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ABSTRACT

The paper provides the main outcomes obtained downstream of a careful survey concerning the damages provoked by the earthquake occurred in L'Aquila (2009) on three naves churches.

A population of sixty-four churches has been considered and classified depending on the typological, structural and architectural features. The most recurring failure mechanisms observed in the immediate aftermath of the 2009 earthquake have been identified and critically analysed, considered both the global structural response of the church and the local mechanisms involving specific macro-elements. Damages related to the local mechanisms have been classified by means of scores, depending on both the severity and extension of the revealed cracks. The single scores have been combined for defining an index that represents a measure of the damage experienced at global level for each church. The so gathered indices of all the elements of the analysed stock have therefore associated with six damage levels, whose frequencies are organized in Damage Probability Matrices. The latters have been used in order to evaluate quantitatively the damage scenarios that the studied population of buildings revealed after the seismic event, as well as to predict the damages that could be expected on similar churches for future earthquakes.

KEYWORDS: L'Aquila earthquake, Cultural Heritage, Masonry churches, Damage index, Vulnerability Assessment, Damage Probability Matrix

1. INTRODUCTION

The seismic event that took place in 2009 in the district of L'Aquila provoked heavy consequences from the social, economic and functional points of view, involving both local and national entities in the management process of the emergency, as well as in the evaluation of the most adequate reconstruction policies.

First and foremost, the earthquake has had dramatic impacts on the people community, due to both the loss of human lives and the distortion of the pre-existing social dynamics in the hit zones. Nonetheless, significant (sometimes irremediable) losses have been registered on the cultural and historical heritage, formed by churches, monumental buildings and historic centres made of valuable dwellings and palaces, in particular in the city of L'Aquila that, during the last millennium, has represented the cultural, social and business hearth of the whole district.

Indeed, after six years, the situation is slowly returning to normality, but the wounds inflicted by the seismic event, are still bitterly visible. In particular, the historical architecture of the province of L'Aquila, which surely represents one of the most important cultural resources of the Abruzzi region, appears deeply affected by several types of damage. These have to be traced back to the intrinsic deficiencies highlighted during the earthquake, namely the poorness of both materials and constructive details and the alterations applied, throughout the centuries, to the original plants of the buildings.

The inspection carried out on churches and palaces in the aftermath of the 2009 seismic event, under the responsibility of the governmental Department for the Environment and Historical Buildings (MiBAC, MInistero per i Beni Artistici e Culturali), highlighted several severe collapse modes. A meaningful example is the Romanesque basilica of Collemaggio, founded by the Pope Celestino V in the 1287 and characterized by a façade that is one of the maximum masterpiece of the Abruzzi art, whose transept was completely burned to the ground. Other relevant cases are represented by the San Giuliano convent and the Abruzzi National Museum, both declared unsafe and in precarious structural conditions after the earthquake. At the same manner, the old palace that host both the National Archive and the Prefecture offices has been completely destroyed, while the Spanish sixteenth-century castle, seat of the Architectural and Artistic Heritage Supervisor, is today totally inaccessible, in particular at the underground storey, where the regional archive is placed.

The above inspections were carried out by a committee of experts (N.O.P.S.A.: Nuclei Operativi Patrimonio Storico Artistico) which was formed by architects, engineers, firemen, experts of MIBAC , as well by people coming from the Italian National Research Centre (ITC-CNR), Italian research institutes and universities. The outcomes of these inspections have been delivered to the MIBAC [1] on the 28th of January 2010, nine months later the mainshock; they regarded a stock of buildings constituting the 90% of the cultural assets of the wide area stricken by the seismic event (i.e. Seismic Crater), the great part of which (about 60%) is formed by churches (see figure 1.a). These results are summarized in figure 1.b with reference to churches and palaces. As it is shown, only the 23% of the 1706 surveyed constructions resulted to be safe, whereas the 50% resulted to be completely unsafe or not usable.

Simultaneously to the inspections described above, which, due to the large number of the treated buildings, were devoted to give a qualitative overview on the post earthquake situation, rather than a quantitative evaluation of the revealed scenarios, many other studies, focused either on single monumental buildings [2] or on a limited stock of them, have been developed [3].

In this framing of research, a detailed survey regarding the sixty-four three naves churches of the two ecclesiastic dioceses of L'Aquila and Sulmona-Valva is described in the following. This activity has been performed aiming to quantify the damage levels on both the single macro-elements and the entire churches, so to gather their frequencies in Damage Probability Matrices to be put in relation with the seismic intensity that shook the studied buildings. These represent a suitable probabilistic tool to be used for calibrating future risk mitigation analyses and to predict potential damages that churches belonging to the whole territorial area of Abruzzi could experience.

The proposed study is therefore a typical example of possible exploitation of a dramatic situation for setting up suitable tools finalized to the achievement of a proper awareness of the current vulnerability of existing buildings.

2. THE CHURCHES OF L'AQUILA PROVINCE

2.1 General

L'Aquila is the capital city of the Abruzzi and is located in the continental part of the region. Its province takes up about half of the regional territory (see figure 2) and covers three ecclesiastical areas, namely the Dioceses of L'Aquila, Avezzano and Sulmona-Valva.

The architectonic identity of the cultural heritage of the region is marked by significant stratifications, because of several reconstructions and restorations carried out following the earthquakes occurred in the past [4], in particular following those ones 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).

For instance, after the 1703 and 1706 seismic events, many cathedrals and others old churches having a Romaseque plant were restored (or partially rebuilt) by using technical and architectonic solutions in vogue in the Baroque period, which were characterized by arches, vaults and rococo decorations [5-6]. Another significant case is represented by the seismic event of 1984 with epicentre in Frosinone (Lazio): although not relevant damages were provoked, effective retrofitting interventions, such as ties, mortar injections and reinforced plaster, were applied in order to improve the local behaviour of the masonry panels. Moreover, interventions based on ring beams surmounted by rigid reinforced concrete slab, aiming at achieving a "box behaviour" of the whole structure, were often implemented. The applied solution completely changed the structural response of the buildings, leading often to worsen the global behaviour, because of the increased mass at the top of the churches.

All the above remarks prove that there is a strict relationship between the current status of the studied churches and their seismic history, which should be carefully identified from the typological, structural, mechanical and geometrical point of view, in order to correctly predict the possible response under future earthquakes.

2.2 Typological classification

Focusing the attention on the two dioceses of L'Aquila and Sulmona-Valva, almost 640 churches, located in seventy-seven municipalities, have been identified. The great part of these is formed by both three naves, whose localization on the 2009 earthquake intensity map (MCS scale) is shown in figure

4, and single-nave churches. The formers represent the 12% of the whole stock (see figure 5.a), whereas the latter (82%) are composed by rural churches, small chapels and buildings enclosed in clusters. This study deals with the first typology only, it representing a more interesting case for risk assessment purposes.

The investigated buildings have been classified according to their foundation period (see figure 5.b). The oldest one, namely the St. Pietro ad Oratorium abbey (Capestrano), dates back to the VIII century. It is an example of pure Romanesque architecture and represents one of the most important monumental buildings of the region. Its current aspect is affected by some stratifications produced in the XII century which are mainly recognizable on the decorations, but the global plant is identical to the original one.

Since the XI to the IXV century, the *medieval* typology developed on the region. This is identifiable on a large number of churches, which represent a percentage of about 60% of the total number. The main architectonic peculiarity is the poorness of the decorations, a typical characteristic of the religious buildings built in this period in the central part of Italy [7]. Some of these churches have today a different aspect from the original one, because of the succeeding interventions carried out following the 1700 earthquakes, made of typical Baroque elliptical vaults and lavish decorations, but a significant group of these (about one third) were partially or completely rebuilt in the XVIII century (see figure 5.c).

Churches built between the XV to the XVII centuries, namely *post medieval* churches, were originally characterized by the typical plant of the Renaissance period, represented by the Latin plan covered by arches, barrel vaults and a dome. Also these churches, indeed most importantly than the previous ones, undertook significant structural variations after the earthquakes occurred in XVIII century and today often present a different plant.

According to the above considerations, three homogeneous classes of churches can be therefore identified: *medieval* (20%), *post medieval* (20%) and *hybrid* (60%) churches. The first two are characterized by a plant that has remained substantially unchanged, whilst the latter is characterized by miscellaneous elements to be attributed to constructive practices dating back to different historical periods. Following this classification, the main characteristics of the churches of the here analysed stock are given in Table 1, where a description of their main features is provided and specific acronyms are defined.

Some meaningful examples of *medieval* churches are shown in figure 6. From the structural point of view, these are characterized by a low seismic vulnerability, because of the rectangular plan, the absence of transept and dome, the presence of light timber trusses supporting timber roofs and a masonry of good quality, thanks to the regular pattern of the stones held together with layers of mortar in far conditions. Good connections between orthogonal walls are often clearly recognizable, as in the case of St. Pelino cathedral (SPE) (Figure 6b), built in the second part of the medieval period and representing one of the most typical gothic church in Abruzzi. Another important feature is represented by the absence of thrusting elements of the roof system, as shown in the example of St. Giovanni Battista abbey (SGT) (Figure 6d).

The *post-medieval* churches, mainly built in the Renaissance and Baroque periods, are characterized by a plant generally composed by rectangular plan with three naves crossed by a transept and surmounted by a dome at the intersection, as it can be observed in the case of the Madonna della Libera (MDL) church, definitely the most important Renaissance sample in the Sulmona-Valva diocese (Figure 7.a), as well as for the main Renaissance example of the diocese of L'Aquila, namely the St. Bernardino church (Figure 7.b). Thrusting roofs covered by heavy vaults (barrel, cross or elliptical vaults) or mixed roofs, as in the case of the St. Maria Maggiore church (SMR), shown in Figure 7.c, are always present. The masonry is commonly made of rubble stones characterized by a chaotic texture, in particular in the external walls, as one can observe in the St. Maria di Picenze Extra Moenia (SMX), shown in figure 7.d. Because of the above structural features, these churches are characterized by a medium seismic vulnerability.

