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

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

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

29 **Reference** to this paper should be made as follows: Ferretti, D, Michelini, E,
30 Pongiluppi, N. and Cerioni, R. (2019) 'Damage assessment of autoclaved
31 aerated concrete buildings: some Italian case studies', *Int. J. Masonry Research*
32 *and Innovation*, Vol. X, No. Y, pp. xxxx

33 **Biographical notes:** Daniele Ferretti is Associate Professor of Structural
34 Engineering at the University of Parma since 2004. He is author of 100
35 scientific papers on reinforced concrete structures (cracking, nonlinear analysis,
36 FRP, FRCM), masonry (AAC, adobe) and structural/seismic behaviour of
37 ancient buildings. He was principal investigator of a dozen of research projects
38 funded by firms or public administrations for the analysis of RC or masonry
39 structures and for the seismic assessment of ancient buildings.

40 Elena Michelini is Assistant Professor of Structural Engineering at the
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42 concrete and masonry structures (cracking, nonlinear analysis, tunnels, precast
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47 Nicola Pongiluppi had a Master's Degree in Civil Engineering and Architecture
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51 buildings, geotechnical works, prefabricated buildings, as well as the
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54 Roberto Cerioni is Full Professor of Structural Engineering at the University of
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59 the Department of Civil and Environmental Engineering and Architecture of the
60 University of Parma (2007-2012) and he was member of judging commissions
61 in the procedures for the selection of public employees, expert in seismic
62 matter.

63

64 **1 Introduction**

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

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

75 The performance of AAC masonry buildings during earthquakes is particularly
76 interesting since AAC technology is so far mainly widespread in non-seismic areas (like
77 Northern Europe), while its use in seismic-prone countries, like Italy, is still limited,
78 although it is progressively increasing in time (Costa et al., 2011). The growing interest
79 towards AAC masonry has led to the development, in the past decade, of a large number
80 of theoretical and experimental studies aimed at better understanding its behaviour under
81 seismic loads, in order to set specific design recommendations for the material, whose
82 peculiarities are quite different from standard masonry (Miccoli, 2018). The most of the
83 tests were performed on full-scale reinforced and unreinforced samples under quasi-static
84 or dynamic in-plane loads (Penna et al., 2015; Rosti et al., 2016; Tanner et al., 2005), and
85 the effects of out-of-plane loads were also analysed (Lönhoff and Sadegh-Azar, 2018).
86 Furthermore, scale models of typical AAC masonry buildings were tested on shaking
87 table (Tomažević and Gams, 2012). Several studies were also focused on framed
88 structures with AAC infills (e.g., Cheng and He, 2018). Experimental results were used as
89 the basis for FE simulations on a number of prototype walls or buildings with different
90 characteristics, corresponding to the most typical situations available on the construction

91 market, so as to assess their performance under seismic events (Costa et al., 2011; Ferretti
92 et al., 2015). However, very few case studies focusing on the damage assessment of AAC
93 masonry buildings during real seismic events can be found in the literature. Indeed, the
94 analysis of masonry behaviour during the major past Italian earthquakes has been so far
95 mainly concentrated on buildings made of stones or fired clay bricks (Adorni et al., 2009;
96 Bracchi et al., 2012; Cattari et al., 2012; Di Ludovico et al., 2017; Fragomeli et al., 2017;
97 Penna et al., 2014). The few available works focusing on the seismic performance of
98 AAC buildings mainly refer to Turkish earthquakes. The most of them are focused on
99 buildings realized with AAC panels (Ilki et al., 2013; Ugurlu et al., 2013), but some
100 information can be also found on the behaviour of monolayer or two-storey buildings
101 made of AAC masonry and subjected to the Marmara's earthquake of 1999. These last
102 studies revealed that AAC masonry buildings did not exhibit almost any sign of damages,
103 mainly due to the better quality of masonry units and to a better construction practice with
104 respect to traditional Turkish masonry structures (Celep, 2005).

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

116 **2 Static damage of AAC buildings**

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

121 Beyond cracks and splits due to temperature effects and to shrinkage (Liu et al.,
122 2011), the most common causes of cracking experienced by AAC elements under static
123 conditions are related to soil settlements or to uneven displacements of other structures,
124 such as floors, or adjacent walls and columns (Piekarczyk, 2018). While uneven
125 displacements of floors sustaining the walls are mainly due to their deformability or, in
126 some cases, to construction errors, uneven displacements of adjacent walls or columns are
127 generally caused by differential settlements, or by a differential elastic shortening of
128 connected members subjected to a different stress level.

129 Typical cracking occurring in AAC partition walls is often due to the deflection of the
130 floor lying underneath the walls themselves. This problem is quite common in Italian
131 residential building realized before 2003, since in many areas of the country seismic
132 prescriptions were not mandatory by law, and the presence of rigid floors was not so
133 frequent. Typical Italian floors are indeed realized with parallel reinforced concrete (RC)
134 joists separated by hollow clay blocks, in some cases without a RC topping (see Schiavi

135 et al., 2010). Besides the intrinsic deformability of the floor, which should be properly
136 checked both at design and construction stages, also the followed construction technique
137 may have a certain influence on cracking appearance in AAC elements. The walls should
138 be indeed built only after the complete removal of props. To reduce crack formation,
139 some Authors also suggest the adoption of normal thickness joints made of cement-lime
140 mortar instead of thin cement mortar joints – which are typical for AAC masonry – for
141 partition and infill walls (Piekarczyk, 2018).

