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Damage assessment of churches after L'Aquila earthquake (2009)

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Abstract L'Aquila earthquake, which occurred on April 6, 2009, proved the high vulnerability of cultural heritage, with particular reference to churches. Damage assessment in the emergency was carried out on more than 700 churches with a methodology aimed at recognizing the collapse mechanisms in the different architectonic elements of the church. The method was developed after the earthquake in Umbria and the Marches (1997) and has been widely used in the last decade; this approach is also very useful for seismic prevention, as it allows one to single out the most vulnerable structures. Some examples are presented in this paper, representative of recurrent damage in the main elements of the church: the façade, the roof, the apse and the belfry. It emerges that, for a correct interpretation of damage and vulnerability, it is necessary a deep knowledge of local construction techniques and of the historic transformation sequence. Moreover, the bad behaviour of churches strengthened by modern techniques, such as the substitution of original timber roofs with stiff and heavy r.c. slabs, was observed. Starting from the observation of some case studies, the paper achieves some worth results, which may be useful for correctly driving future strengthening interventions.

Keywords Vulnerability · Damage assessment · Historical buildings · Macroelements · Strengthening

1 Introduction

The earthquake which struck L'Aquila and the Aterno Valley on 6 April 2009 caused severe damage to churches, in many cases with extensive collapse. This attests to the fact that this type of structure is perhaps the most vulnerable among historical buildings. In fact, history has shown that churches have often registered numerous victims. Therefore, there is a problem of safety for people and the seismic capacity of structures should be improved. However, there

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is also a problem of preservation of the cultural value, both in restoring damaged heritage and in strengthening historical buildings in other areas prone to earthquakes.

The high level of damage in many churches, after L'Aquila earthquake, obliges rebuilding wide parts of the original structures and it is necessary to understand if it is possible to guarantee the required safety with traditional masonry elements. Moreover, the quality of masonry in L'Aquila region is also under investigation, as compatible strengthening techniques may not be sufficient in such a highly seismic area.

The answers to these questions has to be complex and detailed because of the many factors which influenced the seismic behaviour in the historical Aquilan buildings.

First of all, it is important to consider the characteristics of the seismic event. The fault broke very close to the surface (the epicentre was at a depth of only 10 km) therefore the effects were very intense but included a relatively limited area. Such a superficial earthquake produced a very intense and energetic vertical component compared to the horizontal one, which is usually more severe and considered more dangerous to constructions. In other words, the earthquake produced not only horizontal forces creating out-of-plane and in-plane damage mechanisms, but also a strong increase and annulment of vertical action with the result of crushing masonry piers or the loss of stability to domes. Besides that, in this earthquake perhaps more than others, local seismic amplification played an important role: if one analyses the macro seismic effects in many of the historical centres in the Aterno Valley (south-east of L'Aquila), it is immediately apparent that the villages heavily damaged by the earthquake were next to others which sustained little damage. Even within the same historical centre, there are zones where the damage is clearly concentrated.

This paper will be limited to an interpretation of damage to certain building types considering the most vulnerable elements of churches; the collapse mechanisms are in fact different and often easier to identify compared to those commonly found in other buildings in historical centres (Carocci and Lagomarsino 2010; D'Ayala and Paganoni 2011). Following this earthquake, bad behaviour was also caused by the modern reinforcement techniques used, and particularly those which utilized concrete slabs to substitute wooden roofs and diaphragms, which resulted in increased mass and excessive structural rigidity. From the seismic vulnerability observed, it is possible to obtain indications for choosing truly effective seismic improvement interventions. The time has come for a decisive change of direction in seismic consolidation, based on in-depth knowledge of structures, diagnostic interpretation, as well as the use of proven evaluation models of structural safety.

2 Seismic vulnerability and risk prevention of cultural heritage

The meaning of the word vulnerability indicates the predisposition to damage of a building. In the field of seismic risk, vulnerability is one of the steps of the analysis, that establishes the correlation between the seismic input (hazard) and the physical damage for classes of homogeneous buildings. The aim of risk analysis is to evaluate the expected losses in a wide area due to a well defined strong earthquake (scenario analysis) or considering all possible earthquakes (probabilistic risk analysis). In either case, it is necessary to:

(1) identify the elements at risk (residential buildings, public and/or strategic buildings, infrastructure, water and gas lines, etc.);
(2) define an appropriate measurement of direct damage (cracking, usability) or indirect damage (victims, homeless, economic losses);

(3) evaluate the hazard through seismological studies (or the characteristics of the expected earthquake at the site);
(4) estimate vulnerability, or the functional relationship between hazard and damage.

Seismic risk is therefore a combination of three different factors: exposure, hazard and vulnerability. It is higher in urban areas (because of the exposure), and it increases in relation to the seismic hazard of the zone (in Italy, the L'Aquila zone is certainly one of the highest risk areas), but it also depends on the construction characteristics and their vulnerability.

Until the 1990's, cultural heritage was not considered in risk analyses. Due to the unique architectural characteristics of each building, a global evaluation by a simplified model was not thought to be reliable, due to the impossibility of considering the history and construction characteristics of each. But seismic risk to cultural heritage is a real problem in Italy, due to both the high number of protected heritage buildings as well as their high level of vulnerability (as proven by each earthquake).

Studies done on churches, starting from the observation of damage after the Friuli earthquake in 1976 (Doglioni et al. 1994) and more systematically after the earthquakes in Umbria and the Marches in 1997 (Lagomarsino and Podestà 2004a) and Molise in 2002 (Lagomarsino and Podestà 2004c), have demonstrated that damage mechanisms in churches have certain recurring characteristics, notwithstanding the uniqueness of each site. In particular, the interpretation using macro elements has proven very useful, i.e. observation of damage in various parts of churches (façade, nave, triumphal arch, dome, apse, bell tower, etc.), due to the fact that collapse usually occurs locally and in function of the type of macro element (geometrical configuration or construction details).

From the systematic observation of a vast number of churches, in different regions and characterized by different materials and construction techniques, a certain number of possible mechanisms have been identified for each macro element, depicted by easily understood graphic drawings.

