CUMULATIVE DAMAGE ASSESSMENT AND STRENGTHENING EFFICACY OF MASONRY BUILDINGS IN NORCIA AFFECTED BY THE 2016 SEISMIC EVENTS IN CENTRAL ITALY
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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 damage assessment, as it provides an unbiased 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 intervention, in terms of type of collapse mechanism and collapse load factor.

Results show that there is a good correspondence between AeDES and OD 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.

Contents

1. Introduction

The town of Norcia in Abruzzo region is strictly linked to the inclusions, by the Italian government, 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 one of the most prominent cultural and economic urban centers of Valnerina and the birth place of St. Benedict of Nursia, born in 480 and 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 the consequent re-shaping of its urban fabric through the ages. 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 for the development of the town's resilience against destructive natural events.

The recent seismic swarm that hit the Central Italy area within the four regions of Abruzzo, Lazio, Marche and Umbria from August 24th 2016 to the 18th of January 2017, was severely disruptive in terms of damage to both residential buildings and architectural heritage properties. Of particular importance for the town of Norcia were the event on the 26th (M_W 4.5) and the October 30th (M_W 6.5) 2016 event (Luzi et al., 2016). While during the 2016 Central Italy EEFIT mission, it was possible to observe that the damage to the historic town was relatively low, except for apparently minor damage to some of the heritage structures and historic dwellings (D'Ayala et al., 2018), the later 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 the campaign of field damage and safety assessment for post-earthquake usability of ordinary buildings through AeDES forms, whose acronym stands for "building operability and damage in post-earthquake emergency" (Baggio et al., 2007). This activity was disrupted by the late October 2016 events, which caused new additional damage and triggered the re-assessment of the usability of buildings through a new campaign of AeDES forms' compilation.

Notwithstanding the numerous studies on the seismic vulnerability of heritage buildings and historic urban centres (Vicente et al., (2014), Lagomarsino et al., (2010)), the focus on 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.

Recurring observations of damage in earthquake-prone countries worldwide has shown the lack of systematic critical approach towards the evaluating 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 where it is possible to evaluate the

effectiveness of historical and recently implemented strengthening interventions following the destructive seismic events that characterized the history of the town. It also provides a unique opportunity to trace the changes in historic provisions aimed at reducing the seismic damage. Very frequently, regulations developed locally were adopted outside the boundary of the local region, leading over time towards the establishment of the Italian national seismic culture and its regulatory framework (Dolce, 2012).

While anecdotal 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 preliminary considerations on the structural damage to the residential and historic buildings of Norcia after the conclusion of the 2016 Central Italy EEFIT mission (D'Ayala et al., 2018), were later challenged by the two October seismic events. The unique chance to evaluate the pre and post-hoc building damage conditions and the efficacy of the strengthening measures implemented over time, represented the aims of an individual return mission in September 2017, following the award of the 2017 Research Grant Scheme sponsored by EEFIT and the Institution of Structural Engineers UK.

This papers presents in section 2 an overview of the evolution of Code and buildings regulations, both at local and national levels, which determined the implementation of seismic strengthening measures within the historic urban fabric of Norcia, alongside a chronology of destructive events for the town. Section 3 focuses on the methodology used to analyse the damage accumulation due to 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 the results obtained and the critical discussion of both the qualitative and the analytical method used to conduct the analysis.

2. Seismic events and changes in codes and regulations

Although the first urban settlement dates back 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 road directions, namely the SW-NE and the NW-SE (Reale, et al, (2004), Montanari, (2016)). The Medieval addition was built over the remains of the first walls, following the uneven topography of the site, as proved by the considerable variation in walls' height (Montanari, 2017).

Under the Lombard occupation during the 7th century, 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, until the 1860. After becoming the seat of the pontifical prefecture, the fortress 'La Castellina' and the parish house of Santa Maria Argentea were built (Ricci, 2002). According to Bianchi & Rossetti (2001), no significant change to the urban residential layout within the walls has occurred, thus the town has maintained its late-Medieval appearance. However, detailed information concerning the earthquake effects in Norcia and its surrounding areas, recorded since 1328 (Locati et al., 2016), indicate that repairs have been made through time to damaged components of individual buildings.

Figure 1 shows the chronological sequence of seismic events of Norcia in terms of macroseismic intensity (I_{MCS}) (Locati et al., 2016), which correspond to the most destructive seismic events from the 1000 A.D onwards (Locati et al., 2016). Since 1328, when a 6.2

magnitude (M_w) earthquake hit Norcia with an intensity *I* of IX-X, the area experienced at least six further events of I >7 (Pauselli et al., 2010), including the major sequence in 1703. According to Cello et al, (1998), the sequence started with a I_{MCS} = XI (Mercalli – Cancani – Sieberg (Wood & Neumann, 1931)) January event with epicentre in Val Nerina south of Norcia, followed by a I_{MCS} = VIII event in January with epicenter in the mountainous range between Abruzzo and Lazio and finally by a I_{MCS} = X event in February, with epicenter in the L'Aquila valley. During the sequence the death-rate reached 81% (Davinson, 1912), and the town was almost completely razed to ground (Deschamps, et al. 1984).
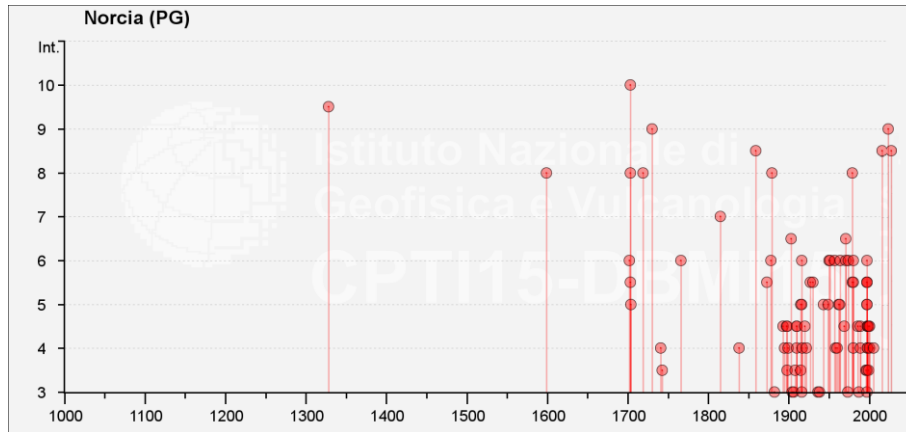

Figure 1: Historic Seismicity of Norcia measured in Microseismic Intensity MCS (Mercalli, Cancani Siebarg (INGV, 2018), adapted by authors to include 2016 events.

Notwithstanding there have been records of previous seismic events highly damaging for the town, it was only after the 1859 earthquake that the first anti-seismic construction regulation was developed. According to Reale et al. (2004), the event happened on the 22nd of August of that year, of local intensity MCS VIII – IX, caused the death of 101 people out of an estimated population of 4000-5000 people, the complete destruction of two neighbourhoods on the town east side and extensive damage to the ancient fortification of 'La Castellina', the City Hall building and to several portions of the city walls. After the event, a commission of scientists and architects was nominated to evaluate the buildings' damage extent and to outline a manual of 'good' building practices to be used for the reconstruction phase. Norcia's building regulation was among the first documents whose redaction was triggered by a highly destructive natural event: the Pombaline Reforms after the 'Great Lisbon earthquake' in 1755 (Brand & Hugh, 2013) and the Instruction for the reconstruction of Reggio of the Bourbons Government after the 1784 earthquake (Brand & Hugh, 2013), are the two more relevant preceding examples. Soon after, other regulations followed the Norcia's Decree, such as the one for the reconstruction of Ischia after the 1883 earthquake (Slejko, 1993) and the Royal Decree n.193 for the reconstruction of Messina (Hobbs, 1090) in which, according to Reale et al. (2004), the use of reinforced masonry was introduced for the first time and suggested as the building material 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). No specific mention is present in literature to better describe the damage categories of the assessment, nor of the criteria or the scale adopted. The damage was mapped and integrated with the appraisals of the Commission in charge (ASCN, 1860). A total number of 749 buildings were assessed out of 934 buildings within the walls, indicating that 80% of the town got damaged. According to Borri et al., (2017) the level of damage recorded after the 1859 event was mainly due to the structural characteristics of the buildings coupled

with the height of the buildings, the slenderness of external walls and the presence of heavy vaults which were not connected appropriately to the sustaining walls.

