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ORIGINAL RESEARCH PAPER

Seismic performance of non-structural elements during the 2016 Central Italy earthquake

D. Perrone[1] · P. M. Calvi[2] · R. Nascimbene[3] · E. C. Fischer[4] · G. Magliulo[5]

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Abstract Non-structural elements represent most of the total construction cost of typical buildings. A significant portion of the total losses in recent earthquakes worldwide, has been attributed to damage to non-structural elements. Damage to non-structural elements occurs at low levels of ground shaking, and can significantly affect the post-earthquake functionality of buildings. However, in Europe, limited prescriptions are provided in the codes for seismic design of non-structural elements and this may partially explain why it is so common for these elements to perform poorly during earthquakes. This paper describes the observed damage to non-structural elements following the 2016 Central Italy earthquake. The most commonly damaged elements were partition walls, ceiling systems, non-structural vaults, chimneys, and storage racks. As a result, it was highlighted the need to introduce seismic regulations devoted to improving the seismic performance of non-structural elements and to reduce the associated economic losses, loss of functionality, and potential threats to life safety.

Keywords Non-structural elements · Central Italy earthquake · Post earthquake reconnaissance

✉ R. Nascimbene
roberto.nascimbene@eucentre.it

[1] University School for Advanced Studies IUSS Pavia, Pavia, Italy

[2] Department of Civil and Environmental Engineering, University of Washington, Seattle, USA

[3] European Centre for Training and Research in Earthquake Engineering, Via Ferrata 1, 27100 Pavia, Italy

[4] Department of Civil and Construction Engineering, Oregon State University, Corvallis, OR, USA

[5] Department of Structures for Engineering and Architecture, University of Naples Federico II, Naples, Italy

1 Introduction

The August 2016 Central Italy earthquake raised, once more, awareness of the seismic vulnerability of Italian buildings both from a structural and non-structural point of view. This seismic event caused the death of 297 people and economic losses estimated around 11 billion euros (Derakhshan 2016). The casualties were mainly attributed to the collapse of old unreinforced masonry buildings, while the estimated economic losses include full rebuilding costs and repair of structural and non-structural damage (Derakhshan 2016). As will be discussed in the following sections, the main non-structural damage was related to the failure of masonry infills and partitions, ceiling systems, storage racks as well as architectural elements in heritage buildings. This outcome is not surprising, considering that non-structural elements (NSEs) make up the majority of the total monetary investment in typical buildings (Miranda and Taghavi 2003) (Fig. 1).

Even if the performance of the structural systems were designed and detailed for seismic forces to allow the immediate occupancy after a seismic event, the failure of NSEs such as partitions, ceiling systems, and piping systems could significantly affect the performance level and the functionality of the buildings after the earthquake event. Hospitals and schools play a critical role in a community after an earthquake. Many schools serve as emergency operating facilities after a major disaster and, therefore, must be able to be occupied after an earthquake. Hospitals and healthcare centres must be fully operational after earthquakes to protect the lives of patients and healthcare workers as well as to provide emergency care and medical treatment to the increasing number of patients who are driven to health facilities in the first hours after significant seismic events. Therefore, addressing non-structural issues is particularly important for critical facilities, such as hospitals and schools.

Previous researchers have shown that after an earthquake, it is common to observe that losses from damage to non-structural components far exceed losses from structural damage (Kircher 2003; Bachman 2004; Filiatrault and Sullivan 2014). These losses can be direct or indirect. Direct losses from the earthquake are related to property loss, while indirect losses can be more difficult to quantify.

Researchers have documented examples of indirect loss due to previous earthquakes. One example is the damage suffered in the Chilean wine industry following the 2010 Maule earthquake (Zareian et al. 2012), as wine production represents one of the major economic driver in Chile. The earthquake caused damage to the fermentation tanks and

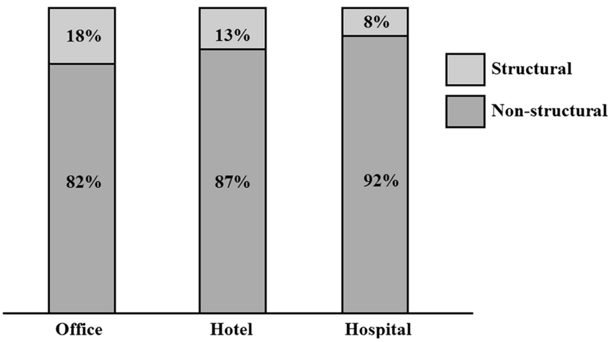


Fig. 1 Relative investments in typical buildings (Reproduced with permission from Miranda and Taghavi 2003)

stacked storage barrels. This damage caused the wine production to shut down for several weeks, with enormous consequences to the Chilean economy.

During the same earthquake, the Santiago International Airport was closed for several days due to significant damage to piping and ceiling systems (Miranda et al. 2012). Four hospitals were closed due to structural and non-structural damage while over 10 lost 75% of their functionality, due to damage to fire sprinklers (Miranda et al. 2012). Recently, the vulnerability of NSEs was also observed during the 2016 Kaikoura earthquake that struck the north-eastern area of the South Island of New Zealand. The main non-structural damage observed during this earthquake was related to the failure of ceilings, cladding, partitions, building services, and plant equipment (Baird and Ferner 2017).

Extensive damage to NSEs has often been observed for less intense earthquakes. For example, Braga et al. (2011) reported extensive in-plane and out-of-plane damage to masonry infills in reinforced concrete buildings during the 2009 L'Aquila earthquake. Significant non-structural damage was also observed following the 2012 Emilia earthquake, where storage rack systems in industrial facilities were the most affected components (Ercolino et al. 2012).