As far as the third class of churches is concerned, some examples are shown in figure 8. As stated before, these are considered *hybrid* because of the many stratification recognizable on the structures. These churches are characterized by an high seismic vulnerability, as the applied structural variations have been often implemented without effective structural design, this leading sometimes to a worsening of the global structural response. For example, in some cases, baroque arches and vaults have been added on the churches that were built in the Middle-Age period without any type of reinforcement of the supporting walls, as it can be seen on the St. Panfilo cathedral in Sulmona (SPA) (Figure 8a). In other cases, structural elements have been added on the façade, as for example for the Santissima Annunziata Church (SSA) (Figure 8b), where pillars have been built on churches constructed in previous centuries. Often, invasive solutions made of reinforced concrete elements have been adopted following the seismic event occurred in the last recent years; a meaningful example is the St. Massimo and Giorgio in L'Aquila (SMG) where a not effective reinforced concrete beam has been added for connecting the transept-nave system (see Figure 8c). To the *hybrid* typology belongs also the St. Maria di Collemaggio (CLM) basilica, which is definitely the most important church in L'Aquila district, being the unique church out of Rome where a Pope was crowned. In the eighteenth century a baroque restoration has been done on the church, while in a recent period the medieval church has been reinstated, but only for a part of the construction, as it can be seen in Figure 8.d. At the end of the nineties the basilica was subject to a seismic improvement intervention. Some horizontal dissipative steel braced frames were applied at the base of the wooden truss system of both the nave and the aisle.

2.3 Structural influence of the main macro-elements

The 59% of the studied buildings is characterized by a *Basilica* plan, whereas the 38% by a *Latin* cross typology (see figure 9.a). This means that only in about half of the cases, some vulnerable elements, such as transept and dome, are present and influence the global seismic vulnerability of the building.

At the same manner, the presence of heavy thrusting roofs (i.e. barrel and cross vaults), strongly influencing the seismic response of the structure, represents the 60% of the cases (see figure 9.b), whilst light elements (i.e. timber truss and coffers or plan vaults) can be observed in the 30% of the churches.

The geometry of the façade also represents an important element to be considered for evaluating the seismic vulnerability of the church. In particular, flat façades, which are present in more than one-third of the total population of analysed buildings (see figure 10.a), seem to be the most vulnerable typology, since the triangular elements at the top of both the sides have not connections with the back. On the other hands, the included façades, confined at one or both their side from others bodies (for instance bell towers), are certainly safer. Among the surveyed typologies, the salient façade is the most recurring one (56%). As this type of element was usually built many years later with respect to the main body of the church, it is frequent to find façades conceived with a different structural (masonry texture) and architectonic features with respect to the other macro-elements.

As far as the columns are concerned, most of the churches (about 70%) present square pillars (see figure 10.b). These are generally composed by an external shell of brick masonry arranged in a good way and by an internal filling of rubble stones held together by poor mortar; for this reason, they are characterized by low strength with respect to both vertical and horizontal forces. On the contrary, circular pillars (25%), typical of the post-Romanesque period, were built with the superposition of monolithic stones, presenting a more adequate structural behaviour.

Apses and the bell towers are macro-elements generally present on all the churches of the analysed population. The formers are made of the same masonry type of the other macro-elements, whereas the latter are usually characterized by a more organized texture, this leading to a better local behaviour, also due to the diffused presence of iron ties and good connections between the orthogonal walls. Nonetheless, both these macro-elements strongly influence the global behaviour of the whole church, they representing, except those few cases in which they do not interfere with the other macro-elements, sources of irregularity.

2.4 Geometrical recurrences

A geometric survey has been carried out with the aim of finding recurrent design rules related to the main macro-elements. Some geometric ratios have been analysed to this purpose, such as the plan width to length, the façade height to width, the nave length to total length and the nave width to total width ratios.

The results allow to state that the churches of the analysed stock presents a width that, in the majority of cases, is about 0.4:0.6 times the length (see Figure 11.a). Indeed some cases in which the aforementioned values are exceeded have been identified (i.e. for the churches of St. Gregorio Magno church (SGO) in L’Aquila and St. Maria del Borgo (SMB) in Vittorito), but this is due to the presence of large apses and presbyteries.

As it is shown in figure 11.b, the façades are always characterized, independently from the period of erection, by height to width ratios that are always larger than 0.4; nevertheless, the fact that in the great part of cases the values ranges from 0.7 to 1, indicates that the façades are basically slender.

As far as the ratio between the length of the nave to the total length of the church is of concern, values of 0.5÷0.7 are always recognizable (see Figure 11.c). This means that, when the system of transept-presbytery-apse is present, the nave length is always about half of the total length, as well as that the length of the nave is generally comparable with the façade width. Finally, it is to be highlighted that the ratio between the nave width and the total width of the church ranges from 0.4 to 0.5 (see figure 11.d), this meaning that the aisle width is generally half of the nave.

3. DAMAGE SCENARIOS AFTER THE 2009 EARTHQUAKE

3.1 Damage survey on the revealed mechanism

Apart from the identification of the churches belonging to the studied population of buildings, also a detailed survey on the damages provoked by the 2009 seismic event has been carried out. The observed damages have been classified for the vulnerable macro-elements defined by the Guidelines for Cultural Heritage [8] and statistically managed in order to detect their frequencies [9]. This activity allowed to note that churches having the same distance from the earthquake epicentre and characterized by both the same geometrical ratios and architectonic features (type of vaults, pillars cross section shape, etc.), apart from the cases in which different retrofitting techniques have been applied, presented similar damage level in terms of localization, extension and severity.

The most recurrent damage type is represented by cross diagonal cracks due to second mode mechanisms. These have been frequently found on lateral walls, bell towers and domes (see figure 12), when they resulted characterized by a poor masonry fabric.

As far as the vault systems are concerned, the most vulnerable resulted to be the elliptical vaults. For these elements, fractures along both the diagonal directions and the circular spring-lines have been highlighted (see figure 13.a). In particular, the last type of cracks appeared to be more accentuated for that churches located on those sites for which the vertical component of the earthquake resulted to be not negligible, as in the case of Goriano Sicoli and in the St. Biagio d'Amiternum church in L'Aquila.

Different type of damages have been observed at the top of the barrel vaults, where longitudinal cracks along the key-stones often recurred in a more or less extended way according to the presence of ties in the orthogonal direction (see figure13.b). On the contrary, less significant damage levels have been detected on the groin vaults, where some fractures developed along the diagonal directories only.

With regard to pillars, vertical cracks due to crushing phenomena have been sometimes surveyed, as in the case of St. Gemma church in Goriano Sicoli. These have been probably induced by the increasing compression stresses, due to the earthquake vertical component, which, even far from the epicentre, resulted significant due to site effects [10]. The above failures are particularly evident on those columns made of rubble masonry, where cracks along the mortar, often followed by significant vertical openings on the elements, have been highlighted (see figure 14.a). On the contrary, in the case of monolithic pillars constituted by superimposed stones, which are frequent for the *medieval* churches, significant damages were not be revealed (see figure 14.b).

Heavy sliding damages have been detected on the churches where reinforced concrete roof or beams have been built in recent years without effective connection with the vertical walls (see figure15.a). This obsolete practice provoked also damages on arches (see figure 15.b), because of the increased outward thrust force on the vertical supporting walls of the heavy roofs. The presence of iron ties certainly constrained this effect; nevertheless, in some cases, punching phenomena of the ties-key (see figure 15.c) have been noted.

Out-of-plane mechanisms represented the most dangerous source of vulnerability of the studied buildings, when these resulted not correctly endowed with a proper number of well dimensioned ties, as for example for the case of the church of San Martino (SMA) in Gagliano Aterno, where ties rupture has been noticed (see figure 15.d). For the churches under investigation, three main out-of-plane phenomena have been recognized: the rigid façade overturning, the façade top-corner overturning and the apse overturning.

For the first type, only one church in the Sulmona-Valva Diocese (St. Gemma church in Goriano Sicoli-SGM) showed a fully developed mechanism, with a detachment between the façade and the lateral walls of about the thickness (see figure 16). On the other hand, this type of mechanism has been diffusely observed in the L'Aquila Diocese, where in some cases it lead to the fully collapse of the macro-element.

The façade top-corner overturning has been revealed for those cases for which, even in presence of longitudinal ties that effectively constrained the rigid overturning of the whole façade, nevertheless the corner connection was clearly inefficient due to the lack of restraining element (see figure 17.a).

Finally, the third type of overturning mechanism concerned the apse. It was generally due to its bad connections or to the presence of wide openings. A meaningful example is the case of St. Martino church in Gagliano Aterno (SMA), where the diagonal cracks, typical of this mechanism, have been revealed (see figure 17.b).

3.2 Damage classification

Consistently with the Italian Code "Guidelines for Cultural Heritage" [8], the classification of the observed damage has been carried out accounting for twenty-eight 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), as shown in Figure 18. For each mechanism, six level of damage d_k (d_0-d_5) have been defined according to the observational criteria introduced by EMS-1998 scale [11], which have been opportunely revised in order to account for the fact that these were originally referred to entire buildings. In particular, for each macro-element, the damage levels have been defined as follows:

- Level d_0: No damage;
- Level d_1: Negligible to slight damage (no structural damage, slight non-structural damage). few hair-line cracks in very few parts of the macro-element, fall of small pieces of plaster only, fall of loose stones from upper parts.
- Level d_2: Slight structural damage and moderate non-structural damage. Many cracks with fall of fairly large pieces of plaster.
- Level d_3: Moderate structural damage and heavy non-structural damage, with large and extensive cracks; failure of individual non-structural elements if present; activation of the first out-of-plane mechanisms.

- Level d_4: Heavy structural damage and very heavy non-structural damage, with complete development of first-mode mechanisms.
- Level d_5: Very heavy damage, with total or near total collapse of the macro-element.

Each level of damage d_k has been associated to a damage score k ranging from 0 to 5. Moreover, for each mechanism an importance factor score (ρ_k), ranging from 0 to 1, has been assigned, in order to account for the influence that the mechanism itself has on the global stability of the whole structure (see figure 18).

A global damage index (i_d) has been therefore calculated, according to equation (1), which is proposed in [8]. The obtained results for the sixty-four observed churches are shown in figure 19.

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

Being the obtained values defined in the real number field, a transformation of the indices into natural numbers, so to get countable level of damages for statistically managing purposes, has been carried out by correlating each damage index i_d to a damage score D_k (ranging from 0 to 5), which is defined in figure 20 similarly to the damage levels defined by Grunthal for the EMS'98 scale. The correlation between the analyzed data has been performed according to Lagomarsino et al. [12], as described in table 2. The so elaborated results are shown in figure 21.

As it can be observed, the majority of the churches presents a global damage level D_k equal to 1 or 2, whereas only fourteen churches suffered a damage level equal to or higher than 3. It is also to be pinpointed that the damage score D_k equal to 5 has been obtained only for the two churches of St. Nicandro e Marciano (SNM) (see Figure 22.a) and St. Gregorio Magno (SGO) (see Figure 22.b) both in L'Aquila. Moreover, In some cases the churches presented damage scores equal to 4 because of the revealed partial collapse of the transept, as in the case of St. Maria di Collemaggio church (CLM) (see figure 23.a) and St. Massimo e Giorgio church (SMG) (see figure 23.b), which were due to past restorations which changed the original structural design leading to a concentration of demand in these limited zones of the churches.

