

Seismic Performance of Strengthened Masonry Structures: Actual Behaviour of Buildings in Norcia and Campi Alto During the 2016 Central Italy Seismic Sequence

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Abstract

The structural response of unreinforced masonry buildings designed for gravity load only or with reference to obsolete seismic provisions is widely studied in the literature in order to define proper strengthening strategies and solution to mitigate the seismic risk. However, the critical analysis of the effectiveness of past used strengthening solution is still lacking. To fill such gap, the present study deals with the evaluation of the seismic performances of buildings in the historical centre of Norcia and Campi Alto struck by the 2016 central Italy seismic sequence. A large part of these buildings was strengthened between 1980 and 2000 during the reconstruction processes following previous earthquakes occurred in 1979 and 1997. The strengthened buildings in Norcia reported limited damage while a significant and widespread level of damage was detected on several strengthened buildings in the hamlet of Campi Alto. The study focuses on such latter aspect with the aim of investigating on the reasons of such unsatisfactory behaviour. Thus, a comparison between seismic action experienced by buildings in Norcia and Campi Alto is initially analysed along with the evaluation of the main vulnerabilities of these buildings. Then, 20 projects of strengthening interventions submitted to the Civil Engineering Department of the Umbria Region between 1984 and 2012 have been herein analysed and discussed in order to focus on the effectiveness of the strengthening solution adopted in the past. The analyses of such projects and of the empirical damage detected after the 2016 seismic sequence is a unique opportunity to derive useful information for future applications.

Introduction

The damage analysis after significant earthquakes allows the empirical identification of the vulnerability of different types of existing structures; thus, a seismic event represents an occasion to better understand the response of existing buildings and, consequently, to define new strengthening strategies and solutions or construction details to reduce the structural deficiencies.

Several studies available in literature focused on the structural response of unreinforced masonry buildings (Sayin et al. 2013, Ortega et al. 2017, Gautam et al. 2016) in case of seismic events. They commonly discuss and analyse the behaviour of existing buildings designed for gravity load only or with reference to obsolete seismic provisions. They evidenced the most critical aspects and vulnerability of such constructions, strongly promoting the development of analytical and experimental studies aimed at the evaluation of new construction techniques or strengthening solutions. Despite laboratory or in situ tests are commonly carried out to validate the effectiveness of a specific strengthening solution, it is very difficult to reproduce and simulate the different state and conditions typical of existing structures, especially in case of masonry buildings. Furthermore, it has rarely been possible to evaluate the real seismic response of a significant number of strengthened masonry structures: a recent study on the effectiveness of strengthening solution adopted in the reconstruction process of past earthquakes has been carried out by the authors (Sisti et al. 2018). It focuses on the structural response of masonry buildings in the historical center of Norcia after the central Italy 2016 seismic sequence. The seismic sequence struck four regions of central Italy (Abruzzo, Lazio, Marche, Umbria) during 2016 and 2017; it was discussed in several studies focusing on: seismological aspects (Chiaraluce et al. 2017; Lanzo et al. 2019; Iervolino et al. 2019); behavior and damage of residential buildings (Fiorentino et al. 2017; Sorrentino et al. 2018), of heritage buildings (D'Altri et al. 2018; Poiani et al. 2018), churches (Penna et al. 2019; Hofer et al. 2018), schools (Di Ludovico et al. 2018, Gara et al. 2017) and infrastructures (Callisto e Ricci 2019). In Sisti et al. 2018, the study evidenced that the structures in the historical center of Norcia, renovated between 1980 and 2000 during the reconstruction processes following previous earthquakes occurred in 1979 and 1997, showed a good response to seismic sequence actions and reported very limited damage.

The present study analyses the empirical damage detected on the buildings of Campi Alto, a small medieval village few kilometers far from Norcia. Although most of the buildings were strengthened in the period 1980-2000, as in the case of Norcia, and in compliance with the same structural code, these buildings showed a very heterogeneous level of damage, from the slight damage to the collapse. In order to investigate on the reasons of such difference, the present study analyses the differences between the two historical centers both in terms of terrain orography and structural characteristics of the buildings and, in particular, it focuses on the analysis of the construction details adopted in the strengthening interventions. The investigation involves the analysis of the data collected through the first level survey forms (AeDES) concerning post-earthquake damage and usability assessments (Baggio et al. 2007); the survey forms were filled after the 2016 and 2017 seismic sequence by the technicians of the Umbria Seismic Risk Office, coordinated by the Italian Civil Protection Department. These data have been integrated by those derived by detailed in situ investigation. Furthermore, the study of the buildings characteristics and strengthening interventions has been integrated by analyzing in details 20 strengthening projects submitted starting from the 1980s to the Civil Engineering Department of the Umbria Region. This to fully correlate the damage detected after the seismic sequence to the buildings' characteristics and details of strengthening solutions that may have strongly influenced the seismic response of such buildings.

Historical Sequence Of Earthquakes In Norcia And Campi Alto

The present study focuses on the behaviour of strengthened masonry buildings located in Norcia and Campi Alto. The presence in this area of a significant number of buildings strengthened after the earthquake occurred in 1979 and 1997 and the occurrence of a recent seismic sequence represents a unique opportunity to analyse the effectiveness of prevention actions and the soundness of strengthening techniques adopted. To this goal, a preliminary analysis of the characteristics of the two locations under investigation is presented in this section.

Norcia is located at 600 m above the sea level near the connecting area between the Santa Scolastica plain, a fault-bounded intermountain basin, and the northern border ridges (Fig. 1a). The city was founded in the 5th century b.c. but the construction of the city walls dates back to the Middle Ages

and the urban layout was modified several times after the strongest earthquakes that struck the city.

Campi Alto is a part of the municipality of Norcia and it overlooks Val Castoriana and stands on the slopes of mount Macchialunga between 900-800 m above sea level. This village was originally built in the mid-13th century and it still preserves the features of a medieval castle that owes its urban layout to the orography of the site, which presents a strong drop in height (around 100 metres between the bottom and the top of the town). The main roads and the terraced buildings are developed on terracing plots, that follow the level curves of the mountain, joined by ramps and orthogonal stairs (Fig. 1b). In (Binda et al. 2007, Binda et al. 2006) a study on construction typologies, typical building geometry, construction details, materials used and maintenance level in Campi Alto is reported. The orography of the terrain has influenced the architectural characteristics of the buildings; they commonly develop on two or three levels (Fig. 2a). First floor, originally used as cellar, store or stable, has access on the road facing downstream, while the last, is usually used for living space. The rooms located on the ground floor were originally characterised by the presence of vaults (typically barrel vaults) and show walls carved straight into the rock.