On the 24th of April 1860 the new Building Regulation was promulgated with a Royal Decree (Archivio Storico Comunale di Norcia (ASCN), 1860a). 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 and repairs to existing/damaged buildings.

In relation to the former the minimum depth required for a foundation plinth was 1.30 m and the maximum building height was set to 8.5 m, which corresponds to 2 floors, possibly with basement. The minimum wall thickness should not be less than 0.6 m, with presence of buttresses of required minimum thickness equal to 0.40 m. The vertical alignment of openings was compulsory and suggestions were given in relation to the minimum distance from the piers, to avoid the weakening of the structure. Great emphasis was put on defining the minimum dimensions of the stones and the quality of mortar used to build the walls. For vaulted structures, only allowed in basements, the minimum thickness at key-point to be guaranteed was 0.25 m, and vaults were to be tied to the walls via metal anchors and ties to contain the thrust. Regarding the roof structures, at that time made predominantly of wood elements, the connection with vertical walls was to be made 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 have the affected floors/part of the structure demolished rather than repaired.

The next destructive earthquake to hit Norcia was the 1979 event in Valnerina. According to Reale et al. (2004) around 773 out of 934 buildings were assessed, corresponding to 83% of the total proportion. Of these, only 10% had ring beams while up to 10% was classified as near collapse and 40% as substantial structural damage (Favali et al, 1980). Among these, several heritage structures previously refurbished (i.e. churches) and extensive portions of the city walls. According to this study, the majority of collapsed buildings were observed along Corso Sertorio, severely weakened after the demolition campaign promoted by the fascist regime (Cederna, 1979), highlighting that the changes in urban layout substantially affected the overall behaviour of the building compounds. The 1979 seismic event triggered the 1981 Regional Law n.34 (Regione Umbria, 1981), which recommended a number of interventions for repair and strengthening of the damage buildings: grout injections of concrete mortar and thick wired meshes and concrete plaster layers (jacketing) on both sides (i.e. internal and external) of the wall connected through the wall's thickness via metal anchors, were two of the suggested practices to stiffen the masonry walls. The placement of internal reinforcement bars grouted with cement mortar injections was advised 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. To ensure the connection between the concrete beams and the masonry walls, reinforcement bars studs were to be used to connect the two parts, placed within the thickness of the wall. It was advised to strengthen the portions of masonry beneath the ring beams through cement mortar injections to guarantee a better connection between the parts.

Two years later, on the 23rd of November 1980, a M_w 6.8 earthquake affected the regions of Campania and Basilicata with registered local intensity X in MCS scale, killing over 3000 people (Westaway & Jackson, 1987). The event enacted the Norme Tecniche per Le Costruzioni In Zone Sismiche (Ministro dei Lavori Pubblici, 1986). These changed radically the approach to strengthening of heritage urban centres, by introducing the complementary concepts of "upgrading" and "improvement" interventions. While the former prescribes that interventions should make the existing building fully compliant with the requirements for new

buildings, the latter allows for interventions to single structural elements, which aim at enhancing the building's safety without modifying the global behaviour.

The Umbria-Marche seismic sequence that started on the 26th of September 1997, with registered local intensity IX in MCS scale (Cinti, 2008), represented another turning point for the seismic regulation of the Italian territory. More than 48 municipalities were affected by the tremors including Assisi, where collapse of the vaults of the San Francesco' Basilica caused the irreversible loss of the Giotto and Cimabue frescos (Spence et al., 1997). The event triggered the emanation of the national law n.61 of 30/03/1998 (Italian Parliament, 1998) which listed the priority actions to undertake to cope with the emergency phase and the various competences at national, regional and local levels to facilitate the reconstruction process. In this latter regard, reference was made to the 1996 seismic code (Ministro dei Lavori Pubblici, 1996) which replaced completely the 1984 version. Among the newer additions of the latest code there was the introduction of the R coefficient to define the seismic forces on the structure.

After the 5.8 M_w earthquake in Molise in 2002, remembered for the death of 27 children and 1 educator in the school of San Giuliano di Puglia, the OPCM n.3274/2003 (OPCM, 2003) was emanated. This transitory document was meant to give a more detailed seismic classification of the Italian territory and to provide technical regulations for the reconstruction following a performance-based approach. The document represented a draft upon which the Commission designated by the Ministry of Infrastructures and Transport, with Ministerial Decree n 113/AG/30/15, worked for the definition of the National Technical code, which followed the Law n. 64/74 of the DPR 380/2001 (Italian Parliament, 2001) In the Ordinanza, all the national territory was classified according to four zones of decreasing seismic risk. The first three classes corresponded to the ones defined by the n.64 law of 1974, while the newly added fourth zone was established to classify the areas for which the adoption of seismic regulations could still remain optional (Italian Parliament, 2001).

The Italian legislation regulating the expected seismicity of the national territory and the corresponding seismic design and strengthening provisions has been further updated in the last decade, by the Ministerial Decree of the 14/09/2005 (Ministry of Infrastructure, 2005) which fully adopted the scheme of the seismic classification outlined in the 2001 Decree.

The 6.3 M_w earthquake in L'Aquila in 2009 with registered local intensity VIII in MCS scale caused the death of 309 people and more than 80000 people to be displaced from their homes, triggered the Ministerial Decree of 14/01/2008, also known as NTC2008 (Ministry of Infrastructure, 2009). Among the major changes with respect to the previous 2005 Code there were the revised concept of 'seismic zone' (i.e. not used to define the value of acceleration at the site which was instead calculated considering the geographic location of the building considered), the compulsory introduction of the ductility check for all the buildings except for the ones in seismic zone 4, and the introduction of geotechnical and structural checks for the foundations (Ministry of Infrastructure, 2009). Of particular importance for the evaluation of the seismic performance of masonry heritage structures and the definition of the most suitable prevention strategies to adopt, the Code for Cultural Heritage and Building Environment Protection was first drafted in the 1974 Seismic Code and later included as a supplementary section within the NTC 2008 (Ministry of Infrastructure, 2009). As stated in the official document, although the steps of buildings' data acquisition are the same as the ones outlined for ordinary structures, the outcome in terms of final safety judgment and actions to undertake to enhance the building performance must be specifically tailored in accordance with the specific heritage value. Consequently, new limit states and new indices of seismic safety are defined in accordance with the historic and architectural value of the building considered and each building undergoes the evaluation both in light of its real use and its class of importance

