# Vulnerability of Architectural Heritage in Seismic Areas: Constructive Aspects and Effect of Interventions

**Maria Rosa Valluzzi and Luca Sbrogiò**

**Abstract** In this chapter, the effects of past interventions applied to historical city centers struck by a series of earthquakes over time are analyzed in terms of local and overall damage. Three villages in central Italy, Castelluccio di Norcia, Campi Alto di Norcia and Castelsantangelo sul Nera, containing overall about 150 buildings, are examined here. Classification of damage was based on the European Macroseismic Scale. The study provided vulnerability maps detailing the influence of interventions on buildings in historical city centers, which may contribute to better evaluation of damage scenario and maintenance plans.

**Keywords** Seismic vulnerability · Survey form · Masonry · Retrofit · Intervention

## 1 Seismic Vulnerability of Existing Masonry Buildings

Architectural heritage is particularly prone to damage in seismic areas, due to construction defects or limitations, which combine, together with the effects of lack of maintenance and deterioration exposure of materials. Common vulnerabilities associated with building construction, often detectable in existing masonry buildings, involve one or more of the following aspects: (i) the poor quality of the masonry; (ii) the scarce connections among components (walls, floors and roof); (iii) the structural irregularities; (iv) the inadequate stiffness of horizontal components (floors and roof); (v) the existence of thrusting structures (e.g., arches and vaults, but also pounding elements in floors and roofs). These deficiencies result in partial or even overall collapses (‘mode 1’ mechanisms), mainly due to overturning and out-of-plane bending of walls and assemblages (e.g., corners), which can occur

---

M. R. Valluzzi (✉) · L. Sbrogiò
Department of Cultural Heritage, University of Padova, Padua, Italy
e-mail: mariarosa.valluzzi@unipd.it

L. Sbrogiò
e-mail: luca.sbrogio@phd.unipd.it

G. Amoruso and R. Salerno (eds.), *Cultural Landscape in Practice*,
Lecture Notes in Civil Engineering 26,
https://doi.org/10.1007/978-3-030-11422-0_14

even at low-medium earthquake magnitudes [12, 3, 20, 16]. In addition, poor-quality masonry, mainly due to the lack of transverse shear elements in multi-leaf walls, irregular texture and composition, low-grade properties of the constituent materials (mortar and bricks/stones), deterioration of binding power in ancient mortars [6, 7], may even involve anticipatory brittle collapse ('mode 0') due to disaggregation of constituent materials, which may occur under even lower seismic magnitudes and before any other sort of mechanism can be activated.

Such brittle behavior (modes 0 and 1) can be inhibited by better quality of materials and more adequate construction systems and details, so that more extensive collaboration among parts can be activated and exploited ('box-like' behavior). This results in overall pseudo-ductile behavior (adequate displacement capacity without collapse), which can concentrate dissipative shear cracks in lintel elements, thus preserving as much as possible the integrity of piers ('mode 2' mechanisms), provided that their continuity in height is ensured by the regular lay-out of openings.

All these behaviors were observed as the effects of a series of seismic events in central Italy from August to October 2016 and are still active, i.e., in the highlands encompassed by Macerata (N), L'Aquila (S), Ascoli Piceno (E) and Perugia (W), known as Sibillini Mountains Park. These areas and their surroundings are some of the most active seismic areas (0.255g expected PGA according to the seismic hazard map; more than 0.7g actual PGA recorded in 2016) [15, 19]. High seismicity in this area has always meant that local population are scattered in many villages and 'castles', so that the very concept of 'cultural landscape' is embodied in them, with the result that they have been built and rebuilt over the centuries after every earthquake. They are the product of traditional building techniques, which gave rise both to their vulnerability and to attempts at avoiding it.

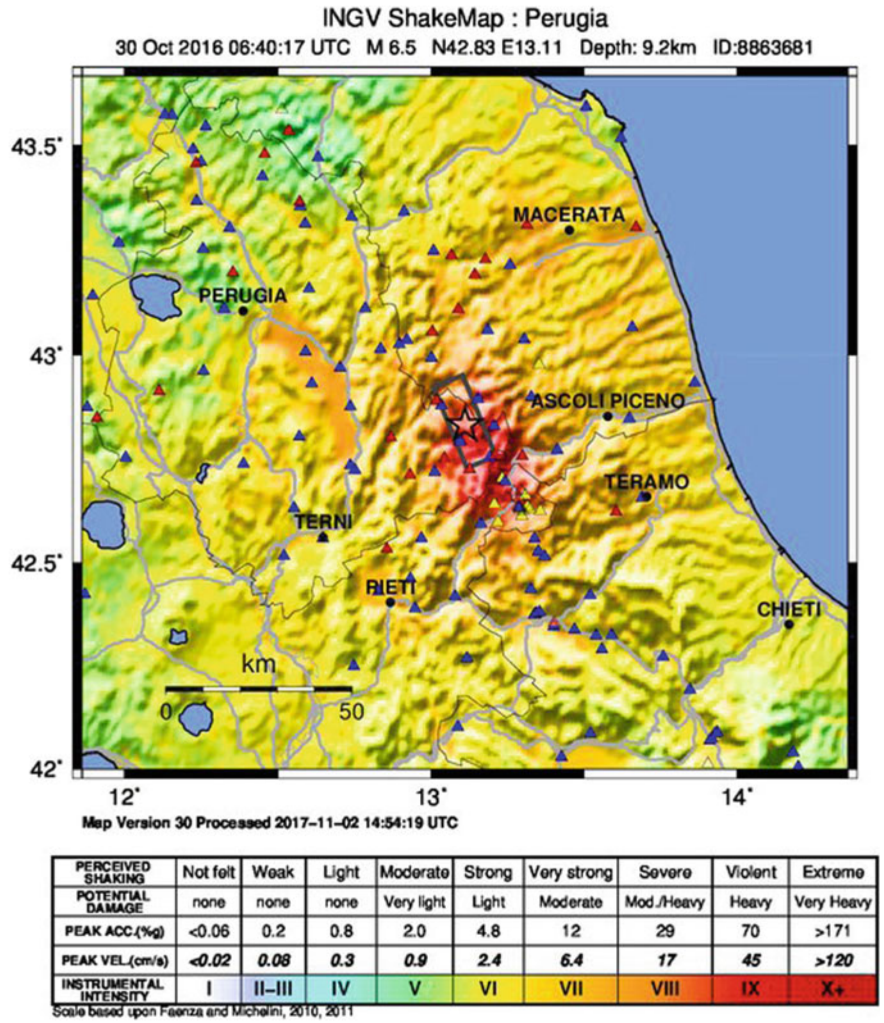
Figure 1 shows the location of the centers studied here, in the area struck by the 2016 sequence: Castelsantangelo sul Nera (province of Macerata: MC), Campi Alto di Norcia and Castelluccio di Norcia (Perugia: PG). They are all fortified villages built in the late Middle Age to keep control of fertile lands and roads between the borders of Norcia and Visso, the two largest, at the time of their expansion.

