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DAMAGE SURVEY OF A HISTORIC TOWN AND COMPARISON WITH PAST EVENTS AFTER THE 2016 CENTRAL ITALY EARTHQUAKE

Luca SBROGIO'[1], Giuliana CARDANI[2],Maria Rosa VALLUZZI[3]

ABSTRACT

Central Italy is an active seismic area and many earthquakes struck the historic centre of Campi Alto di Norcia (Perugia) since its foundation in the 13th Cent. Nevertheless, every time, Campi has been restored without losing its identity, until the shocks occurred in 2016 caused the definitive collapse of a large part of it.

Residential buildings have been restored introducing modern techniques and materials, as injections, jacketing and substitution of structural parts, which showed, already in the 1997 Umbria-Marche earthquake, their inefficiency and incompatibility with historic masonry. Therefore, today we can observe again the effects of the recent interventions and evaluate them on large scale. A first damage evolution is here reported, by mapping the damage levels to evaluate the causes of such a severe scenario.

Surveys and studies after the 1997 earthquake provided the first correlation between structural interventions and damage, but major efforts were put in the definition of collapse mechanisms and in tools which could apply the new approach. Other earthquakes (L'Aquila 2009, Emilia 2012) confirmed the aetiology of certain seismic damages to specific interventions, but only qualitative relations were established. In addition, a description of seismic effects interpreted also as a result of specific interventions is still missing, especially on quantitative basis.

The paper presents a systematic damage survey supported by a GIS system and a specific form, both aimed at defining, if possible, a relation between the damage on each intervention and the damage of a building as a whole.

Keywords: Historic Center; Stone Masonry; Strengthening; Vulnerability; Damage

1. INTRODUCTION

The mountains straddling the Umbria-Marche border, in between Spoleto (PG) and Ascoli Piceno are one of the most seismic areas in Italy, prone to a number of major earthquakes (6-7 ML), which happen about 50 years apart. In particular, the Nera valley and its tributaries (Valnerina), placed just a little northern than Norcia, has been highly active in the last 40 years: great shocks happened in 1979 (5.9 M Valnerina), in 1997 (5.8 M Colfiorito) and in 2016 on October 30th (6.5 M Valnerina), along with a myriad of lesser events (shown in (1), updated to 2015).

The Colfiorito earthquake allowed the Politecnico di Milan and the University of Padua to undertake a thorough investigation on the seismic behavior of historic masonry building already strengthened after the previous seismic event in 1979. Researches focused on four small towns whose buildings belonged to the three main types commonly recognized: isolated buildings (Montesanto), terraced houses (Campi), complex buildings (Castelluccio, Roccanolfi).

The 2016 event may be considered comparable to 1979 quakes, beacause of the proximity of their epicenters, both within 4 km from Campi, while the Colfiorito earthquake happened about 25 km northern (see Table 1). Therefore, among the four towns above mentioned, Campi Alto, a hamlet

[1]Ph.D. Candidate, Dept. of Cultural Heritage, University of Padua, Padua, IT luca.sbrogio@dicea.unipd.it

[2]Assistant Professor, Dept. of Civil and Environmental Engineering, Politecnico di Milano, Milan, IT, giuliana.cardani@polimi.it

[3]Associate Professor, Dept. of Cultural Heritage, University of Padua, Padua, IT mariarosa.valluzzi@unipd.it

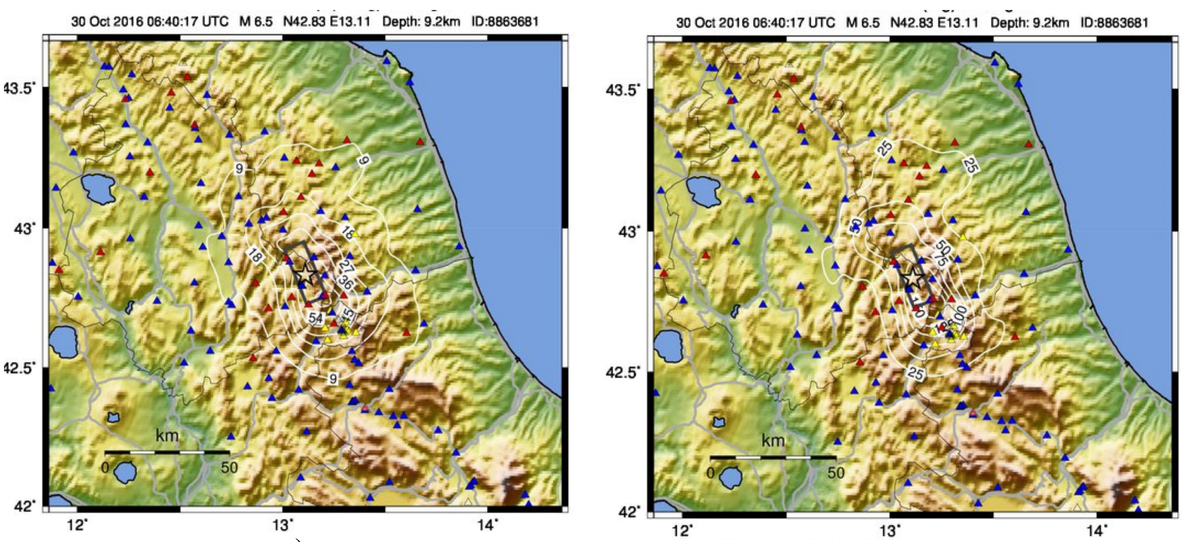
depending on Norcia (PG), appears to be a very interesting case-study.