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

146

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



150

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

157 Another example of a typical damage due to static loads that can be observed in AAC
158 masonry bearing walls is reported in Figure 2, which shows a terraced house in Bologna.
159 In this case, the crack pattern is characterized by the presence of an almost vertical crack
160 at the upper level of the third housing unit, at the connection zone between two
161 perpendicular walls. This type of crack often appears when the two walls are differently

162 loaded, which is a quite common situation in civil engineering, due to the presence of
163 one-way floors and roofs.

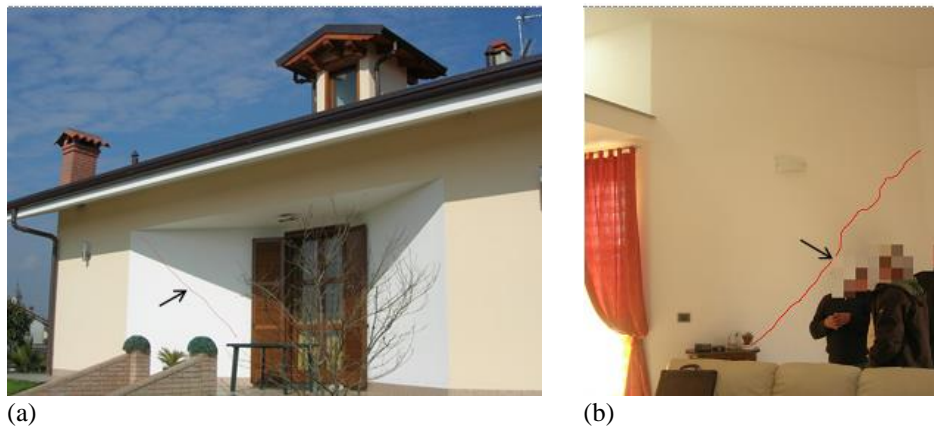
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165 **Figure 2** Example of cracks in AAC masonry walls due to static loads (terraced house in
166 Bologna).



167

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



169

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

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

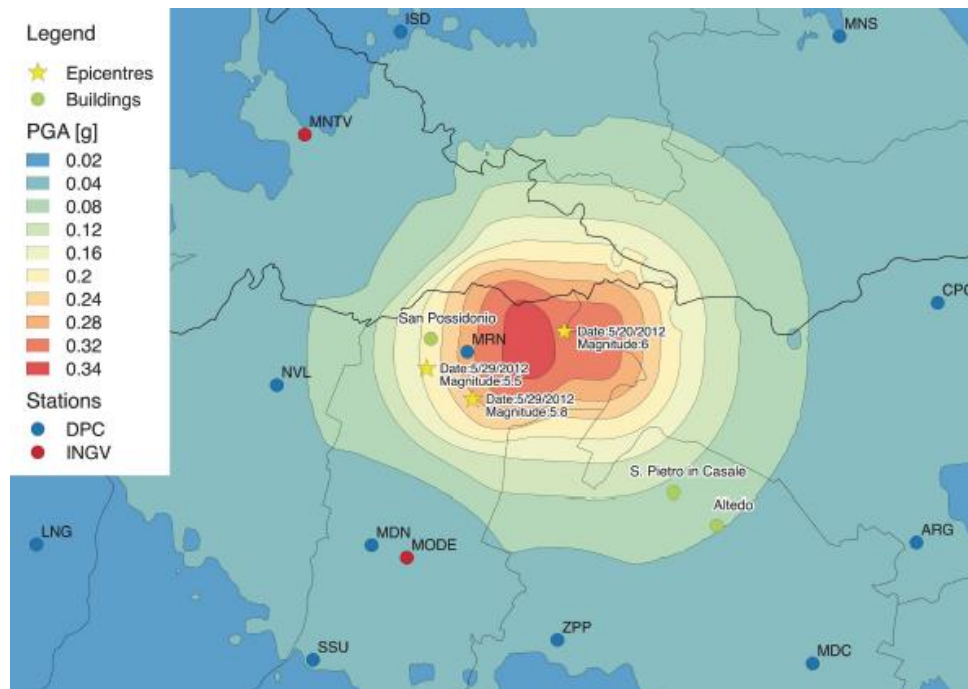
182 **3 Seismic damage of AAC masonry buildings**

