Effectiveness of seismic strengthening to repeated earthquakes in historic urban contexts: Norcia 2016

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Abstract

The seismic swarm that affected Central Italy between August 2016 and January 2017 involved several municipalities including the historic town of Norcia, seat of a medieval Benedictine complex.
Owing to the close vicinity to the Apennine ridge, Norcia has been exposed to several historic seismic events, which have influenced the promulgation of early seismic provisions for strengthening and retrofitting interventions.
Although the masonry buildings of Norcia, seemed to have withstood the August 2016 event, two further strong shocks in October 2016 caused collapses and widespread damage, challenging the effectiveness of the strengthening provisions implemented at urban scale over the past two centuries.
The purpose of the paper is to discuss the dynamics of the evolution of damage to the residential buildings within the city walls during the six-months seismic swarm. This is accomplished by comparing the damage state recorded by the Italian Civil Protection usability form (AEDES form) filled out after each event. These forms are very detailed, but they rely heavily on individual judgement for the attribution of damage levels, and may lack in consistency as they are completed by diverse groups of professionals. Hence AeDES outputs are compared with an empirical damage assessment conducted by means of omnidirectional (OD) imagery collected on site by the authors, focusing on crack patterns and mechanisms of collapse. This technology, which allows for 3d imagery of damaged buildings, is increasingly used to support post-earthquake reconnaissance work, as it provides an unbiased and holistic record of the state of damage.
The damage level attributed with these two techniques is then compared with the analytical vulnerability assessment method FaMIVE, which allows to correlate damage to collapse mechanisms and vulnerability. This approach allows to estimate the efficacy of historic and recent strengthening interventions, in terms of type of collapse mechanism and collapse load factor.
Results show that there is a good correspondence between AeDES and ODC assessments for low to medium damage grades. Discrepancies in higher damage grades are discussed in light of the different level of information that can be recorded by using the two tools.
The efficacy of strengthening is also well captured by the FaMIVE method. The procedure estimates an increase of about 25% of the total number of buildings failing out-of-plane (OOP) when restraining elements are not active.

Keywords

Cumulative Damage, Vulnerability Assessment, Strengthening Measures.

1. Introduction

The heritage town of Norcia, in the Umbria region, is strictly linked to the inclusions, on the tentative list for nomination as world heritage sites, of the “Cascata delle Marmore and Valnerina: Monastic sites and ancient hydrogeological reclamation works” (http://whc.unesco.org/en/tentativelists/2031/) and of “The cultural landscape of the Benedictine settlements in medieval Italy” (https://whc.unesco.org/en/tentativelists/6107/). Historically Norcia has been a prominent cultural and economic urban center of Valnerina and the birth place in 480 of St. Benedict of Nursia, founder of the homonymous monastic system and the Rule (McCann, 1937). According to Fry (1981), after the establishment of the first monastery, which ruled upon the territory in political, economic and religious terms (Kennedy, 1999), similar institutions started spreading throughout Western Europe: monks became landowners, responsible for the welfare of the people living in the area of influence of the monastery, therefore influencing not only the growth of the Christian community but also the diffusion of culture at a wider scale.

The environmental and urban landscape of the Valnerina has also been deeply modelled and formed by its seismological activity (Galli & Galadini, 2000). Norcia has a long history of damaging and destructive earthquakes, which led to several instances of reconstruction and re-shaping of its urban fabric. The economic and political importance of the town, its links to the Papal State and the invaluable contribution towards the transmission of the literature of ancient Rome through the Middle Ages (Lehmann, 1953) became all key factors in the development of the town’s resilience against destructive natural events and its concurrent acquisition of heritage status and value.

The seismic swarm that hit Central Italy from August 24th 2016 to the 18th of January 2017, was severely disruptive in terms of damage to both historic residential buildings and architectural heritage assets. Of particular importance for the town of Norcia were the events of the 26th (M_W 4.5) and the 30th (M_W 6.5) October 2016 (Luzi et al., 2016). While damage caused by the 24th August 2016 event in the historic centre was limited to a minority of heritage structures and historic dwellings (D’Ayala et al., 2018), the October events caused the partial collapse of a number of churches and severe damage to many residential buildings (Castori et al, 2017).

In the aftermath of the August 2016 event, the Italian Civil Protection started a campaign of field damage and safety assessment for post-earthquake usability of ordinary buildings through AeDES forms (Agibilitá e Danno nell’Emergenza Sismica[1], Baggio et al., 2007). This activity was disrupted by the October 2016 events, causing new additional damage and need for re-assessment.

Notwithstanding the numerous studies on the seismic vulnerability of heritage buildings and historic urban centres (Vicente et al., (2014), Lagomarsino et al., (2010)), cumulative damage after multiple events over a short period of time has received so far limited attention (Mouyiannou, et al., 2014). This becomes even more important when the building stock undergoes repeated earthquakes without the opportunity to introduce temporary safety measures that can limit the detrimental effects of subsequent shocks. (Grimaz, 2010)

Recurring observations of damage in earthquake-prone countries worldwide has shown the lack of systematic critical approach towards assessing the effectiveness of strengthening to prevent damage and casualties, while also preserving the architectural value of heritage buildings (D’Ayala, 2014). Norcia represents a unique case to evaluate the effectiveness of

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[1] meaning in English: Building Operability and Damage in Post-Earthquake Emergency

historic and recent strengthening interventions implemented following the destructive seismic events that characterized its history. It also provides a unique opportunity to trace the changes in antiseismic provisions through the ages. Frequently, regulations developed locally were adopted at a wider geographical scale, leading over time towards the establishment of the Italian national seismic culture and its regulatory framework (Dolce, 2012).

While accounts of the performance of strengthened masonry buildings are available in literature (Spence, et al. 1997), a systematic study to investigate cumulative damage to historic urban fabric due to consecutive seismic events still represents a major knowledge gap. The data collection and analysis presented in this paper is the result of a field campaign conducted by the authors, supported by the award of the EEFIT (Earthquake Engineering Field Investigation Team) 2017 research grant scheme supported by the Institution of Structural Engineers, UK.

This paper presents in section 2 an overview of the evolution of Code and buildings regulations, which determined the implementation of seismic strengthening measures within the historic urban fabric of Norcia, alongside a chronology of destructive seismic events for the town. Section 3 focuses on the methodology used to analyse the cumulative damage resulting from the 2016 seismic sequence and to determine the role of strengthening measures to control and limit such damage, both in qualitative and quantitative terms. Section 4 presents a critical discussion of results obtained highlighting the evolution in seismic response at urban level.

2. Seismic events and changes in codes and regulations

Although the first urban settlement dates back to the Neolithic age, according to Galli & Galadini (2000), 'Nursia' was first permanently inhabited by the Sabins in the 5th century BC and bounded within the ancient walls after the Etruscan attempt of military invasion. Coeval to this period is the first urban plan of the town, which was designed according to two main roads oriented SW-NE and NW-SE (Reale, et al, 2004; Montanari, 2016).