(Ministry of Infrastructure, 2009). The Central Italy sequence began with the M_w 6.0 Amatrice earthquake on the 24th of August 2016 with epicentre in Accumoli (i.e. 16.38 km straight line distance from Norcia), continued with two events in October, the M_w 5.9 event on the 26th with epicentre located in Castelsantangelo del Nera near Visso (i.e. 12.50 km from Norcia) and the M_w 6.5 event on the 30th with epicentre at around 7km from Norcia, and concluded with the 5.6 M_w shock in Montereale with epicentre located 31.01 km distance from Norcia. The four main shocks of the swarm are presented in Fig 2: the first three of the sequence registered a local intensity IX in MCS scale, while the last one an intensity of VIII (USGS, 2017).
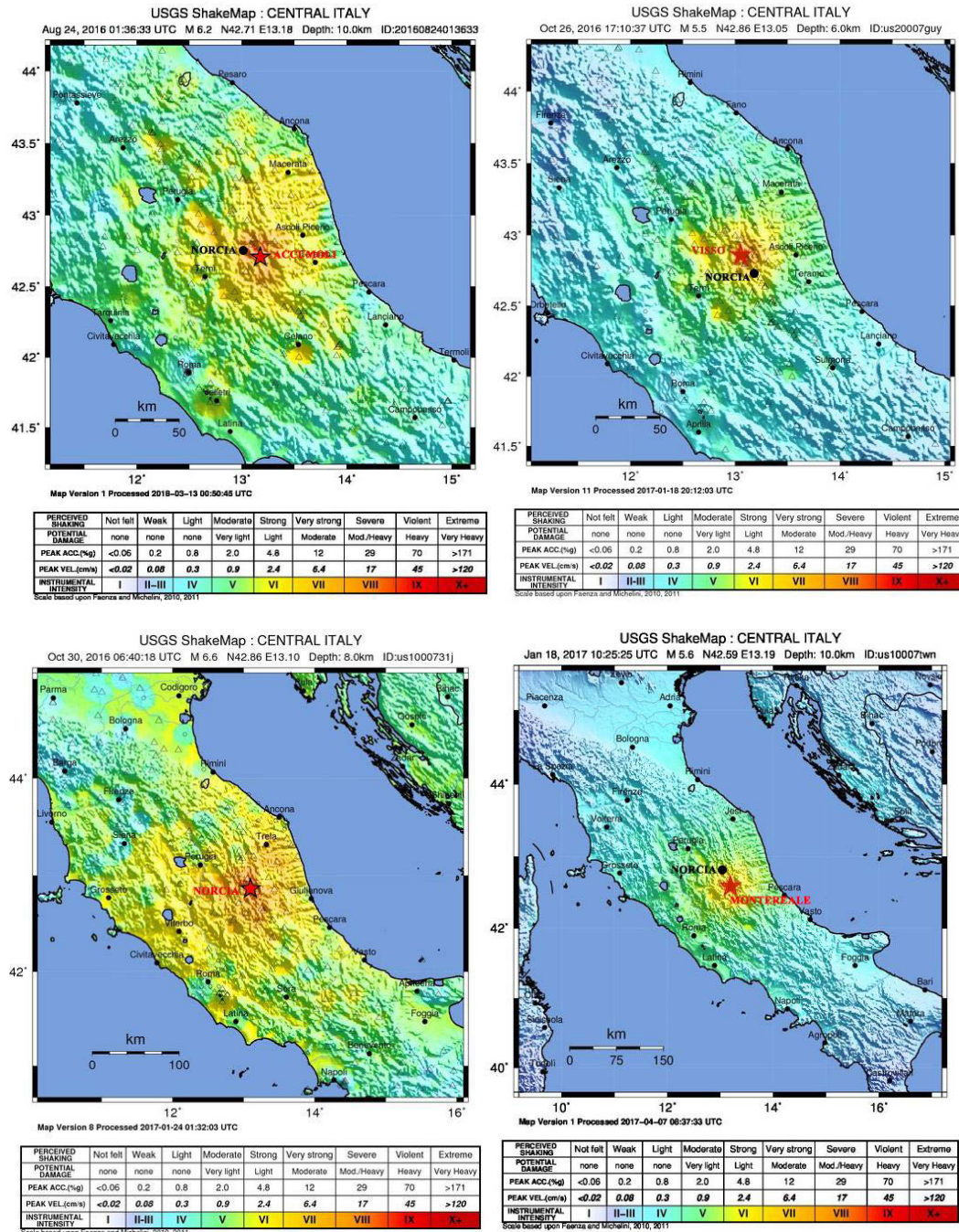
Figure 2: Shake maps of the three main events in the sequence. M_w 6.0 August 24, 2016 (top left), M_w 5.9 October 26, 016 (top right), M_w 6.5 October 30, 2016 (bottom left), M_w 5.6 January 18, 2017(bottom right) (USGS, 2017)

The latest 2016/2017 seismic events triggered the update of the national technical standards (i.e. NTC) later approved with the Ministerial Decree 17/01/2018 (Ministero delle

Infrastrutture e dei Trasporti, 2018). The current seismic code, NTC2018 is the reference document to which interventions for either repair or reconstruction in historic centres, will have to comply in relation to the new masonry buildings construction, the updated version of the code introduced the confined masonry as one of the preferable construction systems in seismic areas, the design of which must follow the UNI EN 1996 (CEN, 2005) and UNI EN 1998 (CEN, 2004); new minimum thickness for masonry brick walls were also introduced, since this highly affect the type of failure mechanisms. Similarly, new minimum thicknesses for mortar joints must be defined according to the height of the structure. With regards to the specific class of heritage buildings at risk, the new Code specified the importance of conducting a preliminary safety check to be followed by an 'improvement'. In addition, particular emphasis is devoted to distinguish the global and the local failure mechanisms, 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 historic building fabric of historic mediaeval 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 at urban level, 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 Apennines. The cumulative effect on damage of such sequences and the quantification of the beneficial effects of strengthening are the focus of the remaining of the paper. The methodology developed to analyse such effects is presented in section 3 while section 4 discusses the results obtained.

3. Methodology

The objective of the study is twofold: to analyse the accumulation of damage due to the sequence of seismic events of 2016 and to determine the role of strengthening measures to control and limit such damage.

3.1 Analysis of cumulative damage

For the analysis of cumulative damage, the damage levels on residential buildings 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 trained personnel of the Seismic Risk Service of Umbria Region. The compiled list of buildings assessed was received *brevi-manu*, after the establishment of an official data protection agreement between the Civil Protection of the Umbria Region (http://www.cfumbria.it/index.php?s=602), and the authors. The AeDES damage levels were further compared with an empirical damage assessment conducted remotely using 'virtual walks-through' the streets of Norcia. This was made possible by the collection of chains of 360-degree images during a survey conducted by the authors in September 2017.

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; Set 2 documents the damage recorded from the 4th of November until the 9th of April 2017; Set 3 documents the situation at September 2017 as surveyed by the authors from the 1st to the 9th of September. In Set 1 the number of buildings assessed was 439, while the number of buildings assessed in Set 2 was 791. This number breaks down into the

following proportions: 352 buildings undergone to a new assessed, 170 buildings were found in a worsened damage condition in comparison to the previous one, 165 building were instead found in an unaltered damage condition and, lastly, 104 buildings whose assessment was taken from the previous results. The number of units surveyed via OD camera in Set 3 was 519. The total number of buildings of which at least one survey has been done is 854, however the number of buildings for which there is information from the three phases is 200. More information regarding the buildings surveyed is provided in the results section.

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 assessment form (Baggio et al., 2007) is the third draft after the very first AeDES form, used after the Umbria Marche earthquake in 1997 and tested again after the Pollino seismic sequence in 1998 (Baggio et al., 2007), and a second draft (05/98), improved after these site experiences. The current version is made of eight sections, namely building identification, building description and metric data, building typology (i.e. horizontal and vertical structures types and layout), damage to structural elements; damage to non-structural components; assessment of external risk induced by other constructions, soil and foundation; and usability assessment. As a result of this data, 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, firstly a screening of the damage to each individual structural element of each individual building is carried out, by analyzing Section 4 (i.e. damage to structural elements) of the AeDES form. The correspondence between the damage levels (D_i) of the AeDES form and the damage grades (DS) of the EMS-98 (Grünthal, 1998) is obtained by correlating the level of damage extension collected (i.e. D_i <1/3, 1/3< D_i <2/3, D_i >2/3) of each of the six structural components (vertical structures, floors, stairs, roof, infills/partitions, pre-existing damage) to each corresponding grade according to a correlation matrix. Previous similar cases have been presented in the work of Augenti et al. (2004), Del Gaudio, et al (2016) and Masi, et al (2016).