In general, the structures which suffered higher damages belong to the L'Aquila diocese, while lower damage levels have been observed for the Sulmona-Valva area, due to the distance from the epicentre location. Nevertheless, in the second case, two exceptions have beens revealed, those are St. Maria Nova church (D_k=3) and the St. Gemma church (D_k=4), both belonging to the Goriano Sicoli municipality. This is consistent with the post seismic territorial map, based on the MCS scale, which underlines the heavy effects of the earthquake on the north area of the diocese, in particular in Goriano Sicoli.

4. DAMAGE PROBABILITY MATRICES

In order to evaluate the damage scenarios observed after the 2009 seismic event from the quantitative point of view, the frequencies of the damage scores D_k revealed for the studied stock of churches have been elaborated in order to obtain the related Damage Probability Matrix, which is shown in figure 24.a.

It must be highlighted that the so obtained frequencies refer to a very extended territory that experienced a macro-seismic intensity going from the fifth to the ninth grade of the MCS scale. As a consequence, the proposed outcomes have to be addressed to those decision-makers that have to manage the seismic risk at regional level. In order to provide results that are usable also for smaller territories, Damage Probability Matrices for churches that experienced a macro-seismic intensities of grades V-VII (named as "Group 1") and VIII-IX ("Group 2"), still evaluated according to the MCS scale, are also proposed separately in figure 24.b.

The interpretation of the obtained matrices led to achieve an important result. In fact, it has been observed that these can be well fitted by the Binomial Probability Density Function (BPDF in figure 24), given in eq. (2), that provide the probability p_k (k=0,1,2,...5) of experiencing a damage score D_k as a function of the mean damage μ_D (shown in figure 24 for the whole population of churches as well for the two groups belonging to Sulmona-Valva and L'Aquila Dioceses, respectively) given in eq. (3), where n is the number of analysed churches.

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

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

Indeed, this outcome confirms the results obtained by other Authors that dealt with different populations of churches, proving that the binomial distribution is particular apt for evaluating potential damage scenarios [12].

Another important result that the observations carried out after the 2009 seismic event allowed to achieve concerns the revealed mechanisms. In particular, once that the twenty-eight mechanisms described in figure 18 have been grouped into nine potential type of damages that the single macro-elements could experience, namely "out of plane" (mechanisms n. 1-10-16 in figure 18), "façade" (2-3-4), "lateral walls" (6-11-17-25), "columns" (7), "chapels" (22-23), "arches and vaults" (5-8-9-12-13-18-24), "dome" (14-15), "roof" (19-20-21) and bell tower (27-28) mechanisms, it has been observed that the Damage Probability Matrices collecting the frequencies of the damage score d_k defined for the mechanisms themselves, can be, again, well fitted (see figure 25) by the Binomial Probability Density Function expressed in eq. (2) whether the mean damage is expressed according to eq. (4).

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

In the above equations *n* is the number of churches, whereas *m* is the number of potential mechanisms.

5. DISCUSSION OF RESULTS AND CONCLUSIONS

The Damage Probability Matrices provided in this paper for the three naves churches of the Dioceses of L'Aquila and Sulmona-Valva represent a powerful tool that might be used for pursuing two different scopes.

On the one hand, the damage scenarios quantified at both global and local levels on the basis of the observed mechanisms that involved the several macro-elements allowed to give some meaningful indications about the measures to be pursued in the reconstruction process. For example, figure 25 evidences that the most critical deficiencies that should be firstly restored are the ones related to the columns, bell towers and lateral walls mechanisms, they being characterized by a higher mean damage level.

On the other hand, the outcomes related to the possibility of fitting the obtained Damage Probability Matrices by means of Binomial Probability Density Functions allow to open new outlooks about the possibility of setting up effective predictive tools for foreseeing potential damage scenarios that might be provoked by future earthquakes on population of churches similar to ones considered in this study. Therefore the obtained results definitely push to seek for empirical methods able to return the expected mean damage μ_D, which is the only variable that allow to assess the damage scenario (eq. 2), on the basis of the constructive features of the analyzed population of churches. This method could provide a useful help to decision makers and stakeholders to schedule adequate interventions of prevention and mitigation, in order to avoid in case of future earthquakes the dramatic consequences registered after the 2009 seismic events.

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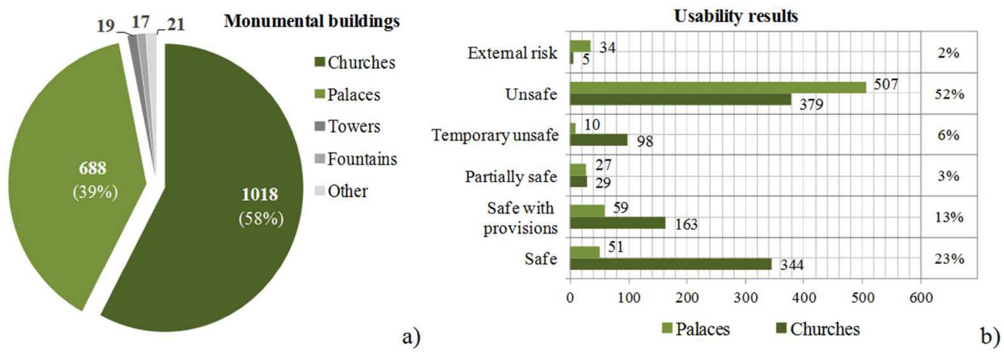

Figure 1. a) Monumental buildings surveyed by the N.O.P.S.A. committee at the 28th of January 2010 and b) results of the survey campaign with reference to churches and palaces [1]
101x35mm (300 x 300 DPI)

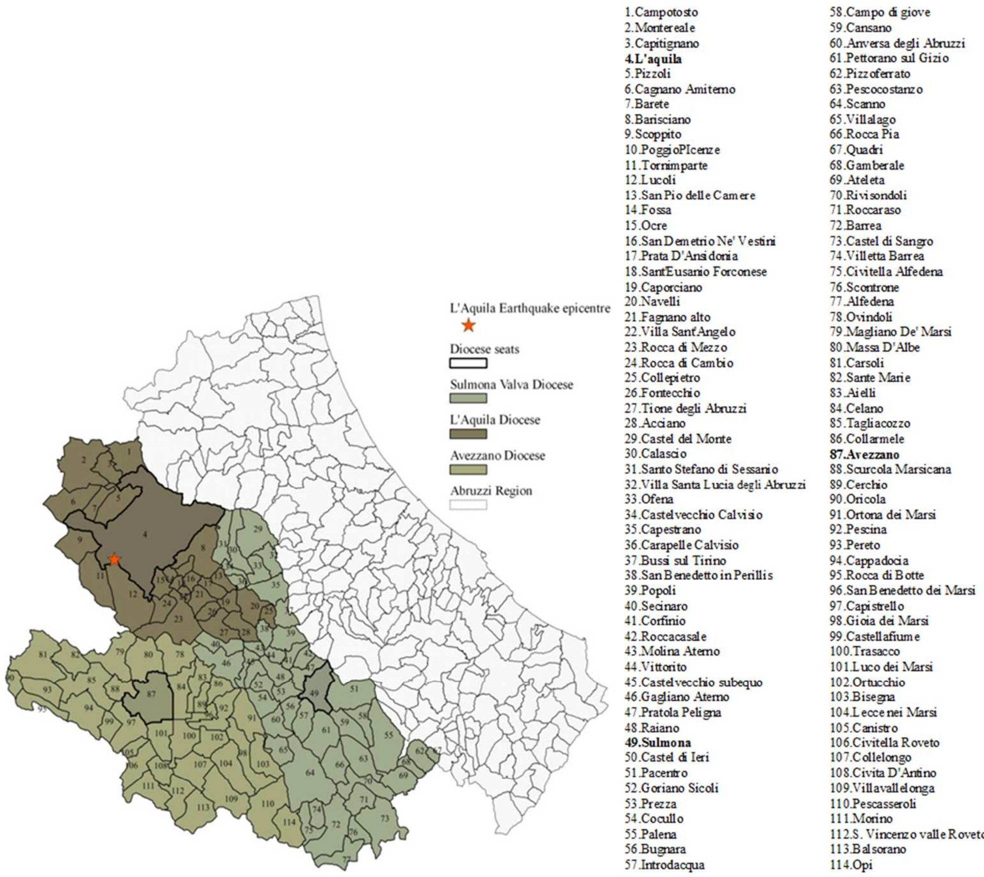

Figure 2. Abruzzi region and ecclesiastical areas of L'Aquila district.
81x71mm (300 x 300 DPI)

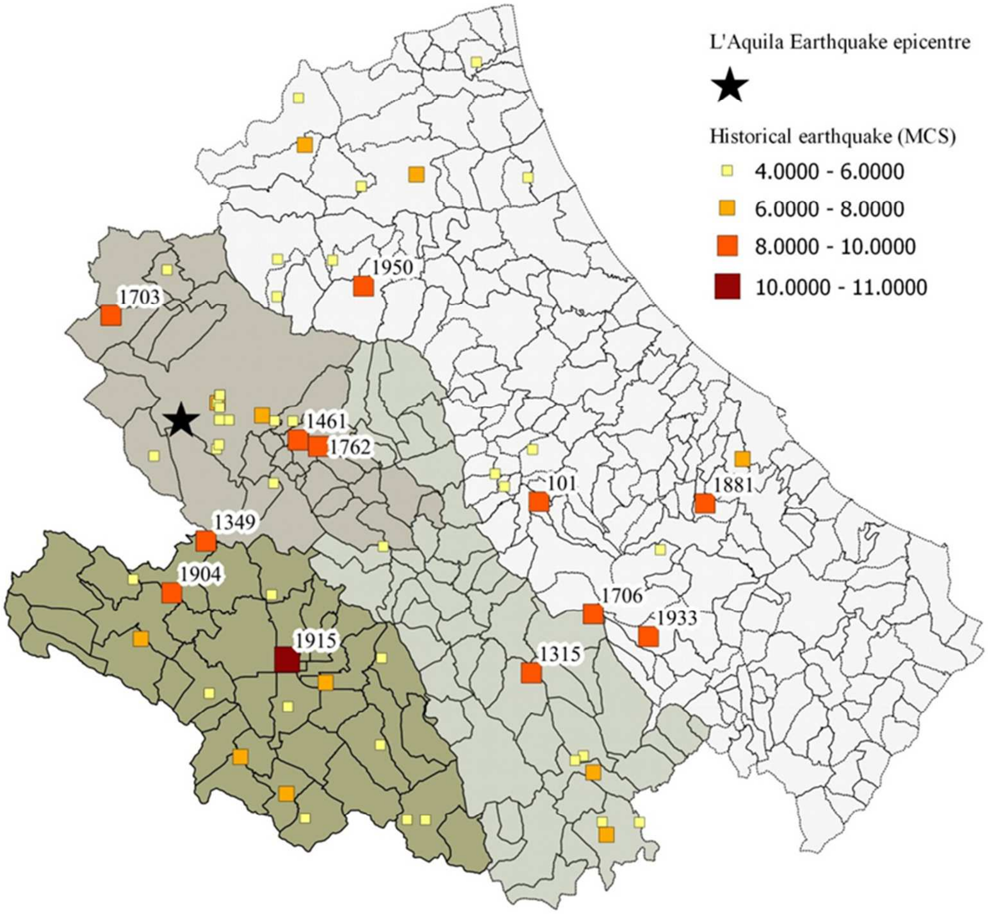

Figure 3. Historical earthquakes in Abruzzi [4]
71x65mm (300 x 300 DPI)