Table 1. Historical seismicity registered in Campi, updated to 2015 (1).

Effects	On the occasion of the earthquake of							
Int.	**Year**	**M**	**D**	**H**	**Epicentre area**	**NMDP** *Num. of punctual data of available intensity*	**Io** *Epicentral Intensity* (MCS)	**Mw**
8-9	1703	01	14	18	Valnerina	197	11	6.92
9	1730	05	12	05	Valnerina	115	9	6.04
8-9	1859	08	22		Valnerina	20	8-9	5.73
7	1979	09	19	21	Valnerina	694	8-9	5.83
6	1997	09	26	09	Valnerina	869	8-9	5.97

1.1 The Valnerina earthquake of October 30, 2016

Recent damages in Campi, as well as many other towns, may be considered as the result of a series of events begun already in August in Amatrice (RI, ML 6) and then slowly migrating northward, with a peak of ML 5.9 in October 26th centered in Visso, just 10 km away from Campi. The proximity of the two events (26th and 30th) did not allowed to lay down buttressing and other provisional structures on buildings, which could have helped to prevent collapses especially in the most vulnerable buildings.
This earthquake has been the strongest in Italy since 1980 (Irpinia), with a registered PGA in the surroundings of the epicenter (Norcia, Preci) ranging between 0,55-0,65g (Figure 1a) (3). Unfortunately, data from the two seismographs placed in Campi area are not available, since they were probably too close to the epicenter.
Pseudo-spectral acceleration, evaluated for T=0.3 s (typical of ordinary structures) with a behavior factor q=1, reached 0,73g and even 1,89g (Figure1b) in the abovementioned stations. These values are not far from the elastic spectral acceleration provided by Italian seismic code (4), although they are closer to ultimate limit state (collapse) rather than the life safety one. It is known that coded spectra underestimate the real event in the neighborhood of the epicenter, but, being the effect of a required generalization, this is not considered as a deficiency (Luzi et al. 2017). Therefore, spectral response given by the code will be used in evaluations.



a) b)

Figure 1. 30/10/2016 earthquake: a) PGA (in % g); b) PSA in % g for T=0.3 s.
The star highlights epicenter (3)

1.2 Campi di Norcia: townscape and building types

Campi Alto is a fortified village set up between 1275 and 1288 along a hillside at 800 m above sea level (Figure 2a, b), in order to control the rich valley beneath and the roads around Norcia (Cardani 2003). The urban layout reminds other villages thereabout, as Visso, Castelsantangelo sul Nera and Pissignano: the space within the boundary wall is left free, except for a tower and a church, in the upper part, while the lower half is occupied by the residential buildings (Figure2c).
Campi Alto lies on the two sides of a limestone outcrop (Cardani 2003) with a high slope (around 80%), forcing houses in long rows parallel to the contour lines, separated one from each other by longitudinal alleys and linked by transversal stairways.
Typology is quite uniform. It consists of a three-storey building, where (i) the stable on the ground floor is accessible only from the front alley; (ii) the first floor is residential and it can be reached only from the (iii) second floor, residential as well, accessible from the upper back alley. Ground floors only show stone masonry barrel vaults perpendicular to the contour lines. Between the vault and the façade a gap is specially left to preserve the vault in case of facade overturning. In fact, many facades are rebuilt, showing the changes in architectural styles over the centuries and they are not interlocked to the rest of the building (Cardani 2003).
Also the churches within the town boundary walls fit ground morphology. Two of them stand at the ground floor of some row buildings, in the place where usually stables lie


a)


b)

c)