The classification into macro elements and collapse mechanisms has allowed the definition of methods to assess damage and to quickly acquire useful information for handling emergencies (first aid interventions, fitness for habitation, economic damage estimates, planning support and project management). The schemes developed after the earthquakes in Umbria and the Marches were later published (G.U. no. 55, 2006) and officially adopted by the system for seismic emergency management as detailed by the Civil Protection Department which presides over cultural heritage in direct collaboration with the Ministry for Cultural Heritage and Activities.

The statistical analysis of damage observed led to the formulation of vulnerability models (Lagomarsino and Podestà 2004b), which allowed us to assign a vulnerability index to each church, taking into consideration both its weakest elements and the preventive constructive details, as well as to estimate damage according to expected earthquake intensity. This model was adopted in the Guidelines (G.U. no. 47, 2011) issued by the Ministry for Cultural Heritage and Activities as a tool for the evaluation and mitigation of seismic risk to cultural heritage as well as to give direction and control to seismic strengthening interventions.

This interpretation of vulnerability and seismic damage in terms of macro elements and collapse mechanisms has also allowed the definition of new mechanical models for the evaluation of seismic response, based on the statics of rigid bodies and the traditional methods of equilibrium limit analysis (Lagomarsino and Resemini 2009). The recent Italian seismic code for constructions adopted this approach (G.U. no. 47, 2009), and has proven very useful in the design of seismic strengthening interventions.

3 The damage assessment of churches and emergency management

Damage assessment and emergency management of cultural heritage has been coordinated by the Vice Commissioner Luciano Marchetti, on behalf of the *Civil Protection Department*, also involving the *Ministry of Cultural Heritage* and ReLUIS, the Italian University Laboratories Network of seismic engineering; moreover, the support of the *Institute for the building technologies* in L'Aquila, which operates inside the *National Research Council* (CNR), has been helpful. Damage assessment has been carried out by teams of technicians with different expertise: architects of the Monuments and Fine Arts Office, structural experts (engineers or architects) from the University, historians for the assessment of artistic assets, engineers from the Fire Brigade (aimed at ensuring safety during the survey and to arrange for the necessary provisional interventions). This assessment was devoted not only to churches and palaces, but also to towers, castles, urban walls, fortified gates, etc.

However, only for churches and palaces there are well defined forms, already mentioned (G.U. no. 55), that allow one to collect data in an effective way, with the aim of: (a) deciding if the building is suitable for immediate occupancy; (b) advising about the need for provisional interventions, in order to prevent further damage due to replica shocks; (c) estimating the restoration costs, in order to find necessary funds and plan the priorities of intervention.

In particular, the church form considers 28 damage and collapse mechanisms that can frequently occur in the different architectonic elements (named macroelements) which compose churches (Lagomarsino and Podestà 2004c). Table 1 shows the mechanisms considered and the related macroelement. Figure 1 shows some typical collapse mechanisms; these schematic sketches are very useful during the survey, to recognize and interpret damage. For each mechanism, the assessment consists of assigning a damage grade (from 0, no damage, to 5, complete).

The collection of damage data in each single architectonic element of the church allows one to single out the need for provisional interventions. Moreover, an automatic procedure was established which estimates the total restoration cost, considering the level of damage in each macroelement and the dimensions.

Damage assessment, by singling out the activated collapse mechanisms and evaluating the damage level for each one, allows one to evaluate a synthetic score, the damage index, which is representative of the average damage in the church (Lagomarsino and Podestà 2004a). The damage index, which ranges between 0 (no damage) and 1 (total collapse), is a weighted average of all possible collapse mechanisms, also considering the ones that were not activated by the earthquake; it is a useful parameter for the preparation of a damage list, in order to compare the severity of damage in churches of different size and typology.

All data was collected in a database, which allows one to manage the emergency actions (plan of multiple surveys, due to replica shocks; news about the safety of the building for the immediate occupancy; need for provisional interventions) and to plan the following phase of restoration interventions.

Thanks to the high number of churches surveyed, the statistical analysis of damage data gives useful information for the validation and tuning of the church vulnerability model, which was developed after the Umbria-Marche earthquake (Lagomarsino and Podestà 2004b). This analysis (Podestà et al. 2010) was performed after an accurate quality control of the completed forms that were filled in by different teams, not all provided with the same expertise, and in some cases without the possibility of a complete survey (for example, some churches were assessed only from outside, for safety reasons). Among the 723 forms of churches surveyed, inaccuracy in compilation has been found in 9% of cases, which were not considered in the statistical analysis.

Table 1 Damage mechanisms considered in the macroelements of the church

Damage mechanisms	Macroelement
1. Overturning of the Façade	Façade
2. Damage at the top of Façade	
3. Shear mechanisms in the Façade	
4. Nartex	
5. Transversal vibration of the nave	Nave
6. Shear mechanisms in the side walls	
7. Longitudinal response of the colonnade	
8. Vaults of the nave	
9. Vaults of the aisles	
10. Overturning of the transept's end wall	Transept
11. Shear mechanisms in the transept walls	
12. Vaults of the transept	
13. Triumphal arches	Triumphal arch
14. Dome and drum	Dome
15. Lantern	
16. Overturning of apse	Apse
17. Shear mechanisms in presbytery and apse	
18. Vaults in presbytery and apse	
19. Roof mechanisms: side walls of nave and aisles	Roof covering
20. Roof mechanisms: transept	
21. Roof mechanisms: apse and presbytery	
22. Overturning of the chapels	Chapel
23. Shear mechanisms in the walls of chapels	
24. Vaults of chapels	
25. Interactions next to irregularities	
26. Projections (domed vaults, pinnacles, statues)	Bell tower
27. Bell tower	
28. Belfry	

The outcome of the safety evaluation for the immediate occupancy is described by Fig. 2, which shows, as a function of the macroseismic intensity, the percentage in the different possible outcomes, according to the classification used by the Italian Civil Protection Department: (A) safe for immediate occupancy; (B) fit for use after provisional interventions; (C) partially unfit for use; (D) temporarily unfit for use (to be examined again); (E) unfit for use; (F) unfit for use due to external reasons. It is worth noting that for $I \geq 8$ MCS all churches are unfit for use (only 15% may be usable after a proper provisional intervention). Moreover, also in the areas which are far from the epicentre ($I = 5$ MCS), only for less than 50% of churches is an immediate occupancy possible; this confirms the high vulnerability of churches, even for low intensity earthquakes.