Under the Lombard occupation during the 7th century AD, Norcia reached its most flourishing period (Sisiani & Camerieri, 2013), both in terms of economic and urban expansion, becoming one of the most important towns in the Duchy of Spoleto (Montanari, 2017). At the beginning of the 8th century Norcia's territory fell under the jurisdiction of the Papal State, lasting until 1860. On becoming the seat of the pontifical prefecture, the fortress 'La Castellina' and the church of Santa Maria Argentea were built (Ricci, 2002). According to Bianchi & Rossetti (2001), no significant change to the urban layout within the walls has occurred since, thus the town maintains its late-Medieval appearance, contributing greatly to its heritage status. However, detailed information concerning earthquake effects in Norcia and its surrounding areas, recorded since 1328 (Locati et al., 2016), indicate extensive repairs and reconstruction of buildings.

Figure 1 shows the chronological sequence of seismic events felt in Norcia since 1000 A.D onwards (Locati et al., 2016). Since the 1328 6.2 M_w earthquake with macroseismic intensity I_{MCS}= IX-X, the town experienced at least six further events of $I_{MCS} > 7$ (Pauselli et al., 2010), including the major sequence in 1703, consisting of three events with epicenters close to the shocks of the 2016 sequence. The death-rate for the 1703 sequence reached 81% (Davinson, 1912), and the town was razed to ground (Deschamps, et al. 1984, Guidoboni et al., 2000).

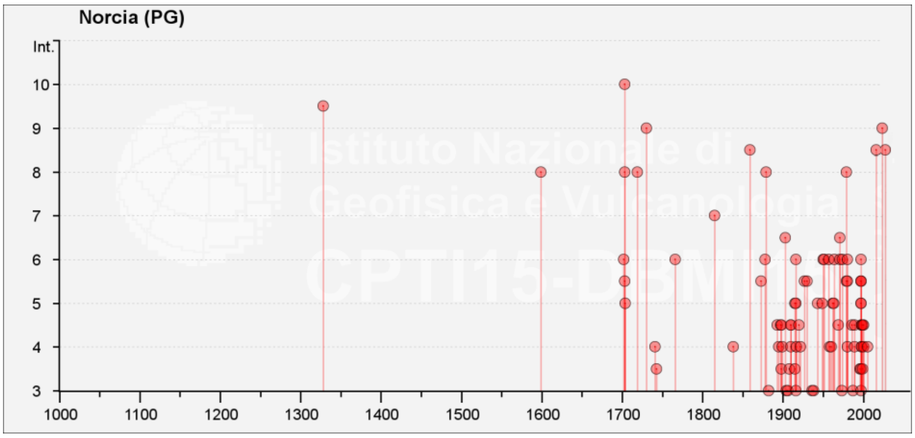


Figure 1: Historic Seismicity of Norcia measured in Microseismic Intensity MCS (Mercalli, Cancani Siebarg (INGV, 2018), adapted by authors to include 2016 events.

The town was largely rebuilt and after the 22nd August 1859 earthquake the first anti-seismic construction regulation for Norcia was developed. According to Reale et al. (2004), the event, with local intensity MCS VIII – IX, caused 101 deaths, the complete destruction of two neighbourhoods on the town east side and extensive damage to La Castellina, the City Hall building and several portions of the city walls. A *Committee* was nominated to evaluate the buildings' damage and to draft a manual of 'good' building practices to be used for the reconstruction phase. Preceded only by the Pombalino's Reforms after the 'Great Lisbon earthquake' in 1755, and the Instruction for the reconstruction of Reggio of the Bourbons Government after the 1784 earthquake (Brand & Hugh, 2013), Norcia's building regulation is among the early documents produced in response to a destructive natural event. This approach became common in the following decades in Italy, the most famous example being the Royal Decree n.193 for the reconstruction of Messina (Hobbs, 1909) which introduced the use of reinforced masonry for new constructions (Barrucci, 1990).

The damage assessment after the 1859 event was carried out through a simplified questionnaire. The buildings were assessed and classified according to five categories of damage (Reale et al. 2004), however the criteria and scale are not documented. The damage was mapped and integrated with the appraisals of the *Committee* (Archivio Storico Comunale di Norcia (ASCN), 1860a). About 80% of the buildings were assessed. According to Borri et al., (2017) the damage recorded was mainly due to excessive height of the buildings coupled with slenderness of external walls and presence of heavy vaults without appropriate restraints.

On the 24th of April 1860 the new Building Regulation was promulgated with a Royal Decree (ASCN, 1860). As reported by Clemente et al, (2015) and Borri et al., (2017), the document listed a series of prescriptions in relation to a broad range of geometric and structural aspects, for both new construction and repairs to existing buildings.

In relation to the former the minimum depth required for foundation plinths was 1.30 m and the maximum building height 8.5 m, corresponding to 2 floors with basement. The minimum wall thickness was set at 0.6 m, with addition of buttresses of 0.40 m minimum thickness. The vertical alignment of opening was compulsory and suggestions were given in relation to the minimum distance from the edge piers. Minimum dimensions of stones and quality of mortar were also prescribed. For vaulted structures, only allowed in basements, the minimum thickness was set at 0.25 m and, to contain the thrust, metal ties were to be included at spring level. Finally, the timber elements supporting the roofs were to be connected to the vertical walls with U-shape metal anchors to avoid sliding or punching actions against the facade. In the case of existing buildings with heavily damaged upper floors, it was recommended to demolish the upper portion. The emphasis and concern of the legislator was on safety rather than preservation of the historic and original construction features. Nonetheless the consistent compliance to these rules and the resulting homogeneity in appearance of the town became a strong element of its character and unique heritage value.

The next destructive earthquake to hit Norcia was the 1979 M_w 5.9 event with epicentre in Valnerina. According to Reale et al. (2004) 83% of the buildings were assessed. Of these only about 10% had ring beams, while up to 10 % was classified as being near collapse, and 40% as having substantial structural damage (Favali, et al, 1980). The 1981 Regional Law n.34 (Regione Umbria, 1981) recommended the following repairs: grout injections of concrete mortar; wired mesh and concrete jacketing of walls on both sides; reinforcement bars grouted in cement mortar to improve the strength of the building corners. The major change with respect to the previous 1859 regulation was the almost complete removal of wooden roofs in favour of concrete slabs. Concrete ring beam were also recommended, to be connected by reinforcement bars studs, to the original masonry walls strengthened with cement mortar injections. Again, structural safety was prioritised with respect to conservation of authenticity, however it can be argued that the overall heritage value of the historic centre was preserved as its urban and architectural fabric were not visibly altered.