Figure 2. a) Campi di Norcia; b) the valley from Campi; c) plan of the village at current state (Cardani 2003)

1.3 Campi di Norcia: earthquakes and repairing interventions

Compared to Norcia, which was completely rebuilt after the1859 earthquake according to on-purpose dispositions and rules, Campi shows, as well as many other villages nearby, clear traces of several past earthquakes. Their buildings show various strengthening solutions, which may be considered as a part of traditional techniques: iron and wood ties, buttresses, spurs, new masonry linings. As the dates shown by these elements testify, they have been able to preserve buildings along the centuries.
Nevertheless, in the '70s and '80s, those traditional repairing systems have been abandoned, following the new standards requirements and pursuing the performances of modern buildings (Penazzi e al. 2000, Binda et al. 2004, Borri 2015).
In 1980 the Umbria region made a recovery plan mandatory for each historic centre hit by the earthquake the year before. This plan brought, among the others, the division of buildings, especially complex ones, into minimal intervention units (called U.M.I.), where to apply homogenous interventions. In addition, the plan provided criteria for structural strengthening and restoration. The

recovery plan of Campi was made by the architect F.M. Poggiolini in 1982, who suggested to remove all the changes made mostly in the early ‘70s, in order to preserve the character and the structure of original buildings, and to avoid heavy structural strengthening and substitution of full parts (Cardani 2003). Those intelligent guidelines were systematically ignored and the typical intervention consisted in: (i) substitution of wooden floors and roofs with modern clay-concrete structures; (ii) strengthening of masonry vaults; (iii) realization of r.c. tie beams at every storey; (iv) cement based grout injections or iron mesh jacketing, also in non-cracked masonry walls.

2. SEISMIC DAMAGE AND INTERVENTIONS

2.1 Good building practice, improvement and retrofitting interventions

In historical masonry buildings it is well known that the box-like behaviour cannot be easily reached, due to the addition of volumes during centuries, as well as the low quality of some materials and the lack of proper connections. All these factors bring to the development of the so-called macro-elements behaviour, as described in (Giuffrè 1993).
In the current Italian seismic code, different approaches to structural strengthening interventions exists; they can refer to ‘improvement’ (strengthening) or ‘upgrading’ (retrofitting) . The upgrading approach dates back to the ‘70s and aims at achieving a safety level comparable to new buildings, that can be significantly different from the original one (5). The latter, more recent, aims at increasing the structural performance of existing buildings to the actions estimated by the code, but without reaching a level as required for new constructions (4). Since they both aim at enhancing the building overall behaviour, the difference is quantifiable in terms of added loads to the existing structures, variations of introduced stiffness, materials discontinuities and of the gradient with which these variations occur.
The upgrading interventions attempt to bring the building to an ideal state or even to a new construction, by forcing its behaviour with significant (and often heavy) changes in stiffness and masses; it can force a building to follow structural schemes which are different and far away from the original or current configurations. (Binda et al. 2007, Cardani et al. 2007, Borri 2015). The improvement concept, instead ,admits that an optimal homogenous situation may never have existed and works on local connections (mainly inspired by traditional techniques) and limited (i.e., light) increases in stiffness and loads (6), thus excluding compromising solutions (e.g. concrete slabs on poor masonry walls) that lead to unpredictable structural behaviours.
In addition, upgrading interventions seem less suitable for preservation, especially in the case of 'minor' architecture (not listed) and in historical towns, where the cultural identity concerns not only the external image but also their fabric and the heritage of traditional techniques (Cardani 2017). However, all those buildings that were repaired or reinforced from ‘70s to the mid-2000s, are definitely easily prone to serious damage in case of future earthquakes, a damage which may be called ‘damage from legislation’ (Borri 2015), particularly in areas where poor quality stone masonry constructions are present, like the seismic area in Central Italy.

2.2 Repairing of seismic damage

Structural interventions on historic buildings can be classified in three main categories, according to their purpose: (i) improvement of horizontal floor connections and thus global behaviour; (ii) stiffening of floors in order to get better redistribution of seismic actions; (iii) reinforcement of masonry structures in order to improve their mechanical strength. This paper refers only to significant alterations where reinforced concrete in floors, roofs and vaults and demolitions or changes in masonry cross-sections are used (Figure3), as described in (Pasta 1999).