Figures 2 and 3 show the typical damage, detected in central Italy after the 2016 earthquakes, encompassing damage modes 0 and 1 (unfavorable conditions), and mode 2 (favorable conditions), due to constructive aspects.

Unfortunately, 'mode 0' failure is a major problem. The supply of building materials near it greatly influences the quality of masonry, which ranges from including very poor sand and clay mortar with almost spherical sandstone rocks (Fig. 2b) to better-dressed limestone with pure lime mortar (Fig. 2a).

Many houses show signs of earthquake damage and also the basic systems used to prevent major damage, ascribed to mode 1: buttressing, tie-bars and special systems, such as the detachment of barrel vaults from the façade to preserve the former when the latter collapses, as already observed in Campi Alto di Norcia [8, 4].

Lastly, the preferred mode 2 occurred in a very few cases and mostly in more recent buildings, dating to the 19th century, when some rules for seismic-proof



| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Mod./Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <0.06 | 0.2 | 0.8 | 2.0 | 4.8 | 12 | 29 | 70 | >171 |
| PEAK VEL.(cm/s) | <0.02 | 0.08 | 0.3 | 0.9 | 2.4 | 6.4 | 17 | 45 | >120 |
| INSTRUMENTAL INTENSITY | I | II–III | IV | V | VI | VII | VIII | IX | X+ |

**Fig. 1** Shake map of October 30 2016 earthquake (not to scale). Case studies are located within the red area, which includes the Sibillini Park [15]

practices (after the 1859 earthquake that struck the region) were issued. However, these regulations apply only to large towns (Visso, Pieve Torina, Norcia), while traditional systems survived in villages.

More commonly, since 1979 (year of the Valnerina earthquake, Mw 5.9) and until the early 2000s (1997 Colfiorito earthquake, Mw 5.8), various retrofitting techniques have been applied to repair damage, mainly substitution of components (especially floors and roofs) and the addition of heavy, incompatible structures (e.g., reinforced concrete).

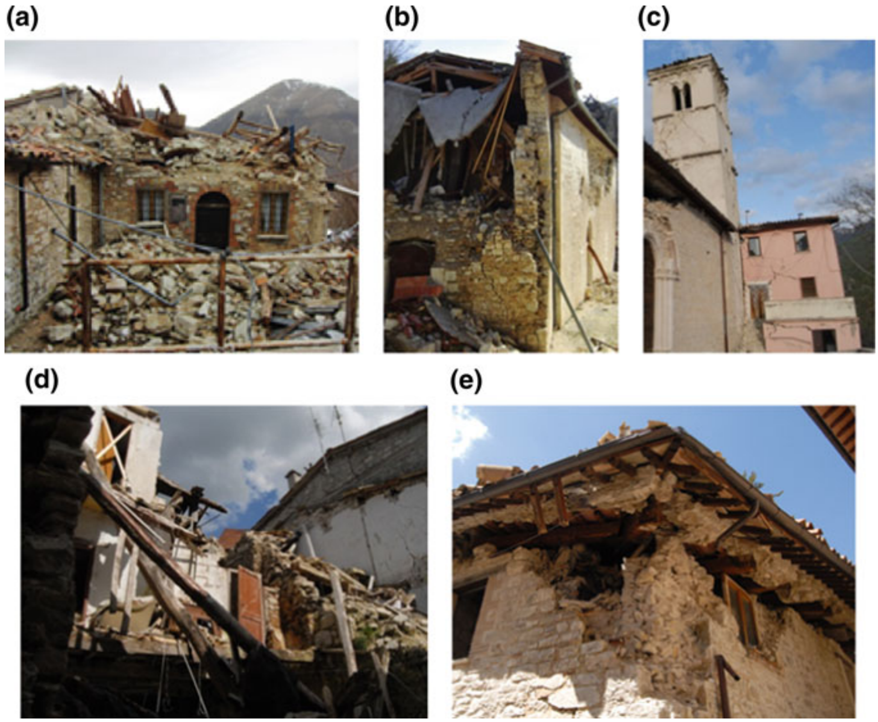


**Fig. 2** Unfavorable behavior of masonry structures under seismic actions. Out-of-plane collapse (modes 0 and 1) due to poor-quality construction: **a** collapse due to poor-quality masonry (Gualdo, near Castelsantangelo sul Nera); **b** local collapse due to lack of connections in multi-layer masonry at corners (Castelsantangelo sul Nera); **c** pounding due to irregular interaction between house and contiguous bell-tower (Castelsantangelo sul Nera); **d** facade overturning in terraced house with original timber floors parallel to façade (Castelsantangelo sul Nera); **e** effect of thrusting roof resting on two-leaf masonry wall (Castelsantangelo sul Nera)

## *1.1 Procedures for Vulnerability and Damage Evaluation*

The earthquakes of the early 1980s stimulated the development of simplified tools and procedures to evaluate both the damage and vulnerability of ordinary masonry buildings, mainly through survey forms. Of these, 'GNDT[1] II level' [2, 13, 11] and AeDES[2] forms [1, 10] are the most used.