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

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

194

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



197

198

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

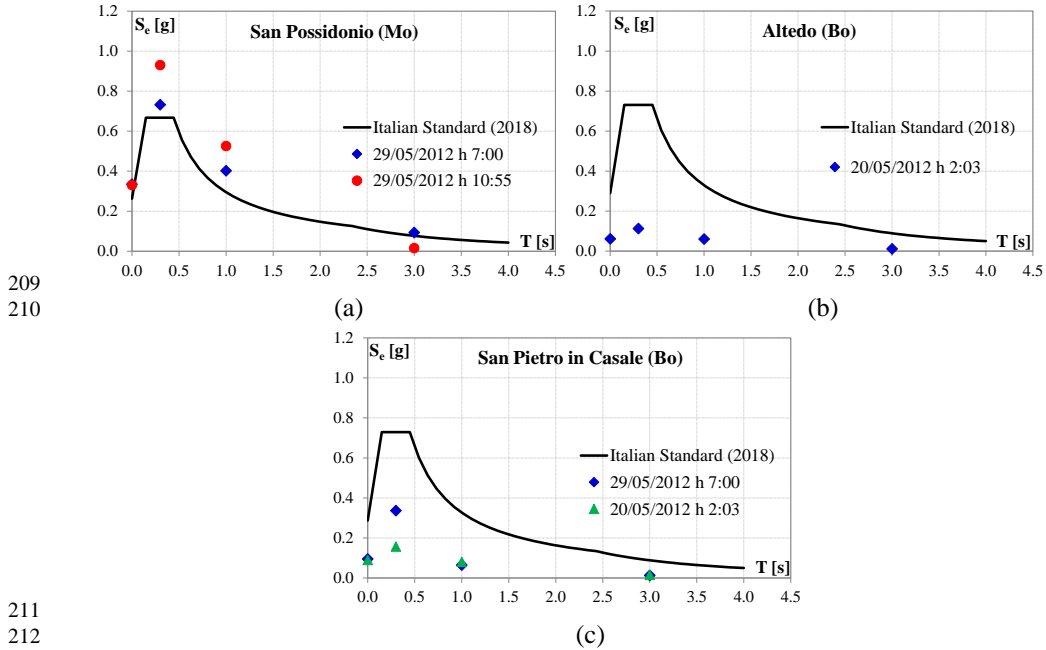
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207 **Figure 5** Seismic spectra to be applied for the considered case studies according to the
208 Italian Standard (2018) and maximum registered earthquake excitation (INGV, 2019).



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

223 It should be observed that most of the masonry buildings located in Emilia were
224 realized without seismic provisions, which became mandatory in this area starting from
225 year 2009. This fact explains the strong damages suffered by some typologies of masonry
226 structures, in particular old rural buildings and two or three-storey houses realized in the
227 period ranging from 1950 to 1980. A description of their damage state can be read in
228 Penna et al. (2014) and Cattari et al. (2012). Although the headquarters of one of the most
229 important AAC Italian manufactures of the past were settled in the Region, the use of this
230 type of masonry was not particularly spread. Probably for this reason, the damage reports
231 available in the literature describe a few (if any) buildings in AAC. In the following Sub-
232 sections, some unpublished case studies (except for the first one, in Section 3.1, which
233 has been partly debated in Pongiluppi et al., 2015) concerning AAC masonry buildings
234 subjected to Emilia's earthquake are presented and discussed, providing valuable
235 information on the behaviour of this type of masonry under seismic events.
236

237 3.1 Two-storey building in San Possidonio (Modena)

238 The first reported case study refers to a two-storey building in San Possidonio (Modena),
239 indicated in the shake map of Figure 4. This building was realized in two main phases.
240 The ground floor, devoted to commercial use and hosting a garage, was built during the
241 '70s, by using a 250 mm thick AAC bearing masonry. The first floor, with residential use,
242 was instead added in the '90s and was characterized by the presence of a not
243 homogeneous masonry, mainly constituted of perforated clay bricks with limited portions
244 made of AAC blocks. A general view of the building is shown in Figure 6, while Figure 7
245 reports a sketch of the plans of the two floors.
246

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



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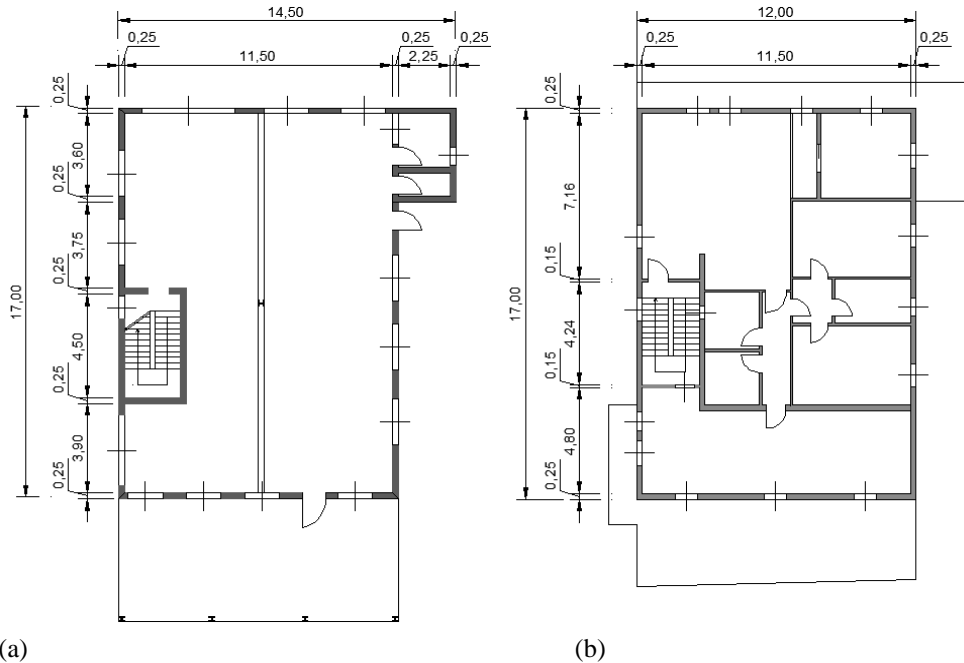
(a)

