Damage assessment of autoclaved aerated concrete buildings: some Italian case studies

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Abstract: The present work deals with the damage assessment of some Italian case studies of structures/walls realized in autoclaved aerated concrete (AAC) blocks. Initially, examples of static damage of walls caused by excessive deformability of the slabs, differential loads on walls, and foundation settlements, are shown. Then, the seismic behaviour of AAC masonry buildings is analysed. In particular, the behaviour of two pre-seismic code buildings damaged by the Emilia 2012 earthquake is described and compared with modern engineered buildings. Then, the behaviour of non-structural walls damaged by the Central Italy 2016 earthquake is reported. Very few case studies focusing on the damage assessment of AAC masonry buildings during real seismic events can be found in the literature. This work provides an opportunity to advance our knowledge on the behaviour of this material.

Keywords: AAC; damage assessment; 2012 Emilia's earthquake; 2016 Central Italy's earthquake; masonry; AAC partitions and infills; shear cracks; sub-vertical cracks; vulnerability; seismic design

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1 Introduction

The paper deals with the analysis of the damages undergone by autoclaved aerated concrete (AAC) buildings in Italy, both under static and seismic conditions.

As known, AAC is a lightweight material that has experienced an increasing diffusion in the construction market for the realization of concrete masonry units (CMUs), thanks to its interesting environmental performances. Due to its porous structure, the material is indeed characterized by a low bulk density, and offers good thermal insulation properties (Aroni et al., 1993). Its quick and easy installation, together with its good fire resistance and high strength-to-weight ratio, make AAC suitable for the realization of bearing masonry walls in low-rise buildings, as well as of infill and cladding panels for concrete or steel framed structures.

The performance of AAC masonry buildings during earthquakes is particularly interesting since AAC technology is so far mainly widespread in non-seismic areas (like Northern Europe), while its use in seismic-prone countries, like Italy, is still limited, although it is progressively increasing in time (Costa et al., 2011). The growing interest towards AAC masonry has led to the development, in the past decade, of a large number of theoretical and experimental studies aimed at better understanding its behaviour under seismic loads, in order to set specific design recommendations for the material, whose peculiarities are quite different from standard masonry (Miccoli, 2018). The most of the tests were performed on full-scale reinforced and unreinforced samples under quasi-static or dynamic in-plane loads (Penna et al., 2015; Rosti et al., 2016; Tanner et al., 2005), and the effects of out-of-plane loads were also analysed (Lönhoff and Sadegh-Azar, 2018). Furthermore, scale models of typical AAC masonry buildings were tested on shaking table (Tomaževič and Gams, 2012). Several studies were also focused on framed structures with AAC infills (e.g., Cheng and He, 2018). Experimental results were used as the basis for FE simulations on a number of prototype walls or buildings with different characteristics, corresponding to the most typical situations available on the construction market, so as to assess their performance under seismic events (Costa et al., 2011; Ferretti et al., 2015). However, very few case studies focusing on the damage assessment of AAC masonry buildings during real seismic events can be found in the literature. Indeed, the analysis of masonry behaviour during the major past Italian earthquakes has been so far mainly concentrated on buildings made of stones or fired clay bricks (Adorni et al., 2009; Bracchi et al., 2012; Cattari et al., 2012; Di Ludovico et al., 2017; Fragomeli et al., 2017; Penna et al., 2014). The few available works focusing on the seismic performance of AAC buildings mainly refer to Turkish earthquakes. The most of them are focused on buildings realized with AAC panels (Ilki et al., 2013; Ugurlu et al., 2013), but some information can be also found on the behaviour of monolayer or two-storey buildings made of AAC masonry and subjected to the Marmara's earthquake of 1999. These last studies revealed that AAC masonry buildings did not exhibit almost any sign of damages, mainly due to the better quality of masonry units and to a better construction practice with respect to traditional Turkish masonry structures (Celep, 2005).

Aim of this paper is providing an insight into the damage assessment of AAC buildings, both under static and under seismic loads. The most common causes of cracking in AAC masonry constructions are first briefly discussed. Some case studies concerning buildings realized with AAC bearing masonry or with AAC partitions and infills, and subjected to the Emilia's and the Central Italy's earthquakes (which took place in 2012 and 2016, respectively), are then presented. The analysed case studies evidence that the major causes of failure are mostly related to systematic or peculiar structural deficiencies in building conception, rather than to the relative low ductility of the AAC material. It is shown indeed that those buildings designed according to good practice rules and incorporating proper construction details were characterized by a rather good seismic performance, remaining almost undamaged.

2 Static damage of AAC buildings

It is well known that AAC masonry blocks can be frequently subjected to cracking phenomena also under static loads, due to the limited fracture toughness of the material, which varies almost linearly with the density (and consequently with the compressive strength, see Aroni et al., 1993).