The two settlements are part of Valnerina region (central Italy), a very active seismic zone. Fig. 3 depicts the seismic histories of Campi Alto and Norcia, since 1800 and until the early 2000s (Rovida et al. 2019). The low number of events reported for Campi Alto is due to its smaller size and importance, compared to Norcia, that leads to a lack of information regarding the earthquake that struck this small inhabited center in the historical sources consulted for the construction of Italian Parametric Earthquake Catalogue.

Two main seismic events struck both Campi Alto and Norcia in 1859 and 1979. In Campi Alto, strengthening works carried out after the earthquake of 22th August 1859 are still visible: the downstream façades of most buildings are characterised by the presence of buttresses and spurs, mainly added because of that event. In Norcia, the current buildings' configuration originates from the structural code that drove the reconstruction projects following the 1859 earthquake. This technical document established several structural requirements, such as the minimum thickness of the walls or the maximum height of the buildings both for new buildings and in renovation works on existing ones. A detailed description of such structural code can be found in (Reale et al. 2004) and (Sisti et al. 2018)

In 1979 another earthquake, MCS (Mercalli–Cancani–Sieberg) intensity of 8, hit the area and caused significant damage. In Campi Alto 12 buildings were damaged, most of which were in poor condition before the earthquake. Norcia was seriously damaged: few buildings partly collapsed and 44 strongly damaged buildings were demolished (Boschi et al. 1998). After the event, regional structural code (Regione Umbria 1981) was issued in order to define anti-seismic design procedures and suggest strengthening solutions to repair and improve the performances of structural elements. A large part of the buildings in the historic center of Norcia was renovated following this regional code, which has significantly influenced the current characteristics of the buildings (Fig. 2b).

In 1997, another earthquake hit an area slightly further North-West of Norcia and Campi Alto; given the low macro seismic intensity, only buildings in poor condition reported some damage.

The 2016-2017 Seismic Sequence: Analysis Of Seismic Input In Campi Alto E Norcia

The main shocks of the 2016-2017 seismic sequence of Central Italy are reported in Fig. 4 while Fig. 5 shows the two horizontal components of acceleration and pseudo-velocity response spectra obtained from the recordings of three accelerometric stations of the National Accelerometric Network (RAN) close to Campi Alto and Norcia. The processed strong-motion data are obtained from (Luzi et al 2016).

The CMI station was 1 km far from Campi Alto and thus its data can be considered representative of the seismic input of Campi Alto. This is a temporary station installed after the first earthquake of 24th August 2016 and, unfortunately, there are no records for the seismic event of the 30th October. The NOR e NRC stations are located in proximity of the historic centre of Norcia and they are permanent accelerometers. The spectra are cut short at 2.5 seconds because the masonry structures analysed in this paper certainly have a lower principal period.

Table 1 summarizes the main parameters recorded by these three stations during the seismic sequence: the Peak Ground Acceleration (PGA), the acceleration corresponding to a period of 0.3 seconds ($S_{a,0.3}$), the maximum value of spectrum ($S_{a,max}$) and the corresponding period, the Peak Ground Velocity (PGV), the pseudo-velocity ($S_{v,0.3s}$) corresponding to a period of 0.3 seconds, and the maximum value of the pseudo-velocity spectrum ($S_{v,max}$). Table 1 shows that all seismic parameters resulted generally more severe in the East-West direction with respect to North-South one. With reference to East-West seismic components, it is possible to note that for earthquakes actions occurred on 26th October, the CMI station recorded values significantly higher with respect to those of NOR and NRC stations, Fig. 5 and Table 1. With reference to the earthquake occurred on 30th October, for which only NOR and NRC station records are available, the most severe actions were recorded by NRC station. Both PGA (707 cm/s^2 versus 476 cm/s^2) and $S_{a,max}$ (1991 cm/s^2 versus 1931 cm/s^2) were lower for NRC station with respect to CMI; whereas the parameters corresponding to a period equal to 0.3s were higher for NRC station. This clearly indicates that the seismic actions recorded in Campi Alto were higher or comparable to those recorded in Norcia.

Table 2 summarizes two other seismic intensity measures: the Housner Intensity, I_H (Housner 1952), and the modified Housner intensity, mI_H (Mouyiannou et al. 2004). They are calculated as integral of the pseudo-velocity spectrum between 0-2.5 s and 0-0.5 s, respectively. These parameters

are two energy-based intensity measures that may providing a better correlation with the structural damage with respect to parameters reported in Table 1.

The trend of the parameters reported in Table 2 is similar to that of parameters in Table 1: during the earthquakes of 26th October, CMI station recorded higher values than those of the two stations close to Norcia; however, the values are fully comparable with those recorded by the NRC and NOR stations during the subsequent earthquake of 30th October.

Several studies demonstrated that local seismic effects, due to soil properties and topography configuration, can significantly affect the structural response of structures (Jahromi and Karkhaneh 2019; Panzera et al. 2018). Thus, to understand if the different response of the buildings in the historic centre of Norcia and Campi Alto were affected by different amplification factors, the results of a seismic microzonation study, carried out after the 2016 earthquake by SGA (Studio Geologi Associati -Perugia - Italy), is depicted in Fig. 6.

In this study (available on website www.regione.umbria.it) a monodimensional model was adopted for Norcia, characterised by a flatten topographic surface, whereas in Campi Alto the presence of a complex morphology made it necessary to model the topographic amplification through a bidimensional analysis. Fig. 6 reports three detailed maps describing the areal distribution of the Amplification Factor (AF) for three different period ranges: 0.1-0.5s, 0.4-0.8s, 0.7-1.1s. The centre of Norcia is totally characterised by an amplification factor in the range of 1.1-1.4, regardless of the period of the structures, whereas in Campi Alto two subzones with an amplification factor of 1 or in the range of 1.1-1.4 can be identified. Thus, the amplification factor computed on Campi Alto is in every case lower (or equal) than that related to the centre of Norcia.

Comparative analysis on structural characteristics and damage: buildings of Campi Alto and Norcia

The comparative analysis of buildings characteristics in Campi Alto and Norcia is reported in the following based on the data collected by in situ surveys and relevant AeDES forms (Baggio et al. 2007). The forms were filled by technicians of the Umbria Seismic Risk Office following the 2016 seismic sequence. In Campi Alto, 49 AeDES forms were analysed covering the total number of ordinary buildings inside the walls of the village: 44 masonry structural units (MSUs) of residential buildings and 5 warehouses. By contrast, the data related to buildings in the centre of Norcia involve 670 MSUs but they are not the total number of buildings (i.e. a significant percentage of about 80%).