(b)

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

258 During the Emilia's earthquake, the building was subjected to a maximum PGA of
259 0.33g (see Figure 5a) that caused heavy damages to the masonry, as shown in Figures 6
260 and 8-9. The behaviour was mainly governed by the in-plane wall response, even if some
261 portions of the external walls undergone local out-of-plane collapses (see Figure 8b, over
262 the opening on the right). Diagonal shear cracks in masonry piers of the ground floor,
263 together with crushing phenomena can be recognized in Figures 6, 8 and 9. This
264 widespread damage was the consequence of some deficiencies in the structural
265 conception of the building, which was not designed for seismic resistance, but only for
266 carrying vertical loads. The main element of vulnerability was represented by the lack of
267 a sufficient amount of walls along the two main directions, which was respectively equal
268 to about 2% and 2.6% of the floor gross area. This insufficient “wall density” caused the
269 appearance of high stress levels on the piers at the ground storey, leading to a reduced in-
270 plane deformation capacity for shear mechanisms.

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



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



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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

287 interest of the scientific and technical community in studying the application of several
288 reinforcement techniques (mainly meshes or trusses) to increase wall ductility.

289

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



292

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295

3.2 Multi-storey building in San Possidonio (Modena)

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

306

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

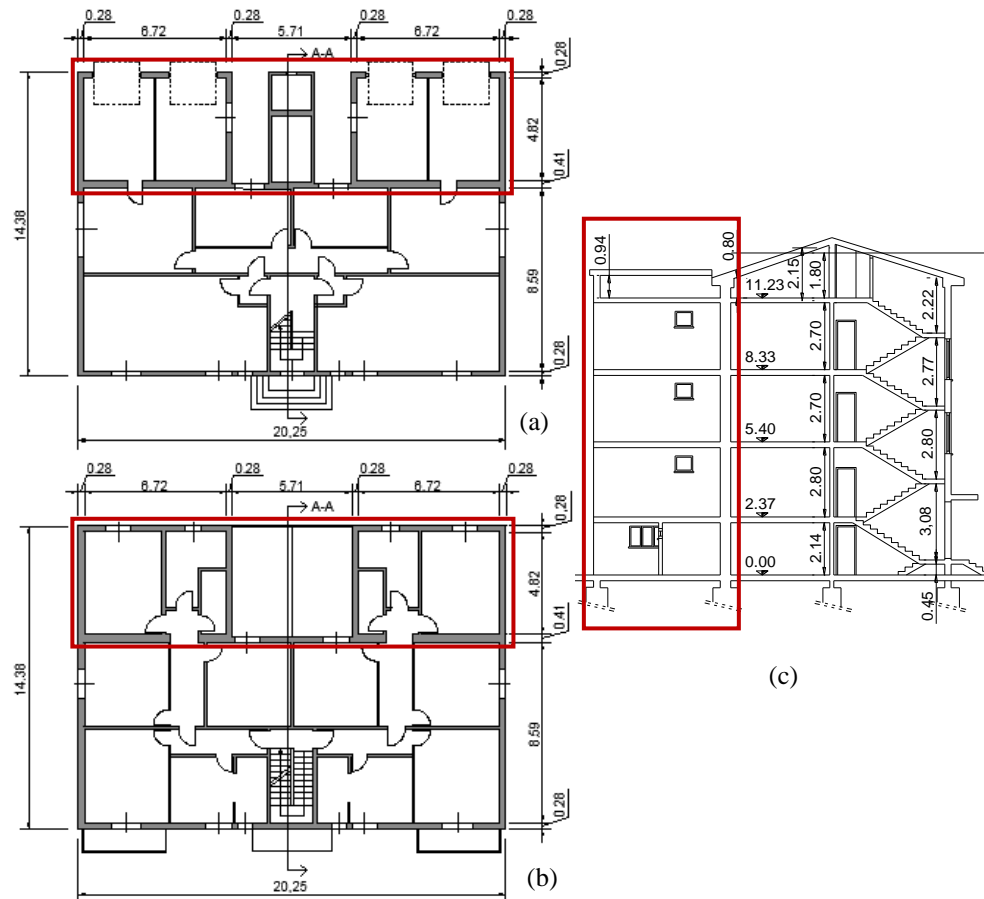


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310

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



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

320 The most significant damages undergone by the building during the seismic shakes
321 were concentrated in the newest part of the building, and are depicted in Figures 13 and
322 14. The maximum attained PGA was also in this case equal to $0.33g$, according to Figure
323 5a. The crack pattern was mainly constituted by sub-vertical cracks, together with
324 crushing phenomena and detachment of large portions of plaster. These damages were
325 primarily localised at the first floor (which is the lower one made of AAC), both at the
326 connection zone between two perpendicular walls and in the masonry piers between two
327 openings.