Beyond cracks and splits due to temperature effects and to shrinkage (Liu et al., 2011), the most common causes of cracking experienced by AAC elements under static conditions are related to soil settlements or to uneven displacements of other structures, such as floors, or adjacent walls and columns (Piekarczyk, 2018). While uneven displacements of floors sustaining the walls are mainly due to their deformability or, in some cases, to construction errors, uneven displacements of adjacent walls or columns are generally caused by differential settlements, or by a differential elastic shortening of connected members subjected to a different stress level.

Typical cracking occurring in AAC partition walls is often due to the deflection of the floor lying underneath the walls themselves. This problem is quite common in Italian residential building realized before 2003, since in many areas of the country seismic prescriptions were not mandatory by law, and the presence of rigid floors was not so frequent. Typical Italian floors are indeed realized with parallel reinforced concrete (RC) joists separated by hollow clay blocks, in some cases without a RC topping (see Schiavi et al., 2010). Besides the intrinsic deformability of the floor, which should be properly checked both at design and construction stages, also the followed construction technique may have a certain influence on cracking appearance in AAC elements. The walls should be indeed built only after the complete removal of props. To reduce crack formation, some Authors also suggest the adoption of normal thickness joints made of cement-lime mortar instead of thin cement mortar joints – which are typical for AAC masonry – for partition and infill walls (Piekarczyk, 2018).

An example of cracking in AAC masonry walls due to the deformability of the floor lying under the walls themselves is shown in Figure 1. The examined case study is located in Genova and is characterized by the presence of a suspended gallery made of bearing AAC masonry, which connects two buildings with different high (Figure 1a).

Figure 1 Example of cracks in AAC walls due to floor deflections: (a) general view of the suspended gallery between two buildings in Genova, and observed crack pattern in its (a) front and (b) rear sides.

As can be seen, the deflection of the floor determined the appearance of tensile stresses both in the front and the rear walls of the gallery, and the observed damage seems to indicate a possible formation of an arch-shaped crack. Figures 1b-c show the upper part of the arch, with an almost horizontal crack placed over the two openings, and the bottom part of the arch, with an approximately 45-deg inclined crack connecting the bottom part of the opening with the wall side.

Another example of a typical damage due to static loads that can be observed in AAC masonry bearing walls is reported in Figure 2, which shows a terraced house in Bologna. In this case, the crack pattern is characterized by the presence of an almost vertical crack at the upper level of the third housing unit, at the connection zone between two perpendicular walls. This type of crack often appears when the two walls are differently loaded, which is a quite common situation in civil engineering, due to the presence of one-way floors and roofs.

Figure 2 Example of cracks in AAC masonry walls due to static loads (terraced house in Bologna).

(a) (b)

Figure 3 Example of cracks in AAC walls due to static loads (detached house in Novara).

(a) (b)

This problem has been recently discussed in Drobiec (2018), through the analysis of the results of full-scale tests on AAC walls connected to each other and unequally loaded. However, it should be remarked that also thermal effects, as well as uneven soil settlements can create a stress concentration near corner walls, and consequently the registered crack pattern can be the effect of different causes acting together, maybe at different times.

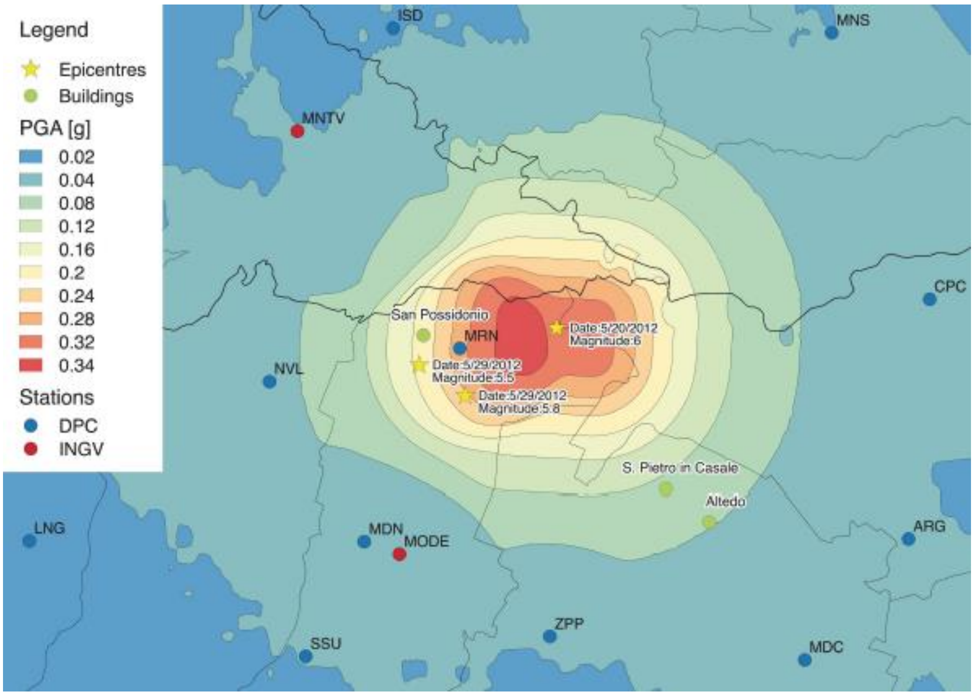
Finally, an example of crack pattern mainly attributable to differential soil settlements is reported in Figure 3, for an AAC masonry building located in Novara. In this case, the differential settlements of the soil under the residential house produced the appearance of tensile stresses in the inclined wall belonging to the building front, near the main entrance. This stress field caused in turn the formation of a typical diagonal crack, almost inclined at 45-deg and interesting the whole thickness of the wall.