The high seismic vulnerability of NSEs can be attributed to two main factors: (1) NSEs do not have the inherent strength and ductility that structural members do, and, therefore, they tend to exhibit damage at low levels of ground acceleration; (2) limited research on the seismic behaviour of NSEs has been conducted and the understanding of their dynamic behaviour is somewhat limited. To overcome this limitation, recent research efforts have been devoted at investigating the seismic vulnerability of some typologies of NSEs such as partitions (Davies et al. 2011; Petrone et al. 2014), ceiling systems (Badillo-Almaraz et al. 2006; Magliulo et al. 2012; Pourali et al. 2017) and piping systems (Tian et al. 2014). In Europe, current codes and guidelines (when available) for NSEs are based on past experiences, engineering judgment and intuition, and are not always implemented in practice. Looking at the European code provisions, uncertainties exist as to how the seismic demand on NSES should be estimated. According to the main international codes (Eurocode 8 2004; ASCE7 2010), the NSEs are generally classified as either acceleration-sensitive or drift-sensitive, based on the main engineering demand parameter affecting their response. By increasing the strength and stiffness of the structure, the storey drift demand may be decreased but, at the same time, the floor accelerations along the height of the building may be increased. As such, it is evident that structural designers are faced with a trade-off between limiting drift and/or acceleration demands. The design of acceleration sensitive NSEs is governed by the peak floor acceleration (PFA) demand of the attachment point at the structure. In the last years some methodologies have been proposed to estimate the PFAs and perform the seismic design of acceleration sensitive NSEs (Pozzi and Der Kiureghian 2015; Moschen et al. 2016; Moschen and Adam 2017). At the same time, some authors have made attempts to propose accurate methodologies to predict floor response spectra for single-degree-of-freedom (SDOF) and multi-degree-of-freedom (MDOF) systems, both for elastic and inelastic structures (Sullivan et al. 2013a, b; Calvi and Sullivan 2014; Calvi 2014; Petrone et al. 2015; Vukobratovic and Fajfar 2016; Adam et al. 2013).

In order to introduce into practice the seismic design of NSEs the use of Building Information Modelling (BIM) technology could be very helpful (Welch et al. 2014; Perrone and Filiatrault 2017), thanks to the detailing of all elements available in Building Information Models. Perrone and Filiatrault (2017) proposed a conceptual framework for the seismic design of NSEs using the Building Information Models. The effectiveness of the procedure has created a simple tool for the automatic seismic design of sprinkler piping systems.

However, despite these and other notable research efforts, significant knowledge gaps still exist and further investigations are required on the seismic performance of NSEs so that structural engineers can design these components and their bracing for imposed seismic demands. This paper describes the most common damage to NSEs observed following the 2016 Central Italy earthquake. The information summarized in the following sections stems mainly from the evidence collected during the post-earthquake inspections and safety assessment. The damage observed during the inspections has been divided by non-structural component: infill walls and partitions, ceiling systems, storage racks, piping systems and architectural elements in heritage buildings. This paper aims to identify the most common causes of damage and failure of these elements. When available, examples of "good practice" have been highlighted for seismic design of bracing for NSEs, to demonstrate how adopting simple seismic measures can prevent non-structural failure, limiting the economic losses and enhancing the level of safety of the buildings.

2 Damage observed during previous earthquakes versus experimental evidence and code requirements

Extensive NSE damage has been observed after all major earthquakes worldwide, leading research efforts to focus on the improvements of NSE performance and on the development of specific guidelines and mitigation details. In this section, a brief overview on the damage observed during past earthquakes and on the experimental evidence for the NSEs analyzed in this paper is provided. In particular, the attention is focused on masonry infills, ceiling systems, piping systems and mechanical equipment.

Lessons from both past and recent earthquakes indicate that the damage to masonry infills and internal partitions is one of the most common observed non-structural damage (Miranda et al. 2012; Braga et al. 2011). Braga et al. (2011) accurately describes the in-plane and out-of-plane failure of masonry infills occurred due to the poor connection with the supporting RC frame after the 2009 L'Aquila earthquake in Italy. The interaction between masonry infills and the RC surrounding frames was widely investigated in the literature both from an experimental (Pujol and Fick 2010; Leal et al. 2017; Petrone et al. 2014; Gallipoli et al. 2010) and numerical (Ricci et al. 2013; Dolšek and Fajfar 2005; Perrone et al. 2016) point of view. Based on the experimental tests, some authors proposed the possible damage mechanisms affecting masonry infilled frames (Shing and Mehrabi 2002; Asteris et al. 2011). Shing and Mehrabi (2002) and Morandi et al. (2017) identified damage typologies for infill walls providing a detailed description of the failure modes that could be observed in masonry infilled RC frames due to a seismic input. The classification proposed by Shing and Mehrabi (2002) takes into account the following four failure mechanisms: mid-height cracking, diagonal cracking, horizontal slip and corner crushing. Sassun et al. (2016) compared the results of different experimental investigations conducted on the most common types of masonry infills present in Italy. The results showed that masonry infills exhibit first signs of damage at drift ratios of less than 0.20%.

According to the experimental studies available in the literature, international codes (CEN 2004; FEMA E-74 2012; FEMA 356 2000) provide some additional measures for masonry infilled framed. FEMA 356 (2000) provides details about the modelling, safety verification and acceptance criteria for concrete existing frames with infills. The code provisions currently in Italy (NTC 2008), and more generally in Europe (CEN 2004), do not provide specific guidance as to how masonry infills should be accounted for in the design process, unless they cause a plan or in elevation irregular behaviour of the building; only some provisions for damage limitation in terms of inter-storey drift are provided. In order to mitigate the damage to masonry infills, the more recent international guidelines suggest to reduce the interaction between the walls and the surrounding frames (FEMA 306 1998; FEMA E-74 2012). The suggested approach generally consists of introducing a gap between the masonry infill and the surrounding frames, along with adequate anchorage details to prevent out-of-plane failure. Innovative solutions have also been recently proposed. One example is the use of sliding joints to simultaneously protect the partition walls from both in-plane and out-of-plane issues (Morandi et al. 2017).

