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Damage assessment and the effectiveness of prevention: the response of ordinary unreinforced masonry buildings in Norcia during the Central Italy 2016–2017 seismic sequence

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Abstract

Four regions of central Italy were struck by the seismic sequence of the 2016 earthquake in the country: Lazio, Abruzzo, Umbria and Marche. This highlighted the different behaviour of masonry constructions depending on the prevention actions carried out after previous earthquakes. In particular, although damaged, the masonry buildings in the historical centre of Norcia (Umbria region) behaved significantly better than those in other regions. Indeed, the strengthening interventions carried out after the earthquakes of 1971, 1979 and 1997 greatly affected the seismic behaviour of masonry aggregates (contiguous masonry structural units, MSUs) in the historical centre, which sustained limited damage and a low number of collapses. This paper discusses the empirical data on damage collected with respect to 670 MSUs by means of the first level survey form concerning post-earthquake damage, and usability assessments (AeDES). The forms completed for the survey relate to MSUs in the historical centre of Norcia and were produced by the technicians of the Umbria Seismic Risk Office. The analysis shows the correlation between the MSU characteristics of: age of construction and renovation work; type of vertical and horizontal structures; roof types and usability rating; and the damage level and extent thereof detected in vertical structures. The effectiveness of previous strengthening interventions and the analyses of the types of strengthening solution are also discussed. A case study aggregate is analyzed in detail in order to illustrate the importance of strengthening interventions on vertical bearing elements. The strengthening interventions resulted in a sound strategy to strongly reduce losses, even in a very vulnerable centre comprised of old residential masonry aggregates.

Keywords Seismic sequence · Usability · Damage · Strengthening interventions · Masonry aggregates

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1 Introduction

A seismic sequence struck four regions of central Italy between August 2016 and January 2017: Lazio, Abruzzo, Umbria and Marche (see Fig. 1a). A first earthquake (Mw6.0, epicentre close to Accumoli—Lazio region) hit the centre of the country on 2016-08-24 at 01:36:32 UTC, causing diffuse building collapses in the municipalities of Amatrice, Accumoli and Arquata del Tronto and about 300 casualties in the Lazio and Marche regions. Significant but less severe damage than in the Lazio and Marche regions was identified in Umbria. The historical centre of Norcia, however, sustained very little damage, with no interruption of commercial activities or homelessness. Then, on 2016-10-26, there were

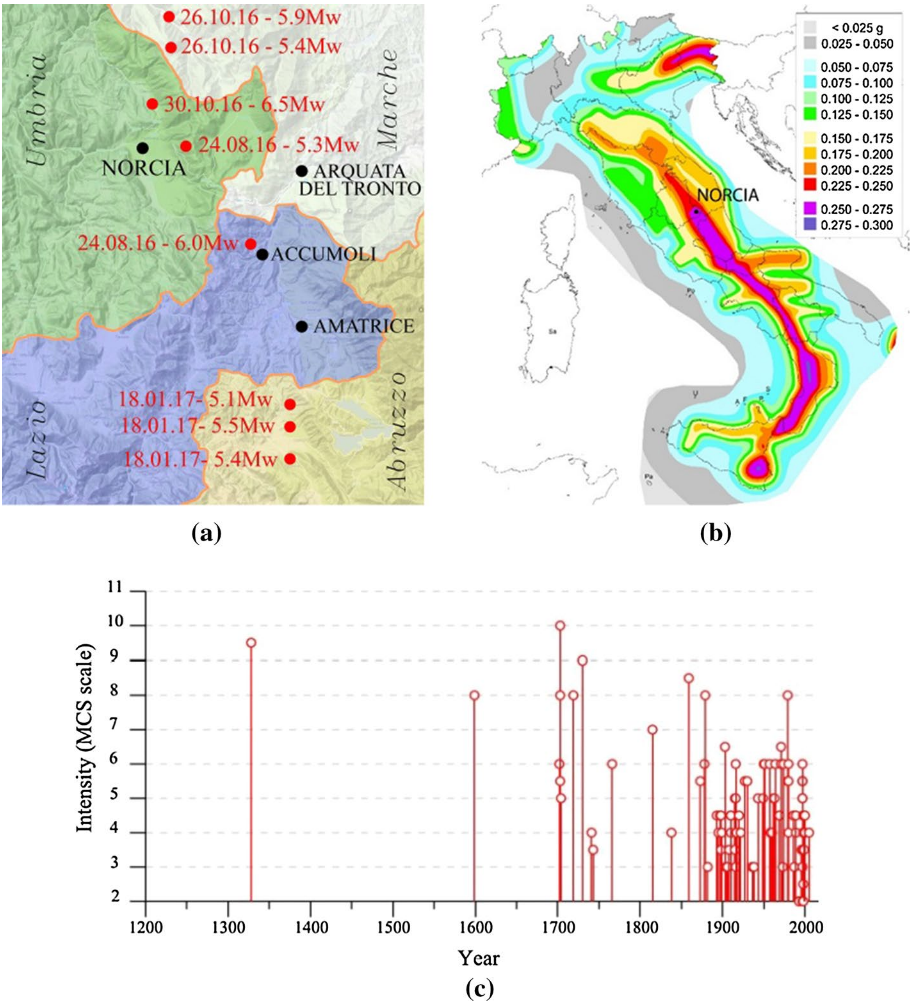


Fig. 1 Seismic sequence in central Italy (**a**); Italian seismic map in terms of peak ground acceleration on rigid and flat soil (return period 475 years) (**b**); and historical sequence of earthquakes in Norcia starting in the XIII century (**c**)

two further seismic events, Mw5.4 (17:10:36 UTC) and Mw5.9 (19:18:06 UTC), and another, Mw6.5 (06:40:18 UTC), 4 days later on 2016-10-30, which struck the area corresponding to the Sibillini mountains, with the epicentre close to Norcia in the Umbria region (see Fig. 1a). These events caused significant damage in several municipalities in the Marche and Umbria regions; several collapses occurred in Norcia's districts (e.g. San Pellegrino and Castelluccio di Norcia), while in the historical centre of the town, the damage was mostly caused to palaces and churches. Residential buildings, although damaged, reported a level and extent of damage that was significantly lower than that observed in other historical centres struck by the seismic sequence. In particular, a strong difference was observed with respect to the damage observed in the historical centre of Amatrice which was characterized by very vulnerable buildings and a limited earthquake activity in the last two centuries (Sorrentino et al. 2018). By contrast, the churches of Amatrice suffered less dramatic damage, probably due to their construction quality and larger demands in the short period range in the epicentral region (Mollaioli et al. 2018).

Finally, on 2017-01-18, a brief sequence of four Mw5+ earthquakes struck 25 km northwest of L'Aquila, in the Abruzzo region (see Fig. 1a). This last sequence caused an increase in the damage level in Norcia's historical centre. By taking into account the intensity, location and sequence of the seismic events, the response of residential buildings in this historical centre was satisfactory. The reason for such behaviour may be related to the past prevention actions taken in Norcia after numerous earthquakes. Indeed, several strong earthquakes have occurred in the area, as confirmed by the current Italian seismic hazard map (see Fig. 1b). According to the Italian macroseismic database (Locati et al. 2016), nine earthquakes with an intensity greater than VIII in the Mercalli–Cancani–Sieberg (MCS) scale have struck the Norcia municipality from the XIII century onwards (see Fig. 1c).