3 Seismic damage of AAC masonry buildings

In this Section, a discussion on the typical damages observed in buildings realized in AAC block masonry subjected to seismic action is presented. The attention is focused on buildings stroke by the seismic sequence that interested Emilia-Romagna Region (Italy) in 2012.

The Emilia's earthquake was characterized by three main seismic events. The 20th of May 2012, a first earthquake of magnitude M_W = 6.0 (depth 6.3 km) was registered, with epicentre between Finale Emilia, Bondeno and Sermide. A second and third seismic event of lower magnitude (M_W = 5.8 and M_W = 5.5, respectively) struck the same area the 29th of May, causing additional damages to the buildings already weakened by the first shock. Figure 4 shows the shake map of the first event, in terms of peak ground acceleration (PGA), provided by USGS (2019).

Figure 4 Shake map of 5/20/2012 Emilia's earthquake with epicentres, seismic reporting stations, and analysed case studies (obtained from the data of USGS, 2019).



In the same Figure, the yellow stars represent the location of the epicentres of the three main shocks and the dots show the position of the stations of the Italian strong motion network (RAN, 2016). More details on the characteristics of the seismic sequence can be read in de Nardis et al. (2014).

Figure 5 Seismic spectra to be applied for the considered case studies according to the Italian Standard (2018) and maximum registered earthquake excitation (INGV, 2019).

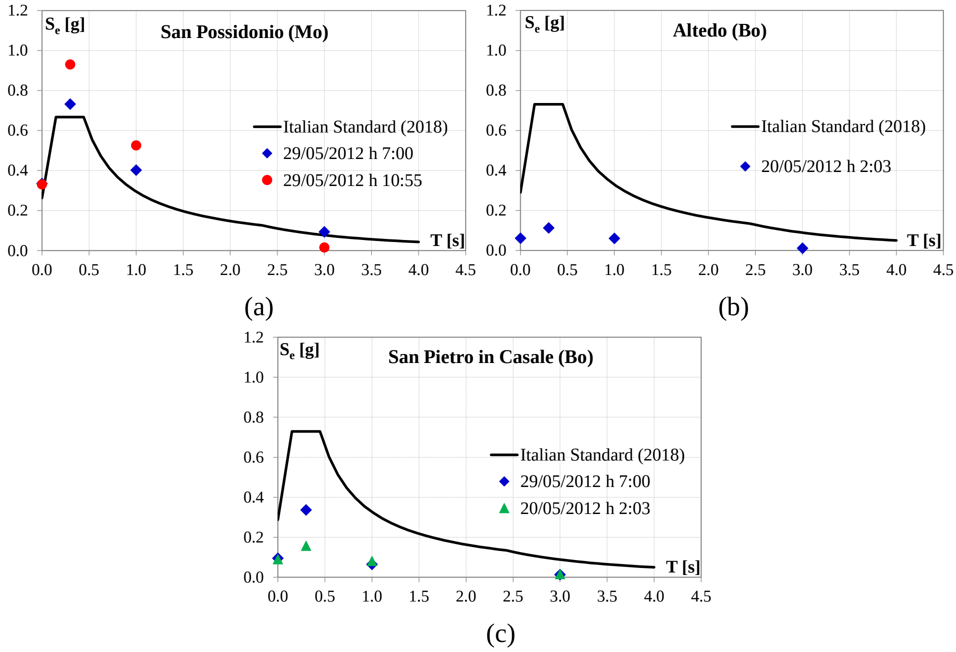


Figure 5 reports the elastic response spectra evaluated according to the Italian Standard (2018) for the analysed case studies. These spectra were calculated under the following assumptions: ground type C without topographic amplification, 5% viscous damping, reference return period equal to 475 years. On the same Figure, the maximum registered earthquake excitation in terms of peak ground acceleration (PGA) and pseudo-spectral acceleration (PSA) is also shown for comparison. To this end, the shake maps referred to earthquakes with magnitude $M_w \geq 5$ (INGV, 2019) were first analysed, and those events that maximised one or more of the considered parameters (PGA, PSA (T = 0.3s), PSA (T = 1s), PSA (T = 3s)) were selected and plotted in the graphs.