The damage assessment conducted via OD camera, a well-established and expeditious tool already tested in other field missions (Stone, Putrino, & D'Ayala, 2018b), was carried out to collect an independent and primary source of damage data by the author to be compared against data collected via AeDES, to evaluate the damage progression across the timeline. The camera model used during September 2017 field investigation was the Ricoh-Theta S. When surveying, the camera was attached to a pole and held above the photographer head while following a number of selected routes previously followed by the AeDES surveyors. The chains of OD images were then uploaded onto the web-platform Mapillary (Mapillary, 2018) and used to conduct a 'virtual survey' to assess the level of damage much in much the same way that engineers completed the field survey. A distance of 8 to 10 meters was left between each photo. The Set 3 of damage data is obtained after having assigned the qualitative judgment of the damage observed to the damage grades scale proposed by Grünthal (1998) as shown in Table 1. This was sometimes difficult to achieve due to poor image quality or objects obstructing the view, especially when assessing lower damage grades. It was therefore decided to aggregate the moderate and substantial damage grades (i.e. DG2-DG3) and the very heavy and destruction grades (DG4-DG5).

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

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. No fall of loose stones from any part of the building.
DG2-DG3 Moderate (MD) to substantial (SD) damage	MD: the building shows deep cracks in many walls. Fall of plaster pieces, collapse of small parts 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

The output of the three sets is mapped on ArchGIS (ESRI, 2011) for comparison. 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. Results are shown and discussed in section 4.1.

3.2 Efficacy of strengthening measures

The efficacy of strengthening measures implemented through the ages and the evaluation of the resulting building performance is quantitatively assessed using the FaMIVE procedure (D'Ayala & Speranza, 2003, D'Ayala Paganoni 2011) This is applied to a subset of 111 facades, corresponding to 82 buildings surveyed by the author.

The FaMIVE procedure provides an on-site investigation form and requires the surveyor to collect a series of information related to the geometry, layout and distribution of openings, the position of restraining elements, and the 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 minimum collapse load factor, i.e. the minimum value of lateral acceleration which will cause their overturning or in-plane failure. The procedure uses the failure mechanism triggered and the value of lateral capacity to assign the building into one of four classes of vulnerability. Previous applications of the procedure (Bernardini et al 2008) have defined a robust correlation between these vulnerability classes, the AEDES classes and the EMS '98 damage scale (Grunthal et al 1998).

The FaMIVE procedure was applied to the set of 111 façades assuming six difference scenarios, each one assuming a different distribution of retrofits, in an attempt to reproduce the structural characteristics occurring at different times in history, ranging from the pre-1959 earthquakes to the condition observed at site during the 2017 campaign.

Case 1 represents the pre-1860 code scenario, where no restraining elements were implemented (i.e. ties and buttresses), 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 and includes f the provisions developed after the 1859 earthquake (i.e. Building Regulation after the Royal Decree). Ties and buttresses started to be implemented but, only to a small portion of the sample (i.e. 13% of the sample, corresponding to half of the real proportion of buildings restrained surveyed by

the author), the horizontal structures were still the original wooden ones in all the buildings, and the majority of buildings were still of no more than 2-floors height. **Case 3** represents the pre-1979 earthquake scenario. According to the macroseismic survey conducted by Favali, et al (1980), there were four main construction classes, namely A, indicating the buildings made with poorly dressed mortar and on irregular stone layout, with roof in 'camorcanna' (local type of wood) and wooden horizontal structures; B indicating the buildings with a better quality of mortar and stones geometric and material characteristics, with roofs made in wood and metal elements; C indicating buildings with ring beams and finally D, used to indicate well designed wood or reinforced concrete structures. Only the first three types were encountered in the historic city centre of Norcia. According to the field investigation and following the proportions of buildings assessed in this study, 58% of the buildings are classified as A, 37% B and 5% C. It is also assumed that traditional restraining elements (i.e. ties and buttresses) were implemented to a wider portion of the buildings sample than case 2 (i.e. 25%, double of the number considered in Case 2 also corresponding to the number of buildings restrained surveyed during the September 2017 campaign), the quality of masonry walls was improved and a minority of the buildings (5%) had ring beams. **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 on top of the external masonry walls and the substitution of wooden horizontal structures with concrete slabs, for both floors and roof. Also a bigger proportion of buildings was also characterized by a better-quality of masonry. **Case 5** shows 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 condition surveyed by the author in September 2017, during which it was possible to observe the implementation of the pre-1860 Building Regulation's prescriptions and some of the ones listed in the 1981 Regional Law, all summarized in Table 2. The scenario 6 also includes the information on horizontal structures, roof type and masonry fabric which, when not accessible during the 2017 campaign, are taken by 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	% encountered in the sample
Post-1860 Code	RE = Ties	25%
Post-1860 Code	RE = 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 to implement within the FaMIVE procedure to resemble the main characteristics of the building sample across the 6 cases.

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

Case	Masonry Type	Assumed FC	Assumed C [MPa]	Floor Type	Roof Type	RE Type	RE %
Case 1	M3	0.3	0.00	WF; VF	100% R1	--	--
Case 2	M3	0.3	0.25	WF; VF	100% R1	T B	25% 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	100% 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	90% R2 10% R1	T B RB	25% 33% 81%

Three different masonry typologies are used, namely M1, M2, M3 to indicate decreasing quality of stones and mortar. This helps differentiating the pre and post-1860 and the following improvements after the 1997 provisions. In combination with the three types of masonry, different values of friction coefficient (FC) and cohesion (C) have been consistently chosen, which change across the cases. In terms of flooring typologies, three different types are used, namely wooden type (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. In case of basement and in consideration of the modest percentage of buildings within the sample, only one type is define, namely barrel vaults (VF), also in accordance with the study of Borri et al (2017). For what concerns the roof structures, the more traditional case of timber joists with mud and tiles (R1) is used to describe the condition pre-1979 while the case of lightweight tiles and concrete beams (R2) indicates the post-1979 replacement. With reference to the restraining elements (RE), the more traditional post-1860 provisions suggest ties (T), buttresses (B) and anchors (A), while the post-1979 provisions refer to the use of concrete ring beam (RB).

The material parameters and the type of structures, both the flooring and roof systems, presented in Table 3, are further described in Table 4 and 5.

Table 4 Masonry Fabrics: parameters implemented in FaMIVE

Masonry Type	Dimensions l x h x w [m]	Overlapping length [m]	Specific weight [kN/m³]
M1	0.30 x 0.20 x 0.15	0.15	20
M2	0.27 x 0.17 x 0.12	0.12	19
M3	0.25 x 0.15 x 0.10	0.10	18

Table 5 Horizontal structure types (flooring and roof system): parameters implemented in FaMIVE

Horizontal structure	Weight of horizontal structure on façade [kN/m²]	Weight on horizontal structures on side walls [kN/m²]
Wooden Structures WF	2.25	0.7
Vaulted Structures VF	3.5	1.75
Concrete Structures CF	4	1.8
Reinforced Wooden Structures RWF	4	1.2
Timber joists with mud and tiles (R1)	2	0.4
Lightweight tiles and concrete beams (R2)	4	2.4

Evaluating the six cases will show any shift in 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

The empirical assessment carried out to evaluate the progression of damage across the swarm of seismic events was evaluated first in terms of change in usability of the buildings and then in terms of corresponding damage grades. The sample for which set 1 and set 2 of AeDES forms are available is used.