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



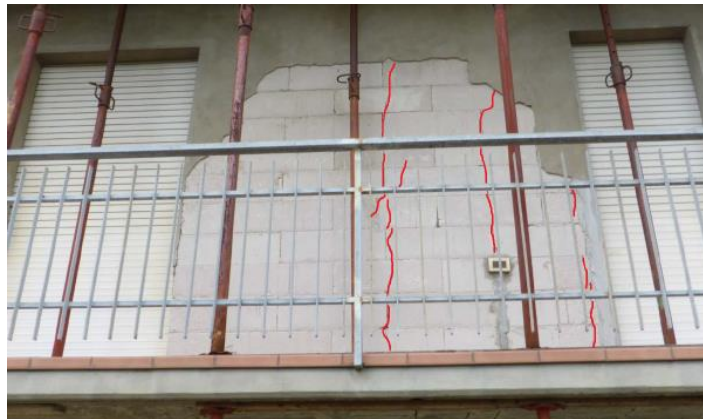
331

332 (a)

(b)

(c)

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



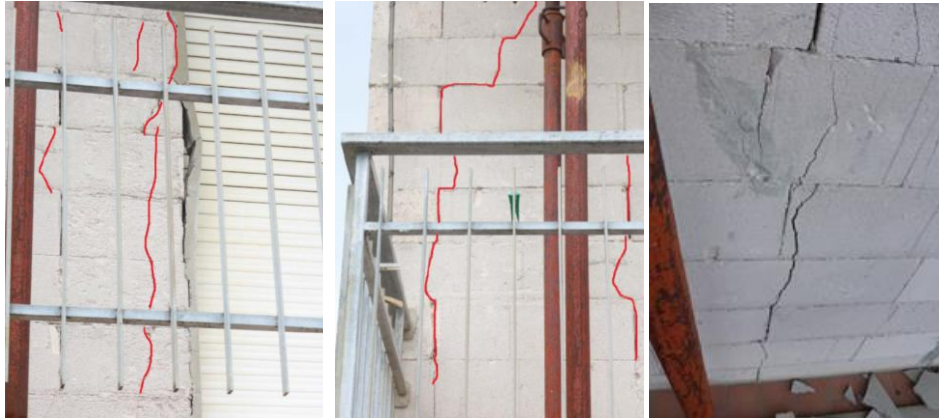
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336

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

348

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



352

353 (a)

(b)

(c)

354

355 *3.3 Undamaged AAC masonry buildings*

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

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

361

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



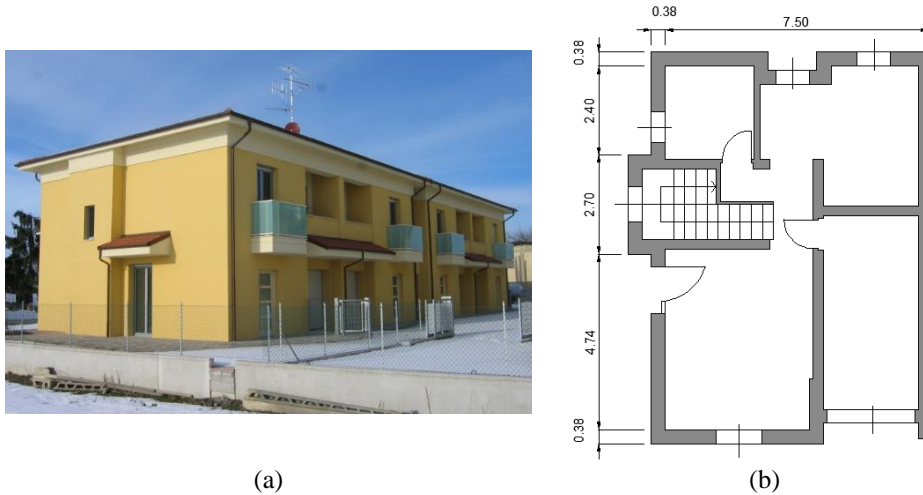
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365 A detailed view of one of the two buildings, together with a sketch of the plan of one
366 housing unit, is reported in Figure 16. As can be seen, the structure is characterized by an
367 adequate amount of walls in the main directions (with a “wall density” ranging from 7 to
368 8%) and concrete ring beams were realized upon the walls. AAC bearing walls have a
369 thickness of 360 mm and are covered by a plaster layer.