It should be observed that most of the masonry buildings located in Emilia were realized without seismic provisions, which became mandatory in this area starting from year 2009. This fact explains the strong damages suffered by some typologies of masonry structures, in particular old rural buildings and two or three-storey houses realized in the period ranging from 1950 to 1980. A description of their damage state can be read in Penna et al. (2014) and Cattari et al. (2012). Although the headquarters of one of the most important AAC Italian manufactures of the past were settled in the Region, the use of this type of masonry was not particularly spread. Probably for this reason, the damage reports available in the literature describe a few (if any) buildings in AAC. In the following Sub-sections, some unpublished case studies (except for the first one, in Section 3.1, which has been partly debated in Pongiluppi et al., 2015) concerning AAC masonry buildings subjected to Emilia's earthquake are presented and discussed, providing valuable information on the behaviour of this type of masonry under seismic events.

3.1 Two-storey building in San Possidonio (Modena)

The first reported case study refers to a two-storey building in San Possidonio (Modena), indicated in the shake map of Figure 4. This building was realized in two main phases. The ground floor, devoted to commercial use and hosting a garage, was built during the ‘70s, by using a 250 mm thick AAC bearing masonry. The first floor, with residential use, was instead added in the ‘90s and was characterized by the presence of a not homogeneous masonry, mainly constituted of perforated clay bricks with limited portions made of AAC blocks. A general view of the building is shown in Figure 6, while Figure 7 reports a sketch of the plans of the two floors.

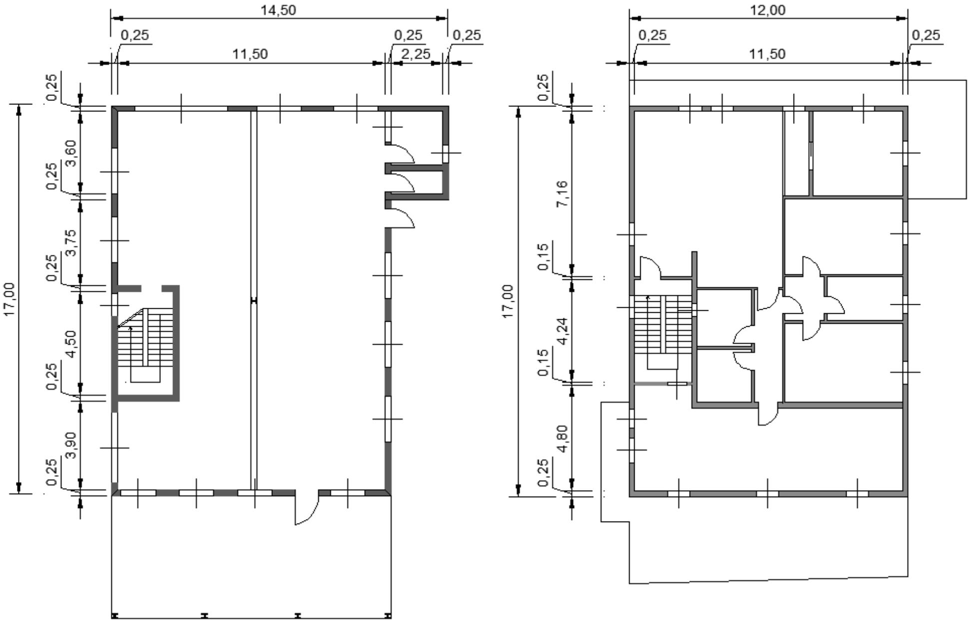
Figure 6 House in San Possidonio: (a), (b) general view of the building and of the external damages caused by the Emilia’s earthquake.

(a) (b)

“Predalles” prefabricated concrete slabs, formed by a 40-50 mm concrete layer, reinforced with trestle frames and completed with polystyrene elements, were used for the inter-storey floor. Predalles slabs were connected to AAC masonry by means of reinforced concrete ring beams. A central steel-frame was used as intermediate support (Figures 7a, 8). The roof floor was realized with sandwich panels connected to a metallic structure. Other details of the building can be found in Pongiluppi et al. (2015).

During the Emilia’s earthquake, the building was subjected to a maximum PGA of 0.33g (see Figure 5a) that caused heavy damages to the masonry, as shown in Figures 6 and 8-9. The behaviour was mainly governed by the in-plane wall response, even if some portions of the external walls undergone local out-of-plane collapses (see Figure 8b, over the opening on the right). Diagonal shear cracks in masonry piers of the ground floor, together with crushing phenomena can be recognized in Figures 6, 8 and 9. This widespread damage was the consequence of some deficiencies in the structural conception of the building, which was not designed for seismic resistance, but only for carrying vertical loads. The main element of vulnerability was represented by the lack of a sufficient amount of walls along the two main directions, which was respectively equal to about 2% and 2.6% of the floor gross area. This insufficient “wall density” caused the appearance of high stress levels on the piers at the ground storey, leading to a reduced in-plane deformation capacity for shear mechanisms.