Along with the masonry infills, ceiling systems represent one of the non-structural element types that is more prone to damage during a seismic event. These systems are both drift- and acceleration-sensitive NSEs. Significant damage to ceiling systems was observed during previous earthquakes (e.g. Filiatrault et al. 2001; Dhakal 2010; Miranda et al. 2012), and it was documented that the collapse of the systems jeopardized the functionality of the buildings, and threatened the safety of the occupants. The most common typology of ceiling systems described by different authors after major earthquakes consists of panels supported on a grid of aluminium beams that are hung through metal wires anchored to the floor above (Miranda et al. 2012; Dhakal 2010). These systems were not generally designed for seismic input. The elements showing considerable vulnerability to ground motion excitation include rivet connections at perimeter fixings, connections between cross tees and splices in main tees (Pourali et al. 2014). Some experimental studies were conducted in the last years to characterize the seismic performance of ceiling systems (Badillo-Almaraz et al. 2006; Gilani et al. 2012; Pourali et al. 2017; Magliulo et al. 2012). Badillo-Almaraz et al. (2006) identified the influence of four main variables affecting the behaviour of ceiling systems: the size and weight of tiles, the use of retainer clips, the use of compression posts and the physical condition of grid components. Four limit states of response that cover most of the performance levels described in the codes and guidelines for the seismic performance of non-structural components were defined using physical definitions of damage. Gilani et al. (2012) and Glasgow et al. (2010) developed an experimental procedure and a performance matrix based on limit states to evaluate and qualify innovations and quantitatively assess the efficacy of various code prescribed design and installation requirements. Magliulo et al. (2012) studied the seismic performance of two types of ceiling systems distinguishing three limit states in order to characterize the seismic response of the suspended ceiling systems.

European codes do not provide specific regulations for the seismic design of ceiling systems, the installation procedures are normally entrusted to the manufacturers (and are therefore based on experience and practical needs). Other standards such as ASTM C635 (2017), ASCE7 (2010) and FEMA E-74 (2012) provide more quantitative guidelines for the seismic design and installation of suspended ceilings. FEMA E-74 (2012) prescribes the maximum allowed spacing between the hanger wires at the perimeter wall locations. In addition, some indications regarding the minimum gap between the perimeter walls and the grid members, to allow the free movement of the suspended ceiling systems, and the installation of the bracing systems are also provided (FEMA E-74 2012).

As for the previous NSEs, piping systems are installed in all building typologies and failure of these systems can significantly affect the functionality of buildings as demonstrated during the 2001 Nisqually earthquake (Filiatrault et al. 2001) and 2010 Maule earthquake (Miranda et al. 2012). For fire sprinkler systems, the damage to sprinkler heads and to piping joints are often identified as the main reasons for unintentional water discharge and interruption of water transportation, which consequently leads to insufficient working pressure for the systems (Tian et al. 2015a). Extensive experimental and numerical studies were conducted by Tian et al. (2014, 2015a, b) in order to evaluate the seismic performance of piping systems. Tian et al. (2014, 2015a) studied the cyclic behaviour of piping joints made by different materials and diameters: three full-scale pressurized sprinkler piping specimens made of different materials and joint arrangements were tested with various levels of seismic bracing under dynamic loading on the University at Buffalo Nonstructural Component Simulator. In terms of seismic requirements for piping systems, the Italian code (NTC 2008) and the Eurocode 8 do not provide specific design prescriptions. The National Fire Protection Association Standard for Installation of Sprinklers Systems (NFPA13 2010) is one of the main standards providing design guidelines for seismic bracing of sprinkler piping systems. In order to resist horizontal seismic loads and to prevent vertical motions Sections 9.3.5 to 9.3.7 of NFPA13 (2010) describe the types of braces and restraints that shall be used.

The performance of storage racks, shelves, and mechanical equipment is particularly important in industrial and in critical facilities, such as schools and hospitals. In industrial facilities, the damage to storage racks and mechanical equipment could cause extensive economic losses and shut down production activities. In critical facilities, the failure of these components can compromise the building's post-earthquake functionality, while representing a threat to the occupants by causing the blockage of escape routes and by releasing dangerous materials in the environment. In order to study the seismic performance of mechanical equipment and to provide fragility functions for loss estimation studies, Porter et al. (2010) provides fragility functions for 52 varieties of Mechanical, Electrical, and Plumbing (MEP) equipment commonly found in commercial and industrial buildings. Recently, Wang et al. (2017) studied the seismic performance of mechanical/electrical equipment with vibration isolations systems. The authors pointed out that the seismic force demand evaluated according to the code provisions might not be appropriate and conservative enough in order to perform the seismic design. Italian and European codes (NCT 2008; CEN 2004) do not provide specific requirements for the seismic design of mechanical equipment, while FEMA E-74 (2012) provides some interesting mitigation details that could be applied to mechanical equipment as well as to architectural contents in order to reduce the earthquake related losses due to the failure of these NSEs .

3 The 2016 Central Italy earthquake

As demonstrated by the seismic sequences occurred during the last century, Italy is one of the most seismic prone areas in Europe. Four mainshocks struck Central Italy between August and October 2016. Figure 2 reports the map of Amatrice-Visso-Norcia seismic sequence from August 24th 2016 to September 30th 2017 (Castello et al. 2017). Other mainshocks followed on January 2017, but reconnaissance missions providing information presented herein precede these last events. On the 24th of August, a moment magnitude (M_w) 6.0 earthquake hit at 1:36 UTC an area of Central Italy close to Accumoli village. The earthquake occurred as the result of shallow normal faulting on a NW–SE oriented fault in the Central Apennines. This event was followed by hundreds of small earthquakes per day until the middle of September when the seismicity rate decreased from about 500 earthquake/day to about 100 (Michele et al. 2016). On October 26th two other mainshocks hit the area of Visso at 14 km NE of Norcia, the two earthquakes occurred at 17:10 and 19:18 UTC, respectively, and were characterized by a M_w equal to 5.4 and 5.9, respectively.