Fig. 7 and 8 show the percentage of MSUs as a function of age of construction (C) and renovation (R), masonry quality, type of horizontal structures, and roof type. Note that for renovation, the year 1982 has been considered as a reference year to distinguish MSUs with renovation works realized before and after the 1979 seismic event; note that UR (unreinforced) means that no renovation works were recorded.

The majority of MSUs (65% and 60% for Campi Alto and Norcia, respectively) has been built before 1982 and strengthened after this date. However, there are no MSUs dated after 1982 in the sample related to Campi Alto. Thus, only few MSUs in Campi Alto (6%) have regular layout/good quality masonry, while 55% show irregular layout/bad quality masonry and 29% is characterised by both types of masonry (namely "mixed"). By contrast, the quality of masonry of MSUs in Norcia is evenly spread in the sample: regular layout/good quality masonry (27%), mixed (34%) and irregular layout/bad quality masonry (38%). Fig. 9 reports a comparison between Campi Alto and Norcia typical masonry types. The masonry of buildings in Campi Alto generally consists of rough stone elements (generally limestone, conglomerates, or travertine). It is commonly strongly irregular, and it is rarely possible to recognise the presence of horizontal bed joints (Fig. 9a,b). Furthermore, in several cases the masonry is made by disconnected layers, small elements and powdery mortar with lack of any cohesiveness. By contrast, the masonry of buildings in Norcia is mainly characterized by worked stone elements placed in a regular way (Fig. 9c,d). However, in some cases also in Norcia irregular masonry can be found as depicted in Fig. 9e. Furthermore, buildings of Norcia are commonly plastered.

The difference of MSUs in Campi Alto and Norcia is related not only to the masonry quality but also to the type of horizontal structures. Buildings in Norcia mostly presents beams with Rigid or Semi-Rigid (R/SR) slabs on each floor (i.e. 56% of the dataset) while in Campi Alto this kind of horizontal structures are often limited to the upper floors and on the ground floor there are Vaults (R/SR+V in Fig. 8). Finally, in terms of roof types, the most significant difference between Campi Alto and Norcia is related to the presence of Non-Thrusting Heavy structures (NT-H), 63% and 81% of the MSUs dataset for Campi Alto and Norcia, respectively. Non-Thrusting Light (NT-L) roofs represent 10% and 9% of the dataset for Campi Alto and Norcia while Thrusting Light (T-L) and Thrusting Heavy (T-H) roofs are uncommon.

In the AeDES form (Baggio et al. 2007) different usability ratings are reported: A. Usable buildings; B. Building usable only after short term countermeasures; C. Partially usable building; E. Unusable building. Fig. 10a shows that in Campi Alto 92% of the residential MSUs (45 MSUs) resulted unusable (E rating), and the remaining 8% (4 MSUs) usable only after short term countermeasures or partially usable (B/C rating). In Norcia, the percentage of usable MSUs (A rating) was strongly greater than in Campi Alto and equal to 26% of MSUs; the remaining part was almost equally distributed in B/C or E rating (42% and 32%, respectively). This clearly indicate a better response of MSUs in Norcia with respect to Campi Alto. To better understand the differences in the behaviours of the MSUs, the Damage Index (DI) obtained from the damage levels and extent occurred on vertical structures, according to (Dolce et al. 2017), is investigated. It varies from DI 0 to DI 5 and the percentages of DI levels related to Norcia and Campi Alto are depicted in Fig. 10b. The figure clearly confirms that a more severe level of damage was detected on MSUs of Campi Alto with respect

to Norcia: a DI lower or equal to 2 was detected on 78% of MSUs in Norcia against 26% in Campi Alto. Furthermore, in Campi Alto 29% of MSUs resulted affected by local or global collapse, DI 5. The plan distribution of DI in Campi Alto and Norcia is reported in Fig. 11 while Fig. 12 reports the cumulative percentages of MSUs with a DI lower than a fixed value. In particular, the trends are plotted with reference to MSUs built after 1982 ($C > 1982$) or before such year ($C < 1982$) but renovated before or after 1982 ($R < 1982$; $R > 1982$) or unreinforced (UR). It is noticeable that in Campi Alto 80% of the MSUs renovated after 1982 has a damage index lower than or equal to 3 (usually only local damage), while those renovated before 1982 reach the 50% mark. All the unreinforced MSUs had a damage index equal to 5.

For the dataset of MSUs in the historical center of Norcia, it resulted that 97% of MSUs renovated after 1982 and about 95% of those renovated before 1982 show a damage index equal to or lower than 3.

Furthermore, according to AeDES forms and *in situ* inspections specifically carried out by the authors resulted that in Campi Alto 13 MSUs collapsed (i.e. 9 full collapse and 4 partial collapse, see Fig. 13), corresponding to 26% of the entire built-up area. In particular, the full collapses affected 4 MSUs never consolidated, 4 renovated before 1982, and 1 renovated after 1982 while 4 partial collapses affected MSUs renovated after 1982. Fig. 13 also shows the three collapses that affected cultural heritage buildings inside the walls of Campi Alto: Santa Maria della Neve's church, Sant'Andrea's church and Madonna di Piazza's church; the latter two were examined in Penna et al. 2019. In Norcia, only 4 MSUs collapsed and 7 partially collapsed corresponding to about 2% of the dataset. However, the damage on cultural heritage buildings was diffused and severe also in Norcia as demonstrated by the collapse of several churches and heritage buildings inside the city walls.

The diffuse and severe level of damage on cultural heritage buildings both in Norcia and Campi Alto is a clear consequence not only of the high vulnerability of such constructions but also of the severe intervention restrictions imposed on these buildings in order to preserve their original characteristics.

Critical analysis of strengthening intervention effectiveness

The data discussed in the previous sections show that, even if most of MSUs in Campi Alto and Norcia were renovated following the 1979 seismic events, the damage provided by the 2016 seismic sequence was more severe in Campi Alto with respect to Norcia. To focus on such a different behaviour, a detailed analysis of 20 strengthening projects (related to 26 MSUs) realized in Campi Alto between 1984 and 2012 is herein reported, see Fig. 14. The original documentation has been examined thanks to the collaboration with Umbria Region offices, and it involves 26 MSUs corresponding to 53% of the entire built-up area of Campi Alto. Thus, the sample of data may be reasonably representative of the strengthening works carried out in Campi Alto. A summary of building characteristics (number of stories and average floor surface) and of relevant strengthening intervention data (year of project of the intervention, type of the intervention on vertical and horizontal structures) as well as details on empirical damage detected after the last seismic sequence (damage index and type of external damage) on such MSUs is reported in the Annex section.