Even if it is not possible, for safety and responsibility reasons, to establish a direct correlation between usability and damage index, it emerges that usually when the damage index is greater than 0.3 the church is unfit for use. The same result was obtained after the Umbria-Marches (1997) and Molise (2002) earthquakes, thus supporting the reliability of the survey procedure. However, a low value of the damage index results in a church with a local collapse in one macro element and with slight damage in the other elements, but it should be classified as unfit for use.

The statistical analysis of damage data to churches after the various earthquakes that have occurred in Italy in the last 30 years allowed us to proposed a methodology for preventive vulnerability evaluation, to be used in seismic risk analyses. The survey of construction details in each macroelement, some of them positive while others are negative for the seismic

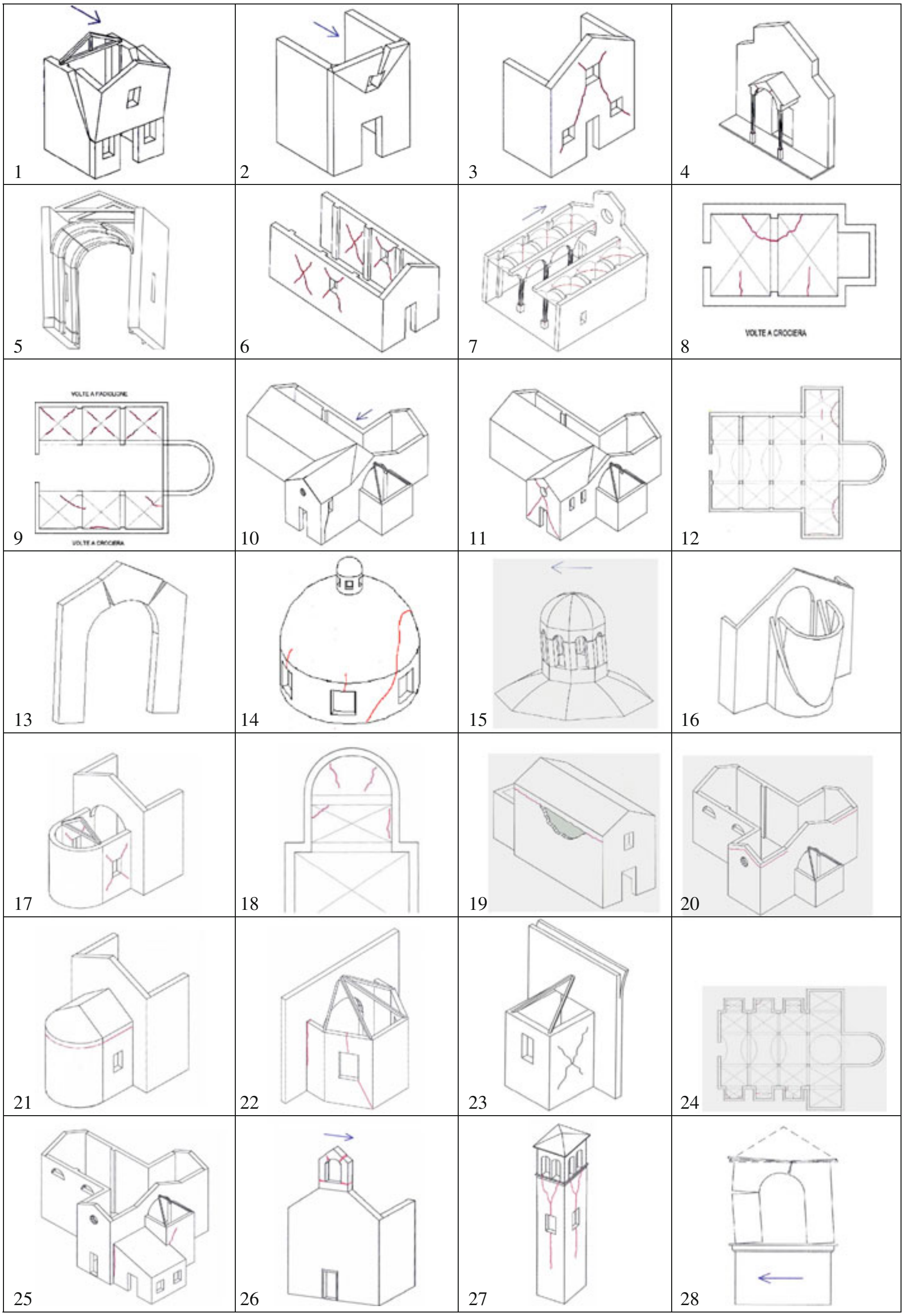

Fig. 1 Damage mechanisms considered in the vulnerability method

behaviour, allows one to assign a vulnerability index I_V (which ranges between 0 to 1) to each church and, consequently, a vulnerability curve (correlation between the macroseismic intensity and the mean damage grade, related to the damage index). Since the observed damage

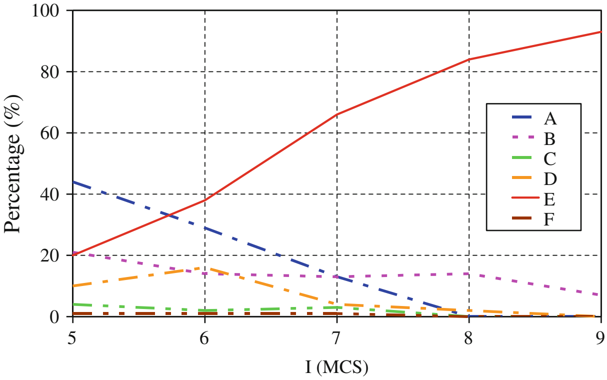

Fig. 2 Results of safety evaluations for the immediate occupancy of churches for different values of the macroseismic intensity (the macroseismic survey in Italy was made by MCS scale)

Table 2 Mean damage grade observed to churches in different Italian earthquakes, as a function of the macroseismic intensity