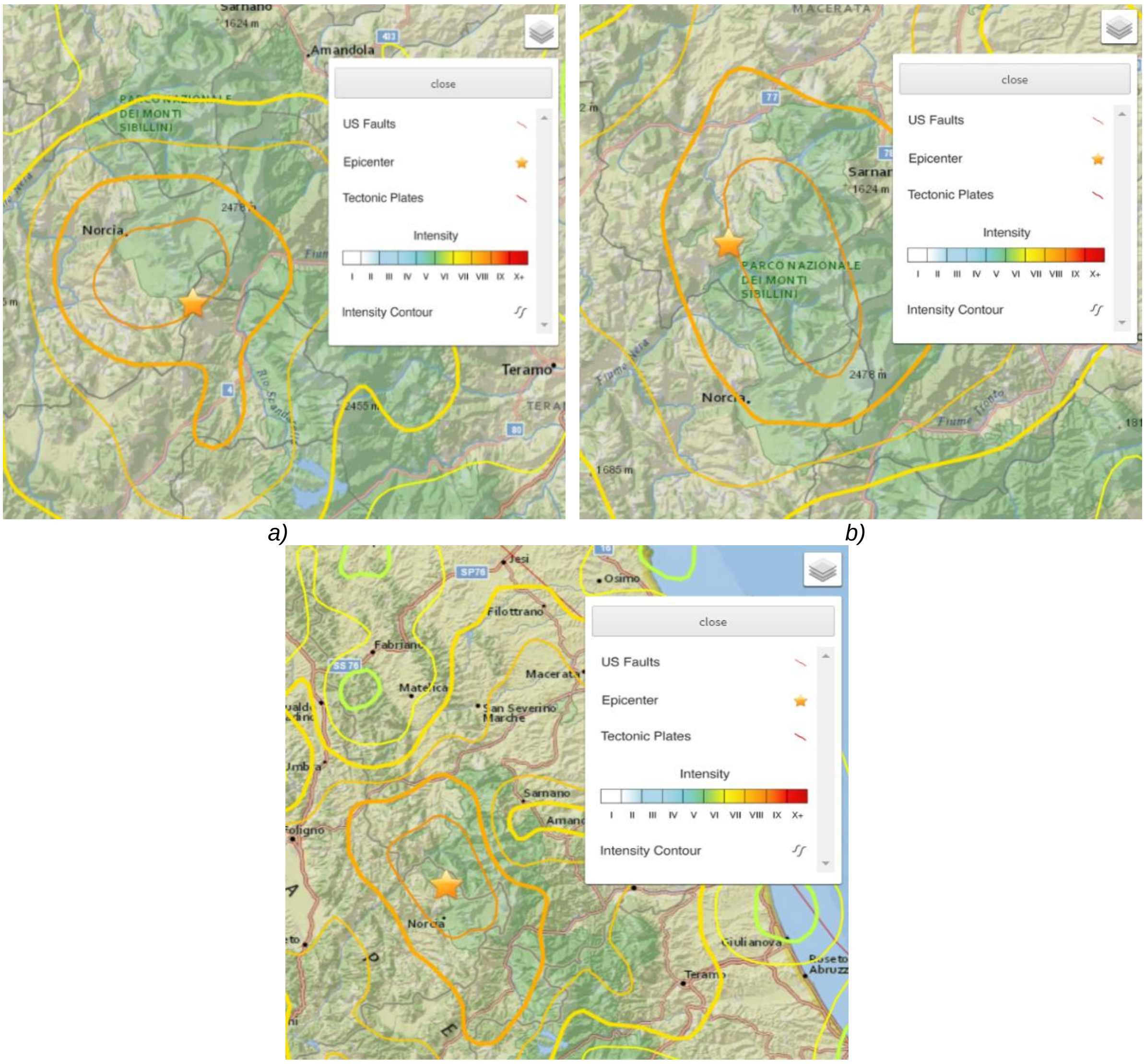
The devastating effects on historic urban centres of the 1974 M_w 6.5 Friuli earthquake, the 1979 event and the 1980 M_w 6.8 Irpinia earthquake, led to the redaction of the Norme Tecniche per Le Costruzioni In Zone Sismiche (Ministro dei Lavori Pubblici, 1986). These changed radically the approach to strengthening heritage buildings, by introducing the complementary concepts of “upgrading” and “improvement”. The former prescribes that interventions should make the existing building fully compliant with the requirements for new buildings, while the latter allows for interventions to single structural elements, which aim at enhancing the building’s safety without modifying the global behaviour and its appearance. The requirement was applicable to any historic building in seismic zone, undergoing any type of refurbishment, whereby the demonstration of safety enhancement was compulsory, but not the full “upgrading”.

The Umbria-Marche seismic sequence of September 1997, with epicentral intensity IX in MCS scale (Cinti, 2008), represented another turning point for ~~natural~~ disaster management in Italy. The law n.61 of 30/03/1998 (Italian Parliament, 1998) was enacted, listing the priority actions for the emergency phase and the competences at national, regional and local level to facilitate the recovery process. It indicates the Civil Protection as the agency supporting the Ministry for Culture and the Environment to determine suitable intervention measures for the protection of cultural heritage from natural hazards. This cooperation resulted in the productions of “The Guidelines” (MIBAC, 2007) which were eventually aligned to the Technical Construction Code (NTC2008, Ministry of Infrastructure, 2009) in 2010 (Circolare 26. 2010).

The Italian national seismic code was further updated in the last decade, in 2005 (Ministry of Infrastructure, 2005) and in 2009 (NTC2008, Ministry of Infrastructure, 2009) in response to the 5.8 M_w 2002 Molise earthquake and the 6.3 M_w 2009 L’Aquila earthquake. The NTC 2008 includes clauses of particular relevance for the evaluation of the seismic performance of heritage structures and the choice of suitable prevention strategies. In particular, it recommends that the safety judgment and the actions to enhance the structure’s performance must be specifically tailored to the specific heritage value of the building.

The 2016 Central Italy sequence began with the M_w 6.0 Amatrice earthquake on 24th August, (epicentre at 16.38 km from Norcia), continued with two events in October, the M_w 5.9 Visso, event on 26th (epicenter at 12.50 km from Norcia) and the M_w 6.5 Norcia earthquake on the

30th (epicentre at 7 km from Norcia). Figure 2 presents the macroseismic contour maps for the three events, clearly showing that the most damaging for Norcia was the last one.



a) b)

c)

Figure 2: USGS interactive Macro seismic contour maps of the three main events in the 2016 sequence; a) M_w 6.0 August 24, 2016, b) M_w 5.9 October 26, 016, c) M_w 6.5 October 30, 2016, (USGS, 2018)

The current seismic code, NTC2018, enacted by Ministerial Decree 17/01/2018 (Ministero delle Infrastrutture e dei Trasporti, 2018), is the reference document to which interventions for either repair or reconstruction in historic centres, will have to comply. This version confirms the approach allowing safety improvement measures for historic buildings. In addition, particular emphasis is devoted to tailor the building assessment in light of its structural behaviour, both as an ‘individual’ building and as ‘part of a compound’.