Fig. 15 shows the distribution of the damage index evaluated according to data collected in the post 2016 earthquake sequence by AeDES forms and *in-situ* inspections carried out by authors. Note that in the latter case, it was possible only to evaluate the external condition of the buildings, whereas the AeDES data considers also the internal damage (unless the building was inaccessible). The 26 MSUs have been grouped in three categories based on the amount and type of damage detected by surveyors: MSUs with no external damage (N.E.D.); MSUs with external damage (E.D.), and partially collapsed MSUs (P.C.).

In general, the analysis of the documentation related to the 26 MSUs (see Annex) showed that the intervention on vertical structures commonly involved the replacement of existing vertical walls of the floors above ground floor, combined with strengthening of undemolished walls portions by using several solutions: grout injections (G.I.), reinforced plaster jacketing (R.P.), steel connectors (S.C.) and tie rods (T.R.). In particular, G.I. was often combined with a wide use of S.C. at the orthogonal wall intersections. The R.P. was used to strength the bearing walls in only 6 projects, however this intervention rarely involved all the walls. Moreover, the architectural restriction of maintaining the fair-faced aspect of the masonry forced to apply R.P. only on the internal side of the external walls.

The intervention on horizontal structures involved, in all cases, the strengthening of existing vaults through the removal of the filling material and the construction of a RC slab at the extrados. Furthermore, existing wooden slabs were always replaced by new ones made of: RC beams and hollow bricks (9 projects); new wood beams (4 projects); steel beams (1 projects); or a combination of the previous ones (5 projects). The existing roofs were in most cases replaced by RC structures or wooden beams (10 and 7 projects, respectively), by steel beams in 2 projects. The new horizontal structures were connected to the surrounding walls by a RC ring beam partially built in the masonry wall thickness (or with the same wall dimension in case of demolition and reconstruction).

In the N.E.D. group, 3 MSUs had a damage index equal to 0 or 1, see Fig. 16. Although different in size and number of floors, a common factor on such MSUs was the extensive use of strengthening intervention on vertical walls. In particular, the walls that suffered severe damage after the 1979 and 1997 earthquakes were restored by means of several local dismantling and subsequent rebuilding (the so-called "*scuci-cuci*" intervention), and strengthened through G.I. or combining G.I. and R.P. (e.g. project 10, see Annex). Connections between orthogonal walls were improved by inserting S.C. or T.R. (e.g. project 17 and 18, see Annex). Furthermore, a strong replacement of existing walls was carried out by using block masonry (project 10a) or stone masonry (project 17). Thus, extensive intervention on both vertical and horizontal structures clearly led to satisfactory seismic

performances of the MSUs. In the remaining 7 MSUs, the damage index resulted in the range of 2-3, however the lack of visible damage prevents understanding the problems that affected these buildings.

In the E.D. group (i.e 10 MSUs) the damage index resulted always equal or greater than 2; in 5 MSUs, horizontal cracks, mainly localized at the level of intermediate floors, were detected (see Fig. 17). The width of the cracks was millimetric and revealed the activation of mutual translation between the two portions of the building, above and below the crack. This type of damage was detected on buildings where the upper floors were completely rebuilt, and the cracks were localized on the contact surface between the new floors and the existing ones. The behaviour of such buildings clearly confirms that, in case of reconstruction of floors, it is crucial to properly connect the new floors to the existing ones and vertical structures to horizontal ones. Indeed, in such 5 MSUs the poor attention to details in the adopted strengthening solution was the main reason of the damage detected after the earthquake.

In the remaining 5 MSUs with external damage, the damage was caused by deficiencies correlated to the original vulnerability of the building which were unsolved by renovation works: lack of connections on orthogonal walls and insufficient use of steel connectors as a strengthening technique, (see Fig. 18 related to MSU of project 13); reduced distance between openings and/or presence of openings close to the corners of the building and insufficient use of strengthening aimed at increasing the vertical walls bearing capacity, (see Fig. 19 related to MSUs of projects 6 and 7). In this latter case, MSUs belonging to a row building (adjacent masonry structural units related to each other) reported damages localized at its far end. By analysing the ground floor plan (Fig. 19a), it can be noted that the openings are very close to the corners and the distance between openings is very small; these two features cause a lack of masonry area that led to the formation of shear cracks in two bearing walls (Fig. 19b and Fig. 19c).

The P.C. group involved 6 MSUs with a damage index ranging between 3-5. In all cases the bad quality of masonry led to partial collapses. In particular, the uncomplete replacement of original existing wall in the strengthening interventions designed after 1979 seismic events led to partial collapse of ground floor with limited damage on the upper ones. In particular, the load-bearing walls of the first, second and third floors were demolished and rebuilt with block masonry while ground floor vertical walls were strengthened by G.I. in project 4, see Annex A and Fig. 20. After the 2016 seismic sequence the building experienced a rigid rotation of the three upper floors (with no damage, Fig. 20a) with respect to the ground floor where a large portion of the façade collapsed (Fig. 20b). Thus, the G.I. on ground floor resulted ineffective or insufficient to improve the quality of the masonry at the ground floor and this, along with the presence of two too wide openings in relation to the wall dimension, led to the crumble of the wall; tie rods were clearly ineffective because of poor quality of masonry wall. Similarly, the masonry at left corner of ground and first floor crumbled due to masonry bad quality in the MSUs of project 8 (see Fig. 21a); also the upper floors suffered damages limited to the walls that were not rebuilt after 1979 seismic events. In the MSU of project 2 an extensive collapse was detected: the original stone masonry of the ground floor and first floor crumbled (Fig. 21b); in addition, the external layer of stone masonry, applied only for aesthetic reasons, collapsed due to the lack of connections with the load-bearing block masonry behind it.

Severe damage after the 2016 sequence was also observed in case of MSUs strengthened by using a very heavy and rigid roof on a bad quality walls which were not adequately reinforced by extensive use of G.I. and R.P. as originally designed, (e.g. MSU of project 11, see Annex A and Fig. 22).

Declarations

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Conclusion

The study analyses the response of buildings in Campi Alto and Norcia after the 2016 seismic sequence. A large part of these buildings was strengthened in the past 30 years following previous earthquakes occurred in 1979 and 1997. The empirical damage detected on these buildings according to the visual inspections carried out after the 2016 seismic sequence, showed that the behaviour of buildings in Campi Alto was considerably less satisfactory than that observed in Norcia. However, the analysis of the seismic input allowed to exclude that such different behaviour was due to a significant variation of the excitation: the seismic intensity parameters recorded during the two earthquakes occurred on 26th October 2016 by the accelerometric station near Campi Alto (CMI) were comparable with those recorded during the earthquake of 30th October 2016 by stations located near Norcia (NOR and NRC). In addition, the microzonation studies exclude that Campi Alto was subjected to a major amplification due to morphology. As a result, the main reason of the different behavior may be related to two factors: the original vulnerability of buildings (i.e. buildings in Campi Alto are mostly irregular in elevation due to the area orography, characterized by the presence of fair faced masonry, and their masonry quality is generally poorer with respect to buildings in Norcia); the insufficient effectiveness, in some cases, of strengthening interventions executed after past seismic events. To better investigate on such latter aspect, 20 projects of strengthening interventions submitted to the Civil Engineering Department of the Umbria Region between 1984 and 2012 have been herein analysed and discussed. The analyses of such

projects along with the evaluation of the empirical damage detected after the recent seismic sequence represented a unique opportunity to investigate on the effectiveness of past strengthening solutions. The projects involved 26 structural units of Campi Alto corresponding to 53% of the entire built-up area of Campi Alto; thus, the outcome of the analysis may be assumed reasonably representative of the strengthening works carried out in Campi Alto.