Figure 7 Plans of the two floors of the building: (a) ground floor; (b) first floor.



(a) (b)

Figure 8 (a) Internal view of groundfloor and (b) detail of diagonal cracks in masonry piers between adjacent openings.

(a) (b)

This problem was further increased by the large distance between the bearing walls sustaining the horizontal forces (respectively equal to 12 and 17 m in the main directions, Figure 7), the relatively small thickness of the walls (250 mm), and the presence of large openings, with the consequent formation of squat masonry piers (i.e. Figure 8). Finally, Figure 9a shows the crack pattern registered at the connection zone between two perpendicular walls, near the stairs' door. From Figure 9b, it can be also seen that remarkable masonry disruption took place in AAC walls. This fact explains the rising interest of the scientific and technical community in studying the application of several reinforcement techniques (mainly meshes or trusses) to increase wall ductility.

Figure 9 (a) Crack pattern at the connection zone between perpendicular walls and (b) diagonal cracks in a masonry pier.

(a) (b)

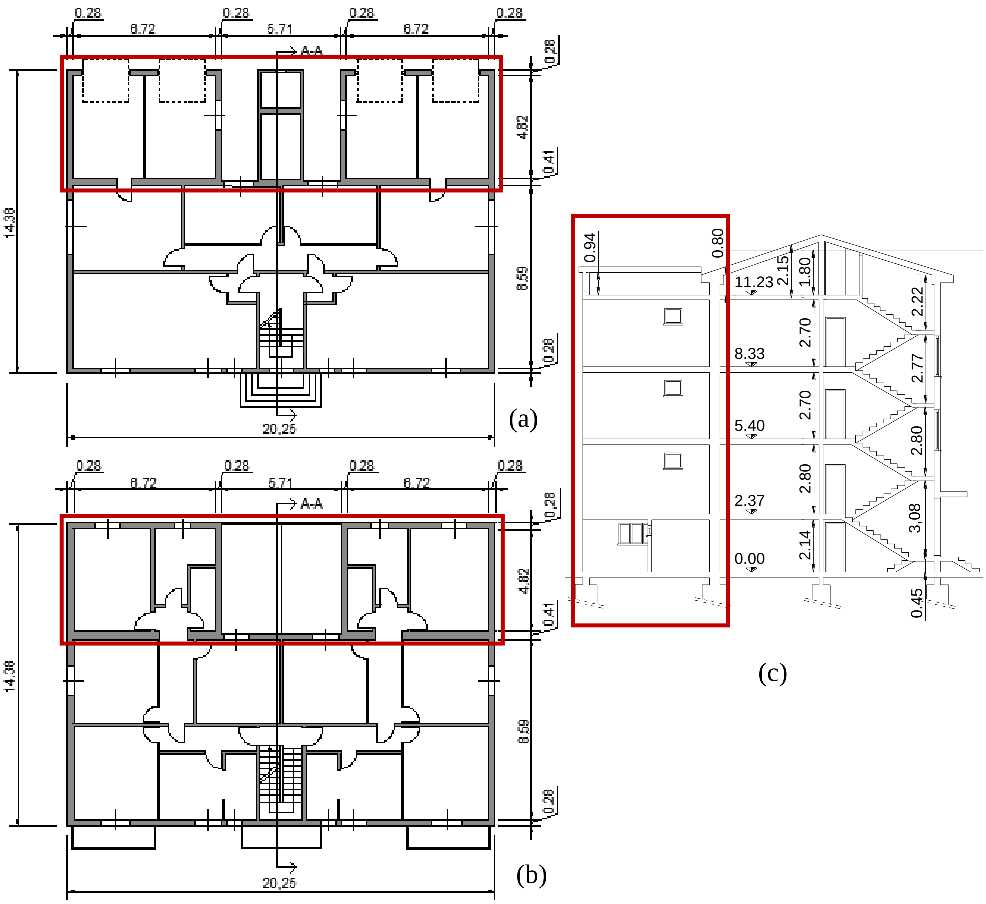
3.2 Multi-storey building in San Possidonio (Modena)

Another example of AAC masonry structure not designed according to seismic rules and heavily damaged during the Emilia's earthquake is the 5 storey building depicted in Figures 10-11. The building, located in San Possidonio (Modena, see Figure 4), was formed by two parts, realized in different times. The first and ancient part (Figure 10a) was built in the '60s by using solid clay bricks, transversally disposed within the wall thickness and forming a single-leaf masonry (header bonding). Inter-storey floors were realized with parallel RC joists separated by hollow clay blocks, while the pitched roof was made with precast "Varese" RC joists and interposed non-refractory clay flooring blocks. The second and more recent part, circled in red in the plans of Figure 11 and corresponding to the rear of the building (see also Figure 10b), was added during the '70s.