Fig 3 top let 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 October events (Fig 3 top right), over 40% of buildings were rated temporarily unusable (class B), while 32% were categorised in class E. This increment in damage is to be ascribed to the repeated seismic activity. The fact that the October events recorded a greater acceleration in Norcia and hence caused higher damage is detected by the increase in buildings classified as B, C and E in the set of building for which there was no prior assessment, hence no damage from previous event (Fig 3 bottom). It is noticeable that this set has a lower proportion of building in class E than the set undergoing repeated assessment.

Usability Results Post 24/08/2016 event

Usability Results Post 30/10/2016 event

Usability Results Post 30/10/2016 Event - Set with no prior assessment
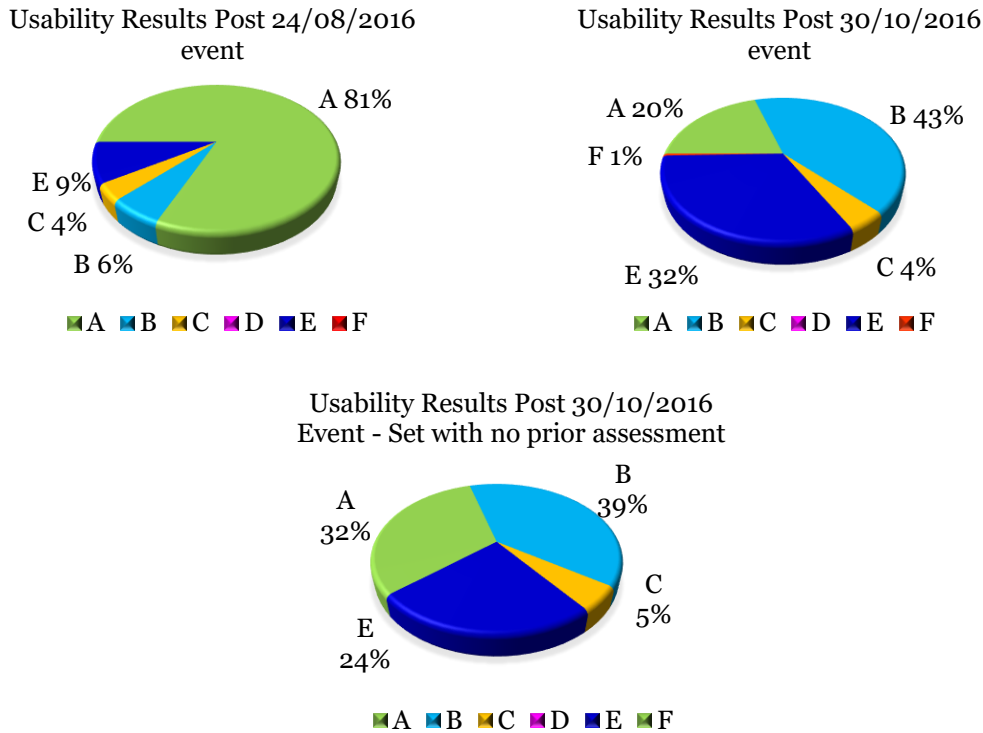
Figure 3 Comparison between pre and post-October events of usability judgments (AeDES)

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. Most importantly there were no casualties associated with the October events.

Because the 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. It is hence appropriate to compare the results obtained in terms of damage classes with a totally independent survey, such as the one constituting set 3. A clearer understanding of the progression of damage across the pre and post- October 2016 seismic events (via AeDES forms) and the September 2017 damage condition (via OD imagery), can only be achieved by comparing the buildings'damage conditions ranked according to the EMS-98 damage scale (Grünthal, 1998). This second assessment makes use of a smaller dataset of buildings, namely 200 buildings, for which all three assessments are available.
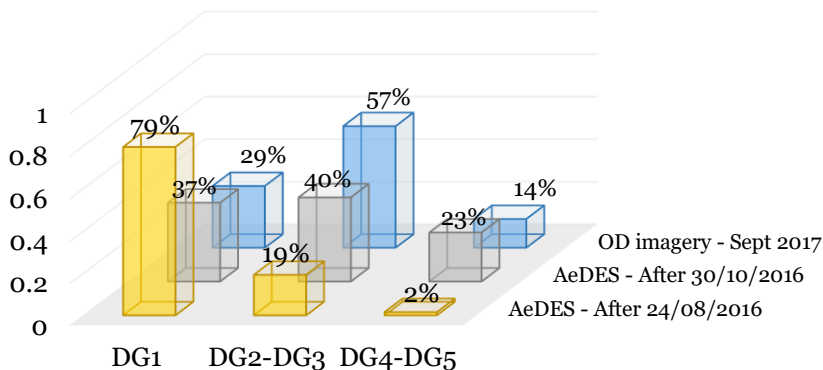
Figure 4 Comparison of all the proportions of buildings via AeDES and OD imagery

Figure 4 confirms the substantial shift in damaged buildings between the two sets of AeDES surveys, which demonstrates the effects of the seismic events on the building fabric of the town. 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 damaged' or 'slightly damaged' drops to more than half of the pre-October event phase (from 79% 37%). A discrepancy of up to 20% is present between the AeDES form and the OD based survey, with an apparent overestimate of damage DG2-DG3 in the OD 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 the they will be assigned a minimum damage level DG4. Moreover, while the AeDES forms benefit from internal access to the buildings, the OD 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 OD compares well with the ones computed 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 a very similar trend to the one presented in Figure 4. While there is an increase in undamaged building with respect to the whole sample in the first set of data, the second and third, collected after repeated shaking, do not show a substantial difference, highlighting the limited capacity of these strengthening techniques to withstand repeated seismic action.
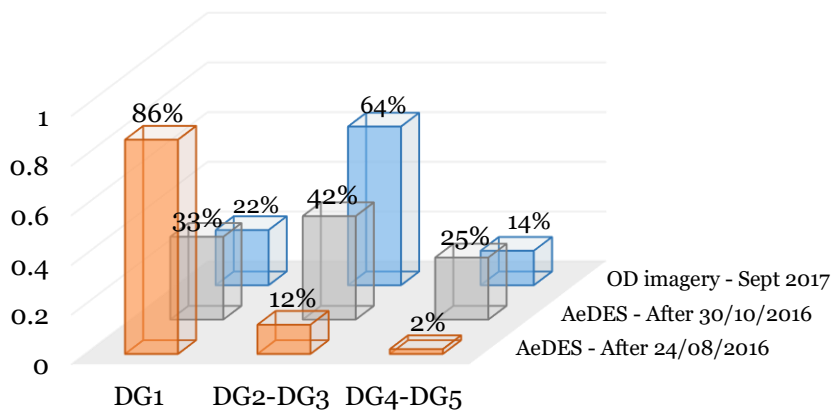
Figure 5 Comparison between proportions of damaged buildings traditionally strengthened across the seismic events

The results presented in Fig 4 and 5 are also mapped, to allow the visual correspondance between damage distribution and traditional strengthening measures implementation within the subset of buildings surveyed. Fig 6 shows the comparison in terms of damage grading between the AeDES survey conducted after the 24/08/2016 event and the corresponding assessment after the October events. A substantial proportion of buildings worsened the damage condition toward moderate/structural damage, with very few cases of buildings undergoing to heavy damage leading to collapse, confirming that building at risk of collapse had been damaged in the previous events.