Earthquake	I (MCS)					
	IV	V	VI	VII	VIII	IX
Irpinia (1980)	–	1.21	1.41	1.86	2.71	3.25
Tuscany (1995)	–	–	1.13	–	–	–
Umbria (1997)	–	1.00	1.30	2.15	2.90	–
Marche (1997)	–	1.10	1.45	1.80	3.20	–
Lazio (2000)	–	–	1.38	–	–	–
Molise (2002)	0.4	0.54	1.28	2.9	–	
Piedmont (2003)	–	–	1.28	–	–	–
Salò (2004)	–	1.19	1.42	–	–	–
L'Aquila (2009)	–	0.73	1.28	1.97	2.60	3.43

histograms, for different macroseismic intensity, are well fitted by a binomial distribution, through the vulnerability curve it is possible to obtain the Damage Probability Matrix for a given church. Podestà et al. (2010) shows the damage histograms obtained for the set of 654 churches, damaged by the L'Aquila earthquake, even in areas quite far from the epicentre.

Table 2 allows one to compare the mean observed damage grade, due to different Italian earthquakes, as a function of the macroseismic intensity. The robustness of the damage assessment methodology and the reliability of the vulnerability model are evident, for there use in risk analysis. In Fig. 3 the observed damage data is compared with the analytical vulnerability curves, for usual values of the vulnerability index I_V, from 0.2 to 0.6 (Lagomarsino and Podestà 2004b).

This vulnerability model, as already mentioned, is at the base of the model proposed in the Guidelines (G.U. no. 47, 2011) issued by the Ministry for Cultural Heritage and Activities as a tool for the evaluation and mitigation of seismic risk to cultural heritage; in this case a correlation between intensity and peak ground acceleration was adopted.

The statistical analysis may be done not only on the average damage but also considering the typology of macroelements and the related damage level. Podestà et al. (2010) show some

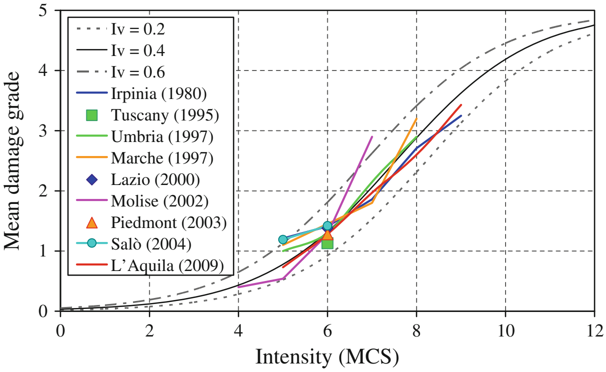

Fig. 3 Comparison among the vulnerability curves for most of the churches (I_V between 0.2 and 0.6) and the damage observed data, after Italian earthquakes of the last 30 years

interesting peculiarities of churches in L'Aquila. Most churches have only one nave, without a transept or lateral chapels; structural vaults are present only in 40% of cases, while the bell tower is present only in 35% of churches. Perhaps the awareness of ancient builders of the high seismic hazard in L'Aquila area suggested the adoption of simplicity and regularity. It is worth noting that the macroelements which are present in a few cases are the most vulnerable ones: the dome (seriously damaged in 80% of cases); the vaults in the central nave and, in particular, in the lateral aisles (damaged in more than 70% of cases).

In this paper, instead of considering the vulnerability from a statistical point of view, some specific cases are considered, which however can be considered representative of typical recurrent mechanisms, according to the methodology described above.

4 The earthquake in L'Aquila on April 6, 2009

On April 6, 2009 at 3:32 a.m. a $M_w = 6.3$ earthquake with shallow focal depth (10 kilometres) struck central Italy in the vicinity of L'Aquila, a town of about 73,000 people, capital of the Abruzzo region. The earthquake killed 305 people, injured 1,500, destroyed or damaged more or less 10,000–15,000 buildings, prompted the temporary evacuation of 70,000–80,000 residents and left more than 24,000 homeless. This event was the strongest of a sequence that started a few months earlier and numbered 23 earthquakes of $M_w > 4$ between September 2009 and April 2010, including a $M_w = 5.6$ on April 4 and a $M_w = 5.4$ on April 9 (Bazzurro et al. 2009).

A total of 81 municipalities were affected by the earthquake and 49 of them were in the list of highest hazard areas in Italy. The population of L'Aquila includes 14 surrounding boroughs such as Onna, Paganica, and Tempera. The total population of the other 48 high hazard towns is 60,352; most range in size from 1,000 to 3,000 people, with two larger towns of 5,000 and 8,500 inhabitants.

The historical centres of villages in the Aterno River valley, southwest of L'Aquila (such as Onna, Paganica, Castelnuovo and Villa Sant'Angelo), were essentially obliterated, with shaking intensities of up to X MCS. Conversely, damage did not exceed MCS intensity VI nearly anywhere to the northwest of L'Aquila. This south-eastward elongation of the damage pattern probably reflects a combination of rupture directivity and seismic lithostratigraphic amplification effects.

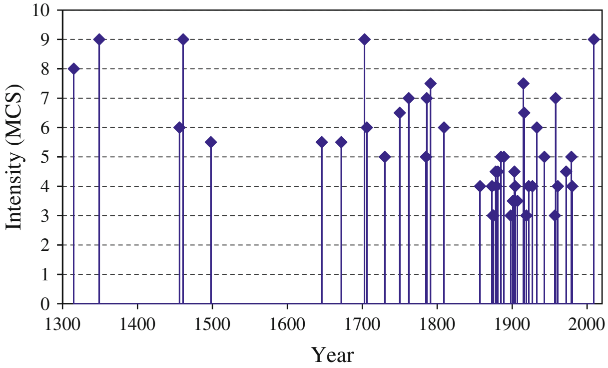

Fig. 4 Historical MCS macroseismic intensity of the major events in L'Aquila (source: INGV database macrosismico Italiano-2008, http://emidius.mi.ingv.it/DBMI08/)

Figure 4 shows the earthquakes that have struck the city of L'Aquila and the villages around it since 1300 (Stucchi et al. 2007; Rovida et al. 2009). L'Aquila has been severely damaged at least 5 times in the last 700 years, specifically in 1315 ($M_w \approx 6.7$), 1349 ($M_w \approx 6.5$), 1461 ($M_w \approx 6.5$), 1703 ($M_w \approx 6.7$), and 1915 ($M_w \approx 7.0$). The 1,461 event shows a damage distribution similar to that of the April 6, 2009 earthquake, although it was shifted to the east by a few km.