The above digression, presenting the evolution of seismic strengthening provisions alongside the occurrence of seismic events, shows that these two factors are inextricably linked in the resulting heritage value of historic towns in Italy. Norcia, however, represents a unique case, as the early measures taken after the 1859 earthquake, had an important role in moderating the damage caused by the 1979 earthquake. Again interventions implemented following this event, had a beneficial effect on the buildings’ performance in the 2016 sequence when compared with the destruction faced by Amatrice or Accumoli. However, current provisions are designed to resist one damaging event, with a certain probability of occurrence, rather than repeated major shakings in a short period of time, as characteristic of the seismicity of this section of the Appenine. The cumulative effect on damage of such sequences and the quantification of the beneficial effects of strengthening are the focus of the reminder of the paper.

3. Methodology

3.1 Analysis of cumulative damage

For the analysis of cumulative damage, the damage levels recorded after the August 2016 event, after the October 2016 events and in September 2017 were compared. The primary data is obtained from the AeDES forms (Baggio et al., 2007) compiled by technical volunteers for the Seismic Risk Service of Umbria Region[2]. However, as AeDES forms are collected by different operators with variable level of training, and not for the primary purpose of assessing damage, various types of bias might affect their outcome. Hence an independent survey was conducted by the authors.

Three sets of data are considered in the damage assessment timeline:

- Set 1 documents the damage caused by the event of August 2016 and collected between the 27th of August and the 26th of October 2016 via AeDES forms;
- Set 2 documents the damage recorded from the 4th of November until the 9th of April 2017 via AeDES forms;
- Set 3 documents the damage state at September 2017 as surveyed by the authors from the 1st to the 9th of September, using ‘virtual walks-through’ the streets of Norcia, by remotely assessing chains of 360-degree images.

The number of buildings assessed is 439 in Set 1, and 791 in Set 2. Of the latter, 352 buildings were new assessments, 170 buildings were found in worsened damage conditions, 165 buildings were in an unaltered damage condition and 104 buildings where not reassessed. The number of units surveyed via omnidirectional camera (ODC) in Set 3 is 519. The total number of buildings for which at least one survey has been conducted is 854, however the number of buildings for which there is information from the three sets is 200. Outcome of these assessments is discussed in details in section 4.

The collection of post-earthquake damage data for the usability assessment via the first level AeDES forms was established in Italy by the DPCM 05/05/2011 (Consiglio dei Ministri, 2011). The current version of the forms includes building identification, description and metric data, typology of horizontal and vertical structures, damage to structural elements; damage to non-structural components; assessment of external risk induced by other constructions, soil and foundation; and usability assessment. The form categorizes buildings into six classes of usability, from A, good for immediate occupancy, to B, C and D, requiring different extent of repair before occupancy can be restored, to E and F for which either immediate demolition or shoring provisions need to be implemented to ensure public safety.

The data gathered with the AeDES form can also be used to determine the level of damage to the building, and hence allow comparisons with other damage assessment methods (Bernardini, et al, 2008). To achieve this, a screening of the damage to each individual

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[2] Unpublished compiled data received through personal communication, after underwriting of official data protection agreement between the Civil Protection of the Umbria Region and the authors (http://www.cfumbria.it/index.php?s=602).

structural element of each building is carried out. The correspondence between the damage levels (D_i) of the AeDES form and the damage grades (DG) of the European Macroseismic Scale (EMS-98) (Grünthal, 1998) (Table1) is obtained by using the correlation matrix proposed by Augenti et al., (2004). Interpretation of AeDES damage levels in EMS-98 terms are presented in Del Gaudio et al., (2017) and Masi et al. (2016).

Set 3 of damage data, gathered with the use of ODC, a well-established and expeditious tool already tested by the authors in other field missions (Stone et al., 2018), aims to provide an independent and primary source to compare with AeDES data. The camera model used is the Ricoh-Theta S ©, with a resolution of 14.4 MP translating in a flat image of 5376x2688 pixel resolution. The camera uses two back-to-back image sensors, each fronted by a fisheye lens facing in opposite directions which capture a 180 x 180-degree field of view. The high resolution and fish-eye technology allow to capture the full height and width of the façades together with details such as cracks and mortar joints (see Figure 3).

Figure 3 Fish eye image of damaged facades along a street in Norcia captured with RicohTheta-S © camera. Note the ability to capture the urban layout, construction details such as buttresses and finer details including line cracks.

When surveying, the camera was attached to a pole and held above the photographer's head, along selected routes overlapping as much as possible with the AeDES survey, given access limitations. The chains of ODC images were then uploaded onto the web-platform Mapillary © (Mapillary, 2018) and used to conduct a 'virtual survey' to assess the level of damage in much the same way that engineers completed the field survey. The use of web-platforms is essential to properly visualize and share the omnidirectional images among surveyors which might be located anywhere. However, it should be borne in mind that on uploading, images are automatically processed by the platform's software which might result in blurring effects or misallocation if the GPS coordinates are not updated. Other limitations include the shelf life of the pictures, which might be updated with pictures from other users over time, and gaps in the continuity of the street survey if pictures are not taken at regular intervals. The latter can be avoided by setting automated shooting time laps and walking at a constant pace.

The Set 3 of damage data is also obtained by correlation of the assigned qualitative damage grade observed to the EMS'98 damage scale (Table 1). Given the uncertainties associated with surveys conducted only from the street without assessing the interior of the buildings, the moderate and substantial damage grades (DG2 - DG3) and the partial and total collapse grades (DG4 - DG5) were aggregated.

The output of the three sets is mapped using ArchGIS © (ESRI, 2011). The presence of strengthening measures such as ties, anchors and buttresses is included to allow for an immediate visual correlation between damage progression and implemented traditional provisions.

Table 1 Correspondence between EMS-98 damage grade scale and criteria adopted to evaluate the damage collected via ODC

EMS-98 Damage Grade Scale	Corresponding damage criteria
DG1 Negligible to slight damage	The building shows hair-line cracks in few walls, affecting only the outer plaster layer.
DG2-DG3 Moderate (MD) to substantial (SD) damage	MD: the building shows deep cracks in many walls. Fall of plaster pieces, collapse of small portions of the wall (i.e. chimneys) which can still be repaired. Roof tiles detached. SD: passing cracks are observed in most of the walls, substantial portions of roof and walls are detached or at the incipient stage of failure. Failure of gable walls.
DG4-DG5 Very heavy (VHD) damage to collapse (C)	VHD: deep cracks in all walls. Serious failure of wall portions showing the inner part of the building. Failure of big portions of roof. C: near or total collapse of the whole building

3.2 Efficacy of strengthening measures

The efficacy of strengthening measures and the evaluation of the resulting building performance is quantitatively assessed using the FaMIVE procedure (D’Ayala & Speranza, 2003, D'Ayala Paganoni 2014) This is applied to a subset of 111 facades, corresponding to 82 buildings surveyed to a greater level of detail by the authors.