Figure 10 (a) Front and (b) rear view of the multi-storey building in San Possidonio.

(a) (b)

Figure 11 Plans of the building: (a) ground storey and (b) typical intermediate storey; (c) section A-A.



This new part was made of 250 mm thick AAC masonry with a density almost equal to 5 kN/m^3, except for the ground storey, which was built again with solid bricks (as can be seen in Figure 12a). Inter-storey floors were similar to those adopted in the older part of the building, but a flat roof was chosen in this case (see Figure 10a). The connection between the two adjacent parts was not realized according to good practice rules and several localized detachment of plaster took place during the earthquake, due to the relative movements of the two parts (Figures 12b,c).

The most significant damages undergone by the building during the seismic shakes were concentrated in the newest part of the building, and are depicted in Figures 13 and 14. The maximum attained PGA was also in this case equal to 0.33g, according to Figure 5a. The crack pattern was mainly constituted by sub-vertical cracks, together with crushing phenomena and detachment of large portions of plaster. These damages were primarily localised at the first floor (which is the lower one made of AAC), both at the connection zone between two perpendicular walls and in the masonry piers between two openings.

Figure 12 (a) Presence of solid clay bricks at the ground level of the newest part of the building, under AAC masonry; (b), (c) general view and detail of the connection between the two parts of the building realized at different times.

(a) (b) (c)

Figure 13 Plaster detachment and sub-vertical cracking in AAC masonry at the first level of the building.

This type of cracks is quite common in slender piers subjected to not negligible compressive stresses and has been also observed in laboratory tests, like those carried out by Rosti et al. (2016). The existence of quite large vertical compressive stresses, which were due to the relatively high number of storey and to the limited ratio between walls and floor area, reduced indeed the displacement capacity of the masonry, so leading to a premature failure. This problem was further worsened by the presence of garage entrances at the ground floor, which further reduced the extension of masonry piers. To a certain extent, it is also possible that the observed failure mode had been influenced by the lack of mortar in vertical joints and by the fact that a common mortar for brick masonry, instead of the specific mortar/glue for AAC, was used for the filling of bed joints.

Figure 14 Details of sub-vertical cracks in the AAC masonry of the rear façade of the building, behind the balconies: (a) near an opening; (b) near the connection between two perpendicular walls; (c) in the central part of a masonry pier.

(a) (b) (c)

3.3 Undamaged AAC masonry buildings

Finally, two cases of "modern" buildings, designed and realized according seismic prescription by using unreinforced AAC masonry with thin glued joints, are presented.

Figure 15 shows a residential complex made of a couple of two-storey terraced houses in Altedo (in the municipality Malalbergo, near Bologna, see Figures 4 and 5b), which was subjected to a maximum PGA of 0.06g during the Emilia's earthquake.

Figure 15 Residential complex made of unreinforced AAC masonry in Altedo (Bologna).

A detailed view of one of the two buildings, together with a sketch of the plan of one housing unit, is reported in Figure 16. As can be seen, the structure is characterized by an adequate amount of walls in the main directions (with a "wall density" ranging from 7 to 8%) and concrete ring beams were realized upon the walls. AAC bearing walls have a thickness of 360 mm and are covered by a plaster layer.

The post-earthquake inspection survey did not reveal the presence of any cracks and damages nor in the peripheral nor in the internal walls. In any case, it should be observed that the building was subjected to a relatively low seismic action, since the reference peak ground acceleration prescribed for that area by the actual Italian Standard Code is 0.21g.

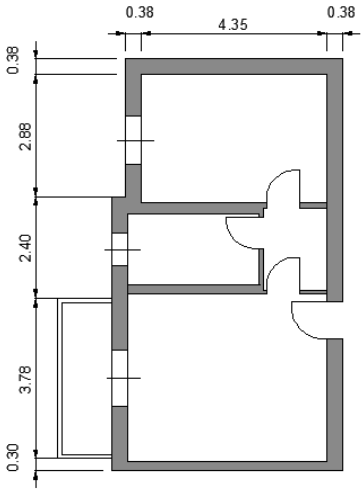
Figure 16 (a) Detail of one building belonging to the residential complex of Altedo; (b) plan of the ground floor of one housing unit.

(a) (b)

Figure 17 Residential complex made of unreinforced AAC masonry in San Pietro in Casale (Bologna).

The second case study is represented by a residential complex made of a couple of three-storey buildings located in San Pietro in Casale (near Bologna), which undergone a maximum PGA of 0.09g (Figure 5c). The buildings, depicted in Figure 17, were designed according to seismic prescriptions, and were realized with 360 mm thick AAC seismic blocks. The reference peak ground acceleration prescribed by the actual Italian Standard Code for that area is 0.208g. No damages were detected during the post-earthquake inspection survey, thanks to the substantially regular shape of the buildings, the use of good quality materials and an adequate care in detailing.