Following the destructive earthquakes of 1859 and 1979, several regulations were issued that required more attention to be paid to horizontal actions both in new constructions and any work renovating existing buildings. This paper focuses on the effectiveness of such prevention measures by discussing the data collected in terms of the empirical damage detected in 670 masonry structural units (MSUs) in the historical centre of Norcia. The data, collected by means of the first level survey forms concerning post-earthquake damage and usability assessments (AeDES), are derived from in situ inspections carried out by technicians from the Umbria Seismic Risk Office. A correlation between usability ratings and/or global damage, measured according to a damage index established with reference to empirical damage observed on vertical structures, is discussed and presented. This clearly shows that the strengthening interventions carried out to reduce the main sources of vulnerability of existing buildings greatly reduced losses and relevant future repair costs in the residential buildings in Norcia's historical centre. It is worth noting that the usability of a building (total or partial) and the limited damage imply the rapid recovery of social activity and great economic savings, as clearly shown by recent loss estimations following the 2009 L'Aquila earthquake (Di Ludovico et al. 2017a, b; De Martino et al. 2017; Mannella et al. 2017). The paper firstly shows the correlation between MSU characteristics and damage, and then focuses on the effectiveness of different strengthening solutions adopted in the past. The analysis of data shows that modern strengthening solutions to reduce out of plane (steel ties or reinforced concrete (RC) ring beam, horizontal–vertical structure connections) or in plane (wall jacketing by means of RC plaster, or masonry strengthening by grouting) mechanisms strongly reduced the damage level and the related occurrence of usability loss in the immediate post-earthquake period. It is worth mentioning that this result is crucial, especially because new, but less invasive and more sustainable, techniques based on the same principles and pursuing the same goals as traditional ones are currently being developed. The use of new materials such as composite systems has largely been demonstrated to be a sound alternative to traditional techniques when it comes to avoiding out of plane overturning phenomena (Sisti et al. 2016; Maddaloni et al. 2016), increasing the in plane shear behaviour of masonry walls (Valluzzi et al. 2002; Balsamo et al. 2011; Babaeidarabad and Nanni 2015; Gattesco and Boem 2015) and reducing the vulnerability of horizontal structures such as vaults (Ramaglia et al. 2017). The on-field validation of traditional techniques may strongly encourage future seismic risk mitigation policies based on the incentive to perform strengthening interventions that, based on the same goal pursued by traditional solutions suggested in the past, are made by new sustainable and effective materials and techniques.

2 Damage assessment of residential buildings in the historical centre of Norcia

After the earthquake of Mw 6.5 on 2016-10-30, the technicians of the Umbria Seismic Risk Office, coordinated by the Italian Civil Protection Department, carried out several inspections in order to evaluate the damage to and usability of residential buildings in the historical centre of Norcia. The AeDES form "Building Operability and Damage during the Post-Earthquake Emergency" (Baggio et al. 2007) was distributed to enable the damage to and usability of buildings to be recorded. In the post-earthquake emergency, usability defines, by means of an expert judgment carried out in a short time, if the building (i.e. structural unit) can still be used with a reasonable level of life safety.

In particular, the AeDES forms were completed with reference to 714 structural units SUs in the historical centre of Norcia: 670 SUs of masonry buildings (MSUs, 94% of the dataset) and 44 SUs of buildings composed of other structural types (6% of the dataset). In the following, the analysis only focuses on the 670 MSUs. The number of MSUs and the relevant cumulative percentages with different characteristics, which may affect their seismic behaviour, are reported in Fig. 2. The MSUs are located in the historical centre of Norcia and are mostly part of building aggregates (contiguous masonry structural units interconnected with each other through more or less effective structural links that involve interaction between the structures under a dynamic action): 94% of the 670 MSUs, out of which 51% are internal parts of the aggregate, with only 5% being isolated buildings and 1% unknown (see Fig. 2a).

Figure 2b shows the age of construction (C) of the MSUs and the period of renovation work (R): 81% of the MSUs were built before 1982 and 12% after 1982. The renovation work involved 72% of MSUs, and they were mostly realized after 1982 (60% of MSUs); only 12% were renovated before 1982 and 9% were not renovated at all (UR). The year 1982 was crucial in the history of Norcia, because starting then the construction of new buildings and the strengthening interventions on existing ones were designed in compliance with the new regulations issued following the 1979 earthquake. Figure 2c summarizes the number of storeys in the MSUs that are mostly composed of two (49% of the dataset) or three storeys (35% of the dataset). This is because after the earthquake of 1859, specific limits were prescribed in terms of the maximum height of buildings in Norcia. The roof types, which play an important role in building behaviour in the face of seismic actions, are shown in Fig. 2d: thrusting heavy (T-H); non-thrusting heavy (NT-H); thrusting light (T-L); and non-thrusting light (NT-L). The NT-H roof type is the most common, comprising 81% of the entire dataset.

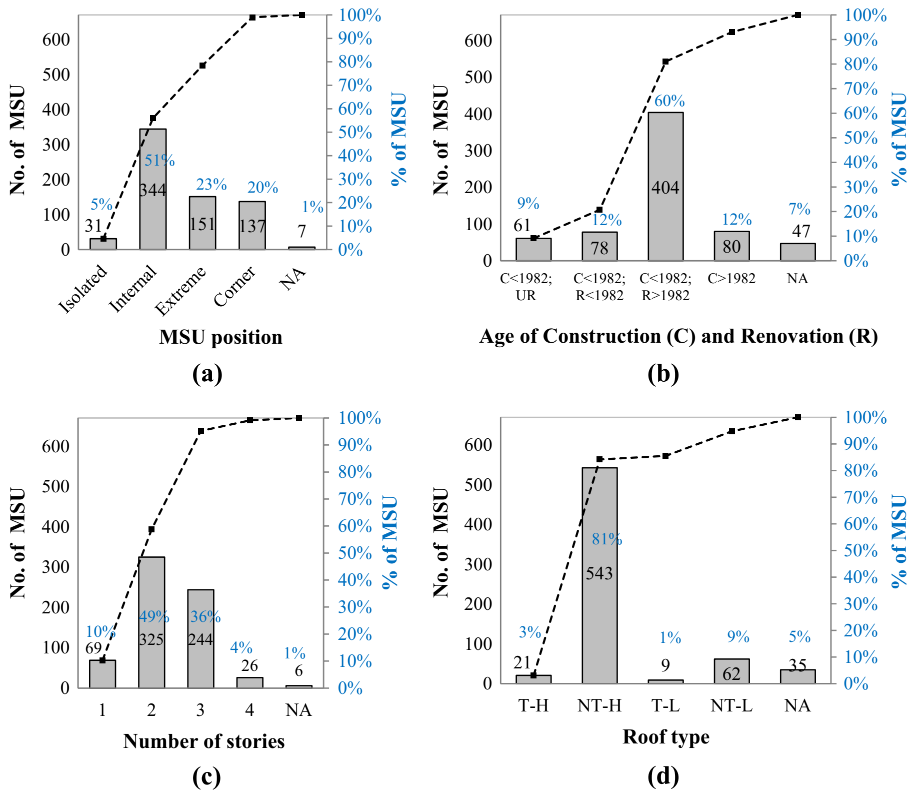


Fig. 2 MSU characteristics: position (**a**); age of construction and renovation work (**b**); number of storeys (**c**); roof type (**d**)

The analysis of the data collected through the AeDES forms and the in situ inspections allowed six main structural classes of MSU to be identified. According to the section 3 "Building typology" of the AeDES form (see Fig. 3b), the definition of these six classes is based on: the type of masonry quality of the vertical structure (regular layout/good quality or irregular layout/bad quality, with or without strengthening interventions carried out in the construction life); and the type of horizontal structure (vaults, beams with flexible slabs, beams with semi-rigid or rigid slabs) (see Fig. 3a).