Among approximately 300 digital strong-motion stations operated by the Italian Strong Motion Network (RAN), managed by the Italian Civil Protection Department, 56 of them recorded the main shock; in addition, 142 broad-band stations recorded it (14 stations are in the Abruzzo region, while the remaining ones are scattered in the Apennines, mostly NW and SE of L'Aquila). This makes the Abruzzo Mw 6.3 event one of the best recorded earthquakes caused by a normal fault mechanism.

Four stations, all on the hanging wall of the rupture, were located within 10 km of the epicentres, and all recorded a horizontal peak ground acceleration exceeding 0.35 g. The stations AQG and AQK are on rock or stiff material, while AQA and AQV are on recent alluvium.

The 5% damped spectra of the two horizontal directions are shown in Fig. 5, compared with the one proposed for L'Aquila by the new Italian seismic code for ground type B (very dense sand, gravel, or very stiff clay, characterised by a gradual increase of mechanical properties with depth), for a return period $T_R = 475$ years; the frequency content is very wide and in particular AQK has significant values also for periods greater than 1 s. The ground motion had relatively short duration: 95% of the energy was released in 10 s or less. Finally, unprocessed data obtained from many stations show permanent displacements of up to 15 cm.

5 Vulnerability of the churches in L'Aquila area

Certain specific characteristics of Aquilan constructions proved to be decisive in analysing and interpreting the damage. Many churches dated back to the Middle Ages and from a typology point of view were simple naves with the typical Aquilan rectangular façade. An essential element to understand the vulnerability of churches and more generally all of the Aquilan buildings as a whole, was the devastating earthquake which hit L'Aquila in 1703 with an estimated intensity in historical documents of I = 9–10 MCS. Nearly all of the

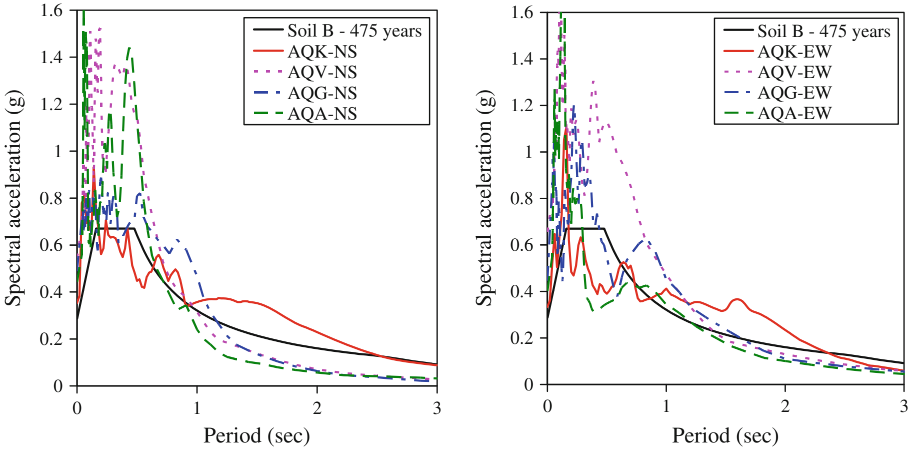

Fig. 5 Response spectra for 5% damping of the 4 recorded accelerograms, compared with the elastic spectrum proposed by the Italian seismic code for ground type B ($T_R = 475$ years)

churches were severely damaged. In some cases, simple repairs and reinforcements were performed, while in others, partial reconstruction (along with important enlargements and modifications to the original structure also linked to the architectural style of the period), and some churches were entirely rebuilt.

These factors contributed greatly to vulnerability, due to discontinuity in the masonry wall (in presence of enlargements), increased height and the reconstruction of collapsed wall portions (rarely efficiently connected).

On the other hand, newer buildings benefited from knowledge of anti-seismic construction techniques always found in territories subject to strong earthquakes and usually handed down to builders over generations. In particular, L'Aquila systematically utilized the technique of "wooden ties" (Fig. 6), which consists in the insertion of horizontal wooden logs built into the masonry during construction and joined at the extremities by small metal plates (fixed to the wood by two nails) and connected to the external wall by means of a small key. This solution was certainly derived from the understanding after the earthquake in 1703 that the first collapse mechanisms were caused by out-of-plane overturning, and for this reason called first-mode mechanisms (Giuffrè 1993).

Therefore, it is necessary to connect each wall to the orthogonally adjoining one well in order to activate in-plane shear resistance (second-mode mechanism, typically characterized by diagonal cracking). An efficient connection between walls at the corners is not usually sufficient, also due to the fact that Aquilan masonry is not necessarily of poor quality but is characterized by small or medium sized, irregular stones. Metallic tie rods are present in L'Aquila only for repair or reinforcement interventions, while the connection between walls is made using "wooden ties", where anchoring is not limited to the extremities but is diffused thanks to friction that develops over the entire wooden log inserted in the masonry. For this reason, the external metal keys are always quite small (nevertheless the weak point is always found at the connection of the two nails between the metal plate and the wooden log).

There was probably another reason the builders of the time used "wooden ties"; to protect against flexional out-of-plane mechanisms, which are activated in central portions of the façade when the internal walls are too far one from the other and the frontal wall is weakened by the presence of openings.

Fig. 6 Some examples of "wooden ties" and connections: **a** "wooden ties" at different levels of the dome of Santa Maria del Suffragio church in L'Aquila; **b** the terminal connection elements, taken from the debris: the key and the steel plate (with two nails); **c** the external key; **d** and external wooden key for the connection of the trusses in Santa Maria del Carmine church in L'Aquila

Roofs also contain elements that clearly necessitate the addition of anti-seismic construction details. The extremities of trusses or roof rafters are not simply placed upon walls, but connected by means of wooden planks that protrude externally and are fixed into the walls by means of a wooden key (Fig. 6d).