Figure 18 Plan of one apartment at the third level of the residential complex in San Pietro in Casale (Bologna).



The plan of one apartment placed at the third level of the residential building, shown in Figure 18, confirms also in this case the presence of an adequate amount of bearing masonry in the two main directions and the relatively small spacing between the bearing walls (lower than 7 m).

4 Seismic damage of AAC infill and partition walls in framed buildings

A description of typical seismic damages observed in AAC masonry infills and partitions is presented in this Section, which is focused on structures hit by the seismic sequence that stroke Central Italy in 2016.

The Central Italy's sequence occurred between August 24th , 2016 and January 18th, 2017 and was characterized by 9 events with magnitude $M_W \geq 5$ and hypocentres between 8 and 10 km; two of them reached magnitude $M_W = 6$ and $M_W = 6.5$. Figure 19 shows the shake map of the area, in terms of envelope of PGA of the nine events provided by Shakemap Working Group (2016). The same Figure shows the location of the epicentres, indicated with stars, and their magnitude. A comprehensive description of the characteristics of the seismic sequence can be read in Mollaioli et al. (2018).

Furthermore, Figure 20 reports the elastic response spectra evaluated according to the Italian Standard (2018), as well as the maximum registered earthquake excitation in terms of PGA and PSA (for T = 0.3, 1 and 3s) for the two analysed case studies, respectively placed in Muccia (Macerata) and Amatrice. The graphs were obtained under the same hypotheses already described in Section 3, but for the building placed in Amatrice a ground type B was considered.

The earthquake caused collapses and strong cumulative damages to cultural heritage, RC framed buildings, and masonry structures (Mollaioli et al., 2018; Sorrentino et al., 2018). In that area, AAC masonry was used in the past mainly for fire-partitioning walls in industrial buildings and, more rarely, for infills.

Figure 19 Envelope of shake maps of Central Italy's earthquake with epicentres, seismic reporting stations, and analysed case studies (obtained from the data of Shakemap Working Group, 2016).

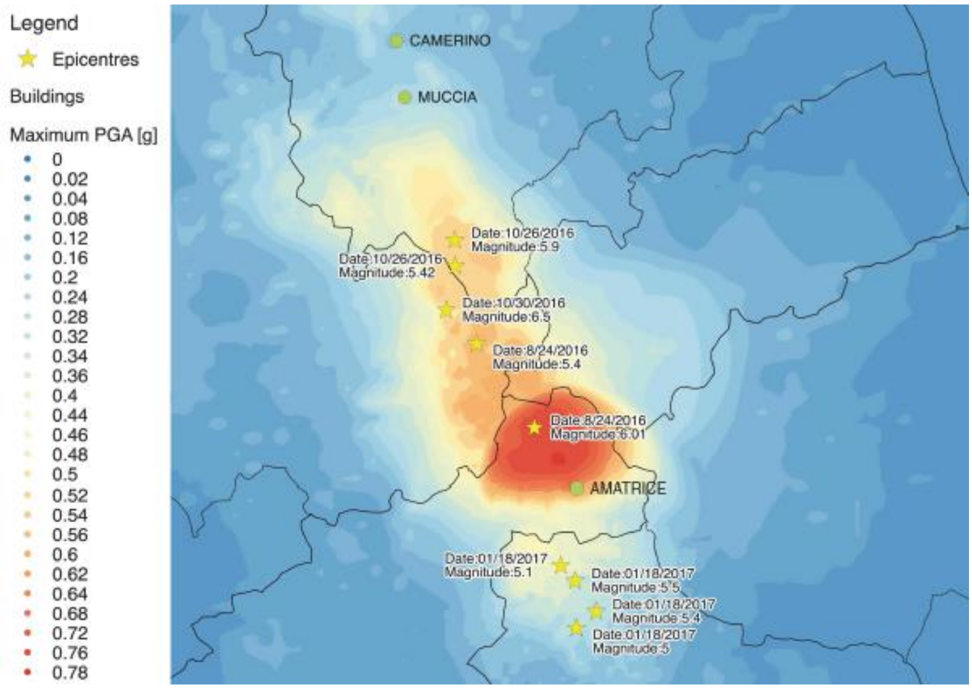
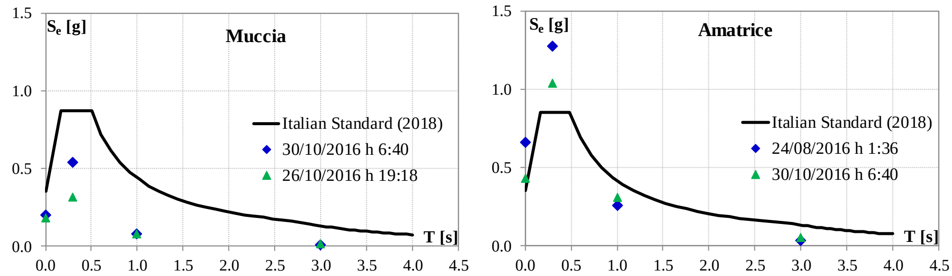


Figure 20 Seismic spectra to be applied for the considered case studies according to the Italian Standard (2018) and maximum registered earthquake excitation (INGV, 2019).