The GNDT form evaluates a normalized index (Iv) with three levels of vulnerability, which can be related to verbal assessment of the overall vulnerability of a building (from 'very high' to 'very low'), as shown in Table 1 [9].

---

[1] Acronym for 'Italian Group of Defense against Earthquakes'.

[2] Acronym for 'Level 1 Form for Post-Earthquake Damage and Usability Assessment and Emergency Countermeasures in Ordinary Buildings'.

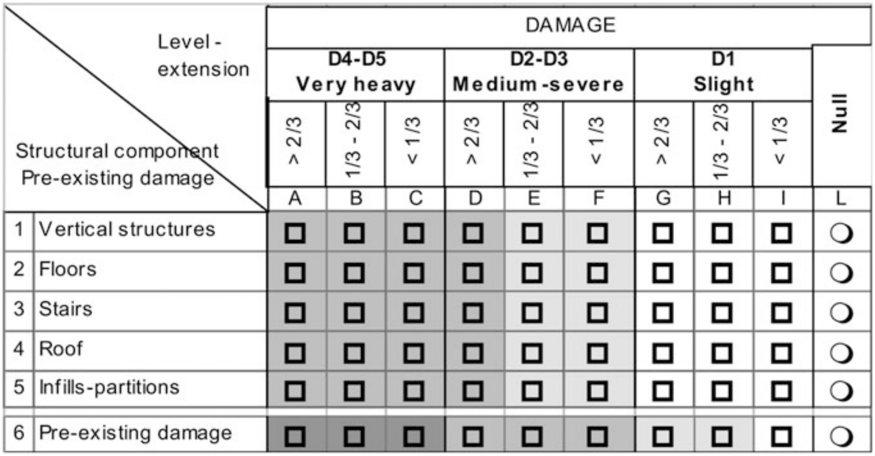
**Fig. 3** Favorable behavior of masonry structures under seismic actions. In-plane damage limited to repairable elements without collapse (mode 2): shear failure mainly extensive in masonry piers **a** (Castelsantangelo sul Nera) and, more favorably, on lintels **b** (Pieve Torina, MC)

**Table 1** Correlation between GNDT form scores and vulnerability classes according to EMS 98 (from [9])

| GNDT form score | Iv normalized | Iv range | EMS 98 vulnerability class | Verbal assessment |
|---|---|---|---|---|
| 0 | 0 | 0.00–0.10 | C | Retrofitted |
| 52.5 | 0.13 | 0.11–0.20 | | Very low |
| | | 0.21–0.40 | B | Low |
| 203.75 | 0.51 | 0.41–0.60 | | Medium |
| | | 0.61–0.80 | A | High |
| 393.75 | 1 | 0.81–1.00 | | Very high |

The AeDES form dates back to the 1997–98 seismic events which struck the Umbria and Marche regions and which has been extensively validated in many post-earthquake contexts (Molise 2002, L'Aquila 2009, Emilia 2012). It relates the grading of damage levels of five main components, according to the European Macroseismic Scale 1998 (EMS 98) [14], also taking into account the extent of damage throughout the building in question (Fig. 4). Evaluation requires simpler information than the GNDT form, because it was designed for on-site use, just after seismic events.

These tools have been used in vulnerability and damage evaluations since the early 2000s for case studies throughout Italy's central regions. However, recent events have shown that they would need updating, in order to represent better the peculiar actual conditions of built heritage all over Italy, seriously affected since the adoption of r.c.-based techniques.



| Level - extension<br>Structural component<br>Pre-existing damage | | DAMAGE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | D4-D5<br>Very heavy | | | D2-D3<br>Medium-severe | | | D1<br>Slight | | | Null |
| | | > 2/3 | 1/3 - 2/3 | < 1/3 | > 2/3 | 1/3 - 2/3 | < 1/3 | > 2/3 | 1/3 - 2/3 | < 1/3 | |
| | | A | B | C | D | E | F | G | H | I | L |
| 1 | Vertical structures | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 2 | Floors | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 3 | Stairs | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 4 | Roof | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 5 | Infills-partitions | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |
| 6 | Pre-existing damage | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ○ |

**Fig. 4** Damage evaluation module in AeDES form [18]

## 2 Aim and actual effect of interventions

Interventions in masonry buildings in seismic areas mainly focus on rehabilitating collaboration among parts, at both local (cross-section, texture, connections) and more extensive building scales (strengthening of structural components and assemblages, overall working). Table 2 lists intervention techniques aimed at reducing the possible vulnerability of masonry buildings and their structural components.

The proper design of interventions according to the vulnerability in question, the adoption of compatible materials and techniques, and the suitable installation are all essential requisites, if effective results in enhancing structural behavior are to be attained [5, 17, 21].

Nonetheless, analysis of historic city centers struck by earthquakes in the last 40 years in Italy has revealed severe damage and collapse attributable to additional vulnerability triggered by heavy retrofitting techniques: although they were ideally conceived to improve mutual collaboration among the structures, in actual fact they entail more complex and hybrid behaviors (Fig. 5). It is the case of the use of r.c. to substitute floors and roofs (aimed at increasing the in-plane stiffness), to strengthen vaults (to prevent collapse), or applied as ring beams at floor and roof levels (to connect walls against overturning). This practice was commonly adopted in masonry buildings from the 1980s onwards, according to the knowledge and recommendations available then. However, even more recent techniques, thought to be more compatible with ancient fabrics, e.g., horizontal steel trusses as ties, have proved to be inadequate, mainly due to the lack of connections to masonry.