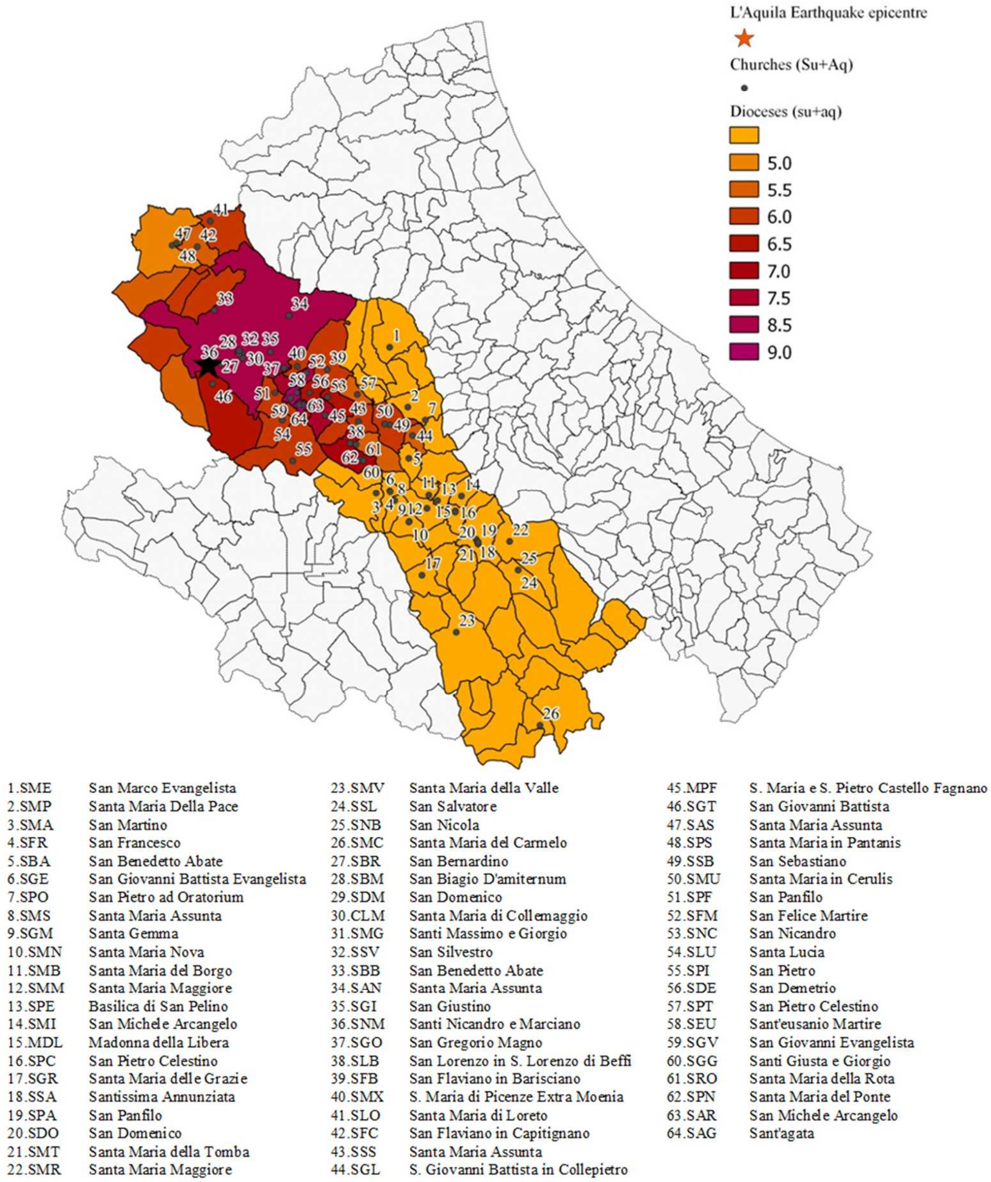

Figure 4.The three naves churches in L'Aquila and Sulmona-Valva dioceses: localization on the 2009 earthquake macro-seismic intensity map (MCS scale)
82x98mm (300 x 300 DPI)

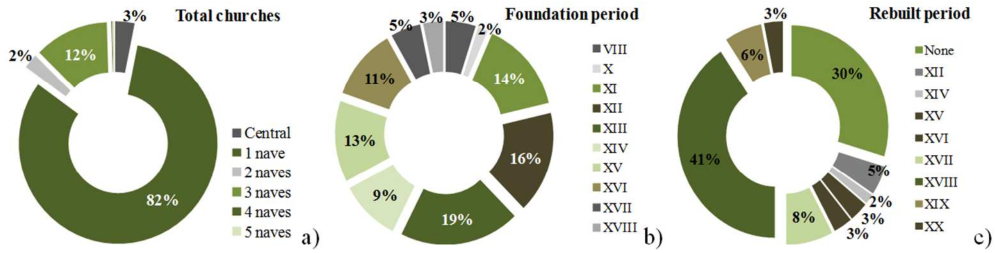

Figure 5. a) Churches belonging to L'Aquila and Sulmona-Valva dioceses, b) Built and c) Re-built period.
108x29mm (300 x 300 DPI)

Figure 6. Medieval churches: a) St. Domenico Church, L'Aquila (SDM), b) St. Pelino in Corfinio (SPE), c) St. Pietro ad Oratorium in Capestrano (SPO) and d) St. Giovanni Battista abbey (SGT), Lucoli.
76x70mm (300 x 300 DPI)

Figure 7. Post-medieval churches: a) Madonna della Libera in Pratola Peligna (MDL), b) St. Bernardino Church in L'Aquila (SBR), c) St. Maria Maggiore Church in Pacentro (SMR) and d) St. Maria di Picenze Extra Moenia church in Barisciano (SMX).
77x69mm (300 x 300 DPI)

Figure 8. Hybrid type churches: a) St. Panfilo Cathedral in Sulmona (SPA),b) Santissima Annunziata in Sulmona (SSA), c) St. Massimo e Giorgio in L'Aquila (SMG, after the 2009 earthquake) and d) St. Maria di Collemaggio in L'Aquila (CLM).
76x70mm (300 x 300 DPI)

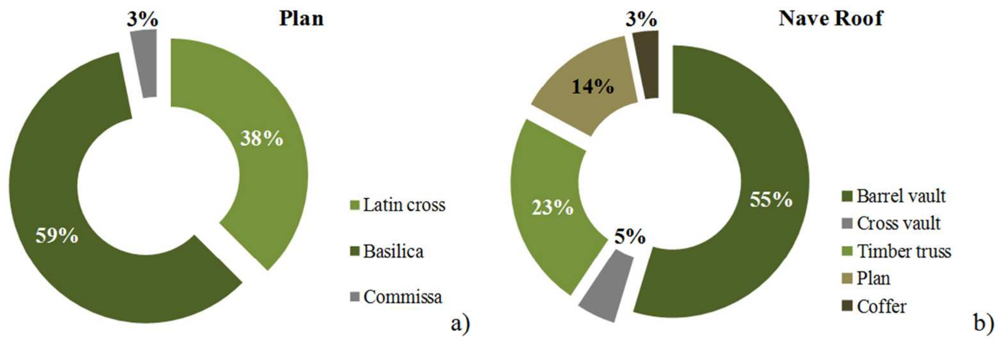

Figure 9. (a) Plan configuration and (b) nave roofing system of the studied churches.
96x33mm (300 x 300 DPI)

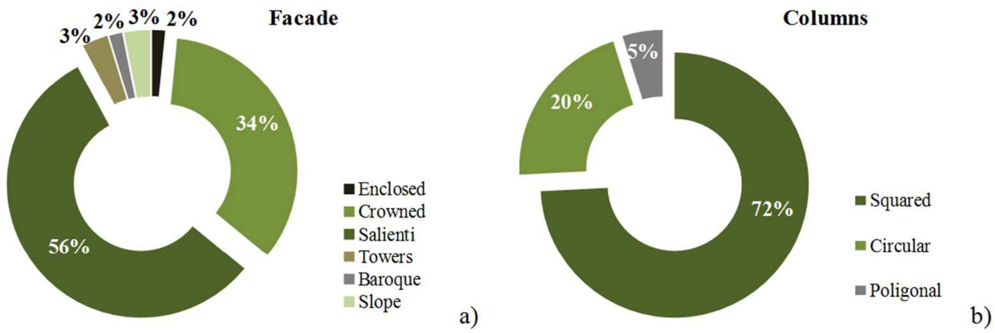

Figure 10. (a) Façade and (b) columns typologies revealed on the studied churches.
98x33mm (300 x 300 DPI)