The study showed that a very low damage level (50% of buildings with a damage index lower than 2 and the remaining 50% with a damage index equal to 3) was achieved in case of extensive interventions on both vertical and horizontal structures. Although a seismic input with S_a ranging between 1193-1572 cm/s^2 (for structural periods $T=0.1\text{s}-0.5\text{s}$) was recorded on buildings in Campo Alto, the reconstruction of walls that suffered severe damage after the 1979 and 1997 earthquakes combined with the strengthening of the remaining walls through grout injections or combining grout injections and reinforced plaster as well as the proper use of connections between orthogonal walls led to very satisfactory seismic behaviour. By contrast, significant damage was detected on buildings where the upper floors were rebuilt in block masonry while the ground floor was not adequately strengthened. Indeed, the absence of strengthening solution at ground floor, mainly related to preservation issues led to unsolved deficiencies like as insufficient masonry mechanical strength.

Furthermore, the reconstruction of entire floors needs to be accomplished by strong attention on the use of proper connections between new and existing floors in order to avoid the presence of horizontal cracks at the floors interface. This crack pattern reveals a lack of connection between the new horizontal structures and vertical ones (new or existing) and suggests adopting appropriate solutions if similar intervention is carried out in future applications.

When external walls were rebuilt in block masonry and an outer cover of stone masonry is built for aesthetic reasons it is necessary to carefully connect this layer with the load-bearing block masonry behind it otherwise collapses may occur.

Reduced distance between openings and presence of openings close to the corners of the building strongly affected the performance of MSUs by reducing their in plane seismic capacity; a strong and diffuse use of in plane strengthening solution should be used in such situations.

The use of connectors at building corners is crucial to avoid significant damage and collapses and they should be adequately designed (i.e. number, length). Finally, the realization of new heavy roof should be accomplished by strong intervention aimed at increasing the mechanical properties of bearing walls or it can result detrimental for the MSU seismic performances.

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Tables

Table 1 Seismic intensity parameters: earthquakes of 26th and 30th October 2016

	Epicenter distance	East-West component						North-South component					
		PGA	Sa_0.3	Sa_max	PGV	Sv_0.3	Sv_max	PGA	Sa_0.3	Sa_max	PGV	Sv_0.3	Sv_max
		[km]	[cm/s ²]	[cm/s ²]	[cm/s ²]	[cm/s]	[cm/s]	[cm/s]	[cm/s ²]	[cm/s ²]	[cm/s ²]	[cm/s]	[cm/s]
<i>26th October 2016 (19.10) earthquake</i>													
CMI	3.7	-707	1484	1991	56	71	130	335	599	1193	19	29	51
				(0.36s)			(0.67s)			(0.12s)			(0.50s)
NOR	9.5	157	357	389	-22	17	52	-163	633	633	16	30	30
				(0.75s)			(1.10s)			(0.30s)			(0.30s)
NRC	9.4	295	577	664	-26	27	40	-258	522	637	17	25	30
				(0.22s)			(0.67s)			(0.18s)			(0.38s)
<i>26th October 2016 (21.18) earthquake</i>													
CMI	7.1	-638	1719	2153	44	82	127	303	806	1005	26	38	56
				(0.36s)			(0.38s)			(0.10s)			(0.38s)
NOR	13.3	211	439	522	-21	21	43	118	238	437	-15	11	28
				(0.42s)			(0.85s)			(0.19s)			(1.10s)
NRC	13.2	248	350	552	-16	17	38	-366	383	1446	12	18	39
				(0.17s)			(0.55s)			(0.17s)			(0.18s)
<i>30th October 2016 (07.40) earthquake-</i>													
CMI	-	-	-	-	-	-	-	-	-	-	-	-	-
NOR	4.7	-306	720	1236	56	34	206	-288	560	902	48	27	138
				(0.85s)			(1.30s)			(0.95s)			(1.00s)
NRC	4.6	476	1863	1931	-48	89	140	365	1100	1600	41	52	108
				(0.36s)			(0.38s)			(0.10s)			(0.18s)

Table 2 Housner Intensity (I_H) and modified Housner Intensity (mI_H).

	East-West component		North-South component	
	I_H [cm]	mI_H [cm]	I_H [cm]	mI_H [cm]
<i>26th October 2016 (19:10) earthquake</i>				
CMI	130	31	41	13
NOR	75	7	39	7
NRC	65	10	40	9
<i>26th October 2016 (21:18) earthquake</i>				
CMI	142	31	63	14
NOR	62	9	51	5
NRC	51	8	48	11
<i>30th October 2016 (07:40) earthquake</i>				
CMI	-	-	-	-
NOR	253	13	180	11
NRC	204	23	151	16

Figures



Figure 1

Views of Norcia (a) and Campi Alto (b) before the 2016-2017 seismic sequence (pictures from websites www.umbriaoggi.it and www.iluoghidelsilenzio.it)

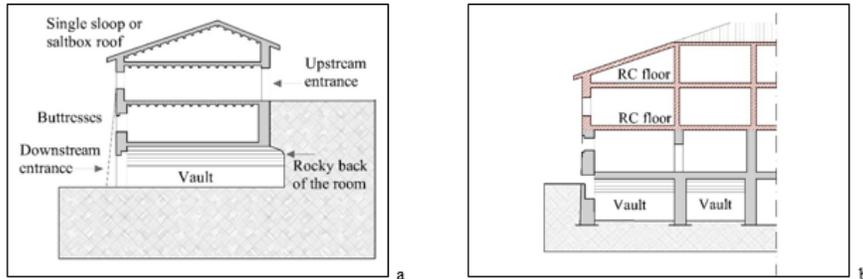


Figure 2

a) Typical section of terraced houses of Campi Alto (adapted from Cardani, 2003). b) Typical section of building in the historical centre of Norcia: typically, the upper floors (dashed line halftone) were rebuilt with reinforced concrete (RC) floors and block masonry