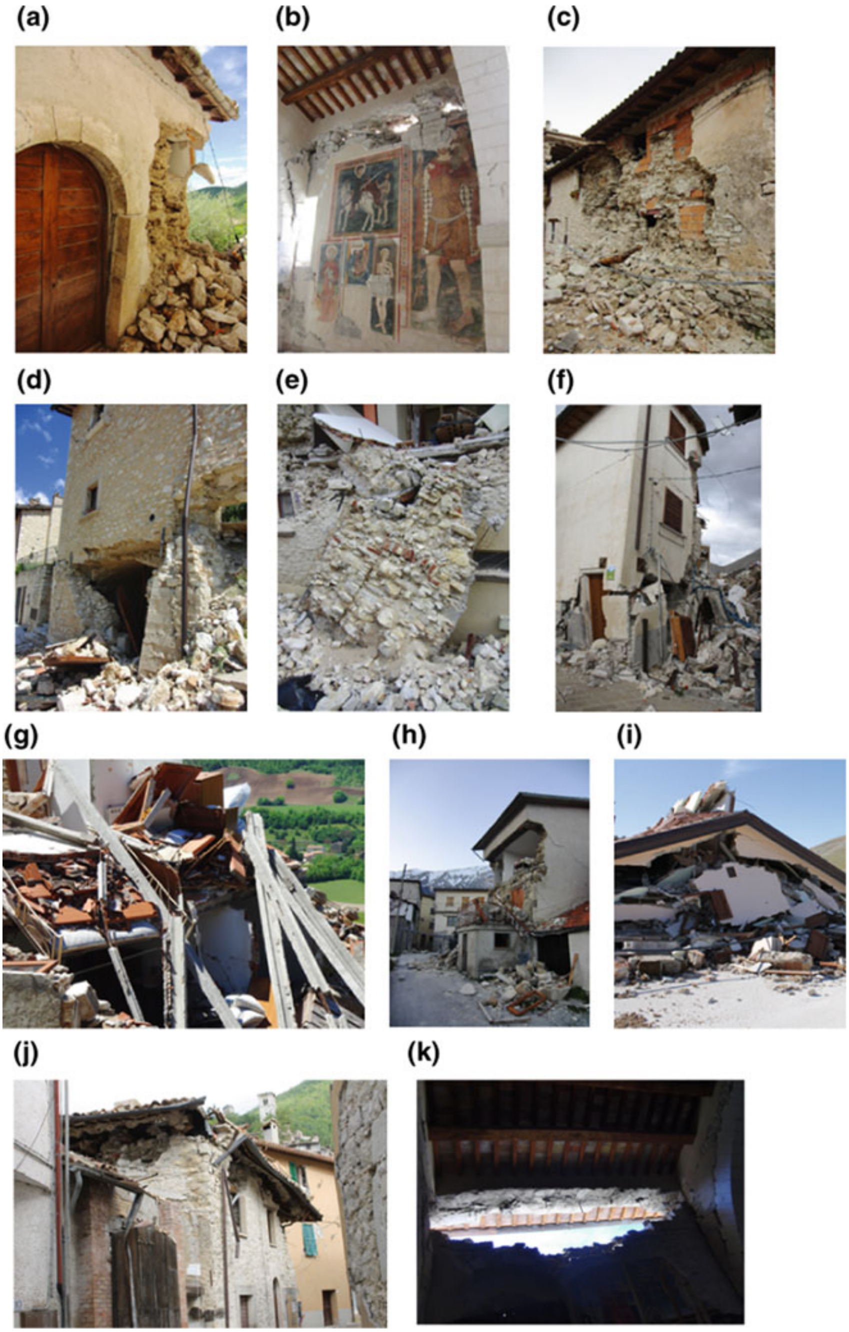
**Table 2** Intervention techniques to reduce vulnerability in masonry buildings

| Failure mode | Building component | Vulnerability | Damage | Intervention technique | Main improvement | Main prerequisite for effectiveness |
|---|---|---|---|---|---|---|
| Mode 0 | Wall | Low masonry quality | Disaggregation | Grout injection | Inner compactness, homogeneity | Presence of voids (e.g., incoherent core in multi-leaf walls) |
| | | | | Jacketing (r.c., composites) | Collaboration among layers | Connections applicable throughout thickness |
| | | | | Repointing | Mortar quality | Regular texture |
| Mode 1 | Wall | Slenderness | Out-of-plane deformation | Intermediate connections (ties, confinement rings) | Constraints along wall | Good-quality masonry |
| | Wall-to-wall assembly | No or insufficient connections | Overturning | Tie-rods | Connection of opposite walls | Good-quality masonry |
| | | | | Ring beams | Force redistribution among walls | Good-quality masonry |
| | | | | Confinement rings | Connection among walls | Good-quality masonry |
| | | | | Stitching | Local connection at corners | Good-quality masonry |
| | Floor | No diaphragm effect, inadequate floor-to-walls connection | Beams sliding at supports, pounding | Overlap of timber boards, diagonal strips, thin r.c. shells | In-plane stiffening | Effective connectiosn between new and old elements |
| | | | | Substitution (same concept) with steel/r.c. precast beams and hollow bricks | In-plane stiffening | Strong masonry |
| | | | | Substitution (different concept) with r.c. beams, hollow bricks and thin r.c. shell | In-plane stiffening | Strong masonry |

(continued)