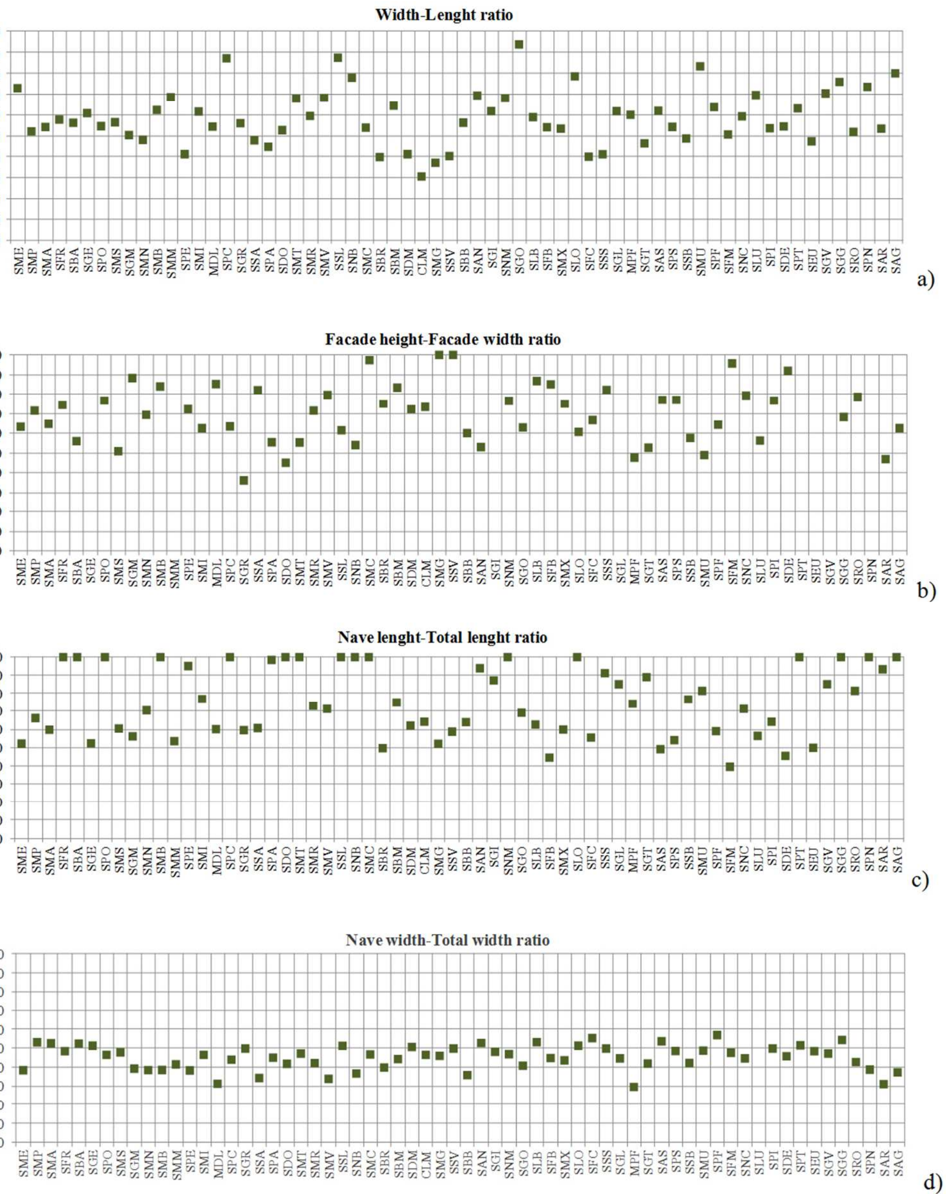

Figure 11. (a) Plan width/length ratio, (b) Façade height/width ratio, (c) Nave length/Total length ratio and (d) Nave width-total width ratio.
104x127mm (300 x 300 DPI)

Figure 12. Diagonal cracks on wall after the 2009 seismic event. a) Bell tower of the St. Bernardino church (SBR) in L'Aquila and b) St.Eusanio Martire church (SEU) in Sant'Eusanio Forconese. Damages on the dome and the presbytery in c) St. Felice Martire church (SFM) in Poggio Picenze and d) St.Eusanio Martire church (SEU) in Sant'Eusanio Forconese.
83x70mm (300 x 300 DPI)

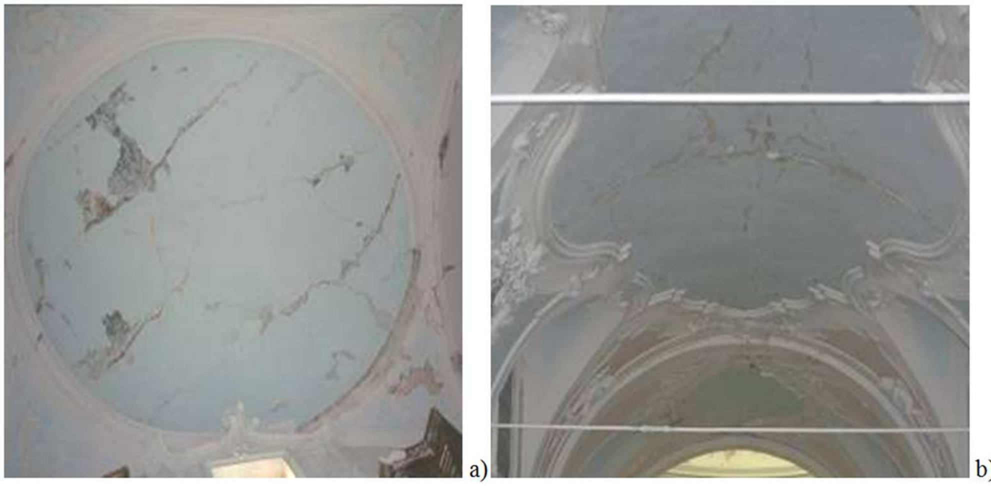

Figure 13. Observed damages on a) elliptical vaults and b) barrel vaults of St. Maria Nova church (SMN) in Goriano Sicoli after the 2009 seismic event
86x42mm (300 x 300 DPI)

Figure 14. Observed damages after the 2009 seismic event on a) rubble masonry pillars of St. Gemma church (SGM) in Goriano Sicoli; b) not damaged monolithic columns in St. Pietro ad Oratorium (SPO) in Capestrano.
78x56mm (300 x 300 DPI)

Figure 15. Effects of the 2009 seismic event on local elements of the studied churches: a) sliding cracks due to the reinforced concrete roof; b) damages on arches, c) punching phenomena and d) tie breaking.
84x63mm (300 x 300 DPI)

Figure 16. Façade overturning in St. Gemma church (SGM) in Goriano Sicoli.
83x58mm (300 x 300 DPI)

Figure 17. a) Top-corner overturning on St. Maria della Pace church in Capestrano and b) Apse overturning on St. Martino church in Gagliano Aterno.
86x39mm (300 x 300 DPI)

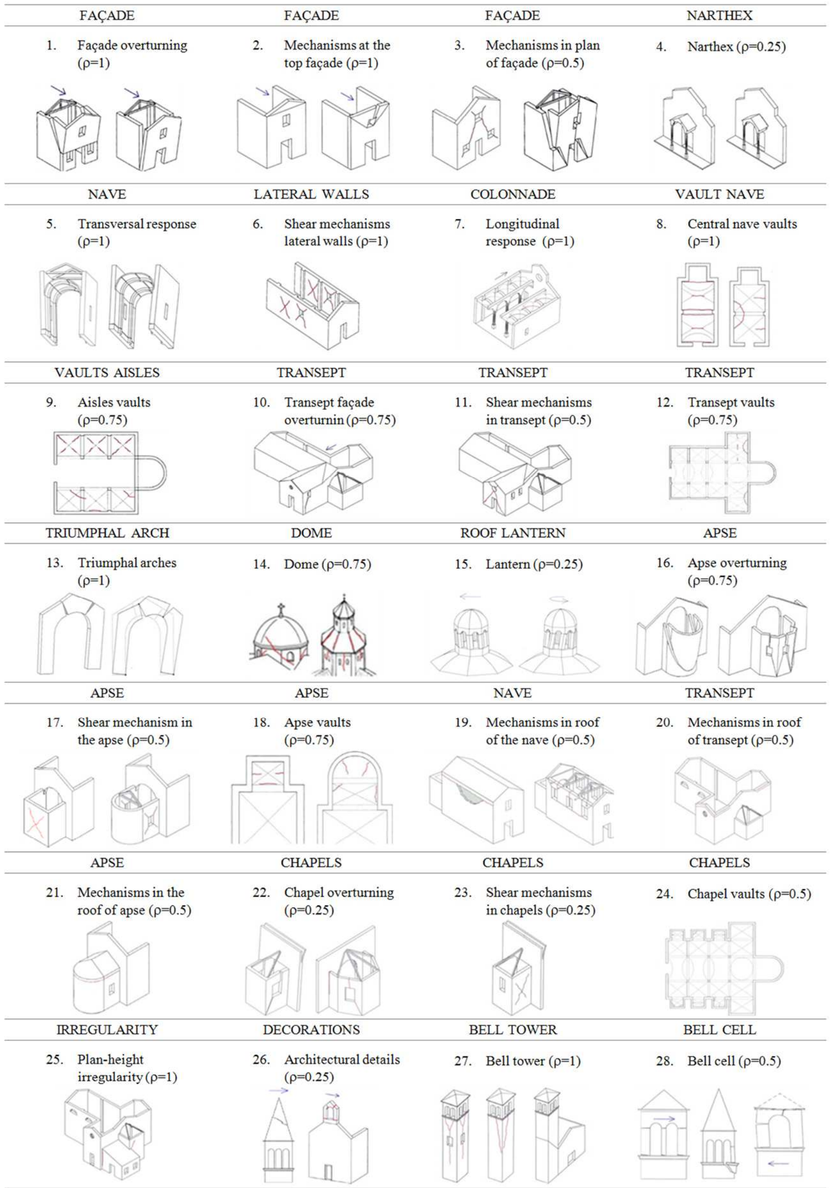

Figure 18. Classification of mechanisms for religious buildings (source: Guidelines for Cultural Heritage 2011, [7]).
100x144mm (300 x 300 DPI)

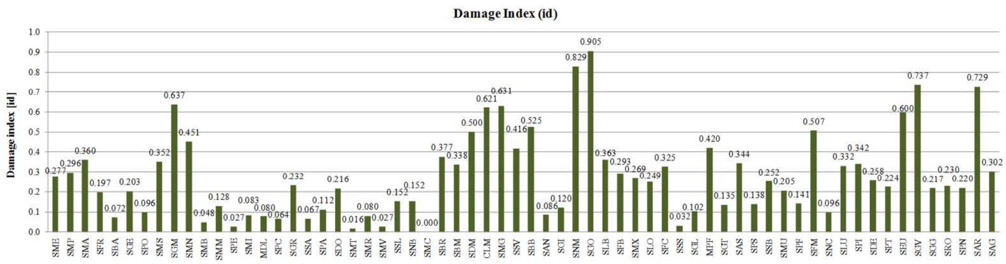

Figure 19. Damage indices for the 64 observed churches.
148x39mm (300 x 300 DPI)