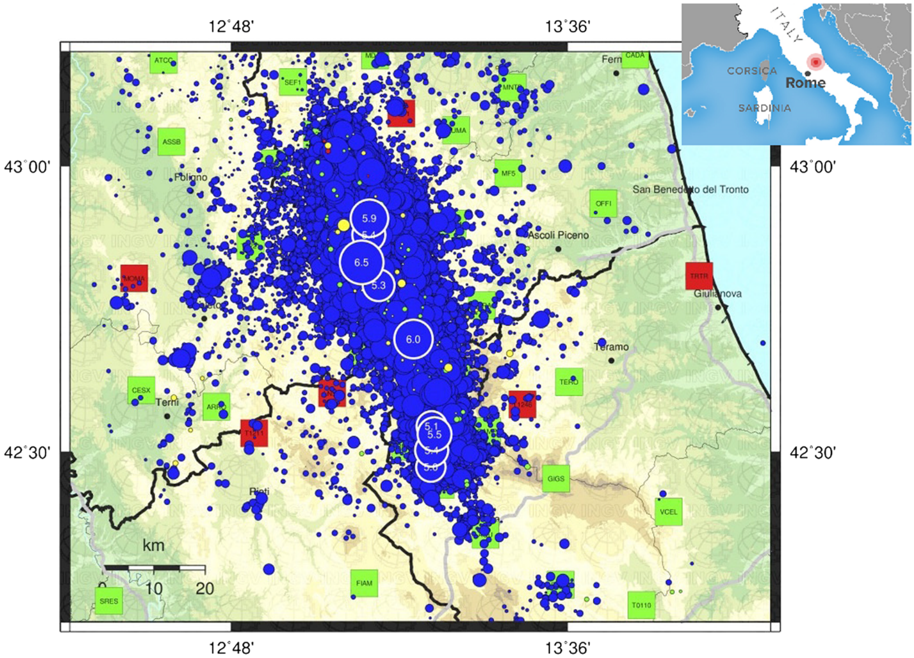


Fig. 2 Map of the Amatrice–Visso–Norcia seismic sequence (Reproduced with permission from Castello et al. 2017)

These events preceded of few days the largest event (M_w 6.5) occurred on October 30th in the middle of the same fault system activated 2 months before by the 24th August sequence (Chiaraluce et al. 2017). The earthquake distribution shows the activation of a normal fault system with a main SW-dipping fault extending from Amatrice to NW of Accumoli village for a total length of 40 km (Michele et al. 2016).

In the same area, several large earthquakes occurred in the past: according to the historical catalogue available in the Istituto Nazionale di Geofisica e Vulcanologia (INGV) website (www.ingv.it), the strongest earthquake occurred in 1703 destroying many villages in the neighbourhood of Norcia. The Italian Accelerometric Network (managed by the Department of Civil Protection) and the Italian seismic network (managed by INGV) recorded thousands of signals (Luzi et al. 2017), that were partially analysed by Iervolino et al. (2016) to evaluate acceleration and displacement spectral ordinates, integral parameters and measures of duration.

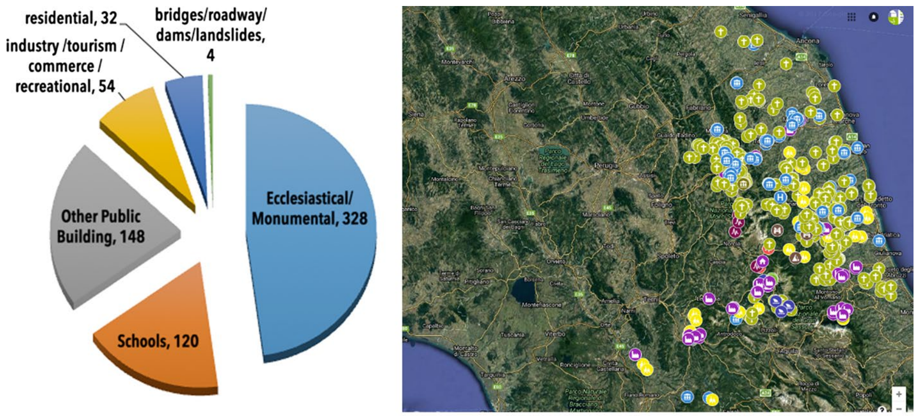
4 Seismic performance and damage observation of NSEs

Following the seismic events, thousands of inspections were performed to evaluate the seismic performance of buildings in the affected areas. The Italian National Order of Engineers, the Network of Seismic Engineering University Laboratories (ReLUIS) and the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) were the principal units involved in the survey activities that followed the events.

These units were coordinated by the Italian Department of Civil Protection (DPC). About 700 inspections were completed in the aftermath of the seismic events. Most of these inspections were performed on critical (schools, hospitals and public) and ecclesiastical/monumental buildings. Figure 3 provides a summary of the types of building inspected by the EUCENTRE team, along with their distribution across the Italian territory (Casarotti 2017). The results of the inspections highlighted once again that churches represent the most vulnerable building typology (about 60% of surveyed churches could not be occupied after the event).

In most instances, the overall performance of the inspected buildings was heavily affected by the damage of the NSEs. Non-structural damage was widespread and varied based on the typology of building. Reinforced concrete buildings, particularly if not designed according to modern seismic regulations, experienced significant damage to masonry infill walls. Historical buildings and churches mainly reported damage to non-structural vaults, stuccoes, frescoes, and decorations. In addition to the obvious financial losses and the destruction of cultural heritage, the downfall of these heavy components represented a threat to the safety of the occupants. Residential buildings suffered damage to partitions, chimneys, roof tiles, and contents. Issues related to chimneys and roof tiles were very common and mostly attributed to poor anchorage of these elements.

Typical examples of non-structural damage observed in industrial and commercial buildings were related to storage racks, infill walls, and coatings. Non-structural damage in industrial buildings was the determinant factor causing the interruption of production and the shutting down of the activities for several days, obviously impacting the economy of the affected areas. Many hospitals that did not have any structural damage were observed to have non-structural damage to the masonry infills and non-structural vaults, causing their inoperability. A brief overview of the most common non-structural damage observed during building inspections is provided in the following sections.