**Table 2** (continued)

| Failure mode | Building component | Vulnerability | Damage | Intervention technique | Main improvement | Main prerequisite for effectiveness |
|---|---|---|---|---|---|---|
| | Roof | No diaphragm effect, thrust | Beams sliding at supports, overall sliding | Overlap of timber boards, diagonal strips, thin r.c. shells | In-plane stiffening | Effective connections between new and old elements |
| | | | | Substitution (same concept) with steel/r.c. precast beams and hollow bricks | In-plane stiffening | Strong masonry, inhibition of thrust |
| | | | | Substitution (different concept) with r.c. beams, hollow bricks and thin r.c. shell | In-plane stiffening | Strong masonry, inhibition of thrust |
| | Vault | Thin cross section, thrust | Overturning at abutments, deformation, collapse | Tie-rods, transverse stiffening walls | Reduction of trust and deformability | Good-quality piers |
| | | | | Thin shells (r.c., composites) | Stiffness, holistic unity | Effective connection/ bonding |
| Mode 2 | Piers and lintels | Irregular distribution of openings | Shear failure in piers or lintels | Pier reinforcement (see ‘wall’) | Mechanical strength | ‘box-like’ behavior |
| | | | | Lintels repair/substitution | Mechanical strength | |


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)

◂**Fig. 5** Damage caused by unfavorable interaction of existing masonry structures with retrofitting techniques: **a** corner overturning due to r.c. ring beams (Campi Alto di Norcia); **b** damage at interface between r.c. beams and masonry (Castelsantangelo sul Nera); **c** disaggregation of ancient masonry together with new masonry (Gualdo, near Castelsantangelo sul Nera); **d** unreinforced first-floor overturning under reinforced upper storeys (Campi Alto di Norcia); **e** collapse of jacketed multilayer masonry (Nocelleto, near Castelsantangelo sul Nera); **f** failure due to irregular distribution of r.c. jacketing (Castelluccio di Norcia); **g** shear failure in precast r.c. beams and consequent overall collapse due to lack of horizontal floor diaphragms (Campi Alto di Norcia); **h** partial collapse due to poor-quality masonry under heavy r.c. floors (Pretare, near Arquata del Tronto, AP; **i** overall (Castelluccio di Norcia) and **j** partial (Castelsantangelo sul Nera) collapse under heavy r.c. floors and roofs; **k** V-shaped overturning under r.c. ring beam, even in presence of anchoring rebars (Castelsantangelo sul Nera)

## 3 Vulnerability Maps of Historic Centers

Due to extensive observation of unfavorable effects of modern interventions after the 2016 seismic events in central Italy, a new form has been proposed to flank the assessment procedures mentioned above (i.e., GNDT II level and AeDES forms). This form collects information on interventions and modern alterations of heritage buildings as part of a purpose-designed method able to implement data collected on entire (small) historic towns in GIS [19].

Among others, the three villages studied here (Campi Alto di Norcia, Castelluccio di Norcia, Castelsantangelo sul Nera) offer an interesting overview of damage mechanisms proper to 'original' buildings, i.e. with only traditional interventions, as well as 'altered' buildings affected by invasive techniques.

Campi Alto di Norcia and Castelsantangelo sul Nera have a similar layout: an egg-shaped boundary wall built on slope with terraced houses on the lower half, and a tower and church at the top. Instead, Castelluccio di Norcia is built on a small cliff overlooking the surrounding plain with a curtain wall at its base. Over the centuries, these 'castles' have been abandoned because of the development of *extra moenia* suburbs, closer to the road systems, like for Castelluccio di Norcia and Castelsangelo sul Nera. Campi Alto di Norcia, being further from the valley road, is now almost completely abandoned (Fig. 6).

The new procedure collects data on interventions, both architectural (e.g., changes in plans' layouts of openings distribution) and structural, with reference to vulnerability assessments and damage states available over the last 40 years (i.e., from 1979 onwards), according to building types existing in the three centers (Fig. 7).

In particular, comparisons between the conditions and the damage scenarios surveyed after the 1979 and 2016 seismic events provide significant results in terms of evaluation of intervention effects. Figure 8 shows a considerable shift towards higher damage states in Campi Alto di Norcia: no cases of collapses can be found in 1979 and 'medium' damage (i.e., D3 category, according to EMS 98) involves much of the building stock. In 2016, damage state surveys show the opposite

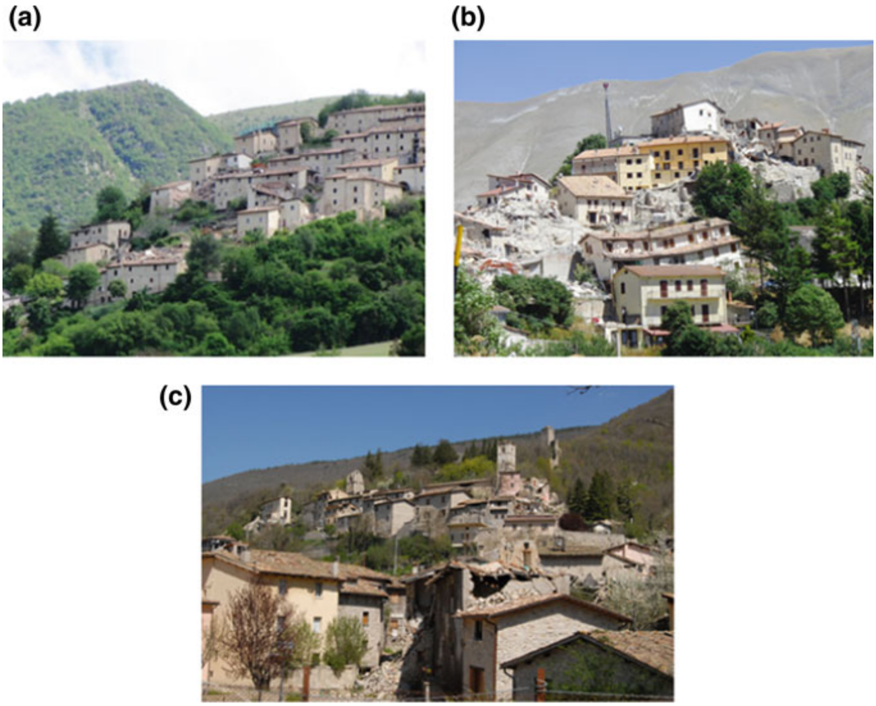


Fig. 6 View of three towns surveyed after 2016 seismic sequences: **a** Campi Alto di Norcia (PG); **b** Castelluccio di Norcia (PG); **c** Castelsantangelo sul Nera (MC)