The FaMIVE procedure provides an on-site investigation form to collect a quantitative data set related to the geometry, layout and distribution of openings, position of restraining elements, and presence of elements which enhance or reduce the building vulnerability. The data is used to develop simple mechanics-based models of the building façades to determine their collapse load factor, i.e. the minimum value of lateral acceleration which will cause their overturning or in-plane failure.

The FaMIVE procedure was applied assuming six different scenarios, each one with a different distribution of retrofits, aimed at reproducing the structural characteristics at different times in history, ranging from the pre-1859 earthquake to the condition observed on-site during the 2017 campaign.

Case 1 represents the pre-1860 code scenario, where no restraining elements were present, the masonry type was of relatively poor quality (i.e. low values of friction and cohesion), the horizontal structures and the roof structures were made of timber. Case 2 reproduces the post-1860 code scenario with the provisions of the Royal Decree Building Regulations summarized in Table 2. Buttresses had been implemented to the full proportion observed by the authors, while ties had been included only to half of the same proportion, the horizontal structures are timber, and the majority of buildings had two storeys. Case 3 represents the pre-1979 earthquake scenario, where it is assumed that in the intervening century restraining elements had been implemented to a wider portion of the buildings sample (i.e. 25%, of the sample), the quality of masonry walls had improved and a minority of the buildings (5%) had ring beams (Table 3). Case 4 reproduces the post 1979-earthquake scenario, with the assumption that the seismic interventions indicated in Regional Law n.34 (Regione Umbria, 1981) were implemented. These corresponded to the addition of concrete ring beams and the substitution of wooden horizontal structures with concrete slabs, for both floors and roof to a large proportion of the building sample. It is also assumed that grouting and jacketing had been implemented to a larger proportion of buildings. Case 5 represents instead the scenario after the 1997 earthquake and before the 2009 L'Aquila event, whereby a return to more traditional structural features was favored such as re-introduction of timber elements, consolidation of timber floors with lightweight slabs in reinforced concrete and grouting in favor of jacketing. Lastly, Case 6 represents the actual condition as surveyed by the author in September 2017 for each of the buildings. Data relative to horizontal structures, roof type and masonry fabric, when not directly observable during the 2017 campaign, were taken from information contained in Borri et al. (2017).

Table 2 Correspondence between seismic provisions and site observation during the September 2017 campaign

Code/Regulation of Reference	Type of implementation measure	% observed on site
Post-1860 Code	Ties	25%
Post-1860 Code	Buttresses	33%
Post-1860 Code	Building height ≤ 8.5	83%
Post-1860 Code	No. floors ≤ 2	76%
Post-1860 Code	Presence of Basement	22%
Post-1860 Code	Regular layout of openings	61%
Post 1979	Ring Beams	52 %

Based on the surveyed condition (i.e. case 6) and in accordance with the evolution of seismic regulations outlined in section 2, Table 3 summarizes the key parameters used in the FaMIVE procedure and their percentage occurrence in each of the six scenarios.

Three different masonry typologies, M1, M2, M3 are used to indicate decreasing quality of stones, mortar and fabric. This helps differentiating the pre and post-1860 and the following improvements after the 1997 provisions including grouting. Corresponding values of friction coefficient (FC) and cohesion (C) are assumed, to determine lateral capacity.

Table 3 Key parameters implemented in FaMIVE to reproduce the six main cases outlined

Case	**Masonry Type**	**Assumed friction coefficient**	**Assumed Cohesion [MPa]**	**Floor Type**	**Roof Type**	**Restraining elements (RE)**	**RE %**
Case 1	M3	0.3	0.00	WF; VF	R1	--	0
Case 2	M3	0.3	0.25	WF; VF	R1	T B	13% 33%
Case 3	58% M3 37% M2 5% M1	0.35 M3 0.4 M2 0.6 M1	0.30	58% WF; VF 37% RWF	R1	T B RB	25% 33% 5%
Case 4	38% M3 28% M2 34% M1	0.35 M3 0.4 M2 0.6 M1	0.4	50% CF 35% VF-WF 15% RWF	60% R2 40% R1	T B RB	25% 33% 90%

Case 5	38% M3 28% M2 34% M1	0.35 M3 0.4 M2 0.6 M1	0.5	30% CF 35% VF-WF 35% RWF	80% R2 20% R1	T B RB	25% 33% 90%
Case 6	38% M3 28% M2 34% M1	0.35 M3 0.4 M2 0.6 M1	0.5	35% VF-WF 65% RWF	80% R2 10% R1	T B RB	25% 33% 81%

Three different typology of floors are used: wooden floors (WF) representative of the pre-1979 condition, concrete floors (CF) which replaced the WF after the 1981 Law n.34 emanation, and reinforced wooden structures (RWF), representative of the post-1997 seismic regulations. Where basements are present barrel vaults (VF) are considered in accordance with the study by Borri et al (2017). For the roof structures, the more traditional case of timber joists with screed and tiles (R1) is used to describe the condition pre-1979 while the case of lightweight tiles and concrete slab (R2) indicates the post-1979 replacement. With reference to the restraining elements (RE), the post-1860 provisions required ties (T) and buttresses (B), while the post-1979 provisions introduced concrete ring beams (RB).

Evaluating the six cases will show any shift in the overall sample's structural behavior, thus allowing for critical evaluation of the advantageous or detrimental effects of the strengthening measures adopted over time.

4. Results and discussion

4.1. Damage progression across the seismic swarm

Data collected with the empirical assessment is evaluated for change in usability grades and corresponding damage grades to determine the progression of damage through the swarm of seismic events. Table 4 shows that the building stock in Norcia withstood well the 24th August event, with 81% of the buildings marked as usable and with no damage (class A), and only 9% severely damaged and unusable (class E). After the 30th October over 40% of buildings were rated temporarily unusable (class B), while 32% were categorised in class E. The peak ground acceleration (PGA) of the October events recorded in Norcia are greater than the 24th August event causing an increase of buildings classified as B, C and E among the ones for which no prior assessment had been conducted. It is noticeable that this set has a lower proportion of building in class E than the set undergoing repeated assessment, providing confirmation of effects of cumulative damage.

Table 4 Comparison between usability results collected before and after the October events

Usability Results	**A**	**B**	**C**	**D**	**E**	**F**
Post 24/08/2016 Assessment	81%	6%	4%	/	9%	/
Post 30/10/2016 Assessment	20%	43%	4%	/	32%	1%
Newly Assessed after the 30/10/2016	32%	39%	5%	/	24%	/

It is apparent that the effects on the building stock in Norcia are relatively contained when compared to the almost total destruction that befell the other towns in the epicentral area (D'Ayala et al., 2018), hence demonstrating that the improved construction quality and the strengthening measures adopted effectively worked in reducing the damage extent, if not preventing it and hence in preserving the heritage of the town. Most importantly there were no casualties associated with the October events.