Another important factor of vulnerability is certainly caused by decay, which can be avoided altogether with proper maintenance. Water infiltration through cracks or due to lack of roof maintenance in many cases hastened the decay of wooden elements especially at the extremities near the connection with the metal plates.

Finally, also the Aquilan churches were found vulnerable due to the bad behaviour of modern interventions of structural strengthening. The term "modern" means building techniques used during the last century and particularly reinforced concrete and steel. Wooden roofs which are relatively light and flexible were often substituted with heavy and rigid reinforced concrete slabs, which almost always resulted in having a negative effect on the structure as well as its preservation (Fig. 7).

6 Interpretation of damage and collapse mechanisms

This paragraph will comment on a few cases of damage to churches in the Aquilan area referring to certain macroelements and the most significant damage mechanisms. The churches

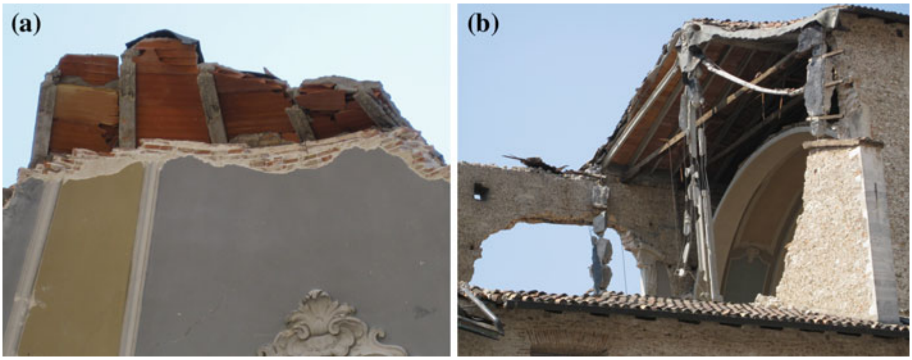

Fig. 7 The modern roof made by r.c. precast elements and unreinforced concrete slab in Santa Maria Paganica church in L'Aquila: **a** the small portion of the dome which did not collapse; **b** trusses with pre-cast r.c. joists

chosen were not necessarily the most relevant to the territory, nor noteworthy of media attention. Damage is interpreted directly, following the prompt approach commonly used during a seismic emergency to determine collapse mechanisms in order to highlight its value as an initial structural evaluation notwithstanding its limits.

6.1 Overturning mechanisms of the façade

Façade walls are almost always among the most vulnerable elements of churches. They are often subject to out-of-plane overturning mechanisms at any height or limited to the tops of the walls (gable).

The typical L'Aquila church façade has a rectangular shape. A summit mechanism that was observed in many cases was overturning of the raised triangle over the line of the roof. The façade is nearly always connected to lateral walls with "wooden ties" and the roof constitutes another connection through the ridgepole and the purlins. The demand for displacement due to the earthquake was therefore concentrated in the only unbound portion, with frequent cases of collapse or disarticulation from the stone ashlars (the façade is in fact often a wall made of poorly mortared, squared off ashlars; the top portions of the wall cannot benefit from the important contribution of friction due to low compression stresses).

One of the emblematic examples is S. Maria degli Angeli, located in Civita di Bagno (Fig. 8), which shows out-of-plane overturning in the upper part of the left side and marked cracking proving an analogous mechanism on the right side, which did not evolve to the point of complete collapse.

The case is interesting because it highlights certain types of construction solutions. The corners were made of squared stones while the façade walls and lateral walls were made of irregular stones. This solution dictated by aesthetic reason but perhaps also by the desire for better connection, represents instead a point of weakness because the connection between the two types of masonry created discontinuity. In this case, an overturning mechanism was definitely activated with a fracture line throughout the plane of the façade rather than in correspondence with the connection to the lateral walls (as usually occurs). One can note the presence of anchoring keys of "wooden ties" which however did not hold in the façade probably due to decay at the extremities of the wooden log.

An interesting case is the façade of the Cathedral of S. Bernardino in L'Aquila (Fig. 9), which did not overturn despite the large and slender raised portion. Rocking of slender

Fig. 8 Santa Maria degli Angeli church, in Civita di Bagno, L'Aquila

masonry elements is a very complex problem, which depends on various factors: characteristics of seismic motion; monolithic nature of the masonry structures; slenderness; size of the element (particularly its thickness). The seismic activation of the oscillation depends on wall slenderness but overturning is strongly related to the thickness. Moreover, in the presence of irregular masonry, a wall cannot oscillate on sharp edges, but localized crushing occurs, with a lesser capacity to withstand repetitive cycles (due to progressive decay). The façade of S. Bernardino was made of excellently hewn marble ashlars and had been reinforced in the 1960's with a reinforced concrete covering to the rear face of the wall. This intervention certainly increased resistance and stability to horizontal actions, but also increased its stiffness; as a consequence, the horizontal equivalent seismic actions were increased, compared with the one that would have occurred in the case of unreinforced walls, with notable compressive stresses at the edges. This was demonstrated by widespread localized crushing at the base of the semi-columns and capitals (Fig. 9). In the absence of r.c. reinforcement, the wall would surely be subjected to wider oscillation but fewer compressive stresses in the edges (and therefore less localized damage).

Another interesting case is the church of the Madonna dei Raccomandati in San Demetrio ne' Vestini (Fig. 10). Here, the façade was erected in Baroque style after the earthquake of 1703 and the gable collapsed in the recent earthquake. It can be observed how the new roof, recently rebuilt with a wooden trussed structure, did not lean on the tympanum, and therefore resulted in a total lack of connection. Within the masonry, a "wooden tie" element was present, made of irregular logs which were too short (in other words, the builder believed that the length of overlapping was sufficient for adherence, which instead proved to be insufficient).