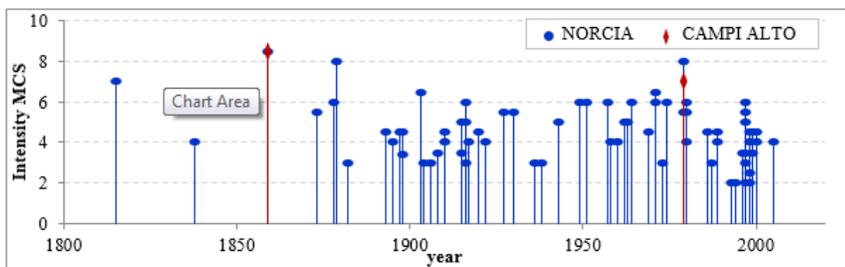


Figure 3

Historical sequence of earthquakes in Norcia and Campi Alto in the period 1650-2000 (from Rovida et al. 2019)



Main shocks	Date and hour (Italy)	Mw	Epicenter
I	24-08-2016 03:36	6.0	Accumoli (RI)
II	24-08-2016 04:33	5.3	Norcia (PG)
III	26-10-2016 19:10	5.4	Castelsantangelo sul Nera (MC)
IV	26-10-2016 21:18	5.9	Castelsantangelo sul Nera (MC)
V	30-10-2016 07:40	6.5	Norcia (PG)
VI	18-01-2017 10:25	5.1	Capitignano (AQ)
VII	18-01-2017 11:14	5.5	Capitignano (AQ)
VIII	18-01-2017 11:25	5.4	Capitignano (AQ)

Figure 4

Regions struck by the 2016-2017 seismic sequence in Central Italy: main shocks and Norcia and Campi Alto location Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

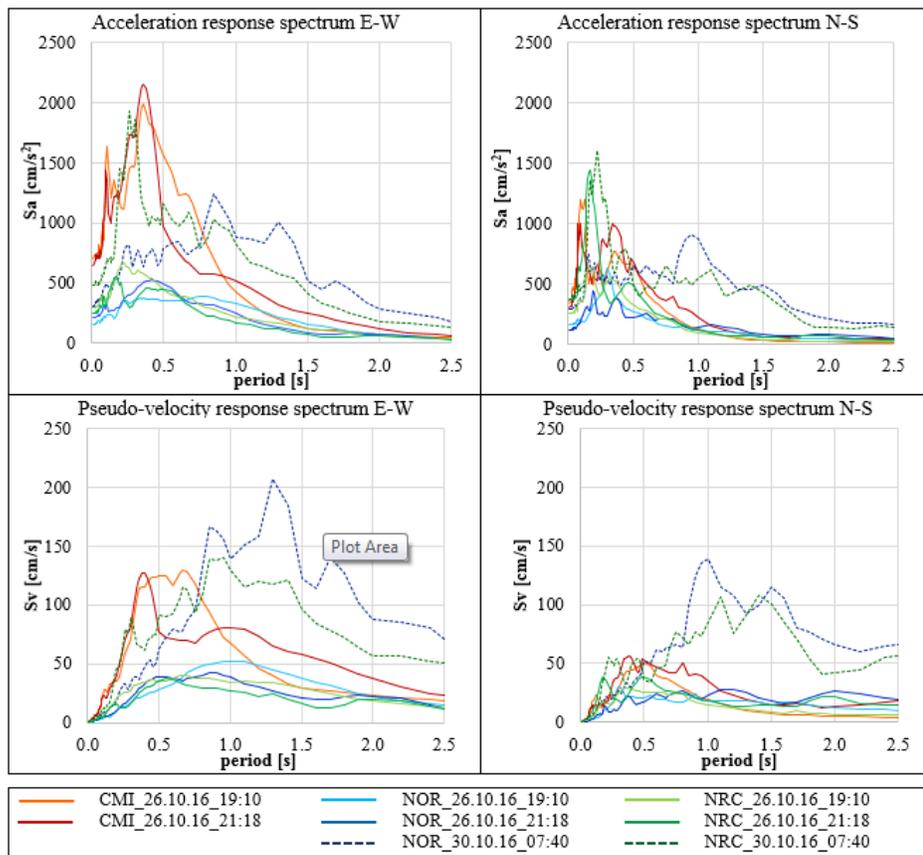


Figure 5

Comparison of the acceleration response spectra and pseudo velocity response spectra recorded by three station of the Italian Strong Motion Network during the earthquakes of 26th and 30th October 2016

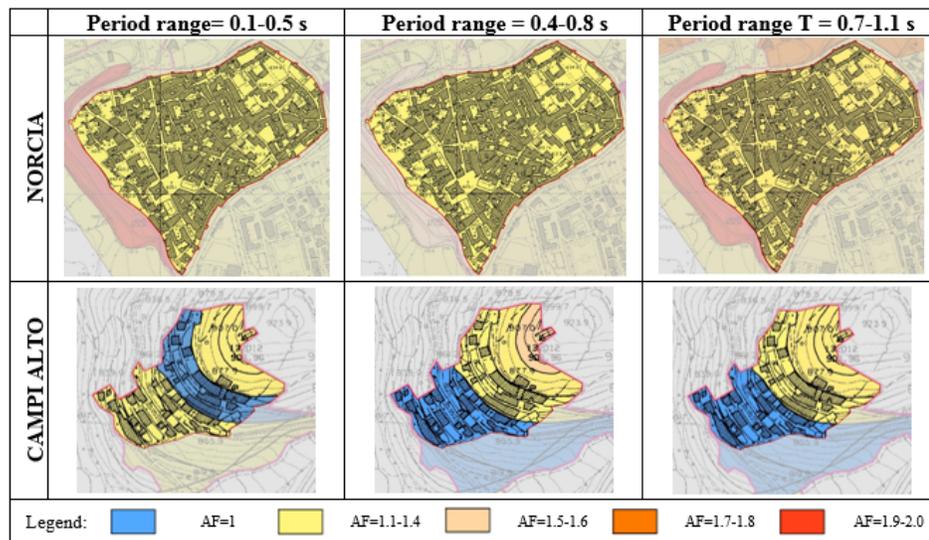


Figure 6

Detailed Seismic Microzonation Maps of the city centre of Norcia and Campi Alto (from the study of microzonation of Norcia carried out by SGA (Studio Geologi Associati) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