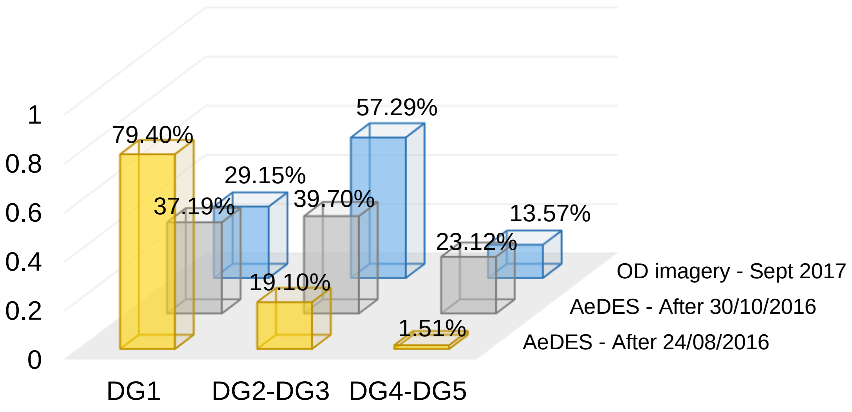

Figure 4 Comparison of damage state attribution for buildings surveyed with AeDES and OD imagery

Figure 4 confirms the substantial shift in damaged buildings between the two sets of AeDES surveys. A steep increase is observed in DG4-DG5 grades from the pre to the post-October event phase: approximately more than 22% of buildings are rated heavily damaged or near collapse. Conversely, the percentage of buildings previously rated as ‘no damage’ or ‘slight damage’ drops to more than half of the pre-October event phase (from 79.40% to 37.49%). The AeDES form and the ODC based survey differ by more than 20%, with an apparent overestimate of damage DG2-DG3 in the ODC and underestimate of higher damage level. This can be explained by the fact that in AeDES building can be classified in class E if they are assumed not to be repairable and they will be assigned a minimum damage level DG4. Moreover, while the AeDES forms benefit from internal access to the buildings, the ODC survey was conducted purely from the street, hence preventing the detection of internal collapse of floors or roof, in some cases. Nonetheless the distribution of damage obtained with the ODC compares well with the ones reported by Borri et al. (2017).

To evaluate qualitatively the effectiveness of traditional strengthening measures in limiting the damage to buildings, the subset with such provisions was analysed. Figure 5 shows that while there is an increase in undamaged building with respect to the whole sample in the first set of data, no clear trend is visible in the other two surveys, highlighting the limited capacity of these strengthening techniques to withstand repeated seismic action.

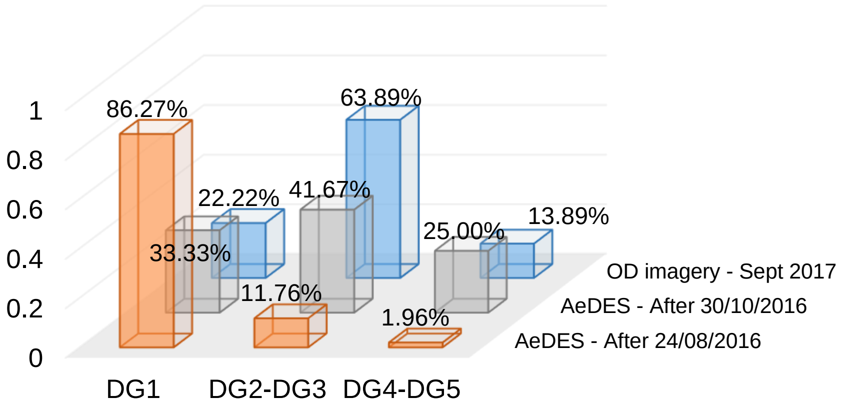

Figure 5 Comparison between proportions of damaged buildings traditionally strengthened across the seismic events