2.3 Seismic damage due to past interventions

The seismic event of 1997 already highlighted that retrofitting interventions (‘upgrading’) were not able to guarantee the expected structural safety, but, on the contrary, caused even more damages, mainly the out-of-plane rotation of the walls, which they were intended to inhibit.
Assessment methods (VET, POR) in use at that time proved their substantial inability to represent

correctly a building behaviour and new criteria based on macro-elements identification and evaluation of activation levels of associated kinematisms (Modena et al. 2006) were proposed.

a) b) c) d)

Figure 3. Examples of 'heavy' interventions on simple historic masonry buildings: a) r.c. tie beams; b) r.c. vaults jacketing; c) grout injections; d) r.c. wall jacketing (Cardani 2003)

Thanks to the codification of all observations, a matrix of damage mechanisms for row and complex buildings was proposed, showing also mechanisms induced by modern interventions, which were mostly out-of-plane collapses (Cardani 2003).

Experience has shown that this kind of damages can be due to (Penazzi 2000): (i) poor materials used in interventions and even poorer technical details and/or implementation; (ii) unexpected behavior in comparison with the design specifications; (iii) irregular behaviors at the interface between original and strengthened parts. Reinforced parts can damage themselves or cause damage in other unreinforced parts that are simply in contact with them. In the following, these damages are described in detail.

2.3.1 Damages due to interventions on horizontal floor connections

The most frequent damages that might be caused by interventions on horizontal components are: (i) horizontal cracks in walls, where r. c. tie beams are inserted in walls (Figure 4a); (ii) tilt or overturning of corners (Figure 4b); (iii) damages in walls ('half-moon collapse') due to the 'beam effect', which leaves the masonry under tie beams almost unloaded (Figure 4c); (iv) the overturning of the entire wall (Figure 4d). R. c. tie-beams can also break due to poor rebar junctions, insufficient stirrups, worn materials or flexural failure if the supporting role of the wall beneath fails during the quake. Furthermore, local damages can be caused by added r. c. lintels in poor masonry (Figure 6a).

a) b) c) d)

Figure 4. Damages induced by r.c. tie beams above poor masonry: a) horizontal crack at floors level, b) overturning of building corners; c) half-moon shaped overturning; d) overturning of entire walls

2.3.2 Damages of interventions on flooring and roofing systems

R. c. tie beams generally go along with r. c. floor slabs and other heavy interventions. Floors and roofs made of precast concrete or steel beams and clay boards are heavy but flexible and, in case of precast

beams, fragile to shear forces (Figure 5a). This kind of floor suffers for bricks and/or beams disjointing and shear failure at supports, adding their noticeable weight to the collapse. Concrete floors with hollow brick blocks are sometimes subjected to collapses for lack of supporting walls (Figure 5b) but more often they induce collapse in walls below due to irregular distribution of loads and hammering (Figure 5c). Vaults suffer the detachment of the r. c. coating from the masonry or mechanisms caused by thickness reduction due to infill removal.
As a general rule, due to the weight of the modern structural interventions, the more harmful they are, the higher their position is: a heavy r. c. roof can cause the complete collapse of the building under its weight, without being particularly damaged by itself (Figure 5d).

a) b) c) d)

Figure 5. Damages in r.c. roofs and floor slabs: a) shear failure in precast r.c. beams; b), c) damage of floors and roofs due to the failure in supporting walls; d) rigid collapse of the roof

2.3.3 Damages due to interventions on masonry walls

Grout injections very likely suffer of poor design and even poorer execution (e.g., a too large grid, no preliminary cleaning of wall interior or injectability assessment, application only to some masonry panels or storeys). As a result, the walls disaggregated, due to local stiffness variations, and cracks or local collapses appeared at the interfaces with walls still in original conditions (Figure 6a), generally at different storeys (Figure 6b). When new masonry is superimposed on the old one, usually all the damage concentrates on the latter (Figure 6c). Rubble stone veneers on new masonry does not behave well either: in total absence of transversal connections between the two leaves, the veneer detaches (Figure 6d). R. c. jacketing, due to a more complex construction procedure, is even more hazardous. Usually, transverse connections between iron meshes on either sides of a wall are scant, or, even worse, the coating lays on one side only (Penazzi et al. 2000): in this case, the reinforcement leaves are stripped off from the wall. Variations on this behavior depend whether the mesh is put too close to the surface (delamination) or it has a good anchorage with the wall first layer, which may come off with the jacket (Figure 6e). Repointing seems to cause lesser damage in buildings, probably thanks to its slighter alteration of masonry mechanical properties.

a) b) c) d) e)

Figure 6. Damages due to irregular interventions on masonry walls: a) damages in lintels and frames due to concentration of action in less rigid parts of wall; b) detachment of external leaf in irregularly reinforced masonry at different storeys; c) effect of new masonry superimposed to an old one; d) detachment and collapse of external leaf in composed walls; e) delamination of iron mesh in r.c. jacketing.