**Fig. 7** Building types in **a** Campi Alto di Norcia (PG), **b** Castelluccio di Norcia (PG), **c** Castelsantangelo sul Nera (MC)

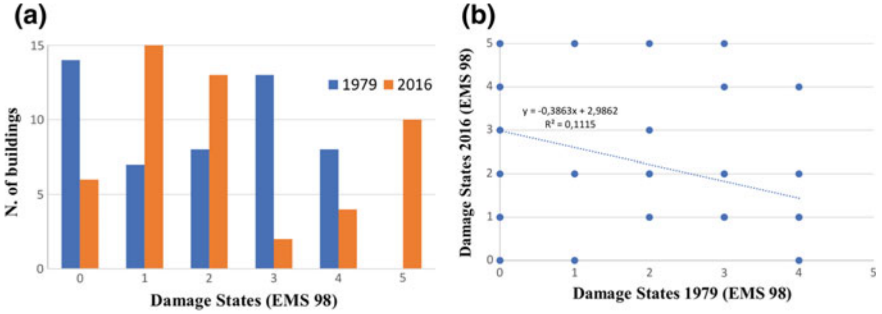


**Fig. 8** Campi Alto di Norcia, distribution of EMS 98 damage states in 1979 and 2016: **a** absolute frequencies; **b** correlation between them

behavior, as most buildings are listed either in EMS 98 classes D1-D2 (low or almost no damage) or D5 (collapse).

GIS mapping clearly shows that, for instance (Fig. 9), the buildings severely damaged in Campi Alto di Norcia in 1979 are now not damaged, and vice versa. On one hand, this means that retrofit interventions have been effective, whereas buildings with generic structural updating became more vulnerable than the previous states. On the other hand, effective interventions imply the complete transformation of the original architectural qualities of a building, because all components (wall, floors, roof) are involved in the strengthening process.

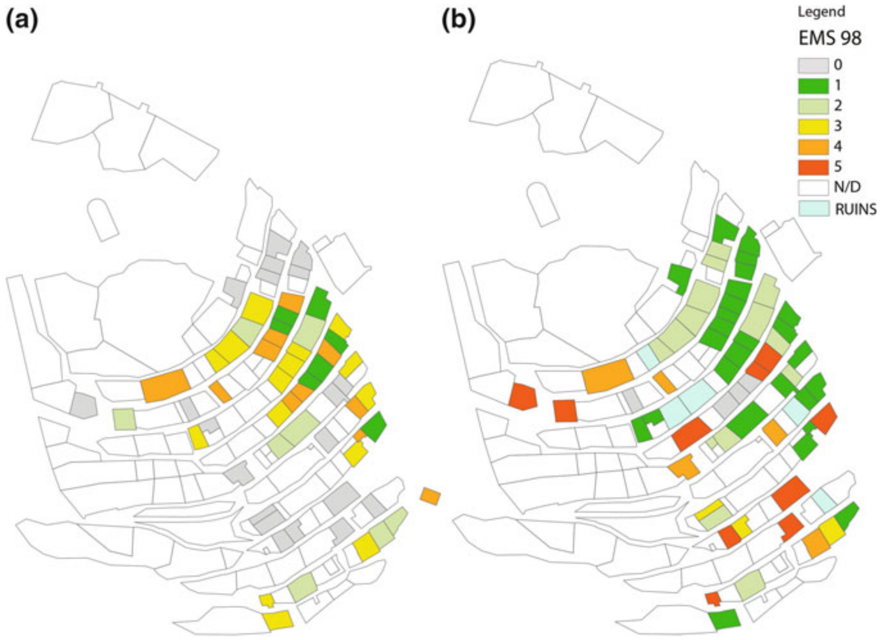


**Fig. 9** Campi Alto di Norcia, comparison between EMS 98 damage level distributions after 1979 **a** [19] and 2016 **b** earthquakes in retrofitted buildings