In details, class I includes MSUs characterized by irregular layouts/bad quality masonry and horizontal structures that can be either vaults or beams with flexible slabs. Renovation work was never executed on such MSUs. Classes II and III differ from class I due to the horizontal structures: class II has vaults and beams with rigid or semi-rigid slabs, while class III has beams with rigid or semi-rigid slabs on each floor. Classes IV and V have horizontal structures equal to those of classes II and III, but they differ due to the characteristics of the masonry: the original irregular layout/bad quality masonry has been strengthened (in these cases one or more tick were marked in the "strengthened" column of section 3 of the AeDES form) or partially replaced by new masonry (in these cases the presence of both regular and irregular masonry is indicated). Finally, class VI includes masonry buildings built after 1982 with regular layouts/good quality masonry and rigid or

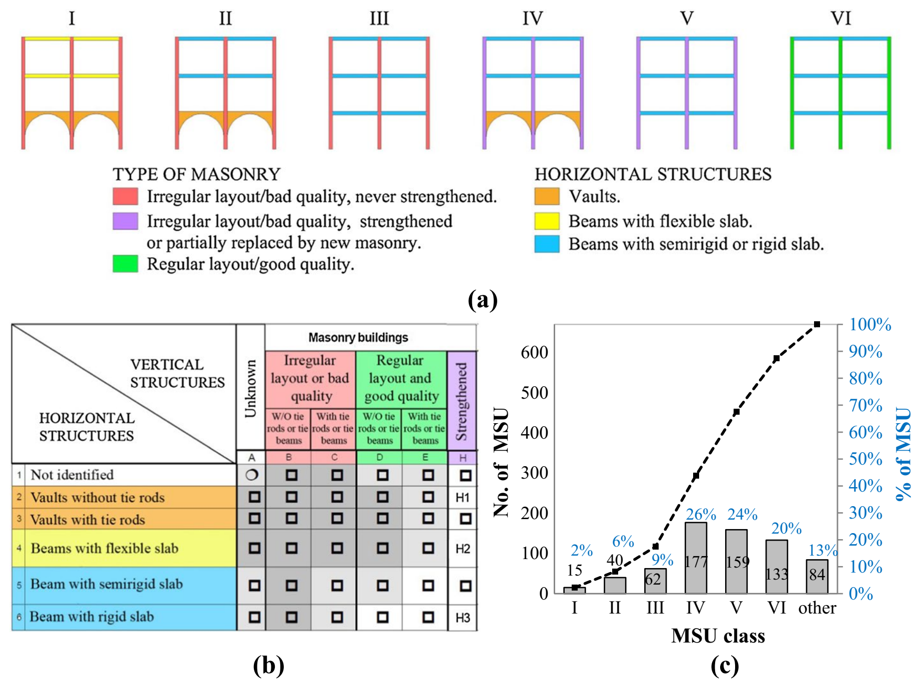


Fig. 3 MSU classes (**a**), AeDES form: ‘‘section 3—Building Typology’’ (**b**); number and cumulative percentage of MSUs for each class (**c**)

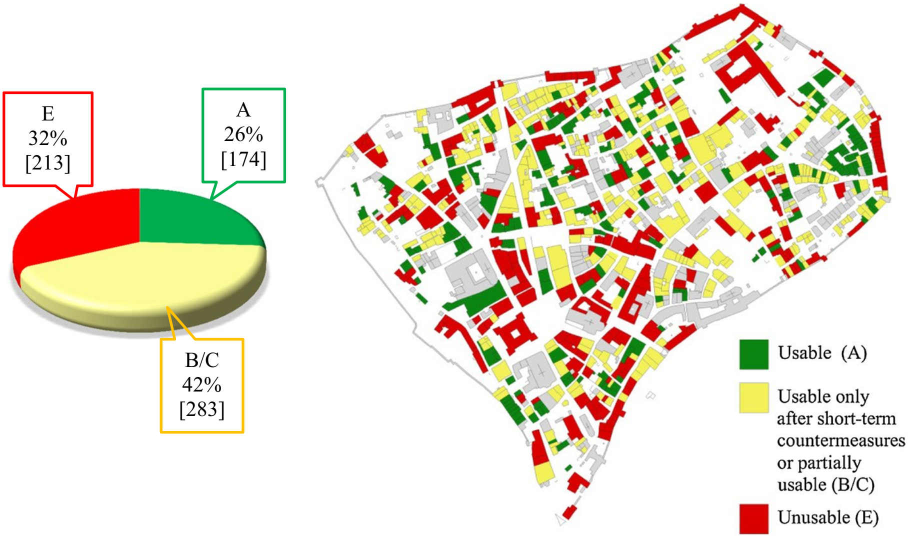
semi-rigid slabs. Figure 3b shows the number and cumulative percentage of MSUs for each class; the most populated classes are IV, V and VI (i.e. 70% of the dataset), while for 84 MSUs the characteristics of the vertical and horizontal structures were mixed in such a way that no class was defined.

According to the AeDES forms, 174 MSUs, corresponding to 26% of the dataset, were assessed as usable (A rating), 32% were unusable (E rating), and the remaining 42% were only usable after short-term countermeasures or were only partially usable (B or C rating, B/C in the following). The ratio of MSUs belonging to each usability rating and the location of the MSUs in the historical centre of Norcia are depicted in Fig. 4.

The lightly or severely damaged MSUs formed the largest part of the structures in Norcia’s historical centre, but only a few residential buildings totally or partially collapsed. The collapses were detected in a few buildings in a poor state of conservation, and often the collapse was a consequence of progressive damage caused by the occurrence of new shocks. Several collapses, however, involved cultural heritage buildings, which were clearly more vulnerable than residential ones.

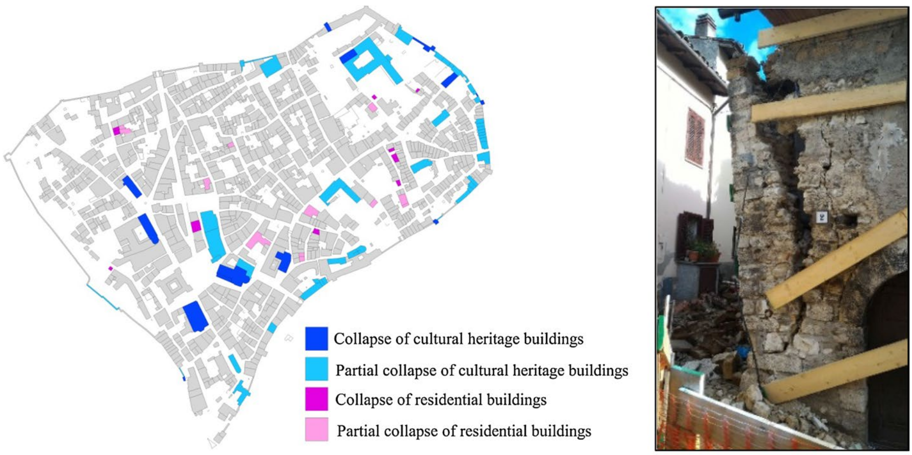
Figure 5 depicts the MSUs affected by collapse in the historical centre of Norcia (blue filled areas in the plan view for cultural heritage buildings and pink filled areas for residential buildings). Note that all the churches in the historical centre collapsed, causing huge losses to the city’s cultural heritage.