6.2 Roof coverings: direct or induced damage

The topic of induced vulnerability by the substitution of original wooden roofs with new rigid and heavy r.c. slabs has been the subject of intense arguments over the last few years (in particular since the earthquakes in Umbria and the Marches in 1997) both in scientific and professional fields. The recent Italian technical regulations (instruction document of the NTC 2008; G.U. no. 47, 2009) states clearly that this kind of interventions should be avoided. Even though there are many cases of severe damage to churches and buildings where the roof was substituted by a r.c. slab, there are still those who argue that a certain amount of stiffness at the roof level may be useful and the mass increase is often low (compared to

Fig. 9 S. Bernardino basilica in L'Aquila: **a** the façade; **b–c** details of some local crushing of marble elements due to out-of-plane overturning mechanism

Fig. 10 Madonna dei Raccomandati church in San Demetrio né Vestini

the total weight of the structure). However, the systematic and often in-depth observation of many cases gave rise to some important beliefs.

One must distinguish between the case of the simple construction of a r.c. stringcourse on top of the masonry from the much more invasive construction of a rigid roof with a thick r.c. slab, which can slide and crumble the masonry due to the low compressive stresses. The realization of a stringcourse at the top can certainly improve the overall behaviour as long as it is not too rigid nor heavy, especially in the presence of flexible walls as is the case in the lateral sides of churches. Efficient stringcourses can be made without using r.c. (reinforced brick masonry stringcourses; horizontal truss of steel plate over the top of the wall;

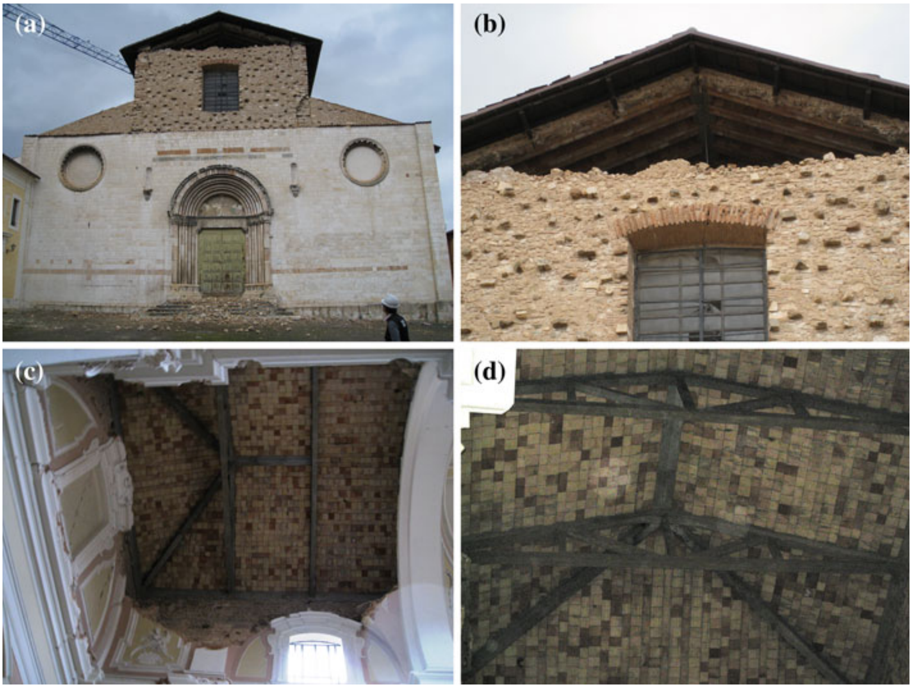

Fig. 11 San Domenico church in L'Aquila: **a** the façade; **b** the collapsed gable of the façade; **c–d** collapse of the transept vault due to substitution of the roof, made by r.c. trusses

stringcourses with external steel plates well-connected through masonry by bolts), but small reinforced concrete ones can also be a good solution.

Instead, the realization of a continuous, rigid and heavy diaphragm is always negative for various reasons:

(1) when the slab is very thick, the increase in mass is significant and the fact that dynamic amplification increases with height should not be overlooked, so adding weight at the top of the construction is certainly a mistake;
(2) adding stiffness to the roof further increases the in-plane action of the façade and in the triumphal arch due to the limitation to transverse displacement in intermediate arch spans (it is better to improve the capacity of the latter rather than expect the façade and the triumphal arch to sustain the seismic actions of the whole nave);
(3) in the case of collapse, the presence of a monolithic element impedes localized damage to the areas concerned, but produces a snowball effect, contrary to modern criteria of the structural robustness (take the example of Noto cathedral, which collapsed in 1996: in absence of the r.c. roof slab, the collapse would probably have been limited to the arch near the pier that collapsed due to crushing).

Another negative effect of stiff r.c. roofs is what they do to the gable of the façade. An example is the church of S. Domenico in L'Aquila (Fig. 11), which can be considered representative of many analogous situations. At first glance, the collapse of the gable seems to be caused by an overturning mechanism, but the stringcourse did not allow that mechanism by creating a connection at the summit. In the presence of a flexible wooden roof, the overturning mechanism is associated with a rise in the gable due to the opening of the hinge

Fig. 12 The apse of S. Eusanio Martyr church in Sant'Eusanio Forconese

at its base; the ridgepole and the purlins lean on the gable, if they are well-connected, and can contrast overturning. Instead in a roof with a r.c. slab, the flexural stiffness opposes the uplift of the gable with a subsequent increase in vertical compression stresses; this compression provokes collapse due to wall crushing. In fact, this was found and caused the masonry wall to crumble rather than overturn as a rigid block. Figure 11d shows that also king trusses are made from r.c.; this is an emblematic case of the faith in this material during the last century for the static restoration of historic constructions (it is important to consider the difficulty of utilizing a material which must be cast on site, necessitates lengthy drying and hardening times, and is subject to "fluage" phenomena; wood or steel are for sure the proper materials for a king truss).

6.3 Apses

The apse is another part of a church frequently subject to damage, which occurs through clearly identifiable collapse mechanisms. The understanding of behaviour and knowledge of construction history of a building is fundamental; the apse is often the oldest part of the church so it is often made of very large, squared stones. Given its vulnerability, however, one may often find frequent repairs or reconstruction following damage after past earthquakes.