3. DAMAGE SURVEY AFTER 2016 EARTHQUAKE

The research campaign performed in 2002-03 provided many information about geometry, damages, structural interventions and functional internal changes occurred to the 59 buildings of Campi, since the recovery plan of 1982. Vulnerability analysis were performed according to (7).
However, previously to any new on-site survey, a complete reordering was needed to find any inadvertent lack of information and to re-align available data to the so called 'knowledge process', as defined by (7). To do so, while keeping the identification system suggested by Poggiolini, who already divided the rows in U.M.I. (groups of buildings units, as in section 1.3) and U.I. (single building units), the whole story of damage and intervention in the last 40 years has been laid down in a GIS system. Therefore, comparisons between old and new data are made simpler by having them in the same format, with the chance of querying only one database.
However, gathering data about earlier phases was not such an easy task, due to the lack of written documents. The list of properties attached to the land registry created in 1820-1835 is the only one, which briefly describes at that date the appearance and the use of buildings. In fact, it is hardly possible to state a precise date only from architectural parts, due to loans of parts among buildings after every earthquake, especially of carved stones (Cardani 2003).

Figure 7. Aerial view of Campi after 2016 earthquake (8)

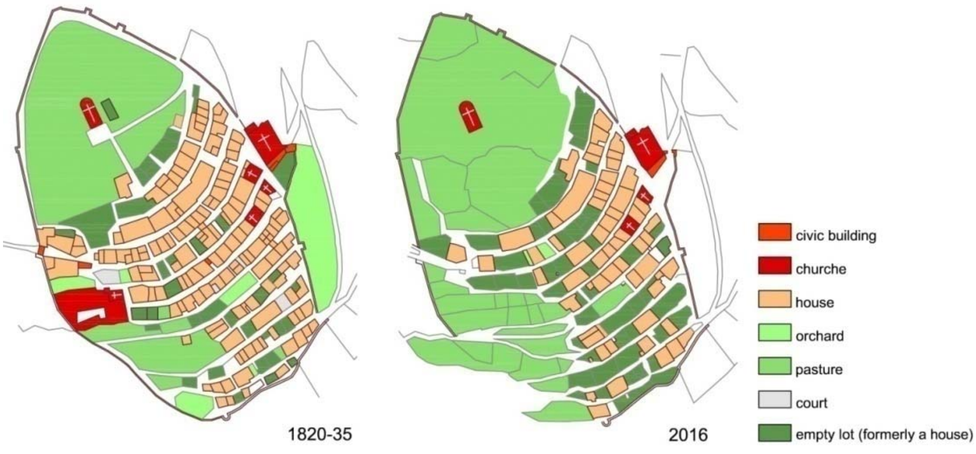


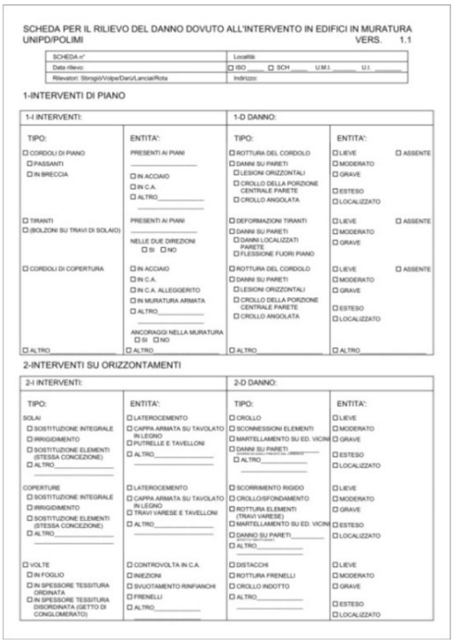
Figure 8. Town plan: comparison between early XIX cent. (1835) and current conditions.
Three important earthquakes (1859, 1979, 1997) occurred in between.