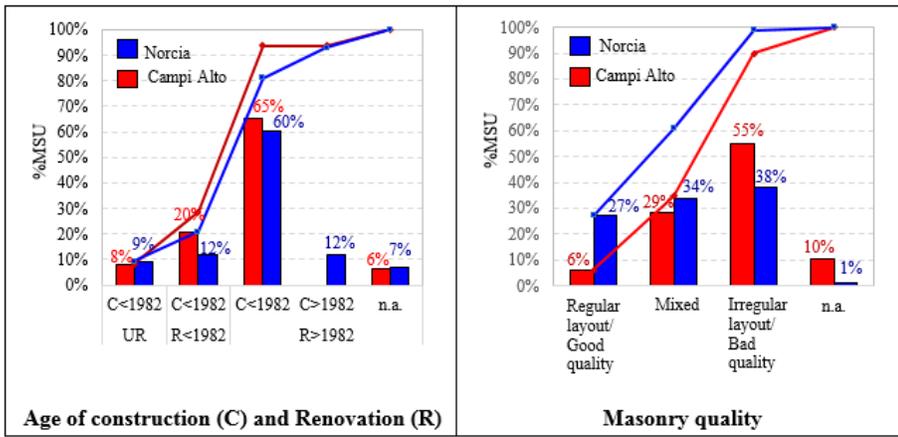


Figure 7
 MSUs in Campi Alto (red) and Norcia (blue): percentages and cumulative trends as a function of age of construction and renovation and masonry quality

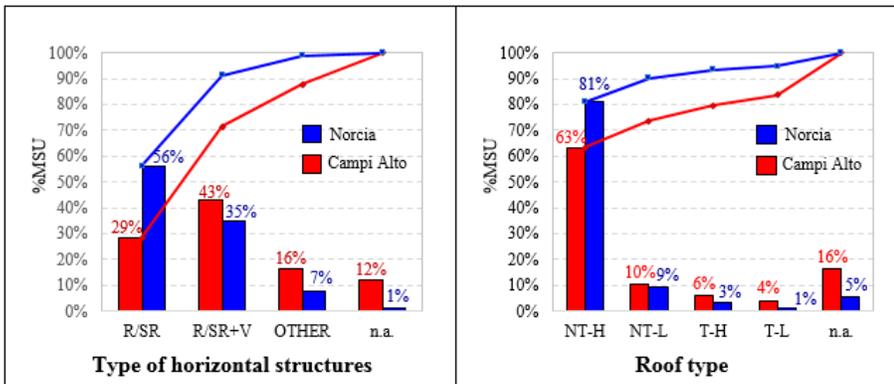


Figure 8
 MSUs in Campi Alto (red) and Norcia (blue): percentages and cumulative trends as a function of type of horizontal structures and roof type



Figure 9
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Comparison between masonry types observed in Campi Alto (a, b) and in the historic center of Norcia (c, d, e).

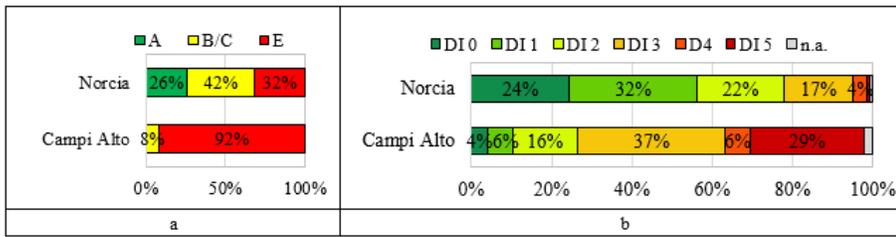


Figure 10

Usability ratings (a) and Damage Index, DI, (b) of MSUs in Norcia and Campi Alto.

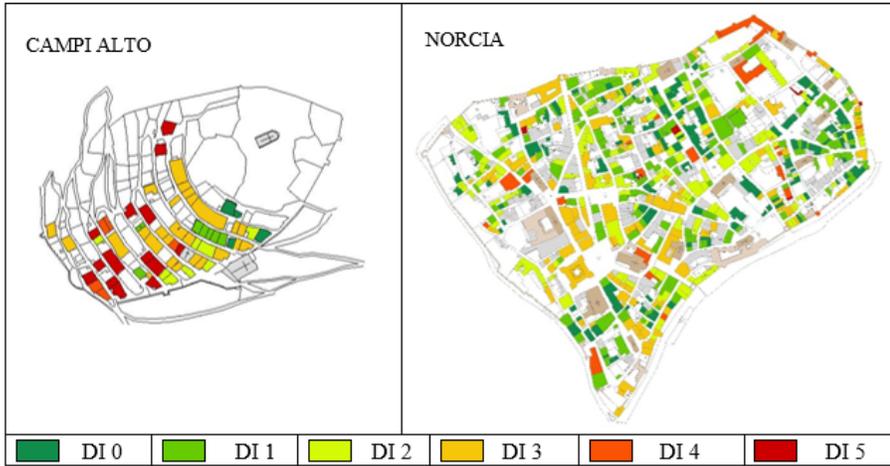


Figure 11

Maps of Campi Alto and the historical centre of Norcia: identification of the damage index rating of residential buildings. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

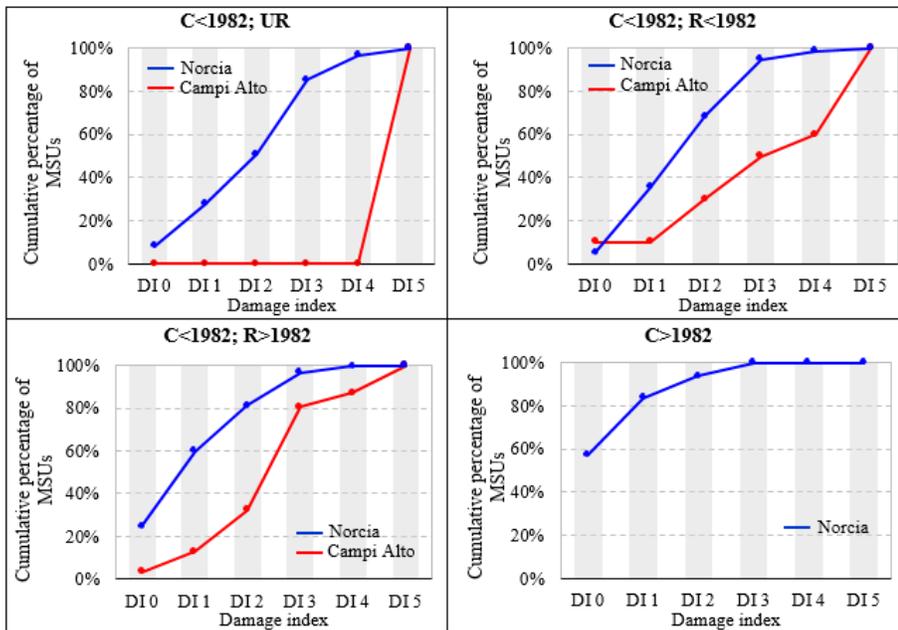


Figure 12

Influence of the age of construction (C) and renovation works (R) on the cumulative percentage of MSUs that attained a damage index DI equal to or lower than a given value.