Figure 6 shows the percentage trend of the usability rating of the MSUs as a function of their position, roof type, masonry quality and structural class. In particular, Fig. 6a shows that isolated MSUs were less affected by damage than those belonging to



(a) **(b)**

Fig. 4 Usability rating of MSUs (**a**); map of the historical centre of Norcia, with identification of residential buildings and their usability rating (**b**)



(a) **(b)**

Fig. 5 Identification of collapse in residential and cultural heritage buildings (**a**); collapse of a masonry unit (**b**)

aggregates. The percentage of usable buildings decreases from 45% for isolated buildings to up to 25% for those belonging to aggregates. The presence of thrusting roofs clearly affected the damage caused to the MSUs. Although the buildings with a thrusting roof number only 30, Fig. 6b shows that about 90% of such MSUs were unusable (B/C or E rating), while the percentage of unusable buildings with a non-thrusting roof

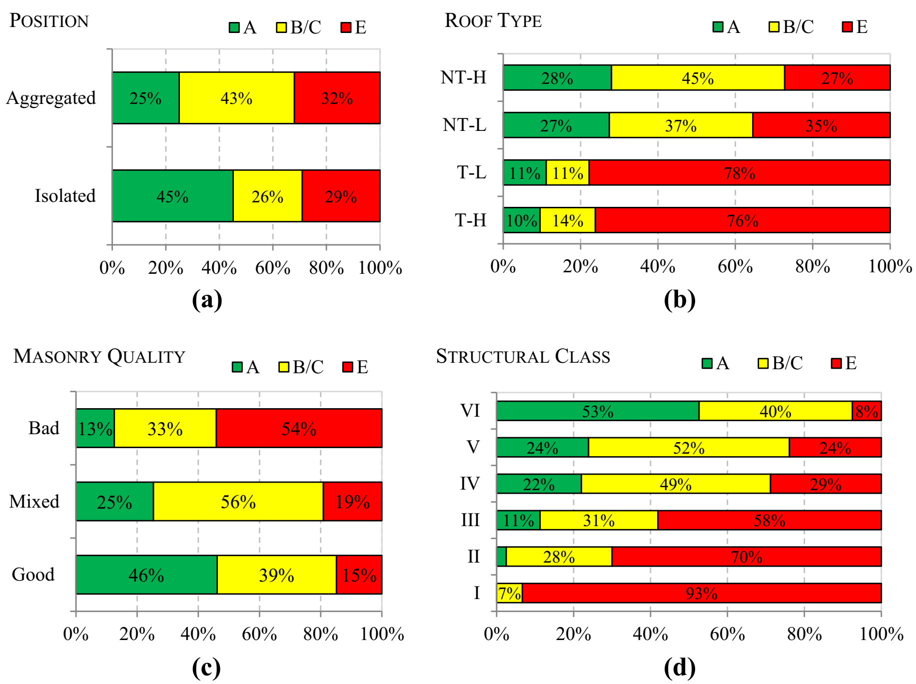


Fig. 6 Usability rating percentages of the MSUs as a function of: position (**a**); roof type (**b**); masonry quality (**c**); structural class (**d**)

was about 70%. This result meets expectations, since the presence of thrusting roofs facilitates the premature failure of masonry walls due to out of plane mechanisms. Indeed, the MSUs with a thrusting roof were mostly unusable, with severe damage caused to structural members (E usability rating).

The influence of masonry quality on usability ratings is shown in Fig. 6c. As expected, MSUs with a bad masonry quality were rarely usable (13%), while those with good quality masonry were usable in 46% of cases. An intermediate situation was identified in cases where there was both good and bad quality masonry (i.e. mixed quality according to the labelling of Fig. 6c). The results about the role of the roof type and masonry quality are comparable to those obtained analysing the performances of the unreinforced masonry buildings during the 2009 L'Aquila earthquake (Zucconi et al. 2018).

To better understand the influence of the structure as a whole by analysing performance against the seismic actions of MSUs that differ in terms of masonry quality and horizontal structural type, Fig. 6d shows the usability trends as a function of the structural classes defined in Fig. 3. The first three classes (I, II and III), characterized by the presence of masonry with irregular layouts/bad quality, became unusable for 93%, 70% and 58% of the relevant dataset, respectively. A decrease in unusable MSUs can be observed for classes IV and V as a result of strengthening interventions carried out by means of renovation work. Finally, buildings in class VI, which includes MSUs with a good masonry quality and rigid or semi-rigid floors, were slightly affected by damage: 8% of the MSUs were unusable and 53% usable.

Section 4 of the AeDES form reports the damage level and extent thereof for structural components. A damage index for each MSU has been estimated by focusing on the damage level and extent detected on vertical structures alone. In particular, the damage index has been assessed according to the approach described in Dolce et al. 2017; the criteria to convert the four damage levels (null damage D0, slight damage D1, medium severe damage D2–D3, and very heavy damage D4–D5) and their relevant extent (lower than 1/3, between 1/3 and 2/3, and greater than 2/3 with respect to the total extent of the component in the building) is summarized in Fig. 7a. Note that according to section 4 of the AeDES form, more than one tick may be used by surveyors for both the damage level and extent (e.g. D1 lower than 1/3 and D2–D3 between 1/3 and 2/3). The damage index obtained according to the conversion table of Fig. 7a ranges between 0 and 5.

Figure 7b, c show the cumulative percentage of MSUs that attained a damage index equal to or lower than a given damage index value; Fig. 7b refers to MSUs composed of different quality masonry, while Fig. 7c refers to different structural classes. The line connecting such points represents the trend relationship between the damage and cumulative percentages of MSUs achieving such damage or less. According to Fig. 7b, only 20% of

D4-D5 Very heavy damage	D2-D3 Medium severe damage	D1 Slight damage	No damage	Damage index
			✓	0
		<1/3		1
		1/3-2/3		
		>2/3		
	<1/3			2
	<1/3	<1/3		
	<1/3	1/3-2/3		
	<1/3	>2/3		
	1/3-2/3	<1/3		3
	1/3-2/3	1/3-2/3		
	1/3-2/3			
	>2/3			
	>2/3	<1/3		
<1/3				
<1/3		<1/3		
<1/3		1/3-2/3		
<1/3		>2/3		
<1/3	<1/3			
<1/3	<1/3	<1/3		
<1/3	1/3-2/3			4
<1/3	>2/3			
1/3-2/3				
1/3-2/3		<1/3		
1/3-2/3		1/3-2/3		
1/3-2/3	<1/3			
1/3-2/3	1/3-2/3			5
>2/3				
>2/3		<1/3		
>2/3	<1/3			

(a)

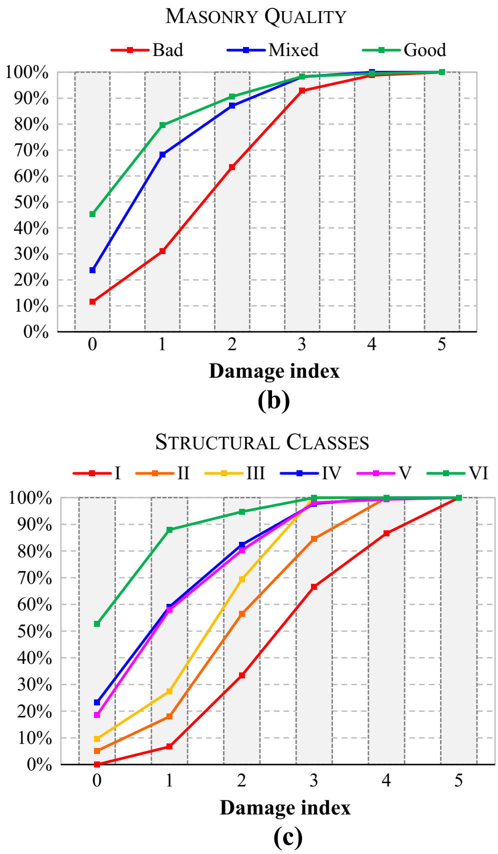


Fig. 7 Conversion table between the damage level and the extent of the damage index (**a**); cumulative percentage of different masonry quality MSUs as a function of the damage index (**b**); cumulative percentage of different structural class MSUs as a function of the damage index (**c**)

MSUs with a good masonry quality have a damage index greater than 1, while this percentage rises to about 70% for those with a poor masonry quality. The greater vulnerability of MSUs with bad quality masonry compared to MSUs with good quality masonry is particularly clear for the damage indices lower than 2.