(a) (b)

Fig. 3 Inspections performed by EUCENTRE following the 2016 Central Italy earthquake. **a** Number and typology of surveyed buildings, **b** territorial distribution of the inspections (Reproduced with permission from Casarotti 2017)

4.1 Infill walls and internal partitions

Different infills and internal partition types were observed during the post-earthquake inspections, according to the age of the building and the construction technology. The infill walls observed in Central Italy are generally made of solid clay brick or hollow clay blocks organized in single or double layer configurations. In particular, for single layer configuration, the presence of masonry infills significantly affects the structural response based on the shear resistance and stiffness of the masonry. In the observed double layer configurations, the two layers were generally not connected to each other. Often it has been observed that the external layer, in the two layer configurations, is placed partially outside the surrounding RC frames. The internal partitions are generally made of hollow clay bricks or natural stone ashlar units with a thickness approximately equal to 10 cm.

Extensive damage to internal and external masonry infill walls was observed after the 2016 Central Italy earthquake (see Fig. 4). The infill walls are typically classified as drift-sensitive NSEs. Their in-plane response is governed by the inter-storey drift of the structure during the ground shaking. However, the out-of-plane response of infill walls has been observed to be significantly affected by floor acceleration demands, in particular if

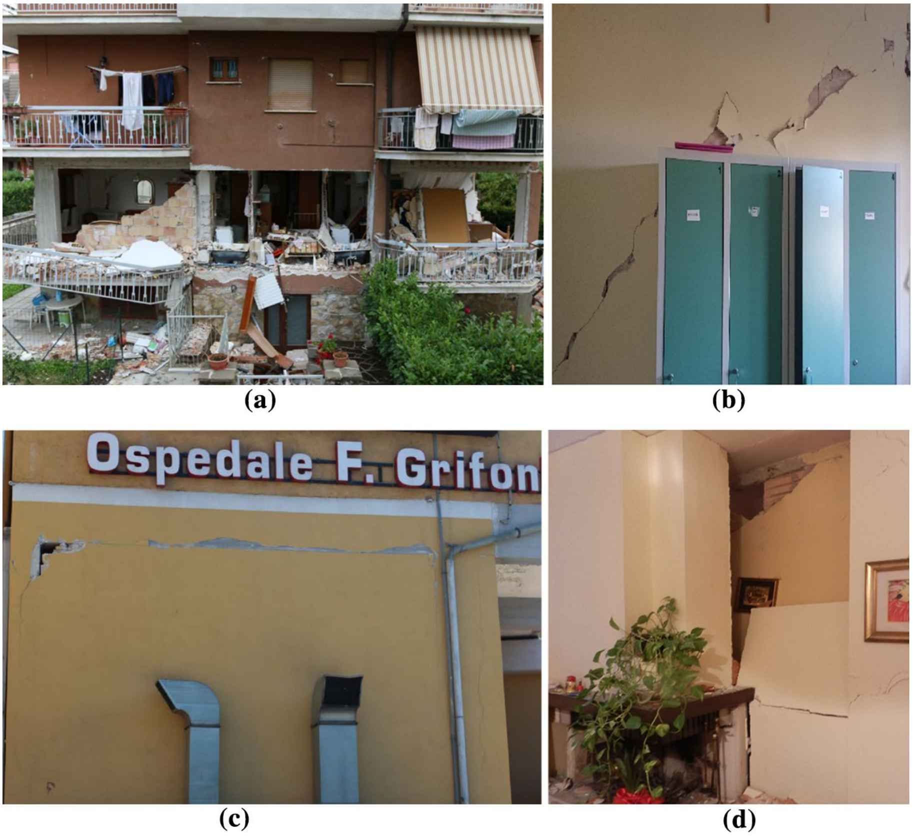


Fig. 4 Typical damage to masonry infills. **a** Collapse of infill panels, **b** diagonal cracking, **c** crushing in the corner, **d** internal partition

heavy secondary systems, such as coating panels or signs and plants, are connected to the masonry infills increasing the inertia forces. The damage to masonry infills was mainly attributed to the fact that most of the buildings in the affected areas were designed and built prior (pre-1970) to the development and implementation of modern design provisions. As a consequence, a large number of the inspected structures appeared to have experienced excessive lateral drift because of their insufficient lateral stiffness. The gaps suggested by the international codes, in order to avoid the interaction between infill walls and surrounding RC frames, were not observed during inspections. Typically, the masonry infill damage is initiated by the disconnection between the panels and the surrounding frame (Fig. 4c), which triggers a "diagonal strut" mechanism. At high drift demands, the strut mechanism leads to the development of diagonal cracks (Fig. 4b), to crushing in the corners (Fig. 4c) or to the complete failure of the masonry panels (Fig. 4a). In some cases, the out-of-plane failure of the masonry infills has been observed. This failure mode is mainly related to the out-of-plane inter-storey drift and accelerations that caused the disconnection of the infill panels with the upper beams. At the same time, the in-plane crashing of the infill walls also increased the probability of out-of-plane failure due to the reduced resistance of the panels.

The high deformation of the infill panels often induced the detachment of the external plaster or damage to the cladding (see Fig. 5). The damage of cladding panels is due to the combination of in-plane and out-of-plane accelerations and it is the result of poor connections with the infill panels or with the structural elements (Fig. 5b). The detachment of the plaster was often observed because this element, generally produced with cement, is very fragile and has no reinforcement to provide any strength (Fig. 5a). This kind of damage often represents a serious life threat because of the possible fall on people walking close to the building.

(a) (b)

Fig. 5 Typical damage in plaster and cladding. **a** Damage to plaster in residential building, **b** damage to cladding in industrial building

Fig. 6 Typical damage to light ceiling systems. **a** Acoustical suspended ceiling, **b** light metallic ceiling system

Fig. 7 Typical damage to heavy ceiling systems. **a** Damage to plasterboard ceiling system, **b** damage to concrete ceiling system

4.2 Ceiling systems

During the Central Italy earthquake, significant damage to both light and heavy weight ceiling systems was observed (Figs. 6, 7). This was likely a consequence of the fact that, in the vast majority of the inspected buildings, the ceiling systems had not been designed taking into account any seismic actions (FEMA E-74 2012). For example, ceiling grids (supporting the ceiling tiles) were connected to the adjacent floors by means of vertical wires, without either diagonal braces or other seismic design strategies. The absence of adequate connections implies that the ceiling systems are unable to accommodate the induced lateral accelerations and relative displacements, resulting in significant damage.