An interesting example of damage in the apse was found in the church of S. Eusanio Martire in Sant'Eusanio Forconese (Fig. 12). There is a very tall semi-circular apse with well-hewn stone masonry walls divided into three parts by two small pilasters. The earthquake provoked the collapse in the external leaf of the masonry in the central portion, which occurred for various reasons:

Fig. 13 Bell cell in the ex-convent of S. Domenico in L'Aquila

(1) the external leaf, though apparently in good condition, was very thin and badly connected to the internal masonry nucleus (this is typical in many hewn ashlar walls);
(2) the pilasters did not have a static function (due to their reduced thickness) and created discontinuity in the external masonry leaf, favouring its detachment in the central portion (note the detachment of the pilaster in the first photograph even when the external leaf did not collapse; certainly, in the absence of the pilasters, the wall would have behaved better);
(3) the roof of the church had recently been replaced (note the stringcourses and concrete elements) and this certainly could have increased the local stresses at the interface between masonry and r.c. elements.

6.4 Belfries

Plane belfries and bell cells in towers are among the most vulnerable elements of a church, according to the statistics of damage assessment. These elements are made of flat or three-dimensional, arch-pier systems, which manifest mechanisms with the formation of hinges at the base and top of the piers or in the arch, even for low value of horizontal components of the seismic action. Moreover, it must be considered that these elements are subjected to a motion at their base which is significantly amplified by the building with respect to the seismic ground motion (actually, the bell cells are at the top of a tower, while plane belfries are at the summit of the façade).

It is therefore almost inevitable that these elements suffer great damage in the case of an earthquake, because of the high displacements imposed at their base. The solution to avoid collapse is to allow displacement, guaranteeing ductility; in other words, allows oscillation without loss of equilibrium or local wall collapse. Regarding the latter, the use of vertical tie-rods with flexible devices may be very useful.

Here are two examples of this concept: the bell tower of the ex-convent of S. Domenico in L'Aquila (Fig. 13); the church of S. Felice Martire in Poggio Picenze (Fig. 14).

Fig. 14 Bell cell of S. Felice Martire church in Poggio Picenze

In the first case, there are "wooden ties" at the base and at the top of the cell; the piers developed an overturning mechanism, which in the upper portions involved the arches; in the absence of tie rods, there were openings of the hinges and sliding in the central ashlar, though limited by the upper wooden tie rod. The possibility of developing this overturning mechanism limited shearing damage to the piers.

On the contrary, in the case of the church in Poggio Picenze, an intervention, debatable even on a formal level, had been carried out, which was aimed at creating better connection but added exaggerated rigidity to the structure. Instead of classic tie rods, small metallic bars connected in pairs had been inserted at the base of the piers and at the base of the arches. The result was that the possibility of deformation was localized only in the piers (due to the fact that the upper section was completely rigid), with subsequent serious damage due to shearing. The photograph clearly demonstrates how complete collapse did not occur only by luck, and nevertheless, the problem of restoring the tower must be dealt with considering the extent of the damage.

It can be concluded that allowing displacement is better, with the subsequent reduction of solicitation induced in the walls, rather than adding rigidity, increasing seismic action and concentrating deformation to limited areas.

Plane belfries are characterized by different behaviour. Being flat structures, they suffer damage to the arch-pier system (in this case, the consideration above for bell cells should be applied), but they are also subject to out-of-plane overturning. Almost always, their thinness induces excessive worries regarding stability; the structure they are built upon is decidedly more rigid and therefore no amplification of the seismic action occurs in their frequency range. In this case as well, the addition of elements which add rigidity to the structure is not positive for seismic behaviour.

The Case of the church of S. Michele Arcangelo in Villa Sant'Angelo is interesting (Fig. 15). The first image shows severe in-plane damage to the three piers and two arches. The belfry was equipped with three external vertical tie rods, axial to the piers and connected to the wall at the extremities and in the centre (please do not confuse them with the horizontal bars put in place after the earthquake for safety measures).

The vertical bars limited the formation of hinges at the base of the piers, but shifted the damage under the anchoring point of the bars themselves. In the upper portion the mechanism formed along the arches with a strong concentration of damage near the connections between the bars and the walls. One can also note the troubling diagonal cracking with displacement under the external pier which was a consequence of the strong shearing action at the base due to the bars which increased stiffness.

Fig. 15 Plane belfry of S. Michele Arcangelo church in Villa Sant'Angelo

Figure 15b is also interesting and shows an out-of-plane oscillation mechanism with horizontal cracking on the side of the façade (directly below the connection of the vertical tie rods) and vertical cracking of detachment to the lateral walls of the church.

7 Conclusions

The damage case studies illustrated herein are by no means exhaustive. With reference to the macroelements considered, the types of damage are in fact numerous and determined by a complex series of factors: geometrical configuration, construction characteristics, the history of transformations and past damage and ineffective strengthening interventions. Moreover, many other elements in churches turned out to be vulnerable after this earthquake: triumphal arches, domes and vaults.

The approach to identify macroelements has also proven to be effective following the earthquake in L'Aquila, because it allows rapid and objective interpretation of seismic behaviour, which is useful in determining fitness for use and the necessary emergency safety measures to be taken. Thanks to this approach, heavy and often useless propping could be avoided since the request for provisional measures must respond to the actual damage mechanisms found with a certain level of severity.

The planning of restoration interventions, the rebuilding of collapsed portions and the design of seismic strengthening should start from the interpretation of the behaviours made after the earthquake on 6 April 2009 by this assessment methodology.

This paper showed the bad behaviour of churches which were strengthened by r.c. elements. In particular the increase of mass and stiffness due to the substitution of timber roofs by r.c. slabs produced a negative effect; these interventions should be avoided in the future.

A topic that should be further investigated is the evaluation of L'Aquila masonry quality. On this point, one must not be limited to a qualitative interpretation, but on-site experimentations are needed to measure mechanical properties. This data is indispensable for verifying safety, by means of proper mechanical models. In particular for churches safety evaluation with regards to a severe seismic action is possible through mechanical and intuitive models, based on equilibrium limit analysis applied to masonry walls, considered as rigid bodies, non-resistant to tensile stresses and equipped with friction. Mechanical models for the displacement based assessment of cultural heritage structures are going to be developed in PERPETUATE project (Lagomarsino et al. 2010).

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