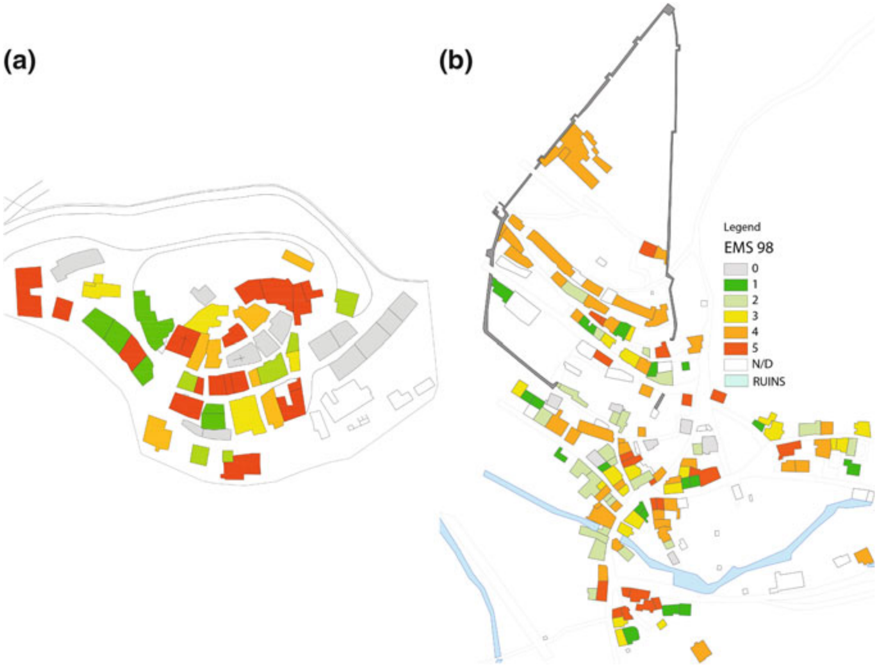


**Fig. 10** EMS 98 damage level distributions in **a** Castelluccio di Norcia and **b** Castelsantangelo sul Nera after 2016 earthquakes

**Table 3** Proposed values to be used in AeDES damage index evaluations

| Structural component | Damage score | Weight |
|---|---|---|
| Vertical bearing structures | 0–9 | 1.00 |
| Floors | 0–9 | 0.85 |
| Stairs | 0–9 | 0.50 |
| Roofs | 0–9 | 0.65 |
| Internal nonstructural partitions | 0–9 | 0.50 |

Also in Castelluccio di Norcia and Castelsantangelo sul Nera, for which no information about damage states after previous earthquakes is available, a certain shift towards higher EMS 98 damage states (D4-D5 compared to D2-D3) can be observed (Fig. 10). This trend may be an effect of the high number of partial ‘mode 1’ failures caused by interventions (mainly installations of r.c. ring beams and floors).

Lastly, a comparison between actual damage states and existing vulnerability assessment procedures (GNDT II level and AeDES forms) has been proposed. To this aim, the AeDES damage module assessment (Fig. 4) has been transformed into a normalized index (Id) with assigned scores of 9 for the worst damage state and 0 for ‘no damage’, and calculation of the weighted average according to the values listed in Table 3.

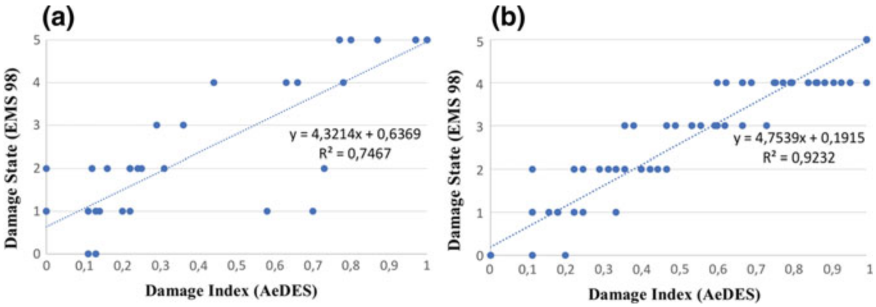


**Fig. 11** Distribution of EMS 98 damage states in 2016: Campi Alto di Norcia (**a**) and Castelsantangelo sul Nera (**b**)

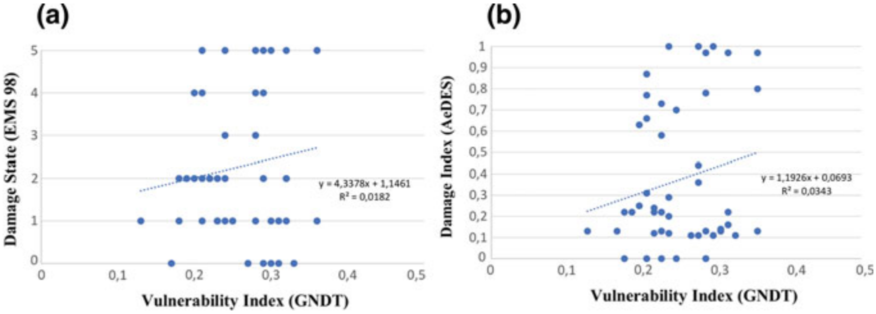


**Fig. 12** Campi Alto di Norcia, correlation between vulnerability index (GNDT II level method) and EMS 98 damage state (**a**) and AeDES damage index (**b**), both showing very little correlation. Iv scale is limited to 0.5, to distinguish among points (max Iv = 1)

Comparisons among the resulting Id to damage states according to EMS 98 show a significant correlation between indexes (Fig. 11). Instead, when Id is compared with a vulnerability estimator such as the GNDT index (Iv), almost no correlation is found (Fig. 12): that is, vulnerability factors identified by the procedure were either wrongly judged or ill-defined, again presumably because of structural interventions.

## 4 Conclusions

The latest earthquakes in Italy in 2016 confirm the essential role played by masonry quality and connections among components for proper functioning of improvement techniques commonly proposed to strengthen horizontal structural components. This aspect is particularly important when heavy retrofitting interventions (substitution of floors and roof, or strengthening of vaults with r.c.-based slabs) are applied to existing multi-leaf masonry structures with few or no inner and/or outer connections.

It is well known that these techniques, widely used in the past after previous earthquakes, greatly influence the seismic behavior of masonry buildings. In particular, with reference to the three city centers analyzed here, research showed that retrofitted buildings suffered severe damage or even collapse. According to EMS 98 damage classification (D3: ‘average’ and D4-D5 ‘high’ damage states), Castelsantangelo sul Nera, Castelluccio di Norcia and Campi Alto di Norcia, showed the following percentages of damaged buildings: 45, 41 and 10% of buildings in D4-D5 and 15, 12 and 4% of buildings in D3.