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.
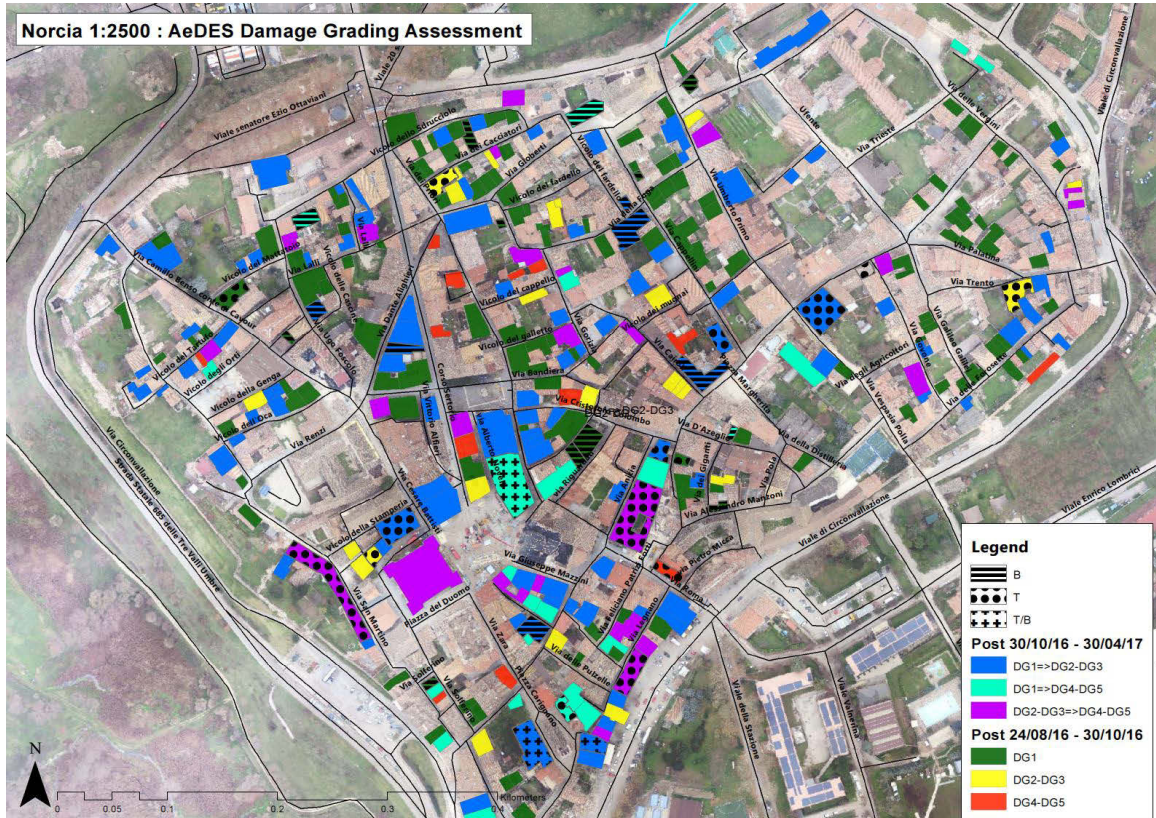
Figure 6 AeDES assessment after the 24th August 2016 event
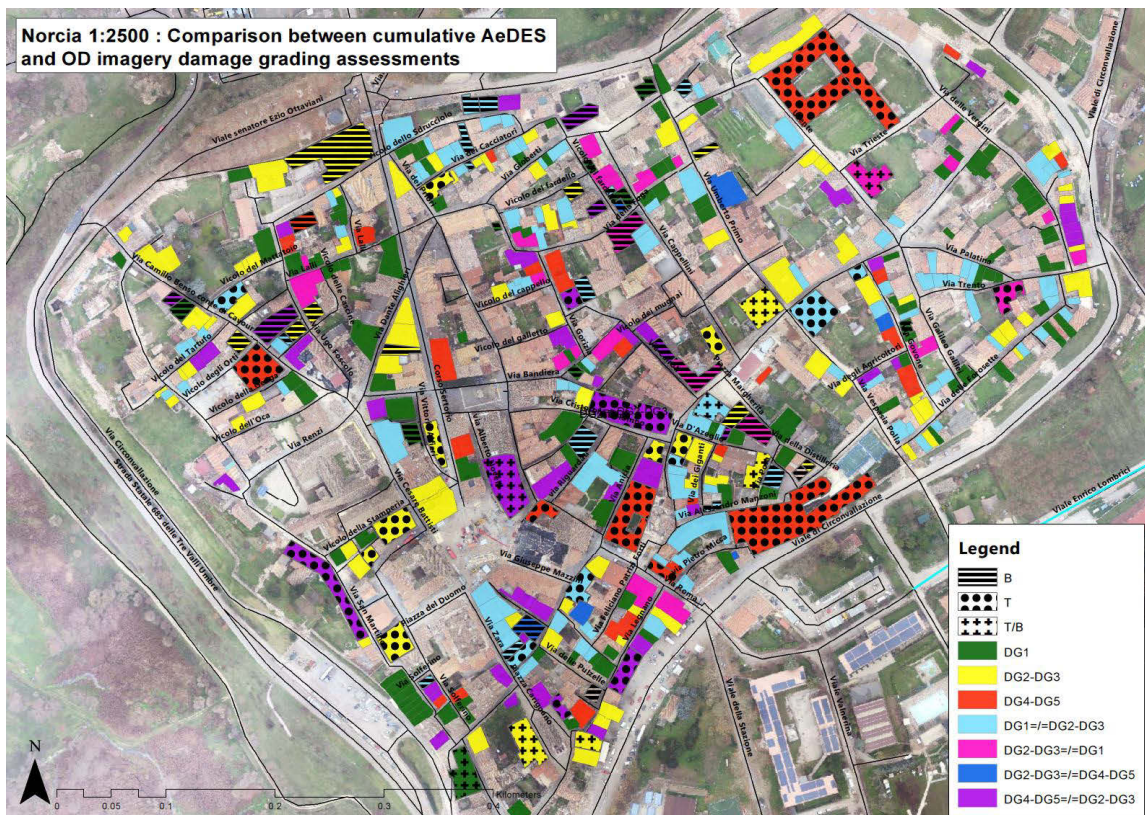

Figure 7 AeDES assessment after the 30th October 2016

After having conducted the qualitative assessment of the damage progression along the timeline of seismic events, the quantitative assessment is carried out via FaMIVE and presented in following section.

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. The six cases presented in section 3.2 are compared in terms of overall vulnerability, for configuration with implemented strengthening and with different types of materials structural characteristics.

4.2.1. Failure Mechanisms and overall buildings' vulnerability

Figures 8 to 12 show the change in failure mechanisms and the change in the overall sample's vulnerability across the six cases.
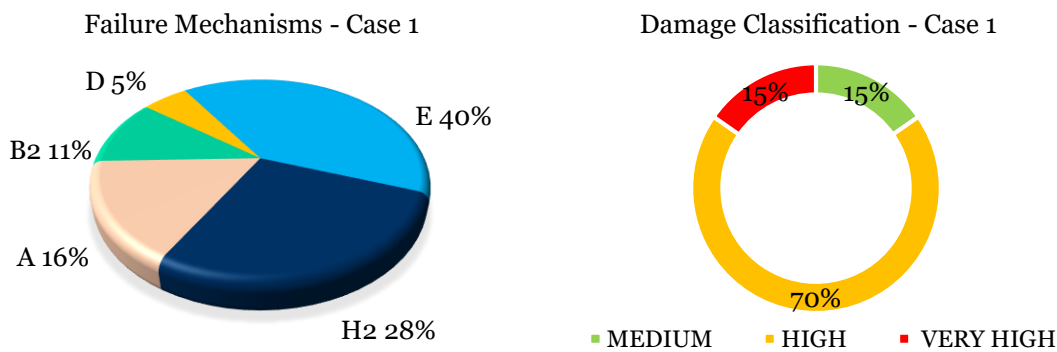
Figure 8 Failure Mechanisms and overall vulnerability Case 1
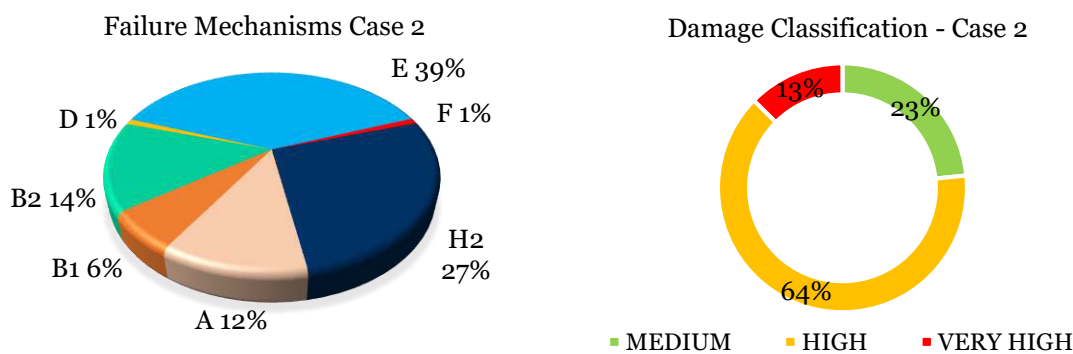
Figure 9 Failure Mechanisms and overall vulnerability Case 2

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.