The vulnerability of the MSUs in terms of the structural classes matches well with the cumulative percentage relationships of Fig. 7c. In the first three classes, only a few buildings have a damage index lower than 2 (respectively 7%, 18% and 27%). By contrast, in class VI, the MSUs are mostly affected by a damage index lower than 1 (88%). The behaviour of classes IV and V is very similar, because almost all the vaults were previously strengthened, and so their presence only slightly affects the damage index.

3 Evolution of sesimic guidelines and suggested post-earthquake interventions in the Umbria region

Seismic codes and design provisions have changed a great deal in the last century in Italy, which is a moderate to high seismic region. At the start of the twentieth century, a first seismic building code was produced (i.e. the royal decree of 1909, R.D. 1909) immediately after the 1908 Messina earthquake (Fralleone et al. 1999). This provided preliminary site-selection criteria and structural typology classifications, as well as detailed provisions for new buildings. The seismic provisions were updated after the 1915 earthquake in the Abruzzo region (Royal Legislative Decree, 1915). The new guidance introduced refined criteria for designs with respect to horizontal actions, as well as criteria to determine the horizontal seismic forces. In the 1970 s, Law n. 64 of February 22 1974 and the Ministerial Decree of March 3, 1975 strongly contributed to refining and updating seismic provisions with respect to the national territory. The evolution of seismic provisions over the last century was mainly linked to the earthquake events and what was understood of their effects on structures. Consequently, seismic hazard zonation evolved very slowly, and only about 25% of Italy had been classified as seismic prone up to 1980. However, several earthquakes struck the Umbria region and the municipality of Norcia in the 18th and 19th centuries. In particular, a strong event was recorded on 1859-8-22 (Catalogue of a strong earthquake in Italy 461 B.C.—1997). The result was that "*out of 676 residential buildings in the Norcia municipality, 195 totally collapsed* (*29%*), *405 partially collapsed* (*60%*), *and the remaining ones* (*11%*) *were strongly damaged*". So, on the basis of official inspections aiming to assess the damage, a proper technical document was issued in order to re-build the municipality using anti-seismic criteria.

3.1 Norcia building regulations

One of the first technical documents issued to drive the reconstruction process was the 1860 Norcia Building Regulations. These stated that both new constructions and renovation work could not be carried out without the approval of the committee, which would verify compliance with the regulations.

Article 16 stated that new buildings should be no more than two storeys high, even if an additional basement was possible, and the maximum height of the building should not exceed 8.5 m. In terms of the renovation work, the demolition of a third storey was required unless this was undamaged. Article 19 listed several rules related to masonry walls: the thickness should be no less than 600 mm; the outer walls, meanwhile, should be strengthened by means of buttresses with a width at least equal to a 20th of the building height; and the perimeter walls had to be well connected to the internal ones.

Article 21 focused on vaults and only allowed them to be constructed in new buildings in the basement. Meanwhile, provided their thrust was eliminated, vaults could be preserved on the ground floor in renovation work on existing buildings. It was also established that the thickness at the crown should be at least 250 mm and at the springing equal to that of any abutments. Finally, the vaults should not be overloaded with useless weight. All these considerations show awareness of the vaults' vulnerability in the face of seismic events.

To avoid premature local mechanisms and ensure the global behaviour of buildings, the regulations established that openings should be aligned and adequately spaced from corners. Furthermore, vertical structures at the roof and floor levels had to be connected through steel ties.

Finally, other rules focused on masonry construction suggestions, known as the "rule of the art", to encourage bricklayers to ensure good mechanical behaviour in the execution of masonry (Borri et al. 2015).

3.2 Technical directives

After the 1979 earthquake, regional technical directives were introduced (Regione Umbria 1981). The purpose of these directives was not only to repair the damage caused by the earthquake, but to also outline rules to make the structures safe in the future. This law identified the steps of the design process. First, it was necessary to recognize the structural systems in the aggregate in order to correctly assess and model the horizontal forces. After evaluating the mechanical properties of the materials, a global analysis was to be carried out using a frame model known as the POR method (Tomaževic 1978). The occurrence of out-of-plane mechanisms had to be verified by considering each wall subjected to a horizontal force equal to 35% of its weight acting upon it. The most important part of the directives was the Appendix, which described several techniques to repair or strengthen masonry structures.

In the case of foundation problems, it was recommended that micro-piles be installed or new foundations added to the sides of the existing masonry (i.e. existing foundation enlargement), with proper connections spaced at 2 m (Fig. 8a). In order to improve the

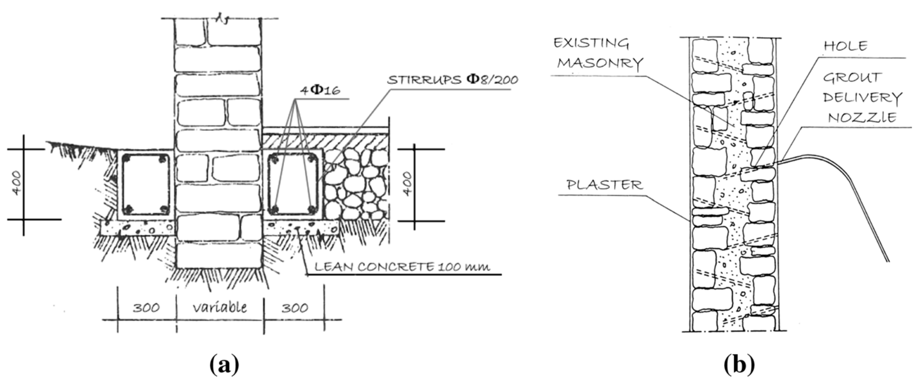


Fig. 8 Existing foundation enlargement, dimensions in mm (**a**), grout injections on existing walls (**b**)

masonry quality, grouting was suggested if voids were found within its core (Fig. 8b); another sound solution technique suggested in order to increase the masonry capacity was the jacketing of walls by means of reinforced plaster applied to both sides of the wall (Fig. 9a) and connected with steel ties, usually 8/m^2 (Fig. 9b). In cases of very poor masonry quality, the use of both grouting and reinforced plaster jacketing was suggested.

Further regulations involved horizontal structures: the slabs had to be strengthened or replaced with new ones consisting of RC beams and hollow bricks (i.e. hollow flooring blocks) (see Fig. 10a). In the latter case, a ring beam, the so-called RC tie, was to be partly built in the masonry; the ring beam should then be connected to the masonry every 2 m through elements called "dovetail", which would cross the entire thickness of the structure (Fig. 10b, c).