In addition, building alterations after such large-scale interventions also affected the ‘representativeness’ of vulnerability assessment methods. The application of common expeditious and simplified procedures (GNDT II level and AeDES forms) to the three city centers repeatedly struck by earthquakes over the past 40 years, with subsequent retrofitting measures, showed high scatter of the vulnerability judgments with respect to the actual damage observed.

Further research will focus on developing calibrated procedures for vulnerability assessment, based on the observations of the effects of intervention techniques on masonry buildings in other historical city centers in the area.

**Acknowledgements** Authors would like to thank D. Darù and M. Vettore for their contribution to on-site surveys. The research is framed within the DPC/ReLUIS 2014–2018 Italian project.

## References

1. Baggio C, Bernardini A, Colozza R (2000) Manuale per la compilazione della scheda di primo livello di rilevamento danno, pronto intervento e agibilità per edifici ordinari nell’emergenza post-sismica (AeDES). Servizio Sismico Nazionale-Gruppo Nazionale per la Difesa dai Terremoti, Roma (in Italian)
2. Benedetti D, Petrini L (1984) Sulla vulnerabilità degli edifici in muratura: proposta di un metodo di Valutazione. L’industria delle costruzioni 19(1):66–74 (in Italian)
3. Binda L, Cardani G, Saisi A, Valluzzi MR (2006) Vulnerability analysis of the historical buildings in seismic area by a multilevel approach. Asian J Civ Eng (Building and Housing), 7(4):343–357
4. Binda L, Cardani G, Saisi A, Valluzzi MR, Munari M, Modena C (2007) Multilevel approach to the vulnerability analysis of historic buildings in seismic areas—Part 1: detection of parameters for the vulnerability analysis through on site and laboratory investigations. Int. J Restor Build Monuments, 13(6):413–426
5. Binda L, Gambarotta L, Lagomarsino S, Modena C (1999) A multilevel approach to the damage assessment and seismic improvement of masonry buildings in Italy. In: Bernardini A (ed) Seismic damage to masonry buildings. Balkema, Rotterdam
6. Binda L, Saisi A (2005) Research on historic structures in seismic areas in Italy. Prog Struct Mat Eng 7:71–85
7. Borri A, Corradi M, Castori G, De Maria A (2015) A method for the analysis and classifica-tion of historic masonry. Bull Earthq Eng 13:1–19

8. Cardani G (2003) La vulnerabilità sismica dei centri storici: il caso di Campi Alto di Norcia. Linee guida per la diagnosi finalizzata alla scelta delle tecniche di intervento per la prevenzione dei danni. Ph.D. Thesis, Politecnico di Milano, Milano, Italy (in Italian)
9. Cifani G, Lemme A, Miozzi C, Russo G (1997) Aspetti metodologici. In: Repertorio dei meccanismi di danno, delle tecniche di intervento e dei relativi costi negli edifici in muratura sisma Marche 1997, Decreto del commissario delegato per gli interventi di protezione civile n. 28 del 10 aprile 2002, pp 233–268 (in Italian)
10. DPCM (2011) Approvazione del modello per il rilevamento dei danni, pronto intervento e agibilità per edifici ordinari nell'emergenza postsismica e del relativo manuale di compilazione. Gazzetta Ufficiale della Repubblica Italiana n. 113 del 17 maggio 2011 (Supplemento ordinario n. 123) (in Italian)
11. Ferrini M, Melozzi A, Pagliazzi A, Scarparolo S (2003) Rilevamento della vulnerabilità sismica degli edifici in muratura. Manuale per la compilazione della Scheda GDNT/CNR di II livello, Regione Toscana, http://www.regione.toscana.it/documents/10180/12262198/vsm_man.pdf/095d3648-191d-43aa-ae88-ad78cff79fb3. Last access June 2018. (in Italian)
12. Giuffrè A (1991) Letture sulla meccanica delle murature storiche. Kappa (ed) (in Italian)
13. GNDT-SSN (1994) Scheda di esposizione e vulnerabilità e di rilevamento danni di primo livello e secondo livello (muratura e cemento armato). Gruppo Nazionale per la Difesa dai Terremoti - Servizio Sismico Nazionale, Roma (in Italian)
14. Grunthal G. (1998) European Macrosismic Scale 1998. Conseil de l' Europe, Cahiers du Centre Europeen de Geodynamique et de Seismologie, vol 15, Luxemburg
15. INGV http://www.ingv.it/it/. Last access June 2018
16. Modena C, Valluzzi MR, da Porto F, Casarin F (2011) Structural aspects of the conservation of historic masonry constructions in seismic areas: remedial measures and emergency actions. Int. J Architect Heritage 5(4–5):539–558. https://doi.org/10.1080/15583058.2011.569632
17. NTC (2008) Approvazione delle nuove norme tecniche per le costruzioni, Gazzetta Ufficiale della Repubblica Italiana, n. 29 del 4 febbraio 2008 (Supplemento ordinario n. 30) (in Italian)
18. Pinto AV, Taucer F (2007) Field Manual for post-earthquake damage and safety assessment and short-term countermeasures (AeDES), in JRC scientific and technical reports. Ispra, IT
19. Sbrogiò L, Cardani G, Valluzzi MR (2018) Damage survey of a historic town and comparison with past events after the 2016 central Italy earthquake. In: Proceeding of ECEE 16th European conference on earthquake engineering, Thessaloniki (Greece), 18–21 June 2018 (12 pp)
20. Valluzzi MR (2007) On the vulnerability of historical masonry structures: analysis and mitigation. Mater Struct 40:723–743. https://doi.org/10.1617/s11527-006-9188-7
21. Valluzzi MR (2016) Challenges and perspectives for the protection of masonry structures in historic centers: the role of innovative materials and techniques. Rilem Tech Lett 1:45–49. https://doi.org/10.21809/rilemtechlett.2016.10