During the inspections three main typologies of ceiling systems were identified. The first typology consists of suspended modular ceiling system with light gauge metal inverted T-sections in a grid pattern (Fig. 6a). This system is often identified as acoustical ceiling system because the ceiling panels are most commonly designed for acoustics and are lightweight. The second typology consists of the suspended heavy ceilings (Fig. 7). This category includes suspended plaster or concrete ceiling systems. These

(a) (b)

Fig. 8 Connection of the "camorcanna" vaults to the floor. **a** Vertical supports, **b** supporting wood structure

(a) (b)

Fig. 9 Typical damage to "camorcanna" vaults. **a** Damage of a rib vault in a school, **b** damage to a barrel vault in a hospital

systems typically have finish material attached to a two-way grid which is suspended from the above. Finally, light vaults suspended by wooden or metallic ties to the upper bearing structures were observed mainly in heritage buildings (Figs. 8, 9); these vaults are constructed out of wooden arches, reeds, and plaster.

The most commonly observed damage of the acoustical ceiling systems was: (1) acoustical tiles falling out of the ceiling system (see Fig. 6a), (2) failure of rivet connections at the perimeter fixings (Fig. 6b), and (3) breaking or buckling of the grid members due to induced compressive and torsional loads. In addition, the dynamic interaction between the ceilings and other suspended elements, such as light fixtures, often appeared as a source of damage.

In many cases, extensive damage was concentrated along the ceiling perimeter. This was possibly due to poor detailing or lack of rivets, which caused the loosening of the boundary supports and the consequent collapse of the grid members. Also, the absence of adequate hanger wires caused spreading of the tees and, in turn, the collapse of the tiles. The observation of these damages demonstrated the importance of providing adequate anchorage in particular to the perimeter tiles as their collapse could induce loss of the stabilizing action and hence a subsequent progressive collapse of the whole ceiling system (Badillo-Almaraz et al. 2006). The observed perimeter issues could be overcome by implementing the recommendations present in international guidelines (i.e. FEMA E-74 2012).

The observed damage to plasterboard and concrete ceiling systems was mainly attributed to poor connections to the supporting floors (Fig. 7). These systems are heavier than their acoustic ceiling counterparts, and their collapse may have more severe consequences.

Lightweight non-structural vaults, referred to as "camorcanna" vaults, were found in many historic buildings and presented extensive damage. 'Camorcanna' vaults are typically composed of reed mats and plaster nailed to an upper wooden framework (Quagliarini et al. 2012). The wooden supporting system is connected to the main structure using wood beams in the two main perpendicular directions. The vaults are often suspended by metallic ties to the upper bearing structures and, in many cases, springs are used to mitigate the vertical vibrations (Fig. 8). Frescoes and stuccoes of artistic and historical value were often observed on the lower surface of these vaults. Typical damage to "camorcanna" vaults is shown in Fig. 9. These vaults were designed and built prior to the development of any seismic design criteria, therefore the somewhat observed poor performance is not surprising. Damage was generally related to the collapse of the plaster along with the reeds, while the supporting wooden framework was generally still in place. The damage to these vaults may represent a significant financial loss, and a destruction of cultural heritage.

4.3 Piping systems

Different typologies of piping systems were observed during the post-earthquake inspections, these piping systems are often rigidly connected to the structure and span from floor to floor. Their performance is therefore controlled by the supporting structure's deformation. In almost all cases, no seismic details were observed and the piping systems were connected to the structures only with gravity load supporting systems.

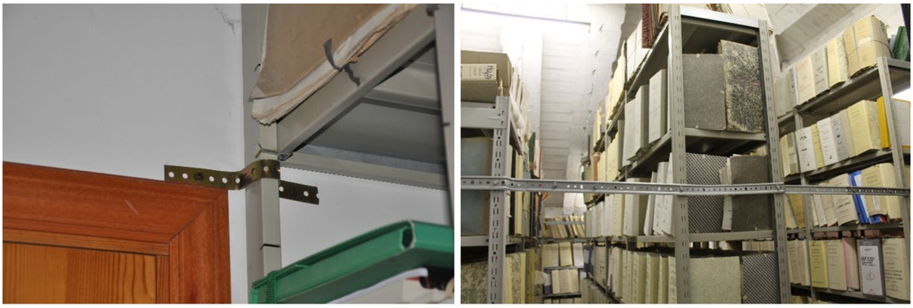
The damage to piping systems observed after the 2016 Central Italy earthquake was mainly related to the failure of the piping joints (Fig. 10). Figure 10 shows two pipelines, made of different materials, in which the failure of the piping joints caused the collapse of the connected pipes that were not braced. At the date of the inspections, the failed pipes were already removed. For this reason it was only possible to see the interrupted pipelines. As reported in previous experimental studies (Tian et al. 2014), the piping joints are the weakest link in the piping systems, particularly in absence of bracing intended

(a) (b)

Fig. 10 Typical damage in piping systems. **a** Failure of PVC piping joint, **b** failure of steel joint

(a) (b)

Fig. 11 Typical damage in storage racks. **a** Overturning of shelves in a school building, **b** collapse of a storage rack in an industrial building



(a) (b)

Fig. 12 Examples of mitigation details for shelves. **a** Attachment to the wall, **b** connection of parallel shelves

to accommodate the earthquake induced demands. It is also important to note that the observed damage is generally close to the change of direction in the piping systems. This observation confirms the effectiveness of the requirements suggested by some guidelines (NFPA13 2010; FEMA E-74 2012) to reduce the spacing between the lateral supporting systems in the proximity of the change of direction in the piping systems.