4 Effectiveness of the prevention actions: behaviour of strengthened buildings

This section focuses on the effectiveness of strengthening interventions on buildings in the historical centre of Norcia. To this end, Fig. 11a summarizes the percentage of usable/unusable structures after short-term countermeasures or partially usable/unusable (i.e. A, B/C, E rating) MSUs as a function of their age of construction and the period when renovation work was carried out. The graph clearly shows that in the group of MSUs realized before 1982 (C < 1982), the strengthening interventions strongly reduced their vulnerability; in particular, the most effective interventions were those carried out after 1982 (R > 1982), leading to a percentage of usable buildings of 25%, while this figure was 15% and 11% for MSUs strengthened before 1982 (R < 1982) or those that were never strengthened (UR), respectively. It is also significant that the trend of the E usability rating was 67% for old buildings that were never strengthened, decreasing to 47% and 27% in cases of strengthening interventions conducted before or after 1982, respectively. The 40% reduction in severe damage (i.e. E usability rating) recorded on MSUs strengthened according to provisions reported in the 1981 regional technical directives confirms the effectiveness of

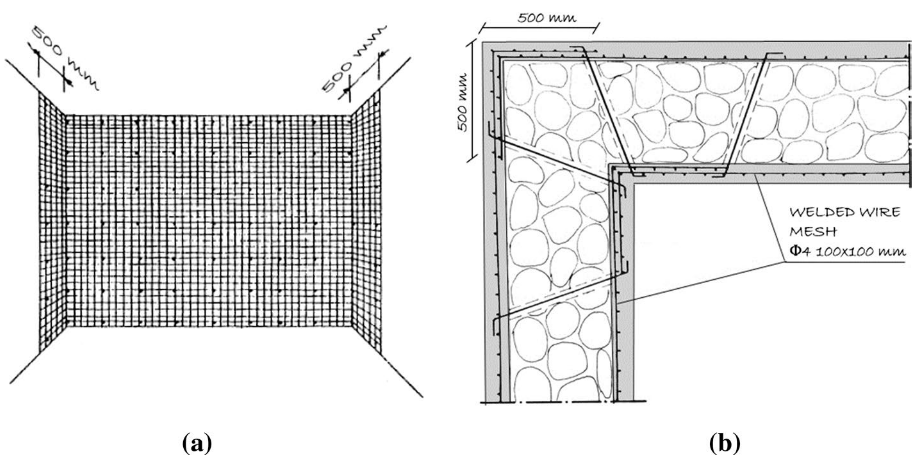


Fig. 9 Welded wire mesh in the jacketing reinforcement, dimensions in mm (**a**); detail of corner connections (**b**)

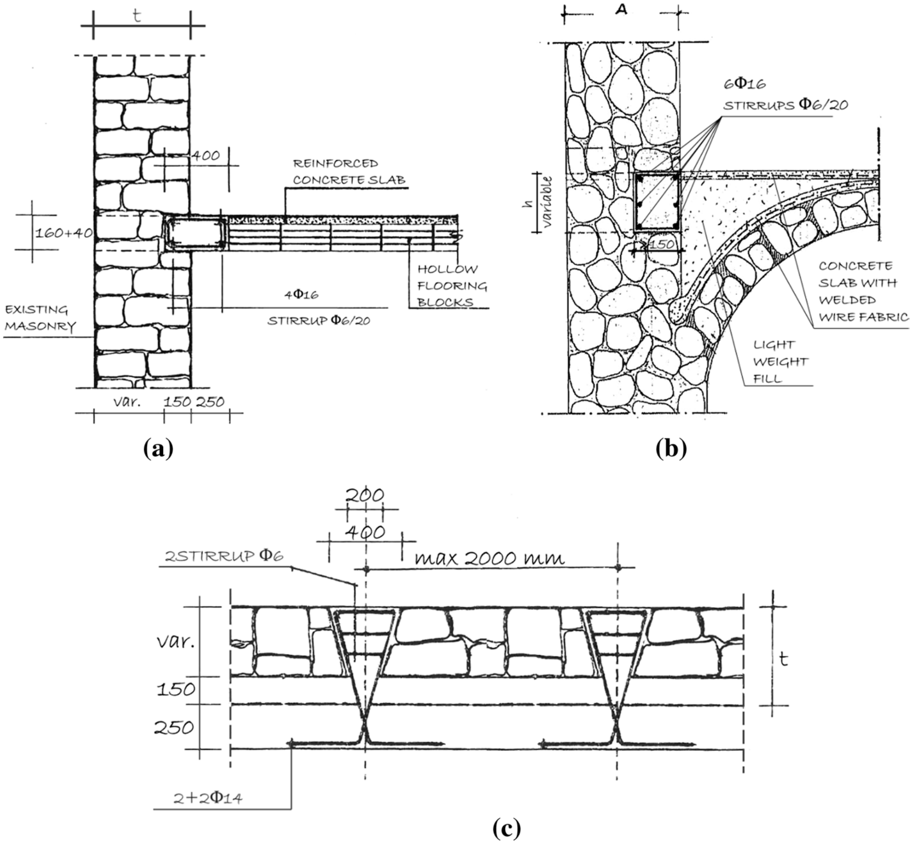


Fig. 10 Replacement of existing floor with new RC floor (**a**); reinforcement of vault with an RC slab applied at the extrados (**b**); connection between ring beam and existing masonry by means of the elements called “dovetail” (**c**). Dimensions in mm

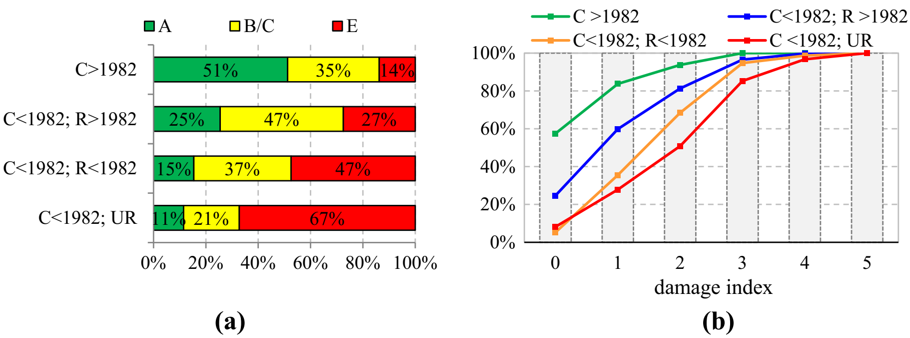


Fig. 11 Influence of the period of construction (C) and renovation works (R) on: percentage of usability ratings (**a**); damage index (**b**)

such strengthening solutions when it comes to improving the seismic capacity of masonry buildings. Furthermore, the rules of the 1981 regional technical directives addressing new constructions were particularly effective, as confirmed by the lowest percentage of the E rating MSUs (i.e. 14%), which was recorded on MSUs realized after 1982. The benefits provided by strengthening interventions or refined provisions for the construction of new buildings against seismic events are better quantified in Fig. 11b. This shows the cumulative percentage trends of MSUs that attained a given damage index as a function of the MSUs' construction age and renovation work. The curves are very different for a damage index lower than 3. It is particularly interesting to note that the curve related to MSUs realized before 1982, but strengthened according to the 1981 regulations, is very close to that of the MSUs built after 1982, when particular attention was paid to seismic events. This clearly demonstrates that strengthening interventions can be very effective. In order to analyse the effectiveness of different types of intervention in detail, the data collected in the AeDES forms (Sect. 3) related to the type of strengthening are discussed in what follows. According to the data collected in the AeDES forms, three types of intervention are reported: H1—masonry strengthened with injections or unreinforced plaster; H2—reinforced masonry or masonry with reinforced plaster; H3—masonry with other or