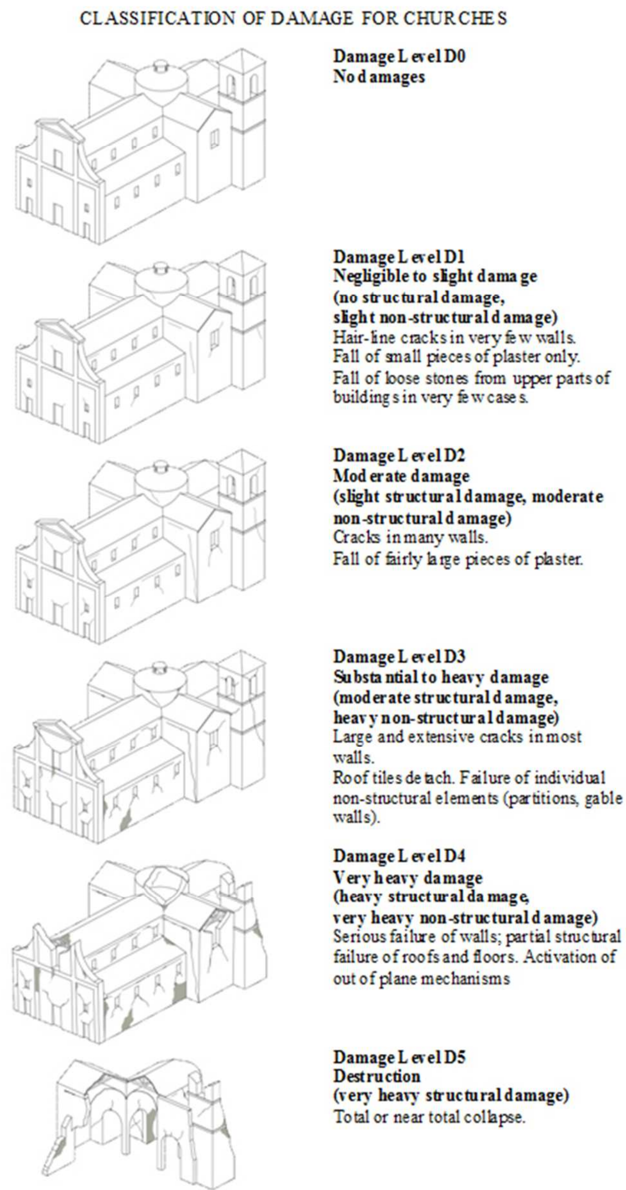

Figure 20. Damage classification for masonry churches
38x70mm (300 x 300 DPI)

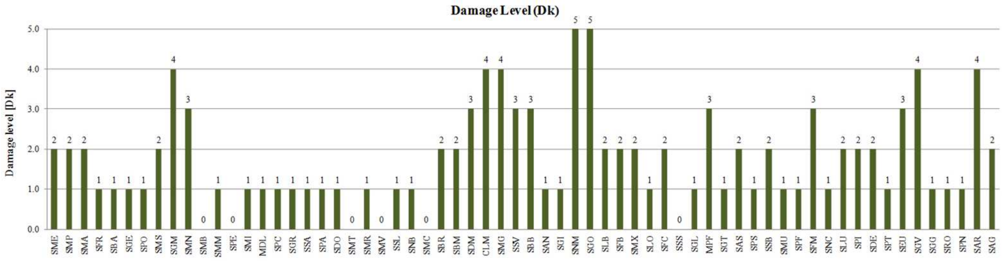

Figure 21. Damage levels (Di) for the 64 observed churches.
132x34mm (300 x 300 DPI)

a) b)

Figure 22. Collapse of the a) St. Nicandro e Marciano Church (SNM) in L'Aquila (Roio Piano) and b) St. Gregorio Magno Church (SGO) in L'Aquila (San Gregorio) after the 2009 seismic event.
85x33mm (300 x 300 DPI)

Figure 23. a) St. Maria di Collemaggio church (CLM) in L'Aquila and b) St. Massimo e Giorgio church (SMG) in L'Aquila.
86x33mm (300 x 300 DPI)

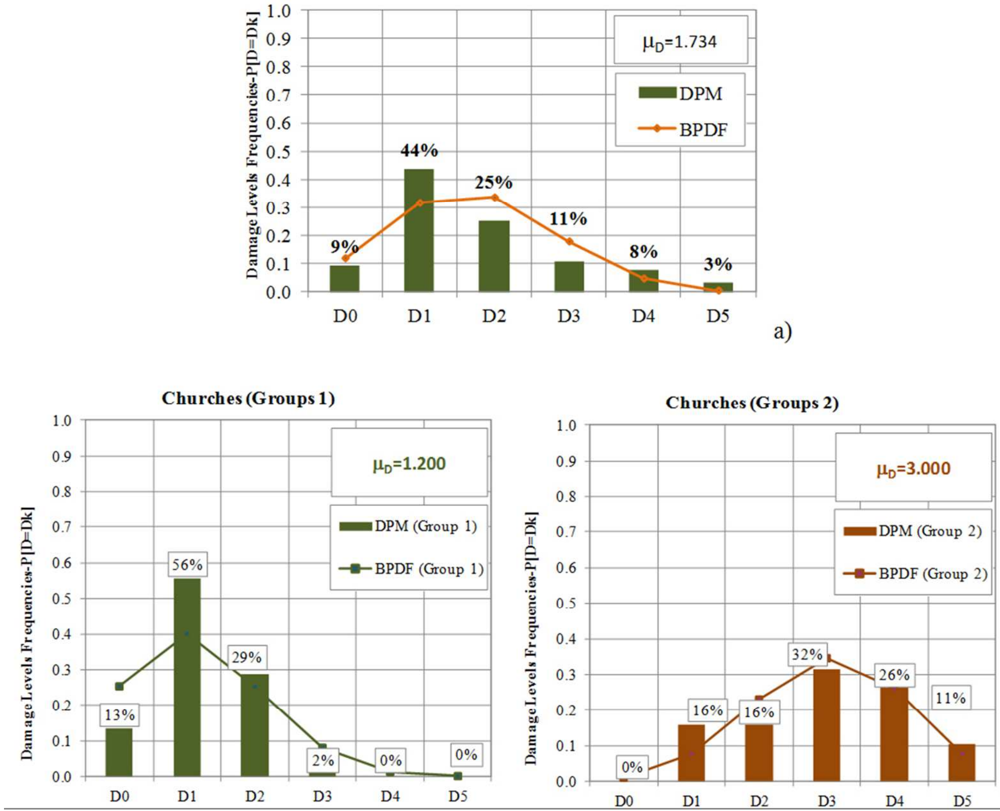

Figure 24. a) Damage Probability Matrices for a) the whole analyzed population of churches and b) by considering two different groups of churches according to the experienced seismic intensities (Group 1 from IV to VI MCS and Group 2 from VII to IX MCS).
87x71mm (300 x 300 DPI)

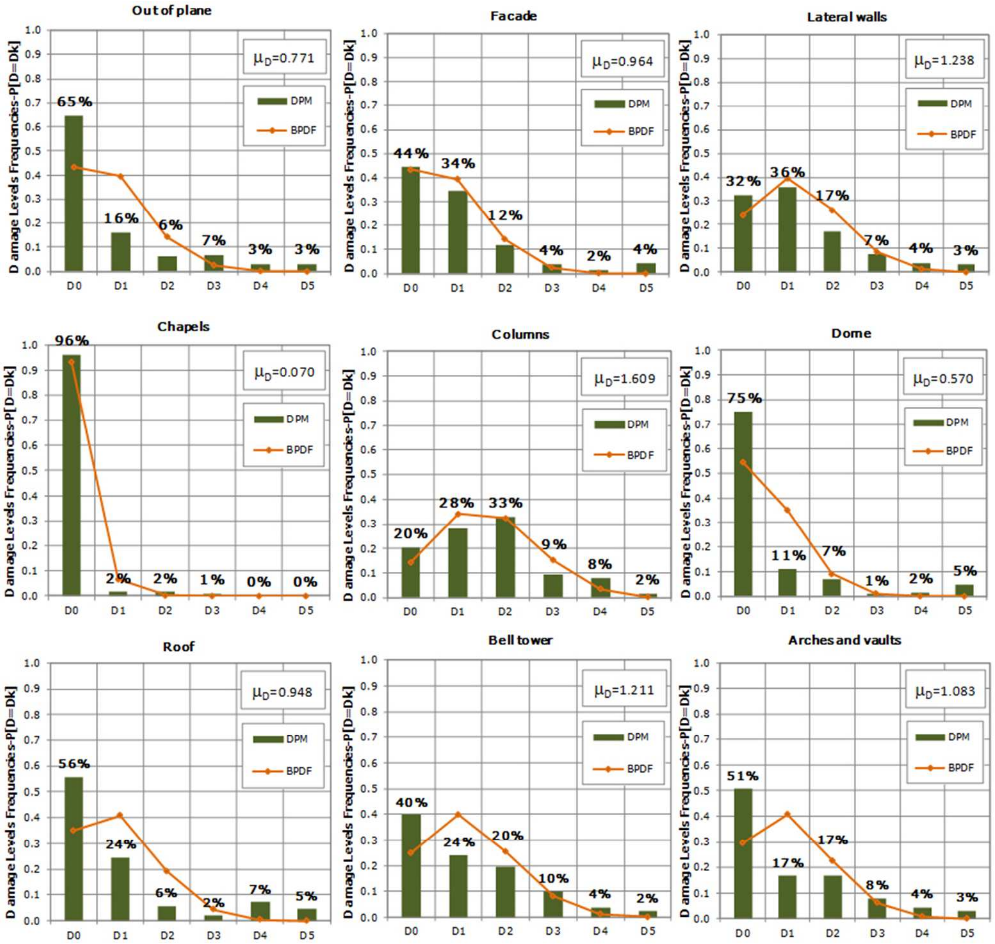

Figure 25. Damage Probability Matrices for the nine mechanisms revealed on the macro-elements of the analyzed churches.
76x72mm (300 x 300 DPI)