A synthetic view of Campi nowadays is shown in Figure 7. The village has suffered most damages in its public buildings (3 out of 4 churches still existing inside walls perimeter collapsed, the tower heavy damaged, the only surviving gate collapsed under the ruins of S. Andrea) and in the road system. Most of the damaged buildings are located in the lower and Western part of the town, a trend which is

confirmed by the comparison between 1835 and 2016 (previous to the earthquake) plans: the number of empty lots progressively increases as ruined houses are not rebuilt anymore (Figure 8).
With such a great deal of work already at disposal, only on-site new damage survey was left, along with a general check of buildings state of maintenance and any new intervention done after the original campaign. As in 2002-03 campaign, the surveys were carried out in cooperation between the Politecnico di Milano and the University of Padua.
However, the peculiar situation of Campi required specific tools to help the on-site surveys, especially to identify and grade the number of modifications every building has suffered in the last 40 years till today and how those have changed their behavior.

3.1 On-site survey form: damage due to structural interventions'

The proposed form is divided into three parts, corresponding to the intervention categories and subsequent damage already described in section 2.3. Each logical part is split into two, one focused on intervention and the other on damages, with two subsections, to describe what is visible and to collect information about their entity (Figure 9).
Interventions are grouped in the first column according to aims and techniques, which may vary according to the building part which they are applied to (e.g., interventions on floors), or to the single strengthening procedure (e.g. on walls) but aiming at the same objective. The second column gathers basic information about materials, consistency and distribution of interventions within a building, which is crucial to understand the amount of added loads and to evaluate their effectiveness. Choices are only allowed between these two columns, thus guiding the surveyor through the form, for an easy collection of data just after a few hours of training.



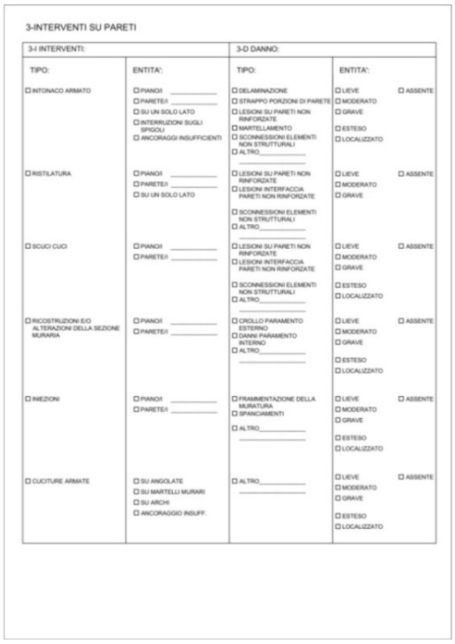


Figure 9. Inspection form for on-site survey of damage due to interventions proposed by the A. (first version)

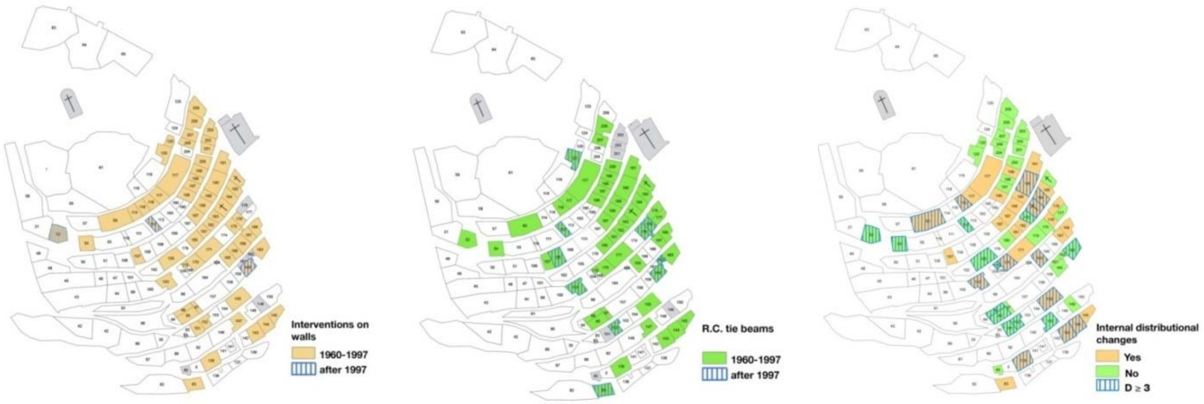
3.1.1 Definition of seismic damage

Thanks to previous experience, a selection of possible damages is already linked to each intervention: they are described as mechanism both on new elements (e. g. cracks or failure in tie beams or floorings) or induced by them on other parts of the building (e.g. cracks and collapses in walls caused by tie beams, detachment due to r. c. wall jacketing, etc.). Seismic damage in the whole building is kept separate.
In the first version of the form, also used in surveys made in Campi, damages were graded from 1 to 3 (slight, moderate, heavy), and the number of elements involved provided further details. When it came

to data analysis, however, it was clear that the two information (consistency and amplitude) had to be combined to simplified procedures. Therefore, the rescaling of damage from 1 to 5 provided a more direct relation with the damage of the whole building expressed according to EMS98 macroseismic scale (Grunthal 1998).