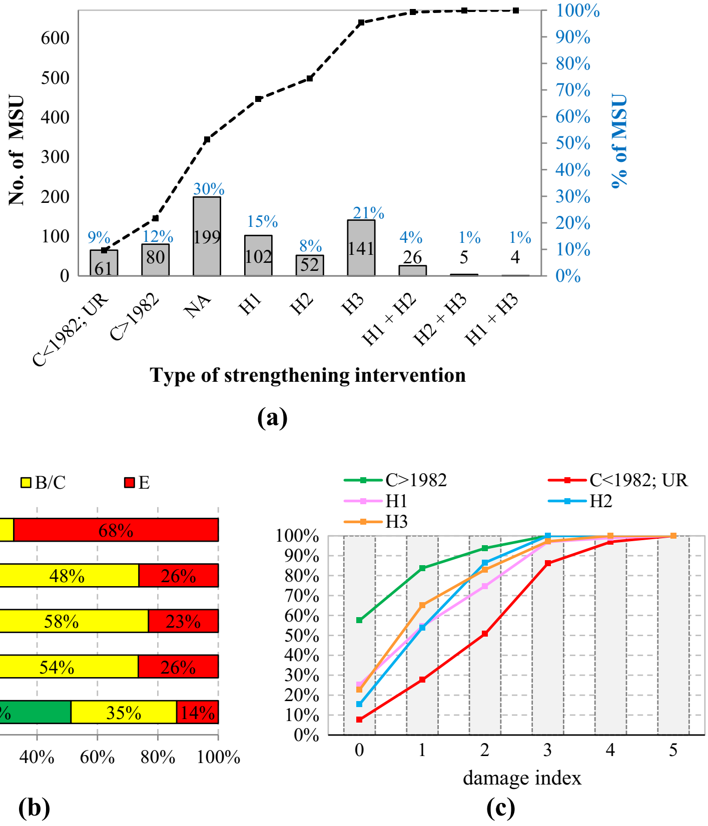


Fig. 12 Number and cumulative percentage of MSUs for each type of strengthening intervention (**a**); influence of the type of strengthening intervention on: the percentage of usability ratings (**b**) damage index (**c**)

unidentified types of strengthening. The number of MSUs and the relevant percentage with respect to the whole database of 670 MSUs strengthened by using one type of intervention or a combination of two interventions are reported in Fig. 12a. The figure shows that 49% of MSUs were strengthened by using H1, H2, H3 or a combination of such techniques, while in the remaining cases it was impossible to determine the type of intervention (NA group in Fig. 12a) or MSUs were built recently (C > 1982) or very old and never strengthened (C < 1982; UR). The most frequent strengthening solution resulted H3 and H1 (i.e. 21% and 15% of the dataset, respectively) while the combination of several intervention types was not very common.

Figure 12b reports the percentage of buildings in each usability class depending on the strengthening solution used in the MSUs. It also compares the performance of strengthened MSUs with C > 1982 or those C < 1982; UR. In cases of strengthening interventions (i.e. H1, H2, H3), the construction behaviour is intermediate between the two limit situations represented by recently built constructions and old and never strengthened ones. However, it is not possible to distinguish a clear trend of usability ratings related to the different types of strengthening solution. This may be a consequence of the very poor information provided by the AeDES forms, which allow the type of intervention to be identified without specifying its location and extent. The cumulative percentage of buildings not exceeding a given damage index is reported in Fig. 12c. Note that damage index 2 is exceeded by 6% and 49% of C > 1982 and C < 1982; UR MSUs, while the presence of strengthening interventions causes the variation of such percentages in a range of 13–25%.

5 Aggregate strengthening analysis

Thanks to the collaboration with the Umbria Seismic Risk Office, it was possible to analyse 35 retrofitting projects submitted in the 1980s and 90s after the 1979 earthquake that affected buildings located in the historical centre of Norcia. The 35 projects concern 63 MSUs corresponding to about 9% of the dataset analysed in the previous sections. On such sub-dataset the usability assessment of MSUs resulted as follows: 24% were assessed as usable (A rating), 32% were unusable (E rating), and the remaining 44% were only usable after short-term countermeasures or were only partially usable (B or C rating). Note that no collapse occurred in such MSUs and that the very heavy damage D4–D5 was observed on 7 cases involving less than 1/3 of the total component surface in the building.

Replacement of existing floors by RC ones with “dovetail” connections (see Fig. 10c) was the most frequent intervention on horizontal structures of such MSUs. Original vaults were mostly strengthened by removing the existing loose top fill and adding a RC layer at the extrados. Note that the new reinforced-concrete horizontal structures and ring beams did not cause the same damages that were observed in many masonry buildings in Umbria and Marche regions after the 1997 earthquakes (Borri and De Maria 2004a, b), despite these buildings had been reinforced in compliance with the same technical directive. This because in Norcia’s buildings the replacement of existing floors has been mostly combined with the strengthening of the masonry vertical bearing elements.

According to the strengthening techniques adopted on vertical bearing elements of MSUs it has been possible to define four categories: MSUs with only some masonry walls strengthened (18 MSUs, named “Partially strengthened” in the following); MSUs with a significant portion of masonry walls strengthened by means of grout injections (16 MSUs, named “Grout injections” in the following); MSUs with a significant portion of masonry

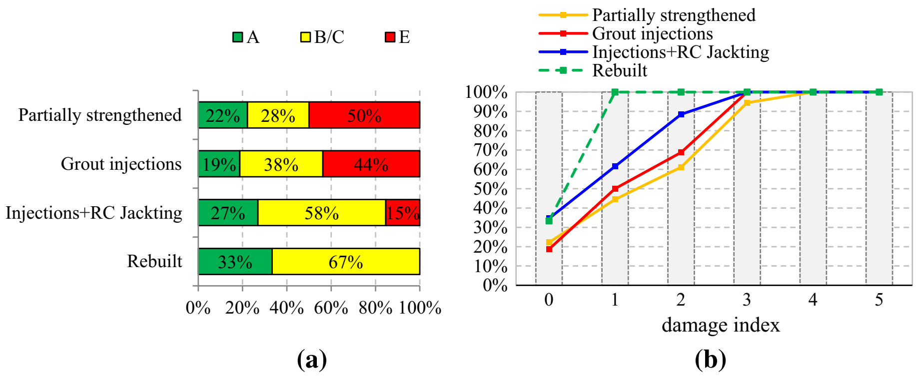


Fig. 13 Influence of the type of strengthening intervention on: the percentage of usability ratings (**a**) damage index (**b**)

Fig. 14 Aggregate case study: MSU location and usability rating

walls strengthened by means of grout injections and RC jacketing (26 MSUs, named "Injections + RC Jacketing" in the following); MSUs with extensive reconstruction of masonry walls (3 MSUs, named "Rebuilt" in the following).

Figure 13a reports, for each group, the percentage trend of the usability rating of MSUs while Fig. 13b shows the cumulative percentage of MSUs that attained a damage index equal to or lower than a given damage index value. They show the "Rebuilt" and "Injections + RC jacketing" groups performed better than other groups and in the category of strengthening solutions the use of combined grout injections and RC jacketing resulted the most effective technique to prevent damage. Note that the effectiveness of RC jacketing is increased because the jacketing was realized on both masonry sides with proper transverse ties in most cases.

Furthermore, in order to illustrate the importance of strengthening interventions on vertical bearing elements, a case study is discussed in depth herein. The case study involves an aggregate with six MSUs in which different levels and types of damage were detected after the 2016-10-30 earthquake (see Fig. 14). In particular, two MSUs were assessed as usable (A rating, MSU II and V, green colour), two were usable after short-term countermeasures (B rating, MSU I and VI, yellow colour), and the remaining two central units were unusable (E rating, MSU III and IV, red colour).

MSUs I, II and IV have three storeys, while the remaining ones have only two. Furthermore, MSUs V and VI have a basement floor. Prior to the strengthening interventions, undressed natural stones (pebbles) with very poor lime mortar comprised all the original walls and there were different types of floor: timber floors, RC hollow brick slabs, and jack-arch floors. Following the 1979 earthquake, damage to the vertical load bearing walls was mainly detected on the first floor of MSUs I, V and VI due to the poor masonry quality and the lack of connections between the orthogonal walls (see Fig. 15). Figure 15 shows the type of damage detected on the MSUs: shear cracks; out of plane displacements; and vertical cracks at wall intersections.