370 The post-earthquake inspection survey did not reveal the presence of any cracks and
371 damages nor in the peripheral nor in the internal walls. In any case, it should be observed
372 that the building was subjected to a relatively low seismic action, since the reference peak
373 ground acceleration prescribed for that area by the actual Italian Standard Code is 0.21g.
374

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

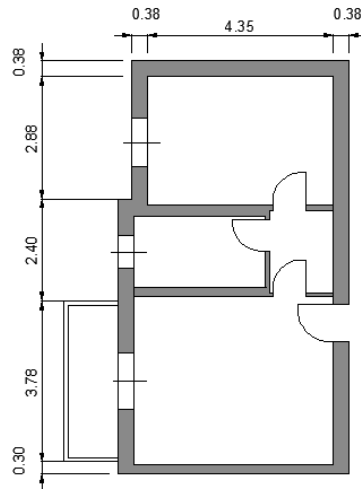


377
378 **Figure 17** Residential complex made of unreinforced AAC masonry in San Pietro in
379 Casale (Bologna).



380
381
382 The second case study is represented by a residential complex made of a couple of
383 three-storey buildings located in San Pietro in Casale (near Bologna), which undergone a
384 maximum PGA of 0.09g (Figure 5c). The buildings, depicted in Figure 17, were designed
385 according to seismic prescriptions, and were realized with 360 mm thick AAC seismic
386 blocks. The reference peak ground acceleration prescribed by the actual Italian Standard
387 Code for that area is 0.208g. No damages were detected during the post-earthquake
388 inspection survey, thanks to the substantially regular shape of the buildings, the use of
389 good quality materials and an adequate care in detailing.

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



392

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

397 **4 Seismic damage of AAC infill and partition walls in framed buildings**

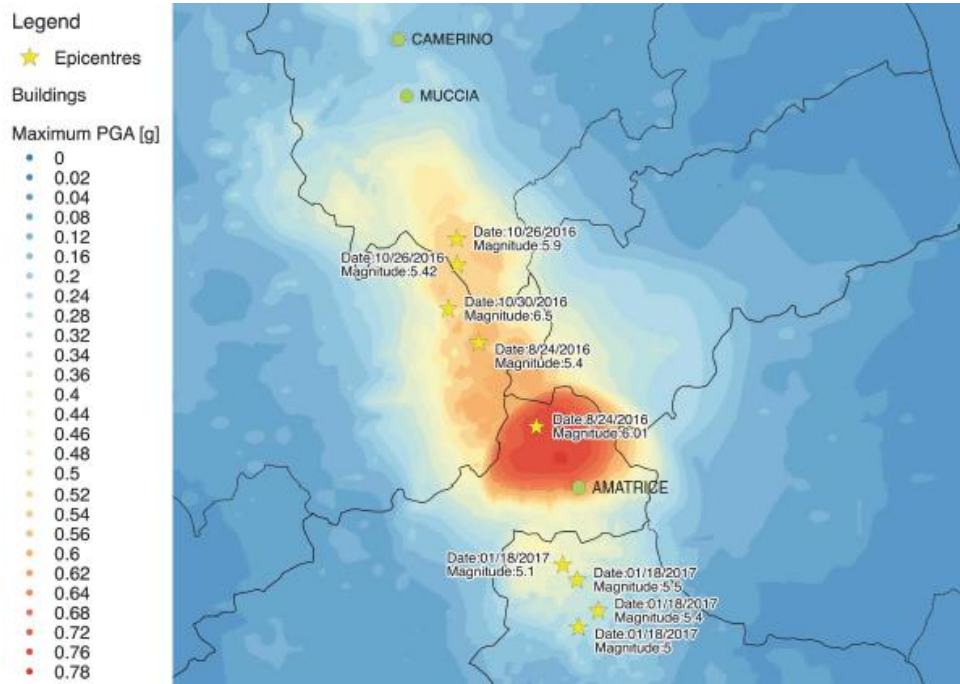
398 A description of typical seismic damages observed in AAC masonry infills and partitions
399 is presented in this Section, which is focused on structures hit by the seismic sequence
400 that stroke Central Italy in 2016.

401 The Central Italy's sequence occurred between August 24th, 2016 and January 18th,
402 2017 and was characterized by 9 events with magnitude $M_w \geq 5$ and hypocentres between
403 8 and 10 km; two of them reached magnitude $M_w = 6$ and $M_w = 6.5$. Figure 19 shows the
404 shake map of the area, in terms of envelope of PGA of the nine events provided by
405 Shakemap Working Group (2016). The same Figure shows the location of the epicentres,
406 indicated with stars, and their magnitude. A comprehensive description of the
407 characteristics of the seismic sequence can be read in Mollaioli et al. (2018).