3.2 Data analysis

GIS querying showed that houses with oldest (early ‘80s or even before) or without interventions, are located in the village lower western part, thus explaining their heavy damage. It cannot be excluded that there was some focus effect on seismic action on this side of the rock bank, since this phenomenon is confirmed over the centuries (Cardani 2003). Queries also showed that only one building has never undergone interventions (UMI 2-UI 85) which is completely collapsed on 2016 October 30th. Thanks to the substantial uniformity in architectural type, the internal layout, the materials and techniques used for restoration since 1979, the whole set of buildings can be considered to belong to the same vulnerability class (Munari 2010). The distribution of the most substantial changes is given in Figure 10.
With reference to changes in the internal layout of houses (e.g., shift in internal partitions, integrations of new stairs, insertion of new walls), Figure 10c shows that there is no meaningful relationship between them and remarkable damage, being equally distributed among the houses.
It is also clear that most interventions were made just after the 1997 earthquake, being documented by the 2002-03 campaign; only a few are more recent but they have been recognized only on-site and not by project documentations, since they are still unavailable. Some building appears as an abandoned construction.



a) b) c)

Figure 10. Distribution of heavy structural and architectural modification in Campi di Norcia (grey means no change): a) strengthening of walls with modern techniques; b) introduction of r.c. tie beams; c) layout and other functional changes compared with 2016 estimated damage D ≥3

Out of 59 buildings (i.e., terraces houses and the two churches inserted at the ground floor of two of them): 13 collapsed (D=5), 4 show major structural damage, 3 are damaged and 13 are slightly damaged (D=2) (Figure 11).

3.3 Comparison with previous analysis

After 1997 earthquake, new procedures for evaluation of seismic vulnerability, i.e. damage susceptibility of groups of buildings, from single aggregates up to entire historic towns, based on macro-element approach have been developed (Munari 2009, Valluzzi 2009). Some of them preserved their original shape, such as GNDT form (7); at the University of Padua some others (e.g., VULNUS VB and C-sisma) were implemented into softwares to speed up calculations. Both procedures, Vulnus VB and GNDT form are here discussed by comparing their results, which have already been calibrated in previous occasions, with the real observed behavior.

The GNDT form assigns points to a set of factors recognized as factors of vulnerability: the higher is the score, the poorer is the building state. Vulnerability is then expressed by a normalized index in the range 0-1. Vulnus VB estimates the seismic coefficient "c", i.e. the multiplier of seismic masses in limit equilibrium conditions, by identifying the most brittle one among nine failure mechanisms and then combines it with a conventional shear resistance and an index extracted from the GNDT form. The result is a brief verbal judgment of vulnerability ranging from 'very low' to 'very high'.