A repair and strengthening intervention design was submitted to the Umbria region in 1984. The strengthening interventions proposed are depicted in Fig. 16, along with their location. The analysis of the retrieved documentation shows that the following interventions were designed:

- The enlargement of the foundations by adding two RC elements placed besides the masonry ones, even if no foundation settlement had occurred.
- The strengthening of masonry walls through grout injections or grout injections plus RC plaster jacketing (violet or blue walls in Fig. 16), and the insertion of steel connectors to improve the connection between orthogonal walls.
- The reconstruction of damaged internal walls, with new walls composed of clay blocks (yellow walls in Fig. 16).
- The replacement of existing timber floors with new RC floors and the reinforcement of the existing steel floors and vaults with an RC slab applied at the extrados (red boxes filled or not filled at the floor location in Fig. 16).
- The construction of RC ring beams at the roof level of each MSU.

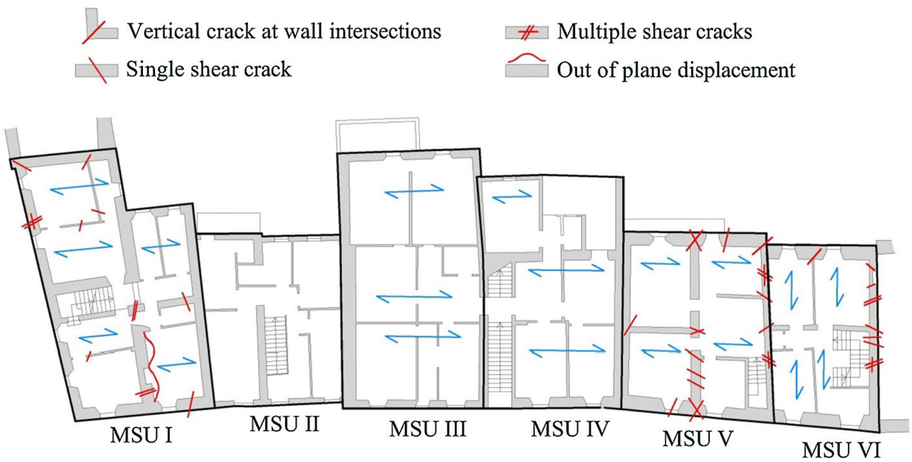


Fig. 15 Crack pattern on the first storey due to the 1979 earthquake. The red lines represent the cracks

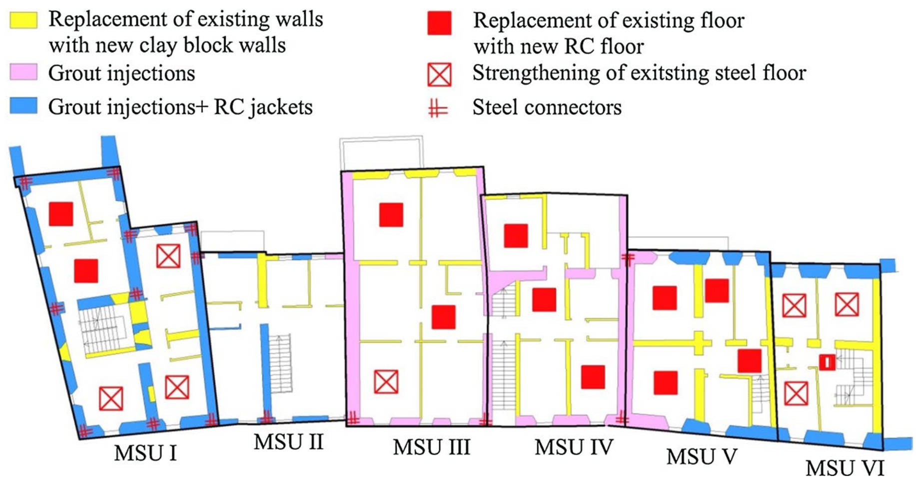


Fig. 16 Strengthening interventions on the first storey of the MSU aggregate

In 1988, some changes to the original projects were made and the vertical masonry load bearing walls of two central MSUs (III and IV) were strengthened by grout injections alone instead of by the combination of grout injections and RC plaster (see Fig. 16).

After the M6.5 earthquake, the two central MSUs (III and IV) were unusable and a medium-severe damage level (D2-D3) was observed on both the vertical load bearing elements and floors. By contrast, no damage (MSUs II and V) or slight and limited damage (MSUs I and VI) was observed in the aggregate parts strengthened according to the original retrofitting project. This clearly confirms the effectiveness of sound strengthening interventions in terms of limiting or avoiding structural damage, even in historical aggregate masonry MSUs.

In particular, Fig. 17a shows the main façades of the six MSUs as they appeared a few months after the 2016-10-30 earthquake. No damage is visible from the outside, except for some shear cracks that start from the windows on a second floor wall of MSU IV, which is assessed as unusable.

6 Conclusion

This paper examines the information collected through AeDES forms related to 670 MSUs of residential masonry buildings in the historical centre of Norcia that was struck by the 2016 central Italy seismic sequence. Although the historical centre of Norcia was very close to the epicentre of the most severe earthquake of the sequence, M6.5 in October 2016, the behaviour of the residential masonry buildings was satisfactory, especially if compared with those of other nearby municipalities, such as Amatrice, which were completely destroyed by seismic events.

At the end of the seismic sequence, 26% of the 670 MSUs under investigation were usable (A), 32% were unusable (E) and the remaining 42% were partially usable or required some short-term countermeasures. It is even more significant to highlight that the very heavy damage level (D4–D5) to the vertical structures was only detected in 96 MSUs (14% of the dataset) and there were very few collapses.

Fig. 17 Façade of the six MSUs (**a**); shear cracks on a second floor wall of MSU IV (**b**) (when the photo was taken, the cracks had already been plastered; for this reason, they are not very evident)

The analysis of the correlation between the structural characteristics of the MSUs and their level and extent of damage showed that:

- A heavy roof does not affect the behaviour of a building if a global strengthening strategy is pursued. Indeed the replacement of old timber roofs with RC roofs in the buildings in the historical centre of Norcia was combined with the strengthening of underlying walls; this avoided the severe damage or collapse frequently observed in recent Italian earthquakes as a consequence of heavy concrete slab insertion without any other intervention. In contrast, the presence of a thrusting roof will lead to an increase in the number of unusable buildings.
- A good masonry quality and the effectiveness of connections between walls and between walls and floors are essential requirements in the good seismic behaviour of a building.
- A large number of the MSUs in Norcia (i.e. 72%) were designed or retrofitted (12% and 60%, respectively) according to the regional technical directives introduced after the 1979 earthquake. In this set of buildings, very few MSUs became unusable or sustained severe damage, while the opposite trend was observed in the set of buildings that underwent no strengthening interventions.
- Clay block masonry buildings built after 1982 demonstrated satisfactory behaviour: 58% of the MSUs were undamaged in vertical structures and 26% reported only slight and limited damage.
- The aggregate case study demonstrates the effectiveness of prevention and the effectiveness of mitigation policies when it comes to greatly reducing the extent of the losses following earthquakes.

The most severe possible test provided by a natural earthquake strongly validated the use of the strengthening solutions suggested in the past to reduce the seismic risk to historical centres. The use of modern, sustainable and effective materials and techniques pursuing the same objectives as the traditional techniques adopted in the past in Norcia's historical centre may be a viable solution for preserving and protecting the precious heritage represented by other Italian historical centres.

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