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

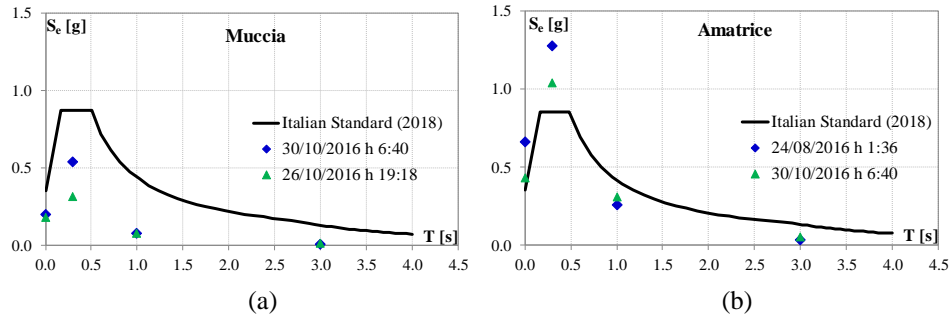
414 The earthquake caused collapses and strong cumulative damages to cultural heritage,
415 RC framed buildings, and masonry structures (Mollaioli et al., 2018; Sorrentino et al.,
416 2018). In that area, AAC masonry was used in the past mainly for fire-partitioning walls
417 in industrial buildings and, more rarely, for infills.

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



421
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423 **Figure 20** Seismic spectra to be applied for the considered case studies according to the
 424 Italian Standard (2018) and maximum registered earthquake excitation (INGV, 2019).



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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.

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



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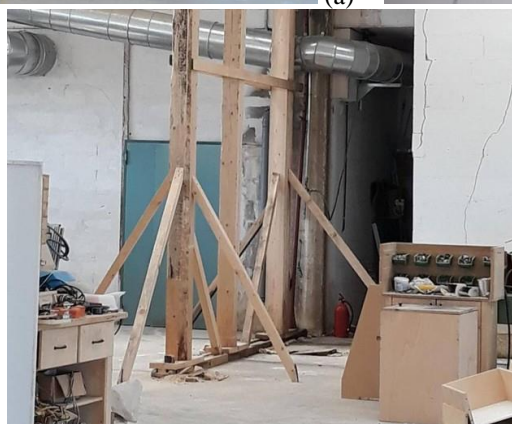
440 **Figure 22** (a) Internal view of the furniture factory in Muccia; (b), (c) crack pattern in
441 AAC masonry partitions.



(a)



(b)



(c)

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444

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.

445 The reference peak ground acceleration prescribed by the actual Standard Code is 0.272g,
446 according to Figure 20a. Although the building was realized according to seismic
447 prescriptions, it presented the typical problems at the connections between columns and
448 beams that are frequent for this typology of buildings (Belleri et al., 2015; Savoia et al.,
449 2017).

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

455 Another interesting case study is a reinforced concrete building in Amatrice, with
456 AAC masonry infills. The photo reported in Figure 23, taken in September 2016, shows
457 that the building survived the first two main shocks, with AAC masonry infills detached
458 from the concrete frame but still in place. The maximum PGA after the second shock was
459 0.66g. The relatively good behaviour of the building can be explained considering that
460 Amatrice was a seismic area since 1915 and the Italian Standard Code prescribes a
461 reference PGA of 0.329g (Figure 20b). For this reason, we are dealing with an engineered
462 building with seismic detailing. Furthermore, the response spectra of the earthquake was
463 less demanding for the periods typical of deformable RC buildings (Mollaioli et al.,
464 2018), as can be seen in Figure 20b.

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

467

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



470

471 **5 Conclusions**

472 This paper wants to provide a first insight into the damage assessment of AAC buildings.
473 To the scope, some real case studies were collected and discussed, concerning different
474 loading conditions (i.e. static and seismic loads) and different structural typologies (the

475 most of the discussed examples concerns URM, but some cases of framed structures with
476 AAC partitions and infills are also treated).

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

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

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503 **References**

- 504 Adorni, E., Amadori, A., Battaglia, R., Belletti, B., Bianchini, M., Borghesi, A., Di
505 Cesare, M., Diotallevi, P.P., Ferrari, C., Ferretti, D., Landi, L., Manieri, G.,
506 Martelli, L., Marziali, G., Milani, E., Passarella, V., Royer-Carfagni, G., Sasso,
507 M.A., Spagnoli, A., Tralli, A., Ubertini, F., 2009. Prime considerazioni sugli effetti
508 del terremoto sulle strutture in muratura in alcune località dell'Aquilano (in Italian).
509 Ing. Sismica 26, 26–39.
- 510 Aroni, S., de Groot, G.J., Robinson, M.J., Svanholm, G., Wittman, F.H. (Eds.), 1993.
511 Autoclaved aerated concrete-properties, testing and design - RILEM Recommended
512 Practice. E&FN Spon, London.
- 513 Belleri, A., Brunesi, E., Nascimbene, R., Pagani, M., Riva, P., 2015. Seismic Performance
514 of Precast Industrial Facilities Following Major Earthquakes in the Italian Territory.
515 J. Perform. Constr. Facil. 04014135. [https://doi.org/10.1061/\(ASCE\)CF.1943-
516 5509.0000617](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000617)