(a) (b)

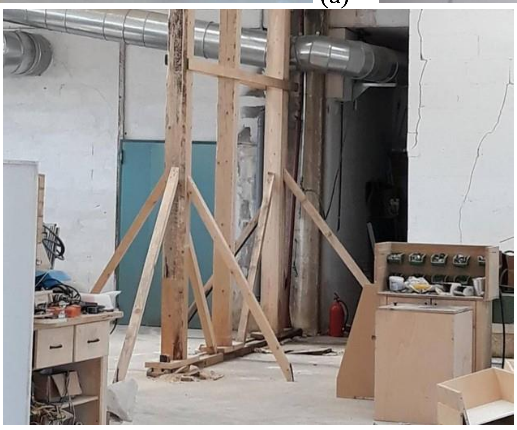
An interesting example where AAC was used for fire-resistant partitions is the furniture factory in Muccia (Macerata), shown in Figure 21. The internal view (Figure 22a) reveals a typical Italian precast concrete building, with prestressed concrete beams, precast thin-walled concrete roof elements (Belletti et al., 2016) and external panels.

Figure 21 External view of the furniture factory in Muccia (Macerata).

Figure 22 (a) Internal view of the furniture factory in Muccia; (b), (c) crack pattern in AAC masonry partitions.


(a)


(b)


(c)

A maximum PGA of 0.20g hit Muccia, which can be found in the shake map of Figure 19. The territory of Muccia is classified as “average seismic intensity” since 1984.

The reference peak ground acceleration prescribed by the actual Standard Code is 0.272g, according to Figure 20a. Although the building was realized according to seismic prescriptions, it presented the typical problems at the connections between columns and beams that are frequent for this typology of buildings (Belleri et al., 2015; Savoia et al., 2017).

AAC masonry partitions presented diffused shear cracks (Figures 22b,c), probably because of the remarkable deformability of the RC structure and the consequent interaction with non-structural walls. This type of damage was documented also in the industrial precast buildings after the Emilia 2012 earthquake, regardless of masonry typology (Savoia et al., 2017).

Another interesting case study is a reinforced concrete building in Amatrice, with AAC masonry infills. The photo reported in Figure 23, taken in September 2016, shows that the building survived the first two main shocks, with AAC masonry infills detached from the concrete frame but still in place. The maximum PGA after the second shock was 0.66g. The relatively good behaviour of the building can be explained considering that Amatrice was a seismic area since 1915 and the Italian Standard Code prescribes a reference PGA of 0.329g (Figure 20b). For this reason, we are dealing with an engineered building with seismic detailing. Furthermore, the response spectra of the earthquake was less demanding for the periods typical of deformable RC buildings (Mollaioli et al., 2018), as can be seen in Figure 20b.

No information is available for the building at the end of the sequence that razed the area with catastrophic damage and an exceptional macroseismic intensity I_{EMS} = XI.

Figure 23 Reinforced concrete framed building with AAC masonry infills in Amatrice (courtesy of Andrea Penna, adapted from Fragomeli et al., 2017).

5 Conclusions

This paper wants to provide a first insight into the damage assessment of AAC buildings. To the scope, some real case studies were collected and discussed, concerning different loading conditions (i.e. static and seismic loads) and different structural typologies (the most of the discussed examples concerns URM, but some cases of framed structures with AAC partitions and infills are also treated).

Regarding static behaviour, the main causes of cracking in AAC bearing walls, typically related to soil settlements, floor deformability and the presence of a different stress level in two adjacent perpendicular walls, are examined.

As concerns the seismic behaviour, the damages observed in AAC buildings during the past earthquakes in Emilia (2012) and Central Italy (2016) are discussed. The considered case studies evidenced the presence of some structural deficiencies typical of structures only conceived to sustain vertical loads. Even if out-of-plane failures were not found, extensive bi-diagonal and sub-vertical cracking was indeed observed at the lower levels of those buildings designed with no specific seismic prescriptions. The major detected problems were the lacking of construction details, an insufficient amount of bearing walls along the principal directions and, to some extent, a relatively high number of storey. On the contrary, the low-rise buildings (with 2 or 3 storeys) designed according to modern seismic requirements evidenced a satisfactory lateral load resistance and did not show any damage or cracking. The conclusions of the present work seem to indicate some lines of research that deserve to be investigated. In particular, further studies relative to the behaviour of full-scale walls under quasi-static in-plane loads (e.g., cyclic shear with compression) could be useful. Future investigations should also deepen several aspects related to structural details, like the connection between perpendicular walls, the presence of concrete ring beams at floor level, and the effect of reinforcement in increasing the ductility of the wall.

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