	ID	CHURCH	ACRONYM	NAVE	FOUNDATION PERIOD	REBUILT PERIOD	VULNERABILITY CLASS	STRUCTURAL TYPOLOGY	ARCHITECTURAL TYPOLOGY AND DECORATION SYSTEM	PLAN	DOME	NAVE	APSE	AISLE	FACADE	COLUMNS	BELL TOWER	MCS	d(epicentro)	Lenght	Width	Facade Height	Nave Lenght	Nave Width	Pillar diameter	Area	Width / Lenght	F. Height / F. Width	Nave Lenght / Total Lenght	Nave Width / Total Width
SULMONA-VALVA DIOCESE	1	SAN MARCO EVANGELISTA	SME	3	XV	-	MV	Post-Medieval	Renaissance	Latin cross	Octagonal	Barrel vault	Squared	Cross	Enclosed	Squared	Enclosed	6	32.85	29.5	21.5	-	15.4	8.3	1.1	634.3	0.7	-	0.5	0.4
	2	SANTA MARIA DELLA PACE	SMP	3	XVII	XIX	HV	Hybrid	Baroque	Latin cross	Octagonal	Barrel vault	Squared	Spherical	Crowned	Squared	Isolated	6	36.74	35.0	18.2	13.0	23.2	9.7	0.9	637.0	0.5	0.7	0.7	0.5
	3	SAN MARTINO	SMA	3	XIV	XVIII	HV	Hybrid	Renaissance	Latin cross	Octagonal	Barrel vault	Poligonal	Spherical	Crowned	Squared	Facade	5.5	38.082	36.4	19.7	12.8	21.8	10.4	1.3	717.1	0.5	0.6	0.6	0.5
	4	SAN FRANCESCO	SFR	3	XIII	XVII	HV	Hybrid	Baroque	Basilica	-	Cross vault	Enclosed	Cross	Salienti	Circular	Enclosed	7	39.796	31.2	18.0	13.4	31.2	8.8	1.0	561.6	0.6	0.7	1.0	0.5
	5	SAN BENEDETTO ABATE	SBA	3	VIII	-	LV	Medieval	Medieval	Basilica	-	Timber truss	-	Timber truss	Salienti	Circular	Bell-gable	5.5	39.841	27.1	15.2	8.5	27.1	8.0	0.8	411.9	0.6	0.6	1.0	0.5
	6	SAN GIOVANNI BATTISTA ED EVANGELISTA	SGE	3	XVIII	-	MV	Post-Medieval	Renaissance	Latin cross	Octagonal	Barrel vault	Enclosed	Cross	Salienti	Squared	Enclosed	7	39.977	27.5	16.7	18.0	14.4	8.6	1.0	459.3	0.6	1.1	0.5	0.5
	7	SAN PIETRO AD ORATORIUM	SPO	3	VIII	XII	LV	Medieval	Romanesque	Basilica	-	Timber truss	3 Circular	Timber truss	Salienti	Squared	-	6	40.337	27.5	15.0	11.5	27.5	7.0	1.1	412.5	0.5	0.8	1.0	0.5
	8	SANTA MARIA ASSUNTA	SMS	3	XV	XVIII	HV	Hybrid	Renaissance	Latin cross	Circular	Barrel vault	Circular	Spherical	Crowned	Squared	Facade	6.5	41.553	31.4	17.7	9.0	19.0	8.5	1.0	555.8	0.6	0.5	0.6	0.5
	9	SANTA GEMMA	SGM	3	XVI	XVIII	HV	Hybrid	Baroque	Latin cross	Circular	Barrel vault	Circular	Spherical	Salienti	Squared	Facade	7	45.914	33.8	17.0	15.0	19.0	6.7	1.1	574.6	0.5	0.9	0.6	0.4
	10	SANTA MARIA NOVA	SMN	3	XVI	XVIII	HV	Hybrid	Renaissance	Latin cross	Octagonal	Barrel vault	Poligonal	Spherical	Crowned	Circular	Isolated	7	45.916	34.0	16.3	11.3	24.0	6.3	0.8	554.2	0.5	0.7	0.7	0.4
	11	SANTA MARIA DEL BORGO	SMB	3	XVI	XVII	HV	Hybrid	Renaissance	Basilica	-	Barrel vault	Enclosed	Spherical	Salienti	Squared	Enclosed	5	46.162	22.0	13.7	11.5	22.0	5.3	0.9	301.4	0.6	0.8	1.0	0.4
	12	SANTA MARIA MAGGIORE	SMM	3	XV	-	HV	Hybrid	Renaissance	Latin cross	-	Plan	Poligonal	Plan	Salienti	Squared	Isolated	5	47.146	28.0	19.2	23.0	15.0	8.0	0.8	537.6	0.7	1.2	0.5	0.4
	13	BASILICA DI SAN PELINO	SPE	3	XI	XX	LV	Medieval	Romanesque	Basilica	-	Timber truss	Circular		Salienti	Squared	Enclosed	5.5	48.01	41.0	16.9	12.2	39.0	6.5	1.2	692.9	0.4	0.7	1.0	0.4
	14	SAN MICHELE ARCANGELO	SMI	3	XIII	XVIII	HV	Hybrid	Renaissance	Latin cross	Squared	Cross vault	Squared	Cross	Salienti	Circular	Back	5	51.391	19.5	12.0	7.5	15.0	5.6	0.6	234.0	0.6	0.6	0.8	0.5
	15	MADONNA DELLA LIBERA	MDL	3	XVI	XIX	HV	Hybrid	Renaissance	Latin cross	Squared	Barrel vault	Circular	Spherical	Towers	Squared	Towers	5.5	51.723	42.2	22.9	19.5	25.4	7.2	1.9	966.4	0.5	0.9	0.6	0.3
	16	SAN PIETRO CELESTINO	SPC	3	XV	-	MV	Post-Medieval	Renaissance	Basilica	-	Plan	-	Plan	Crowned	Squared	Bell-Gable	5.5	51.723	18.8	16.4	10.4	18.8	7.2	0.8	308.3	0.9	0.6	1.0	0.4
	17	SANTA MARIA DELLE GRAZIE	SGR	3	XVI	-	HV	Hybrid	Renaissance	Latin cross	Circular	Barrel vault	Enclosed	Cross	Crowned	Circular	Facade	5	53.998	32.2	18.0	6.5	19.2	9.0	0.9	579.6	0.6	0.4	0.6	0.5
	18	SANTISSIMA ANNUNZIATA	SSA	3	XIV	XVIII	HV	Hybrid	Baroque	Latin cross	Circular	Barrel vault	Poligonal	Spherical	Baroque	Squared	Isolated	5	57.596	44.4	21.2	17.4	27.0	7.3	1.0	941.3	0.5	0.8	0.6	0.3
	19	SAN PANFILO	SPA	3	XI	XVIII	HV	Hybrid	Baroque	Latin cross	Octagonal	Barrel vault	3 Circular	Cross	Crowned	Circular	Bell-gable	5	57.596	39.6	17.7	9.8	39.0	8.0	0.6	700.9	0.4	0.6	1.0	0.5
	20	SAN DOMENICO	SDO	3	XIII	XVIII	HV	Hybrid	Baroque	Basilica	-	Barrel vault	Circular	Spherical	Salienti	Squared	-	5	57.596	38.0	20.0	9.0	38.0	8.4	0.9	760.0	0.5	0.5	1.0	0.4
	21	SANTA MARIA DELLA TOMBA	SMT	3	XIII	XVIII	LV	Medieval	Romanesque	Basilica	-	Timber truss	Squared	Timber truss	Crowned	Circular	Bell-Gable	5	57.596	28.0	19.0	10.5	28.0	9.0	0.7	532.0	0.7	0.6	1.0	0.5
	22	SANTA MARIA MAGGIORE	SMR	3	XVI	-	MV	Post-Medieval	Renaissance	Latin cross	Squared	Coffer	Enclosed	Cross	Salienti	Poligonal	Back	5	62.926	34.2	20.3	14.5	25.0	8.6	1.1	694.3	0.6	0.7	0.7	0.4
	23	SANTA MARIA DELLA VALLE	SMV	3	XII	XVIII	HV	Hybrid	Baroque	Basilica	-	Barrel vault	Poligonal	Barrel vault	Crowned	Squared	Back	5	65.693	28.0	19.1	15.2	20.0	6.5	0.7	534.8	0.7	0.8	0.7	0.3
	24	SAN SALVATORE	SSL	3	XII	XVIII	HV	Hybrid	Baroque	Basilica	-	Barrel vault	-	Cross	Salienti	Squared	Back	5	66.936	16.0	14.0	8.6	16.0	7.2	0.7	224.0	0.9	0.6	1.0	0.5
	25	SAN NICOLA	SNB	3	XIII	-	MV	Post-Medieval	Renaissance	Basilica	-	Plan	Circular	Cross	Crowned	Squared	Bell-gable	5	66.936	19.5	15.2	8.2	19.5	5.6	0.6	296.4	0.8	0.5	1.0	0.4
	26	SANTA MARIA DEL CARMELO	SMC	3	XVIII	XX	MV	Post-Medieval	Baroque	Basilica	-	Barrel vault	-	Spherical	Towers	Squared	Bell cell	4	88.262	21.0	11.3	11.0	21.0	5.3	0.8	237.3	0.5	1.0	1.0	0.5
L'AQUILA DIOCESE	27	SAN BERNARDINO	SBR	3	XV	XVIII	MV	Post-Medieval	Renaissance	Basilica	Octagonal	Coffer	Circular	Cloister vault	Crowned	Squared	Enclosed	8.5	6.39	100.5	40.0	30.0	50.0	16.0	2.0	4020.0	0.4	0.8	0.5	0.4
	28	SAN BIAGIO D'AMITERNUM (SAN GIUSEPPE ARTIGIANO)	SBM	3	XIII	XVIII	HV	Hybrid	Baroque	Basilica	-	Barrel vault	3 Poligonal	Spherical	Salienti	Squared	-	8.5	5.92	28.0	18.0	15.0	21.0	8.0	1.0	504.0	0.6	0.8	0.8	0.4
	29	SAN DOMENICO	SDM	3	XIV	XVIII	HV	Hybrid	Gothic-Baroque	Latin cross	Circular	Barrel vault	3 Poligonal	Spherical	Salienti	Squared	-	8.5	5.87	74.0	30.5	22.0	46.0	15.5	-	2257.0	0.4	0.7	0.6	0.5
	30	SANTA MARIA DI COLLEMAGGIO	CLM	3	XIII	XVIII	HV	Hybrid	Gothic-Baroque	Latin cross	Circular	Timber truss	3 Poligonal	Timber truss	Crowned	Poligonal	Bell-Gable	8.5	6.35	98.0	30.0	22.0	63.0	14.0	1.8	2940.0	0.3	0.7	0.6	0.5
	31	SANTI MASSIMO E GIORGIO	SMG	3	XIII	XVIII	MV	Post-Medieval	Baroque	Latin cross	Circular	Barrel vault	Poligonal	Spherical	Crowned	Squared	Towers	8.5	5.92	70.0	26.0	26.0	36.5	12.0	2.0	1820.0	0.4	1.0	0.5	0.5
	32	SAN SILVESTRO	SSV	3	XIII-XIV	XV	LV	Medieval	Gothic	Basilica	-	Timber truss	3 Poligonal	Timber truss	Crowned	Circular	Enclosed	8.5	6.2	59.5	24.0	24.0	35.0	12.0	-	1428.0	0.4	1.0	0.6	0.5
	33	SAN BENEDETTO ABATE	SBB	3	XII	XVIII	HV	Hybrid	-	Latin cross	Circular	Barrel vault	Squared	Plan	Salienti	Squared	Back	7.5	9.92	44.5	25.0	15.0	28.5	9.0	-	1112.5	0.6	0.6	0.6	0.4