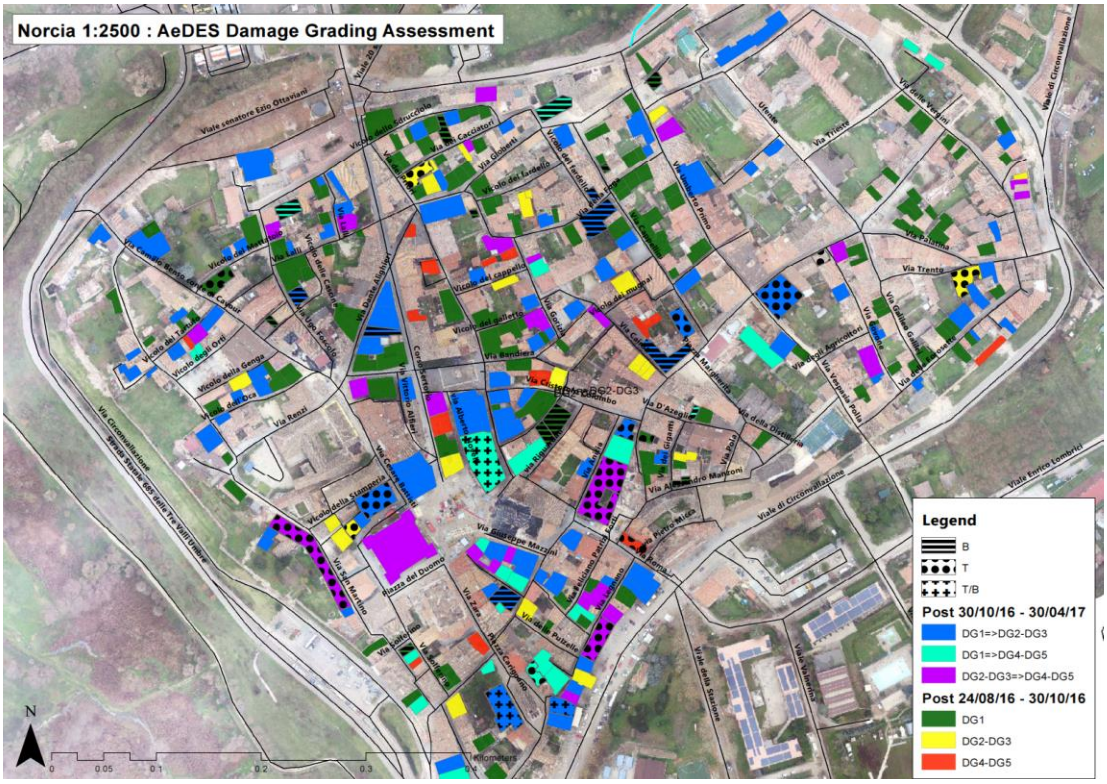

Figure 6 AeDES assessment after the 24th August 2016

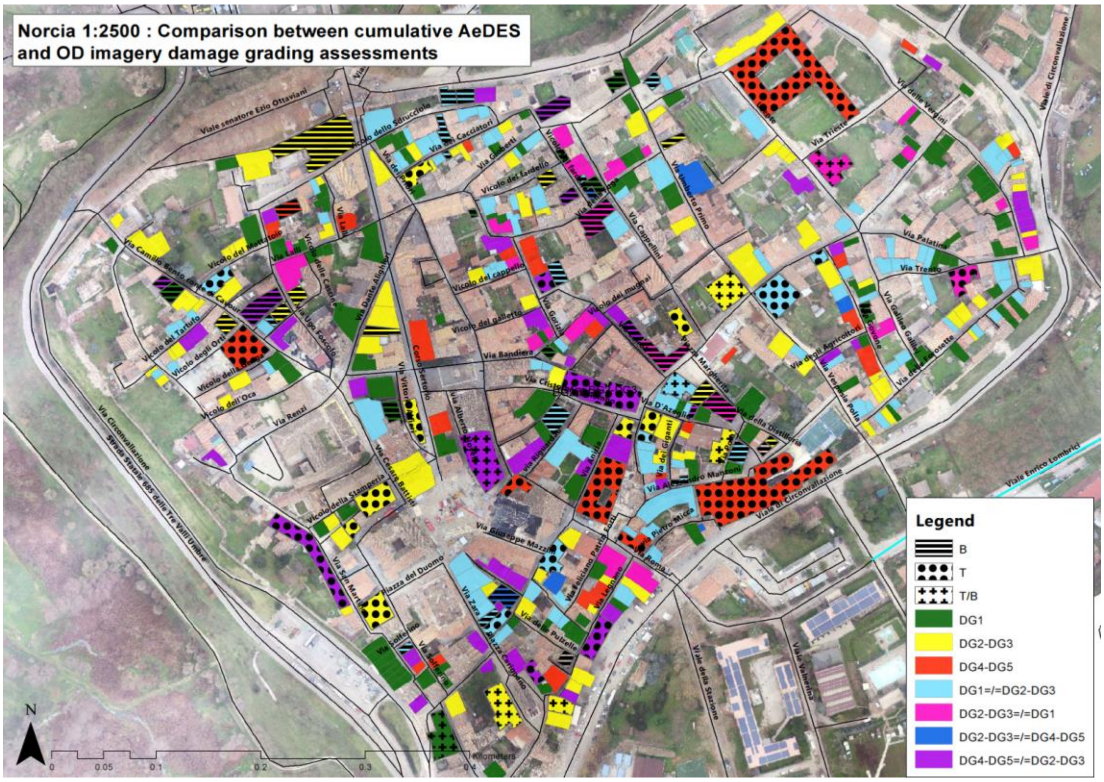

Figure 7 AeDES assessment after the 30th October 2016

The damage progression of individual buildings can be visualised on the map of Figure 6, which confirm that no specific trend is visible for buildings with strengthening devices. Figure 7 allows to visualise the misclassification between AeDES Post October 2016 survey and the OD survey case by case. A consistent pattern associated with the geographic distribution is not emerging, neither it can be associated with the presence of strengthening devices. It is of relevance that the discrepancy in classification occurs for almost 50 % of the sample and this is certainly worth of further investigation.

4.2. FaMIVE assessment and strengthening measure efficacy evaluation

A more detailed understanding of the role of historic and modern strengthening devices on the performance of buildings in historic urban centres can be obtained by conducting analytical vulnerability assessment. The vulnerability analysis of the sample of buildings surveyed in Norcia during the September campaign was performed for 111 facades using the FaMIVE procedure.

Table 5 shows the change in failure mechanisms across the six cases. It can be seen how progressing from case 1 to case 2 representing the effect on performance of the buildings of the strengthening provision provided by the 1860 Royal Decree, there is a reduction of overturning mechanisms A, D, E, which occur for low value of acceleration in favor of the more stable mechanisms B1, B2, which benefit from having a stronger connection of the façade with return walls. Although ties had been implemented, they are to an extent ineffective as the quality of the masonry is relatively poor and hence other types of mechanisms occur for lower collapse load factor before the F mechanism can develop. Case 3 represents the pre-1979 earthquake condition and case 4 the condition after the implementation of the strengthening measures suggested in the Regional Law n.34 (Regione Umbria, 1981). It can be seen that with the implementation of grouting and jacketing there is a substantial reduction of out of plane mechanisms in favor of in-plane mechanism H2 and of mechanism F. This shift corresponds to the expectations of the Code. Case 5 and case 6 represent respectively, the further modifications implemented after the 1997, and the current situation as surveyed. The shift towards the recommended box behavior, marked by the increase of mechanism F with respect to H2 is apparent, even though confined to a minority of buildings. Ring-beams are not as effective as expected, due to other weaknesses.

Table 5 Distribution of collapse mechanisms for the six scenarios

Failure Mechanisms							
Case	A Overturning of whole facade	B1 Overturning with one return wall	B2 Overturning with two return walls	D Simple partial overturning	E Overturning of internal portion of façade	F Overturning restrained by ties or ring-beams	H2 In plane failure
1	0.16	0.00	0.11	0.05	0.40	0.00	0.28
2	0.12	0.06	0.14	0.01	0.39	0.01	0.27
3	0.05	0.12	0.16	0.03	0.32	0.00	0.32
4	0.17	0.04	0.11	0.00	0.05	0.10	0.53
5	0.14	0.05	0.15	0.01	0.06	0.13	0.46
6	0.15	0.05	0.11	0.00	0.10	0.17	0.42

Beside the evaluation of the change in failure mechanisms the cumulative distribution of collapse load factor for each case can be analysed to determine the probability of damage in relation to specific strong motion events. To this end, the values of PGA at the site for the main shocks of August and October 2016 recorded at the station positioned in the main square of Norcia (NOR), (Luzi et al., 2016), closest to the buildings being evaluated, are shown in Figure

8 together with the cumulative probability distributions of lateral capacity obtained with FaMIVE, for the sample of 111 facades for the six cases of table 3.

