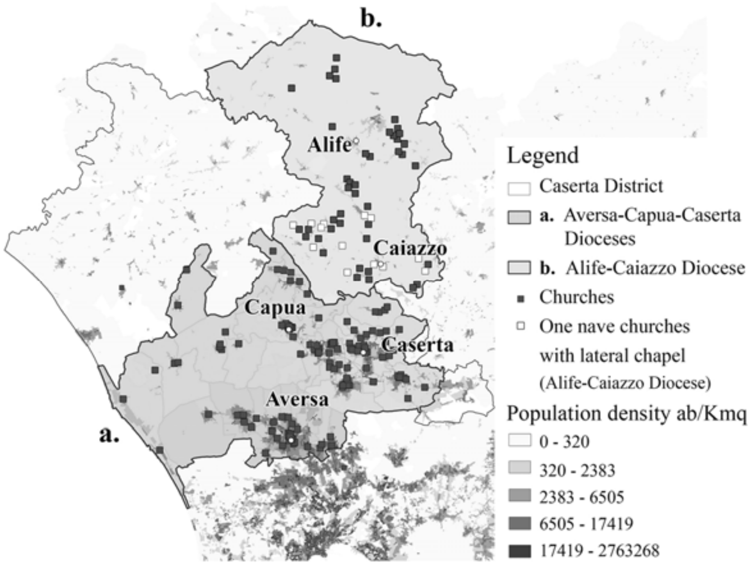


In this diocese, more than 60 churches have been identified. Among them, about 43% are one nave with lateral chapel churches (Figure 19). Therefore, in such area, differently than in Abruzzi, one nave complex (with lateral chapels) churches seems to be the most interesting typology to be investigated.

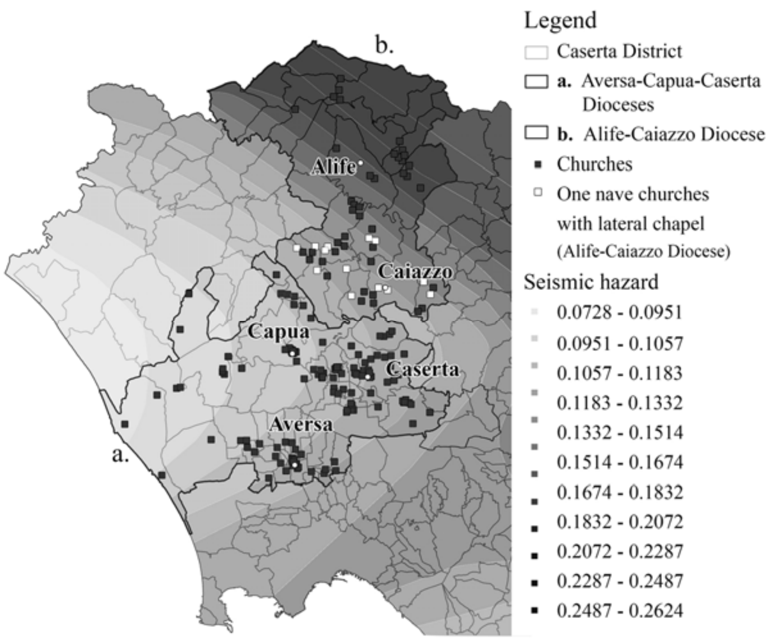
For such a church typology, the 74% has a basilica layout, characterised by a rectangular plan, a central nave and the lateral aisles, without transept; the 26% of churches has a Latin cross layout, with a transept crossing the main body. Façades are often characterised by different structural and architectonic features with respect to other macro-elements, as they were usually erected after the construction of the main body of the church. For the same reason, generally, they are not structurally connected to the transversal walls. One of the most frequent façade layouts is the salient façade (47%), which is characterised by a gable roof with tympanum on the central nave and two rakes upon the aisles. Gabled façades have been detected also in the 47% of the surveyed cases. Finally, only the 5% has a horizontal cornice, where the different height of the naves is concealed.

The top of the façade is in the 37% of cases sailing. This appears to be the most vulnerable typology, as the triangular elements at the top of both sides result very prone to develop overturning mechanisms due to the lack of restraining elements. Heavy thrusting (i.e., barrel and cross vaults) are present in the 63% of the analysed cases, whilst light elements (i.e., visible timber truss and flat soffits) can be observed for the 37% of selected churches.

Figure 18 (a) Correlation between churches in Caserta with population density and (b) seismic hazard



(a)



(b)

Figure 19 Churches typologies belonging to the Alife-Caiazzo diocese

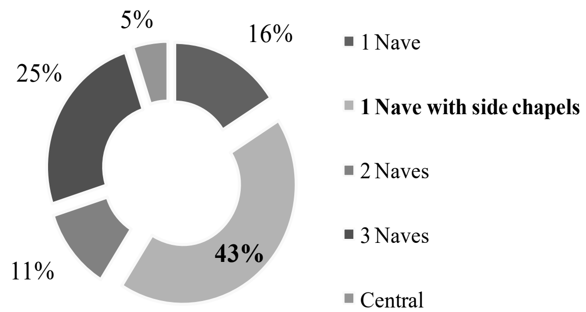
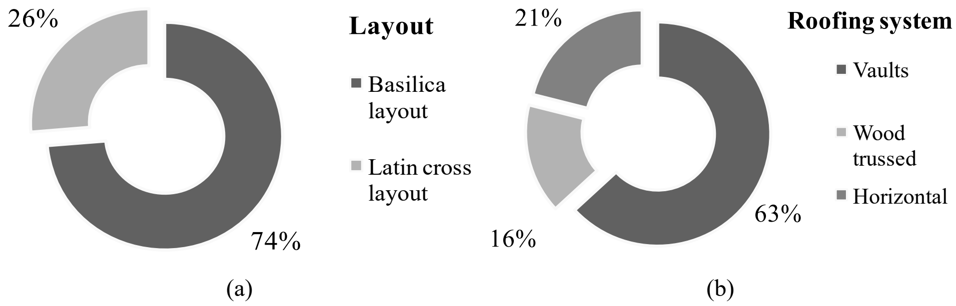


Figure 20 (a) Layout and (b) roofing system for one-nave with lateral chapel churches in the Alife-Caiazzo diocese



5 Concluding remarks

This paper has dealt with the seismic vulnerability of masonry churches in light of the damage scenario observed after the 2009 L'Aquila earthquake. A reconnaissance activity focused on 64 three-nave churches, belonging to a wide territorial area hit by the earthquake, allowed to conclude that the frequency of pre-established damage levels, attained by churches in their entirety, can be well interpreted by a simple probabilistic distribution, that is the binomial probability function, which depends on one parameter only, namely the mean damage. On the other hand, it has been found that the binomial distribution is also able to well fit the frequencies of damage levels occurred for the single macro-elements.

Based on this outcome, a methodology given by literature and suitably modified has been applied allowing the prediction of the aforementioned mean damage level and therefore for a preventive definition of fragility curves. In the whole, the proposed methodology appears to be effective for churches vulnerability assessment at regional scale; hence, it is worthy of being deepened more in details in future researches.

Provided the reliability of considered methodology, an underway research activity is now addressed to outline potential damage scenarios of churches of different Italian territories, focusing the attention on three additional diocese:

1 the Chieti-Vasto Diocese
2 the Lanciano-Ortona Diocese
3 the Alife-Caiazzo Diocese, in Campania.

The results coming out from such studies could be used for defining appropriate strategies for seismic damage prevention at territorial scale.

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