Failure Mechanisms Case 3

Damage Classification - Case 3

Figure 9 Failure Mechanisms and overall vulnerability Case 3

Failure Mechanisms Case 4

Damage Classification - Case 4
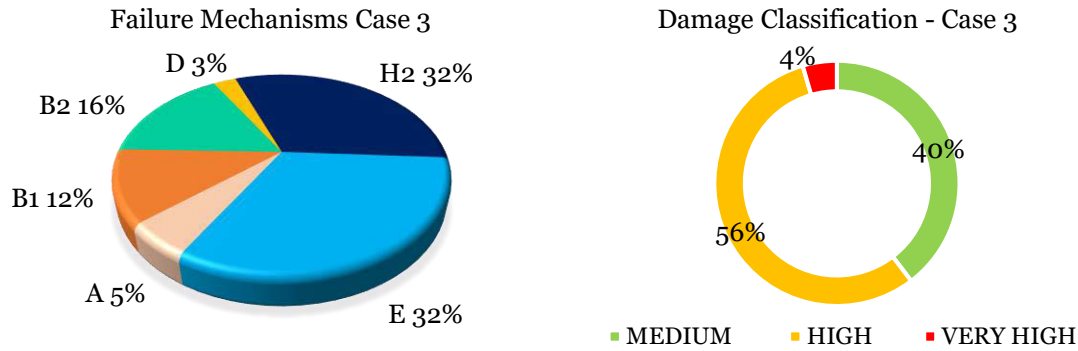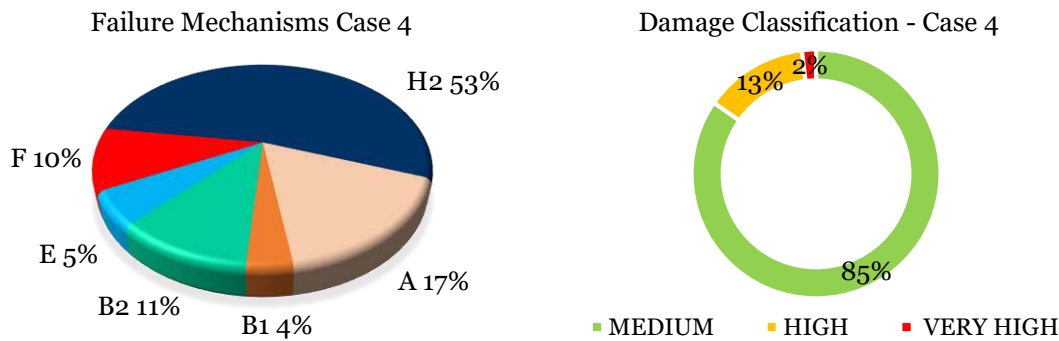
Figure 10 Failure Mechanisms and overall vulnerability Case 4

Case 3 represents the pre-1979 earthquake condition and case 4 the condition where the implementation of the major strengthening measures suggested in the Regional Law n.34 (Regione Umbria, 1981), are in place. 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 expectation of the Code.

Failure Mechanisms Case 5

Damage Classification - Case 5
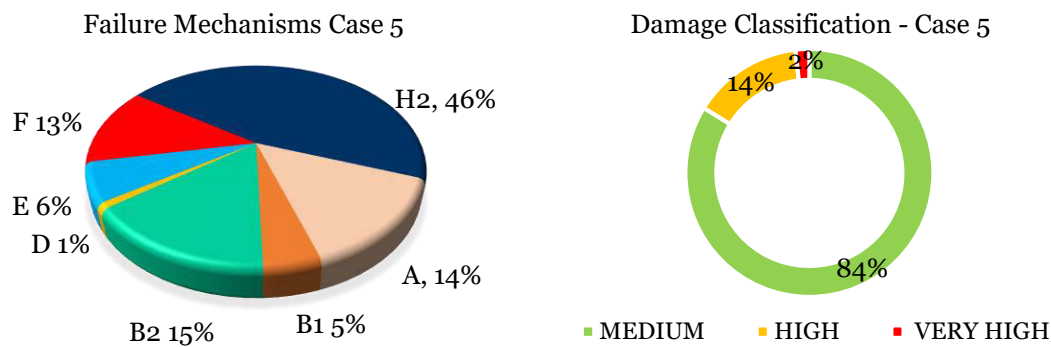
Figure 11 Failure Mechanisms and overall vulnerability Case 5

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 the buildings. The ring beams are not as effective as expected, due to other weaknesses.
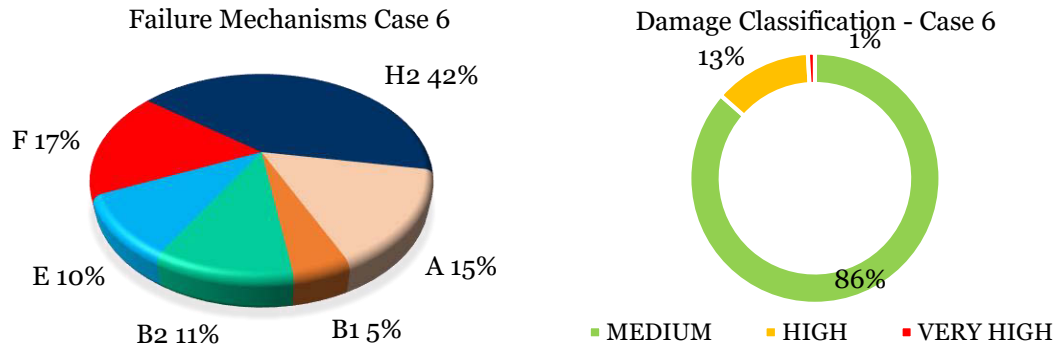
Figure 12 Failure Mechanisms and overall vulnerability Case 6

4.2.2. Damage distribution across the phases of the sample

Beside the evaluation of the change in failure mechanisms the cumulative distribution of collapse load factor for each case can be analyzed to determine the probability of damage in relation to specific strong motion events.