	34	SANTA MARIA ASSUNTA	SAN	3	XIII-XIV	XVIII	LV	Medieval	Romanesque	Basilica	-	Timber truss	Circular	Timber truss	Crowned	Circular	Facade	6	17.04	24.5	17.0	9.0	23.0	9.0	-	416.5	0.7	0.5	0.9	0.5
	35	SAN GIUSTINO	SGI	3	XII	-	LV	Medieval	Romanesque	Basilica	-	Timber truss	Circular	Timber truss	Salienti	Circular	Enclosed	8	11.46	23.5	14.5	-	20.5	7.0	-	340.8	0.6	-	0.9	0.5
	36	SANTI NICANDRO E MARCIANO (S. RUFINA DI ROIO)	SNM	3	XII	XVIII	HV	Hybrid	-	Basilica	Circular	Barrel vault	-	Plan	Salienti	Squared	Back	8	2.26	25.0	17.0	13.0	25.0	8.0	-	425.0	0.7	0.8	1.0	0.5
	37	SAN GREGORIO MAGNO	SGO	3	XIV	XIX	HV	Hybrid	Baroque	Basilica	-	Plan	Circular	Plan	Salienti	Squared	Bell-Gable	9	13.62	19.5	18.3	11.5	13.5	7.5	1.3	356.9	0.9	0.6	0.7	0.4
	38	SAN LORENZO IN S. LORENZO DI BEFFI	SLB	3	XII	XVII	HV	Hybrid	Roman.-Baroque	Basilica	-	Plan	Circular	Cross	Salienti	Squared	Bell-Gable	6	30.25	25.5	15.0	-	-	8.0	-	382.5	0.6	-	-	0.5
	39	SAN FLAVIANO IN BARISCIANO	SFB	3	XI	XVIII	MV	Post-Medieval	Baroque	Latin cross	Circular	Barrel vault	Squared	Spherical	Salienti	Squared	Back	6	21.46	37.0	20.0	17.0	16.5	9.0	-	740.0	0.5	0.9	0.4	0.5
	40	SANTA MARIA DI PICENZE EXTRA MOENIA	SMX	3	XVII	-	MV	Post-Medieval	Baroque	Latin cross	Circular	Barrel vault	Squared	Cross	Salienti	Squared	Enclosed	6	16.03	30.0	16.0	12.0	18.0	7.0	-	480.0	0.5	0.8	0.6	0.4
	41	SANTA MARIA DI LORETO	SLO	3	XIII	-	HV	Hybrid	Roman.-Baroque	Basilica	-	Plan	-	Plan	Salienti	Squared	Enclosed	5.5	25.94	21.0	16.5	10.0	21.0	8.5	-	346.5	0.8	0.6	1.0	0.5
	42	SAN FLAVIANO IN CAPITIGNANO	SFC	3	XII	XVIII	MV	Post-Medieval	Renaissance	Basilica	Octagonal	Barrel vault	Squared	Spherical	Salienti	-	Back	5.5	21.44	45.0	18.0	12.0	25.0	10.0	-	810.0	0.4	0.7	0.6	0.6
	43	SANTA MARIA ASSUNTA	SSS	3	VIII	XII	LV	Medieval	Romanesque	Basilica	-	Timber truss	3 Circular	Timber truss	Salienti	Circular	Bell-Gable	6	28.92	34.0	14.0	11.5	31.0	7.0	-	476.0	0.4	0.8	0.9	0.5
	44	SAN GIOVANNI BATTISTA IN COLLEPIETRO	SGL	3	XI-XII	XV	HV	Hybrid	-	Basilica	-	Barrel vault	Circular	Barrel vault	Salienti	Squared	Towers	5.5	38.92	23.5	14.5	16.5	20.0	6.5	-	340.8	0.6	1.1	0.9	0.4
	45	S. MARIA E S. PIETRO IN CASTELLO DI FAGNANO	MPF	3	XII	-	HV	Hybrid	Roman.-Baroque	Basilica	-	Barrel vault	-	Spherical	Salienti	Squared	Enclosed	5.5	22.94	35.0	21.0	10.0	26.0	6.3	-	735.0	0.6	0.5	0.7	0.3
	46	SAN GIOVANNI BATTISTA	SGT	3	XI	-	LV	Medieval	Romanesque	Basilica	-	Timber truss	3 Squared	Timber truss	Crowned	Poligonal	Back	6.5	3.41	41.0	19.0	10.0	36.5	8.0	-	779.0	0.5	0.5	0.9	0.4
	47	SANTA MARIA ASSUNTA	SAS	3	XV	XVIII	MV	Post-Medieval	Baroque	Latin cross	Circular	Barrel vault	Circular	Cross	Salienti	Squared	Enclosed	5	22.55	31.5	19.5	15.0	15.5	10.5	-	614.3	0.6	0.8	0.5	0.5
	48	SANTA MARIA IN PANTANIS	SPS	3	XII-XIII	XVIII	HV	Hybrid	Baroque	missa" cros	Circular	Barrel vault	-	Cross	Salienti	Squared	Bell-Gable	5	22.75	36.0	19.5	15.0	19.5	9.5	-	702.0	0.5	0.8	0.5	0.5
	49	SAN SEBASTIANO	SSB	3	XVII	XVIII	HV	Hybrid	Baroque	Basilica	-	Barrel vault	Squared	Cross	Slope	Squared	Enclosed	6	34.41	33.9	16.5	9.5	26.0	7.0	1.0	559.4	0.5	0.6	0.8	0.4
	50	SANTA MARIA IN CERULIS	SMU	3	XI	XIX	HV	Hybrid	Romanesque	Basilica	-	Timber truss	2 Semicircola	Timber truss	Salienti	-	Bell-Gable	6	33.5	27.0	22.5	11.0	22.0	11.0	-	607.5	0.8	0.5	0.8	0.5
	51	SAN PANFILO	SPF	3	X	XVI	LV	Medieval	Romanesque	Basilica	-	Timber truss	3 Squared	Timber truss	Crowned	Squared	Bell-Gable	6	13	22.0	14.0	9.0	-	-	-	308.0	0.6	0.6	-	-
	52	SAN FELICE MARTIRE	SFM	3	XV	XVIII	MV	Post-Medieval	Baroque	Latin cross	Circular	Barrel vault	Circular	Spherical	Salienti	Squared	Facade	8.5	17.65	45.5	23.0	22.0	18.0	11.0	-	1046.5	0.5	1.0	0.4	0.5
	53	SAN NICANDRO	SNC	3	-	XVII	HV	Hybrid	Roman.-Baroque	Basilica	-	Barrel vault	Poligonal	Cross	Salienti	Squared	Enclosed	6	22.3	24.5	14.5	11.5	17.5	6.5	-	355.3	0.6	0.8	0.7	0.4
	54	SANTA LUCIA	SLU	3	XI	XII	LV	Medieval	Romanesque	missa" cros	-	Timber truss	-	Timber truss	Salienti	Squared	Bell-Gable	6	16.65	23.0	16.0	9.0	13.0	18.0	-	368.0	0.7	0.6	0.6	1.1
	55	SAN PIETRO	SPI	3	XVI	-	HV	Hybrid	-	Basilica	-	Plan	-	Plan	Crowned	Squared	Back	6	23	-	-	-	-	-	-	-	-	-	-	-
	56	SAN DEMETRIO	SDE	3	XIV	XVII	HV	Hybrid	Baroque	Latin cross	Circular	Barrel vault	Squared	Cross	Salienti	Squared	Back	6.5	18.91	34.0	18.5	17.0	15.5	8.5	-	629.0	0.5	0.9	0.5	0.5
	57	SAN PIETRO CELESTINO	SPT	3	XI	XVI	HV	Hybrid	Baroque	Basilica	-	Barrel vault	-	Cross	Salienti	Squared	Back	5.5	27.38	23.0	14.5	-	23.0	7.5	-	333.5	0.6	-	1.0	0.5
	58	SANT'EUSANIO MARTIRE	SEU	3	XII	XVIII	HV	Hybrid	Roman.-Baroque	Latin cross	Circular	Barrel vault	3 Circular	Timber truss	Crowned	Squared	Bell-Gable	9	16.72	37.0	17.5	-	18.5	8.5	-	647.5	0.5	-	0.5	0.5
	59	SAN GIOVANNI EVANGELISTA	SGV	3	-	-	HV	Hybrid	Roman.-Baroque	Basilica	-	Barrel vault	Circular	Cross	Salienti	Squared	Enclosed	8	15.96	27.0	19.0	-	23.0	9.0	-	513.0	0.7	-	0.9	0.5
	60	SANTI GIUSTA E GIORGIO	SGG	3	XIV-XV	-	HV	Hybrid	Romanesque	Basilica	-	Plan	-	Cross	Crowned	Circular	Bell-Gable	5.5	32.28	29.0	22.0	15.0	29.0	-	-	638.0	0.8	0.7	1.0	-
	61	SANTA MARIA DELLA ROTA	SRO	3	XV	-	LV	Medieval	Romanesque	Basilica	-	Timber truss	Squared	Timber truss	Crowned	Circular	Bell-Gable	5.5	32.79	27.0	14.0	11.0	22.0	6.0	-	378.0	0.5	0.8	0.8	0.4
	62	SANTA MARIA DEL PONTE (S. MARIA ASSUNTA)	SPN	3	XI-XII	XIV	HV	Hybrid	Gothic	Basilica	-	Cross vault	-	Cross	Salienti	Squared	Back	6	29.18	24.5	18.0	-	24.5	7.0	-	441.0	0.7	-	1.0	0.4
	63	SAN MICHELE ARCANGELO	SAR	3	XIII	-	LV	Medieval	Romanesque	Basilica	-	Timber truss	Circular	Timber truss	Crowned	Squared	Bell-Gable	9	18.6	30.0	16.0	7.5	28.0	5.0	-	480.0	0.5	0.5	0.9	0.3
	64	SANT'AGATA	SAG	3	-	-	HV	Hybrid	-	Basilica	-	Plan	-	Timber truss	Slope	Squared	Back	8	17.89	20.0	16.0	10.0	20.0	6.0	-	320.0	0.8	0.6	1.0	0.4

Table 1. Typological classification of the observed three nave churches in L'Aquila and Sulmona dioceses.

Damage Level *(D_k)*	Damage Index *(i_d)*	Description
0	$i_d \leq 0.05$	No damage: light damage only in one or two mechanism
1	$0.05 < i_d \leq 0.25$	Negligible to slight damage: light damage in some mechanisms
2	$0.25 < i_d \leq 0.4$	Moderate damage: light damage in many mechanisms, with one or two mechanisms activated at medium level
3	$0.4 < i_d \leq 0.6$	Substantial to heavy damage: many mechanisms have been activated at medium level, with severe damage in some mechanisms
4	$0.6 < i_d \leq 0.8$	Very heavy damage: severe damage in many mechanisms, with the collapse of some macroelements of the church
5	$i_d > 0.8$	Destruction: at least 2/3 of the mechanisms exhibit severe damage

Table 2. Correlation between damage index i_d and damage level D_i [11].