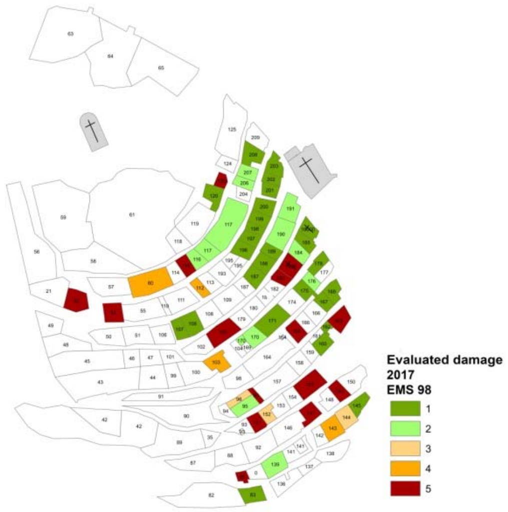
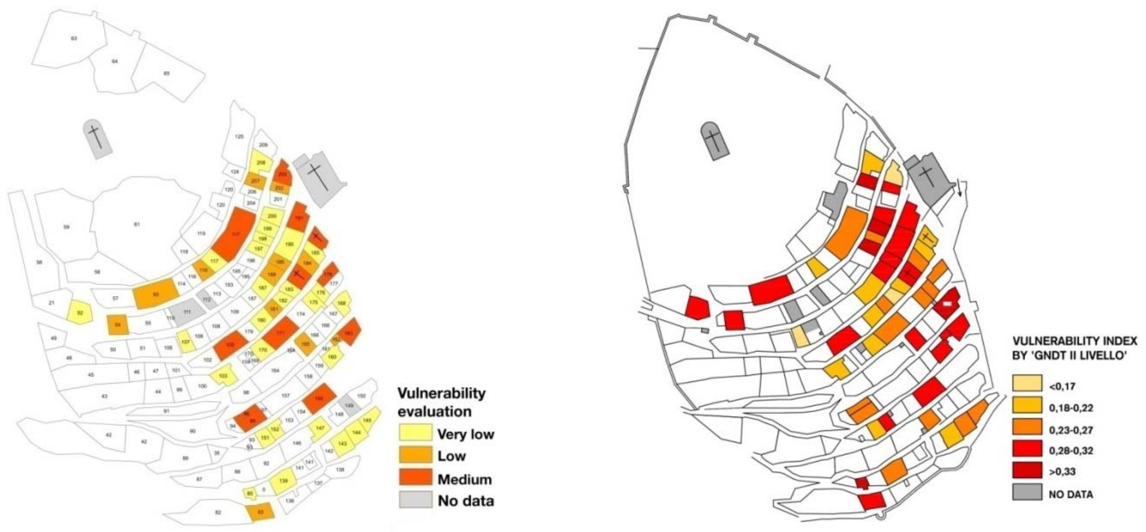


Figure 11. Observed damage in Campi di Norcia after 2016 earthquakes to be compared with Figure 12

GNDT form was used on site, while predictive analyses in Vulnus were made in relation with: (i) response spectrum provided by the new (at that time) technical standards with q=2,25; (ii) a unique value of acceleration correspondent to the macroseismic effects of the 1730 earthquakes, which was one of the most devastating in that region. The former amounts to a/g=0,32, the latter to a/g=0,191 (Munari 2010) and this one highlights behavioral differences better than the higher one, which instead provokes a shift towards the 'high vulnerability' class (Figure 12a). Figure 12b shows values given by the GNDT form, regardless of their usage in Vulnus.



a) b)

Figure 12. Vulnerability distribution: a) according to Vulnus VB procedure for a/g=0,191 (Munari 2010); b) according to GNDT vulnerability form

The comparison between on-site damage (Figure 11) and predictions (Figure 12) shows quite a number of differences. Vulnus and GNDT form both identify as highly vulnerable buildings which actually show slight or even no damage at all, such as those near S. Andrea church (Figure 7), except for the church inside the row which is collapsed (but which was evaluated as averagely vulnerable). In other situations, they may agree but sometimes not: the two isolated houses on the upper left part, which are totally ruined, are identified as almost not vulnerable by Vulnus and highly vulnerable by GNDT form (a glimpse of one of them is in Figure 5a).

4. CONCLUSIONS

Nowadays, the current Italian seismic code focuses more on the need to preserve the many values of historic towns, e.g. architectural, technological end environmental ones. Unfortunately, progressive loss of knowledge and practice in traditional materials, together with an unconditional trust in modern techniques, often led to a-critical applications of interventions altering a building original fabric and structural behavior, while leaving pleasant 'ancient' facades. This practice, even encouraged by past law in the field, added a whole set of new possible damage mechanisms sharing the same nature of the most dangerous one (i.e. tilt and overturning). However, none of them actually enters design procedures, mostly because their description is difficult and they are thought to be eliminated by the strengthening interventions.
The paper proposed a survey form focused on intervention description and effects, which allows further elaboration on recurrent observed damages and which was systematically adopted for the survey in Campi, as well as other villages struck by the 2016 earthquake. Its results enter a GIS system thanks to which information, coming from new and past researches, can be compared These first results, here elaborated on large scale thanks to GIS implementation, showed some inconsistencies between damage scenarios observed for the repaired buildings and predictive analyses carried out on the same buildings according to available procedures of overall seismic vulnerability. This confirms the high level of hybridism achieved by the buildings after retrofitting, and the consequent difficulty of modeling with simplified procedures. Further studies are still in need in this field, able to integrate data collectable on interventions, e.g., information concerning design, execution and effects.

5. ACKNOWLEDGMENTS

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