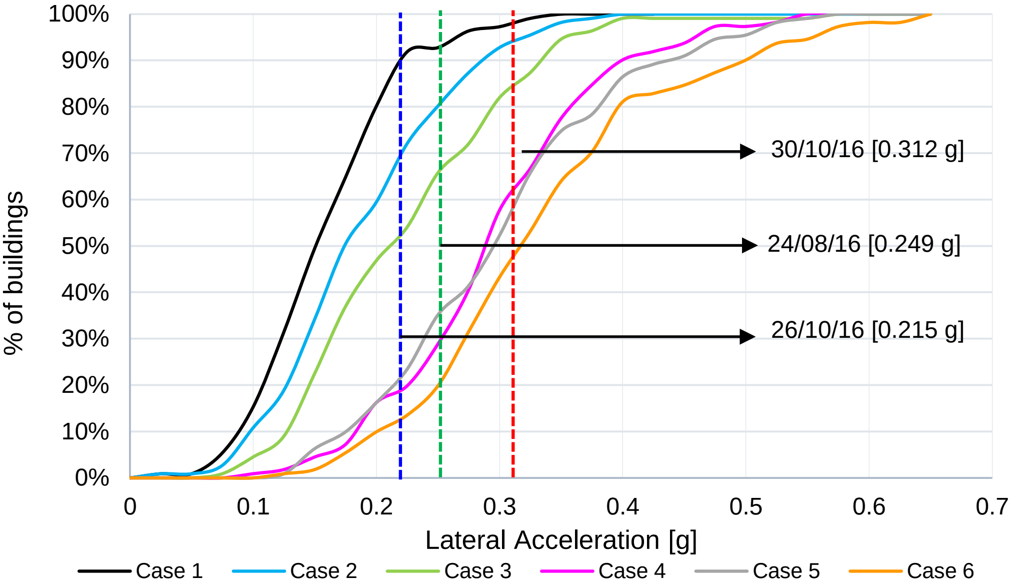

Figure 8 Damage distribution across the six Cases and indication of the 3 main shocks of the 2016 Central Italy sequence.

There is a shift towards the left, indicating an increase of building performance when going from the condition pre-1859 earthquake (i.e. pre-1860 Code) towards the September 2017 building condition. The more evident improvement in buildings behavior is registered from Case 3 to Case 4, which depicts the post-1979 implementation of strengthening. The intersection between the orange curve representative of Case 6 and the three dotted vertical lines indicate the proportional increase in percentage of damaged buildings caused by the 3 events.

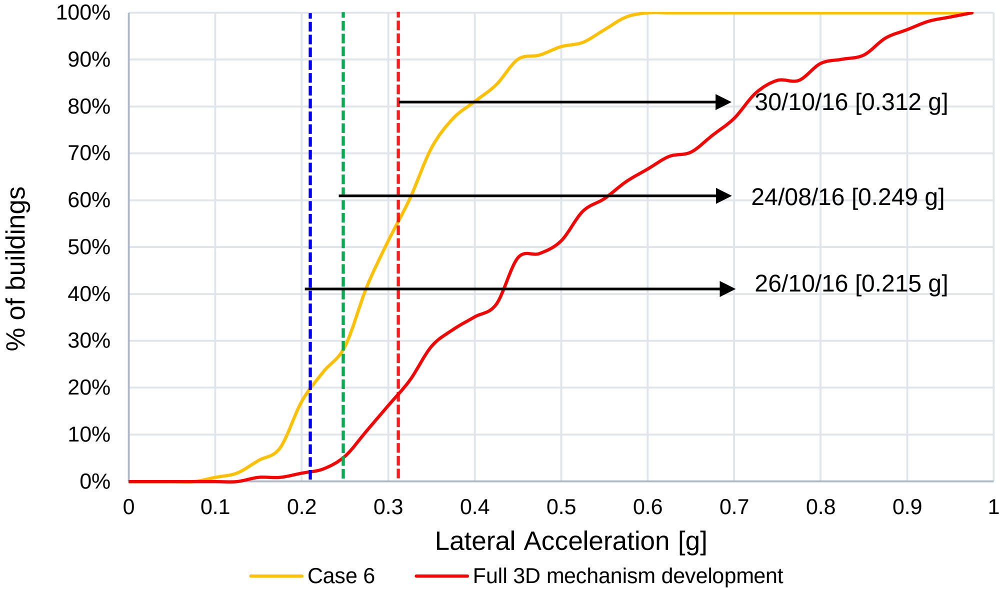

Figure 9: Comparison between latest building condition (as surveyed) and assumed full 3D mechanism development condition

Figure 9 shows the comparison between the condition of the buildings as they were surveyed during the September campaign (i.e. Case 6) and the hypothesis of full box behaviour resulting in 3D mechanisms. This latter condition assumes that only mechanisms F and B activate. The proportions of buildings failing in this latter condition is almost 40%, 25% and 20% less, for the three events respectively. The full 3D mechanism curve shows what would be the full effectiveness of strengthening if grouting improves the masonry fabric, avoiding in-plane mechanisms and disconnections at wall returns. For this work the option of strengthening aimed at local improvements rather than full upgrading, might not work as it allows for the overseeing of hidden weakness by avoiding a full holistic assessment.

5. Conclusion

The analysis of the cumulative effects of damage to the urban historic fabric of Norcia due to the 2016 Central Italy earthquake sequence, and the qualification of the effects of strengthening measures applied over time, have been discussed in light of the evolution of antiseismic building regulations and standards. The provisions of the 1860 Royal Decree were quite bold in terms of changing the appearance of the fabric by introducing buttresses and demolishing floors. They also put emphasis on connections of orthogonal walls and floors to ensure the so call box behavior. While they were not explicitly concerned with issues of authenticity and preservation of historic character, the use of technologies and materials substantially homogeneous to the original ones, delivered good seismic response and contributed to the urban character to the extent that these features today represent the characteristic heritage value of the town. Conversely, the approach to strengthening developed during the 20th century as highlighted in D’Ayala (2014) and discussed in section 2, was possibly more preoccupied with issues of preservation, however the strengthening interventions were substantially driven by concrete technology and structural engineering concepts relating to frame behavior rather than masonry wall response. Ring beams and concrete slabs replaced traditional wooden floors and ties. Traditional appearance was maintained by introducing fake wooden roof rafters. Evidence of the drawbacks of these interventions in terms of seismic capacity are discussed in D’Ayala & Paganoni (2014). From the stand point of enhancement or preservation of the heritage value, it is worth considering that such interventions are conceived to not alter the building “character”, while allowing to improve economic and continued use values. However, the large numbers of severe damage and collapse which can be associated to such interventions in L’Aquila, Amatrice and Accumoli, bring into question their validity.

The analytical approach shows that lightweight floors, connections at corners, use of anchors, and good masonry cohesion obtained through grouting are the combination of interventions needed to ensure limited and repairable damage to the largest portion of the town building stock, ensuring preservation of its architectural heritage for posterity and life safety for its occupants.

The study has also proven that the ODC data capture and subsequent virtual survey can deliver very good results, of a quality comparable with visual rapid survey, but with the potential of much greater coverage, with the same amount of resources and time, and with the benefit of keeping the surveyor away form dangerous conditions. Improvement in the results can be achieved if the data is cross referenced with information on damage obtained by entering a modest amount of buildings to calibrate the assignment to intermediate damage levels.

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