4.4 Storage racks

Extensive damage to shelves and racks was observed following the 2016 Central Italy earthquake, as shown in Fig. 11. The observed damage to shelves and storage racks was mainly associated with overturning issues or with the buckling of the vertical uprights. This type of damage can typically be prevented by anchoring the shelving units to the adjacent walls, and by providing some connections between parallel units. Figure 12 shows examples of properly anchored shelves in a hospital building observed during the post-earthquake inspections for which good seismic performance was observed. The connection of the shelves to the adjacent wall prevented the overturning of the storage unit (Fig. 12a). Unanchored shelves affected by overturning issues were observed in the same building.

Figure 12b shows an example of a mitigation detail in which parallel shelves have been connected to each other using horizontal steel “channels”. This bracing technique prevented damage to the shelves, concentrating damage in the braces. After the earthquake, the original configuration of all units could be restored simply by replacing the horizontal bracing elements.

The bracing of heavy storage racks in industrial facilities can limit damage during an earthquake. An example observed during the post-earthquake inspections is provided in Fig. 13: no damage was observed following the earthquake due to the adoption of a bracing system along with a special base connection, that allows relative movement at the floor level.

4.5 Chimneys, appendages and parapets

Chimneys, appendages and parapets are very common acceleration-sensitive NSEs. Damage to chimneys and appendices was widespread and extensively documented after the 2016 Central Italy earthquake (Fig. 14a). Unreinforced masonry chimneys were most severely damaged, while chimneys and appendages made of other materials, such as steel, were affected to a lesser extent.

Historic buildings and churches often have slender masonry appendages on their roofs, which are subjected to high earthquake-induced roof accelerations. These accelerations can be recorded at low levels of ground acceleration because of the dynamic filtering and amplification. The observed damage ranged from minor cracking to complete collapse of the elements. Similar behaviour was observed with parapets (Fig. 14c) and bell-gable (Fig. 14d). The performance of chimneys, parapets, and appendages can be significantly improved by adopting simple mitigation interventions (FEMA E-74 2012; DPC 2009). These include providing confinement and installing lateral bracing systems to prevent overturning. Figure 14b shows a temporary post-earthquake propping system with a similar configuration to the mitigation details provided by FEMA E-74 (2012). The effectiveness of these simple mitigation measures was demonstrated during the subsequent shocks that struck Central Italy in October 2016.

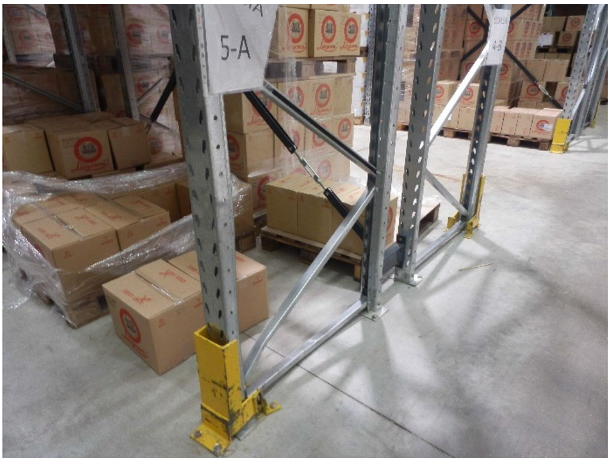


Fig. 13 Example of seismically designed storage racks

Fig. 14 Typical damage to masonry appendices. **a** Damage to chimney, **b** damage to appendices, **c** damage to parapets, **d** damage to bell-gable

4.6 Glazing systems

Damage to glazing systems was less extensive than expected. Glazing systems can be classified drift- and/or acceleration-sensitive elements, depending on how they are connected to the structure. Doors and windows should accommodate the inter-storey drift of the supporting structure (Fig. 15) along with the orthogonal acceleration, while façade elements may be only sensitive to accelerations.

The good performance of glazing systems observed during the earthquake was attributed to the quality of the interface between the glass panels and the supporting frames (generally made of steel, aluminium or wood). This interface was commonly constructed of structural silicon. The high deformability of silicon allowed accommodating the drift during ground shaking. Similar conclusions were drawn following past earthquakes (e.g. Miranda et al. 2012) and are in line with the findings of experimental investigations (Sivanerupan et al. 2014).

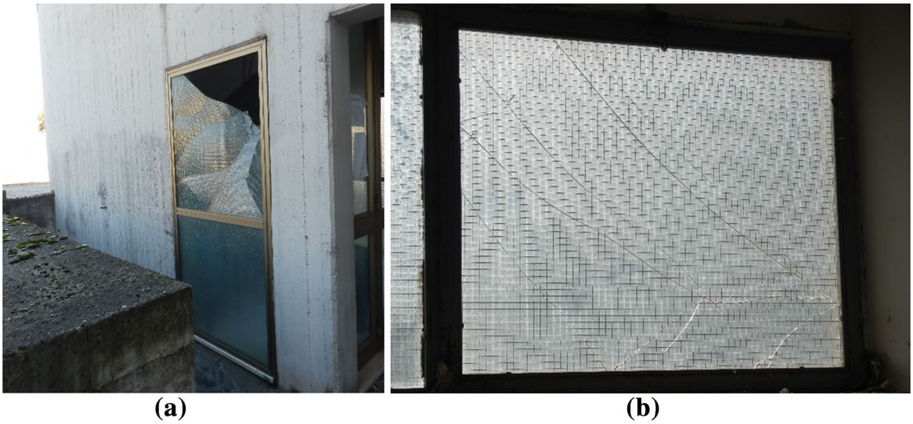


Fig. 15 Typical damage to glazing systems. a Damage to door, b damage to windows

4.7 Mechanical equipment and tanks

Damage to tanks and mechanical equipment can severely limit the functionality of facilities after an earthquake. Damage to tanks was observed in a number of agricultural and breeding facilities. A damaged steel fodder storage tank is shown in Fig. 16. The excessive axial loads resulting from the overturning moment induced by the earthquake inertial forces caused buckling of the tank steel legs. Failure of the connections between the tank legs and the concrete deck was also observed due to the deformation of the steel flanges. These failure modes could have been prevented by providing a bracing system and more robust base connections (FEMA E-74 2012).