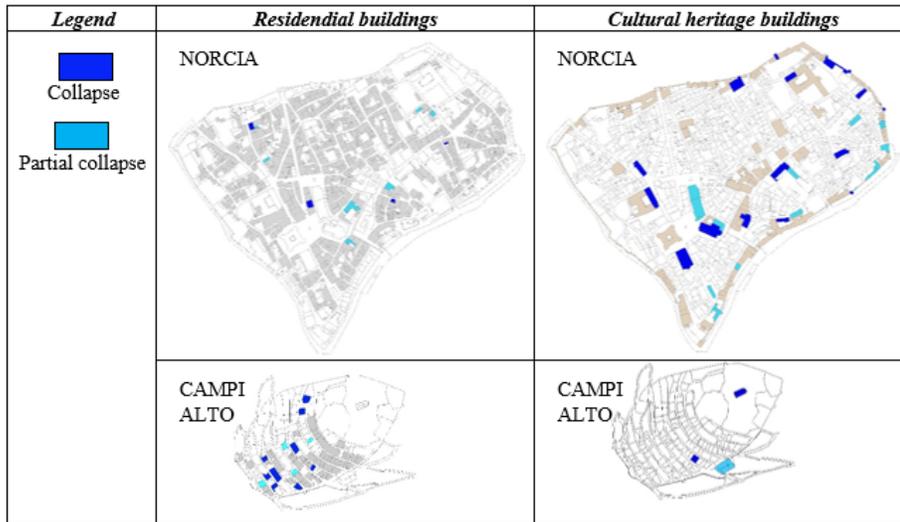


Figure 13

Maps of Campi Alto and the historical centre of Norcia: identification of total and partial collapses in residential and cultural heritage buildings Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

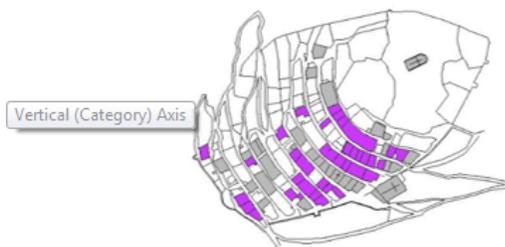


Figure 14

Strengthened MSUs in Campi Alto under investigation Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

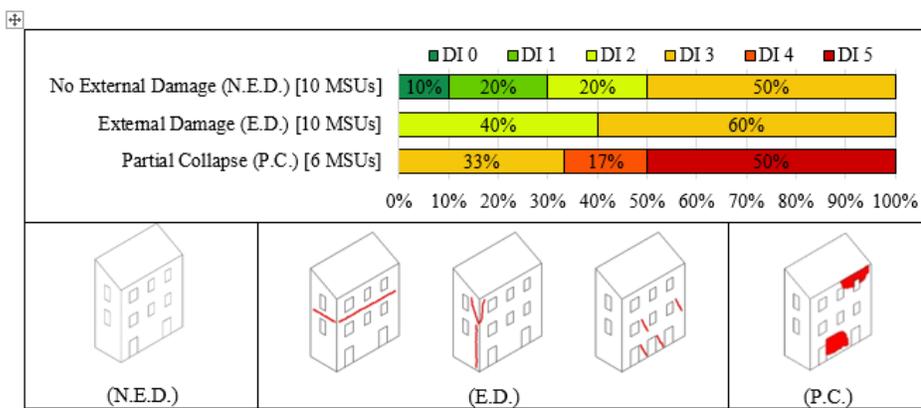


Figure 15

Damage Index distribution on MSUs



Figure 16

MSUs with no external damage and damage index equal to 0 (project 18) or 1 (projects 10 and 17)



Figure 17

Common horizontal cracks at floor level

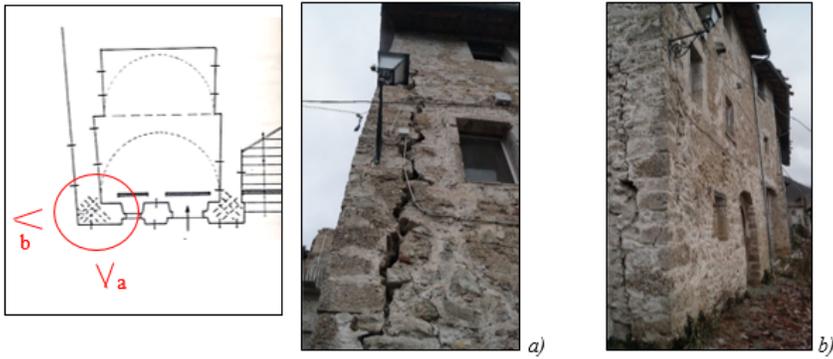


Figure 18

Project 13: poor connection of orthogonal bearing walls

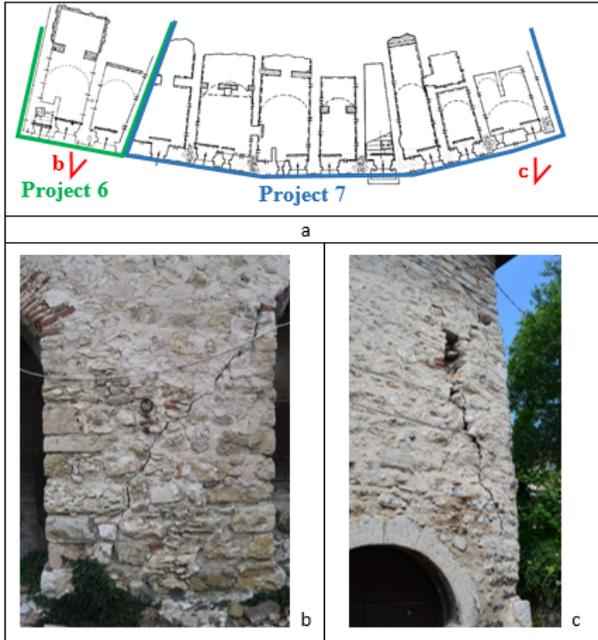


Figure 19

MSUs ground floor plan (a). Damage at the far end of the row building (b) and (c)



Figure 20

Project 4: a) rigid rotation of replaced floors with respect to the ground floor; b) crumble and collapse of poor masonry wall at ground floor



Figure 21

(a) Project 8: crumble of masonry walls at ground floor;(b) Project 2: collapse of the masonry walls at ground and first floor



Figure 22

Project 11: collapse of poor quality masonry walls due to the presence of heavy roof: (a) downstream façade; (b) lateral section

Supplementary Files

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