To this end, the values of PGA at the site extracted from the ESM database (Luzi et al., 2016) for the main shock of August and October 2016. According to database, among the several stations located in the surroundings of Norcia town, the two of relevant in terms of location and quality of records are the NRC and the NOR stations. The former is a free-field station, located just outside the city walls near Porta Orientale, facing NE. The surrounding morphology of the terrain is a slope, with average angle i<=15, in both cases the EC8 soil classification is B. The latter is located at the basement of an historical building facing St Benedict square. According to ESM database, the signals recorded at NRC station are classified as 'good quality records', while the ones of NOR station are defined of 'acceptable quality'. However, since the purpose of the current analysis is to evaluate the extent of damage to the masonry buildings of the historic residential buildings of Norcia, the NOR recordings are considered more relevant. The values of peak ground acceleration (PGA) of the three events recorded at NOR station are taken from ESM database (L. Luzi et al., 2016), and reported in Table 6

Table 6: Summary of PGA values for the three main events of the Central Italy seismic sequence

Seismic event	PGA (g) at NOR station
24th of August – Amatrice	0.249 g
26th of October – Norcia	0.215 g
30th of October – Norcia	0.312 g
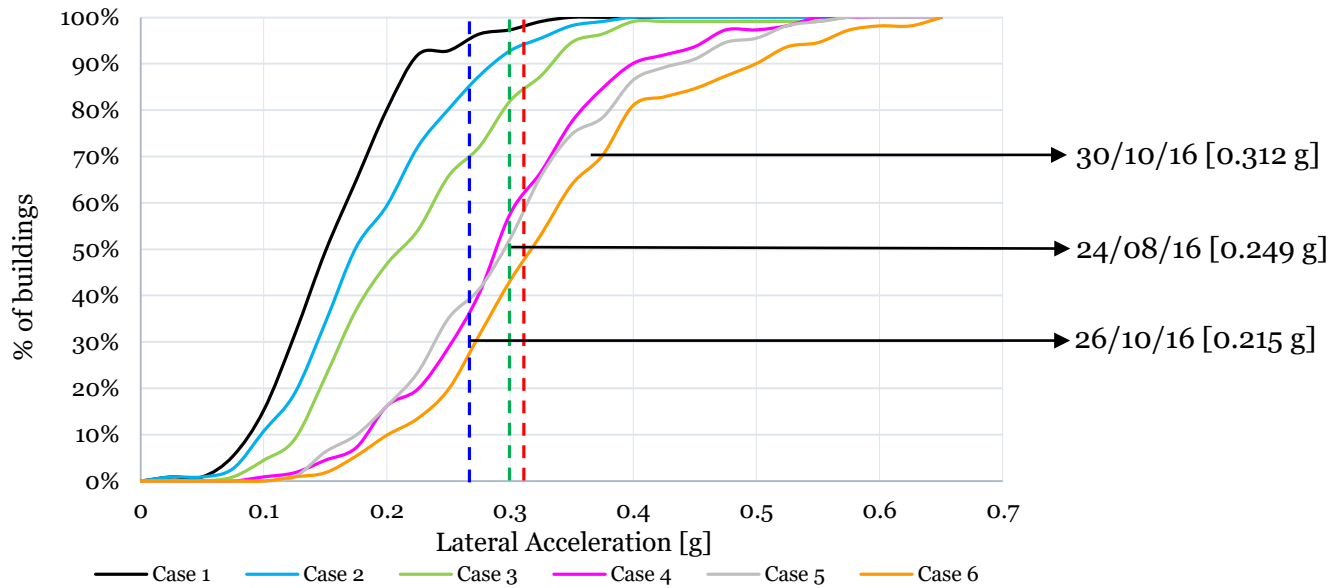
Figure 13 Damage distribution across the six Cases and indication of the 3 main shocks of the 2016 Central Italy sequence.

Fig 13 and Table 7 shows that case 1, referring to the state of the buildings prior to the implementation of any strengthening provision would have experienced up to 30% of building partial or total collapse. However, according to the latest conditions surveyed, only a very modest percentage of buildings would undergo collapse while half would have some moderate to major damage. This might appear at odds with the results from the empirical survey which identified at least 13% of buildings in damage state DG4-DG5. This should be ascribed to the cumulative effect of the repeated strong motions.

Table 7 Distribution of damage states for the six scenario

Damage states			
Case	DG0-DG1 (%)	DG2-DG3 (%)	DG4-DG5 (%)
1	4	66	30
2	8	74	18
3	15	76	9
4	34	63	3
5	35	63	2
6	50	49	1
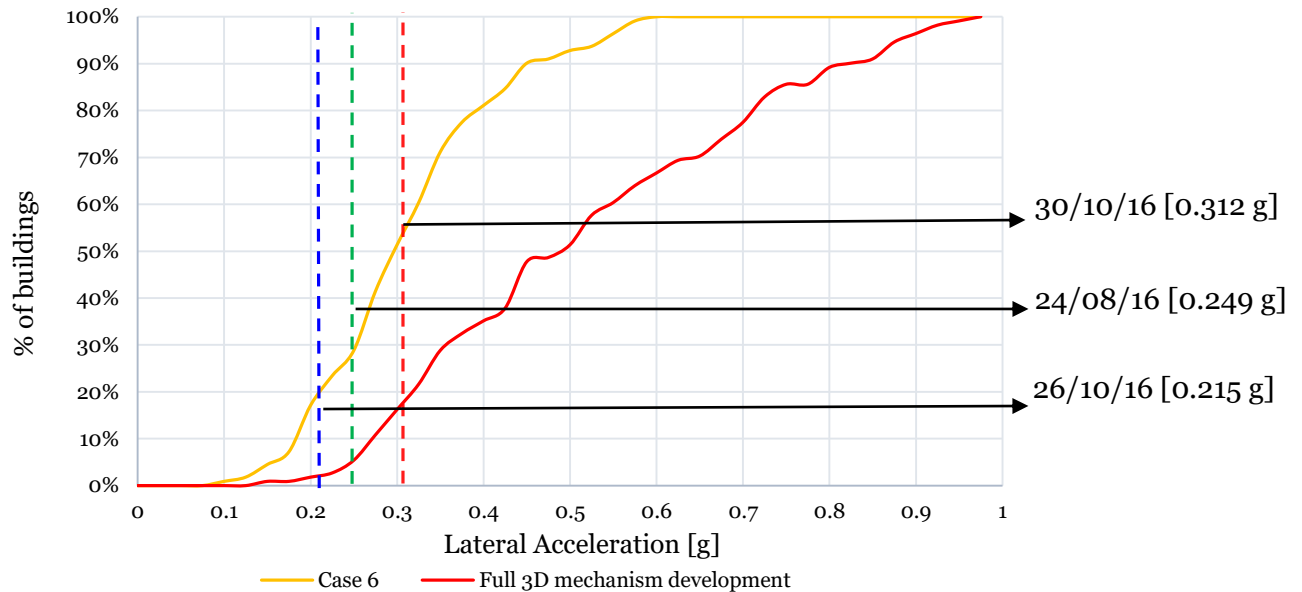
Figure 14: Comparison between latest building condition (as surveyed) and assumed full 3D mechanism development condition

Fig 14 shows the comparison between the condition of the buildings as they were surveyed during the September campaign (i.e. Case 6) and the hypothesised 3D mechanisms behaviour fully activated. More specifically, this latter condition assumes that only F and B1 mechanisms activate, which are two of the mechanisms that are triggered after the restraining elements in place reach failure. The proportions of buildings failing in this latter condition is almost 40% less when considering the latest October event (i.e. red dotted line), 25% less if the Amatrice event (i.e. green dotted line) is considered and around 20% less when considering the early October event (i.e. blue dotted line). The orange curve already indicates a quite substantial reduction in terms of percentage of buildings that get damaged in comparison to previous cases, thus demonstrating that the suggested strengthening measures worked to limit the out-of-plane failure and enhance the box-like behaviour of masonry structures.

5. Conclusions

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 this paper in light of the evolution anti seismic building regulations and standards, both at local and national levels. Different damage assessment methods have been used to carry out the analysis and the results have been compared both in qualitative and quantitative terms. The FaMIVE results, both in terms of failure mechanisms and overall damage states of the sample, show a good agreement with the site observations. The analytical approach is also able to well capture the sample's changes when the different scenarios are hypothesized and outline what retrofit strategy are needed at urban level to increase the resilience of heritage centres.

6. Ongoing work and outcomes

An extract of this research has been published on the Special Issue of Disaster Risk Management of Cultural Heritage of the Disaster Prevention and Management Journal, and is currently under revision process.

7. Acknowledgments

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