In some cases, damage to mechanical equipment anchored to concrete floors was observed. In these cases, the poor performance was attributed to the inadequate base

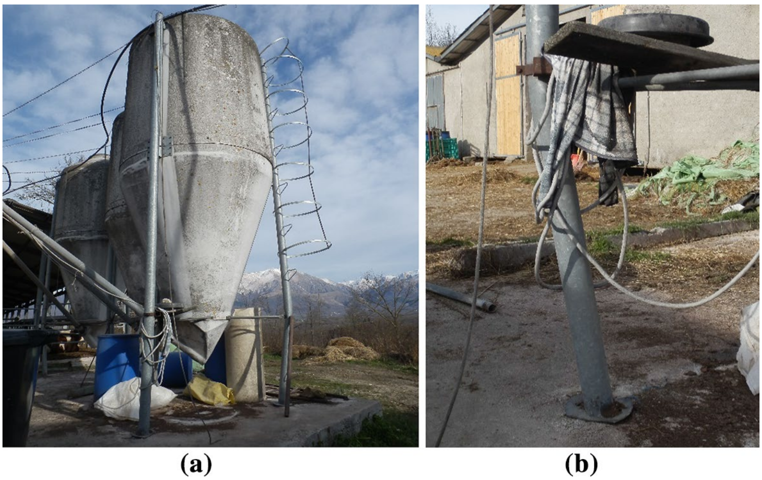


Fig. 16 Typical damage to steel tank. a Steel tank, b base connection

connections, which typically consist of springs intended to mitigate non-seismic vibrations. The vulnerability of mechanical equipment can be partially reduced by positioning elastomeric snubbers alongside the vibration isolation coiled springs (Filiatrault and Sullivan 2014).

4.8 Hospital medical equipment

Hospitals are classified as critical facilities that must be operational after an earthquake. This classification means that both the structural and non-structural components cannot be damaged during the earthquake. A hospital has many different types of NSEs such as medical equipment and all the utilities required to serve that equipment. In addition, in the hospital buildings, ceiling systems are generally installed at all floors to hide the piping systems connected to the slabs; the ceiling systems, based on their typology, can be connected or not to the structural elements. If the ceiling tiles are damaged or collapsed, or if walls are cracked or the plaster has spalled, the rooms cannot be occupied.

After the 2016 Central Italy earthquake, the hospital in Amatrice was completely evacuated, as the building was characterized as unsafe. In the second major hospital, in Amandola, structural damage was not observed after the August 24 event, however, major non-structural damage was reported in one wing of the hospital. This non-structural damage was limited to the masonry infill walls (Fig. 4b, c), masonry façade and ceiling systems (Fig. 9b). None of the medical equipment was damaged after the August 24 event.

4.9 Stuccoes and decoration

Historical buildings including churches, museums and palaces are often adorned with ornamental elements such as stuccoes, decoration and frescoes. The surveys performed after the 2016 Central Italy earthquake reported extensive damage both in churches and

(a) (b)

Fig. 17 Typical damage to stuccoes and decoration. **a** Stuccoes, **b** capital palaces to stuccoes and decorations (Fig. 17). In most cases damage was limited to cracks, but in many cases there was enough movement to cause the detachment of the stuccoes and frescoes. The observed damage is related to the earthquake-induced vibrations and the deformation of the main structures. The stuccoes are generally made with cement plaster and gesso, these materials are very stiff and have no reinforcement to provide any strength, for this reason the cracking of the supporting structures often caused their detachment. The stucco reported in Fig. 17a detached from a triumphal arch in a church and its weight was approximately equal to 9 kg; the collapse of this heavy element posed a serious threat to the safety of the occupants.

4.10 Roof tiles

A large number of buildings in Central Italy has roofs with tiles. The tiles are generally not anchored to the roofs and even low levels of ground acceleration can cause them to displace from their original position. One of the most common damage and hazard for passers-by was related to roof tiles falling off the roof, see Fig. 18.

5 Conclusions

The poor seismic performance of NSEs has been often observed in Italy following major seismic events such as the 2009 L'Aquila earthquake and the 2012 Emilia earthquake. Despite the recognition of the importance of adequate seismic design and securing of NSEs, it has not consistently been incorporated into practice. The 2016 Central Italy earthquake showed once again the vulnerability of NSEs with widespread damage which resulted in enormous financial losses and, in many instances, represented a threat to life safety.

This paper provided an overview of the non-structural damage most commonly observed following the 2016 Central Italy earthquake. A detailed description of the damage observed of infill walls and partitions, ceiling systems, piping systems, storage racks, chimneys, appendages, parapets, glazing systems, mechanical equipment, tanks, stuccoes, decoration, and roof tiles is provided. Based on the damage observed during the post-earthquake inspections the following main considerations can be pointed out:

(a) (b)

Fig. 18 Typical damage to roof coating. **a** Downfall of roof tiles, **b** roof tiles disconnected from the supporting system

- The masonry infill and the partition walls were the most affected NSEs during the 2016 Central Italy earthquake, their damage is mainly related to the excessive lateral drifts of the structures;
- Significant damage to the ceiling systems was documented, in particular to suspended light vaults, due to the interaction with the structures and the absence of bracing systems;
- Acceleration-sensitive NSEs, as chimneys, appendages and roof tiles showed poor seismic performance due to the lack of adequate connections or bracing systems;
- Stuccoes and decorations in churches and historical buildings were significantly damaged during the earthquake;
- In general, the extent of the observed non-structural damage was mainly related to: (1) the lack of proper anchorage of the various elements to the structure, and (2) the absence of seismic design guidelines at the time of construction or installation;
- When simple seismic mitigation measures were adopted, satisfactory NSE performance was observed such as, for example, the good seismic performance of parallel shelves connected using horizontal steel channels.

The outcome of the reconnaissance has emphasized the need for a better understanding of the seismic behaviour of NSEs, which could fill the current knowledge gaps for developing reliable performance-based provisions. The 2016 Central Italy earthquake highlighted the impelling need for the implementation of guidelines for the design and the installation of NSEs and building components.

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