- 517 Belletti, B., Bernardi, P., Michelini, E., 2016. Behavior of thin-walled prestressed
518 concrete roof elements - Experimental investigation and numerical modeling. *Eng.*
519 *Struct.* 107, 166–179. <https://doi.org/10.1016/j.engstruct.2015.06.058>
- 520 Bracchi, S., da Porto, F., Galasco, A., Graziotti, F., Liberatore, D., Liberatore, L.,
521 Magenes, G., Mandirola, M., Manzini, C.F., Morandi, P., Palmieri, M., Penna, A.,
522 Rosti, A., Rota, M., Todelli, M., 2012. Behaviour of masonry buildings in the
523 seismic sequence of 2012 in Emilia (in Italian). *Progett. Sismica* 3, 141–161.
- 524 Cattari, S., Abbati, S.D., Ferretti, D., Lagomarsino, S., Ottonelli, D., Tralli, A., 2012. The
525 seismic behaviour of ancient masonry buildings after the earthquake in Emilia
526 (Italy) on May 20th and 29th, 2012. *Ing. Sismica* 29, 87–119.
- 527 Celep, Z., 2005. Performance of masonry building including AAC products during the 17
528 August 1999 Marmara Earthquake, in: Limbachiya and Roberts (Ed.), *Autoclaved*
529 *Aerated Concrete*. Taylor & Francis, London, pp. 437–444.
- 530 Cheng, C., He, L., 2018. Shaking table test study on a steel frame with autoclaved aerated
531 concrete walls, in: *Ce/Papers- Proc. of the 6th Int. Conf. on AAC (ICAAC)*,
532 Potsdam. Wiley Online Library, pp. 283–289. <https://doi.org/10.1002/cepa.876>
- 533 Costa, A.A., Penna, A., Magenes, G., 2011. Seismic Performance of Autoclaved Aerated
534 Concrete (AAC) Masonry: From Experimental Testing of the In-Plane Capacity of
535 Walls to Building Response Simulation. *J. Earthq. Eng.* 15, 1–31.
536 <https://doi.org/10.1080/13632461003642413>
- 537 de Nardis, R., Filippi, L., Costa, G., Suhadolc, P., Nicoletti, M., Lavecchia, G., 2014.
538 Strong motion recorded during the Emilia 2012 thrust earthquakes (Northern Italy):
539 a comprehensive analysis. *Bull. Earthq. Eng.* 12, 2117–2145.
540 <https://doi.org/10.1007/s10518-014-9614-0>
- 541 Di Ludovico, M., Digrisolo, A., Graziotti, F., Moroni, C., Belleri, A., Caprili, S., Carocci,
542 C., Dall’Asta, A., DE Martino, G., De Santis, S., Ferracuti, B., Ferretti, D.,
543 Fiorentino, G., Mannella, A., Marini, A., Mazzotti, C., Sandoli, A., Santoro, A.,
544 Silvestri, S., Manfredi, G., 2017. The contribution of ReLUIs to the usability
545 assessment of school buildings following the 2016 central Italy earthquake. *Boll. di*
546 *Geofis. Teor. ed Appl.* 58, 353–376. <https://doi.org/10.4430/bgta0192>
- 547 Drobiec, Ł., 2018. Tests of AAC walls subjected to vertical loads- Part 2. Connection
548 zone of perpendicular walls, in: *Ce/Papers- Proc. of the 6th Int. Conf. on AAC*
549 *(ICAAC)*, Potsdam. Wiley Online Library, pp. 329–337.
550 <https://doi.org/10.1002/cepa.823>
- 551 Ferretti, D., Michelini, E., Rosati, G., 2015. Mechanical characterization of autoclaved
552 aerated concrete masonry subjected to in-plane loading: Experimental investigation
553 and FE modeling. *Constr. Build. Mater.* 98, 353–365.
554 <https://doi.org/10.1016/j.conbuildmat.2015.08.121>
- 555 Fragomeli, A., Galasco, A., Graziotti, F., Guerrini, G., Kallioras, S., Magenes, G.,
556 Malomo, D., Mandirola, M., Manzini, C.F., Marchesi, B., Milanese, R.R., Morandi,
557 P., Penna, A., Rossi, A., Rosti, A., Rota, M., Senaldi, I.E., Tomassetti, U., Cattari,
558 S., da Porto, F., Sorrentino, L., 2017. Performance of masonry buildings in the
559 seismic sequence of Central Italy 2016 - Part 1 : Overview. *Progett. Sismica* 8, 49–
560 77. <https://doi.org/10.7414/PS.8.2.49-77>
- 561 Ilki, A., Demir, C., Ugurlu, K., 2013. An overview of seismic performance of buildings
562 constructed with reinforced AAC panels, in: *Sustainable Building Concepts in*
563 *Earthquake Regions & Energy Efficient Buildings*. Istanbul, Turkey.
- 564 INGV, 2019. Shake Maps <http://shakemap.rm.ingv.it/shake/index.html> (accessed April

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

- 2019)
- 565
566 Italian Standard - DM 17/01/2018: Aggiornamento delle “Norme Tecniche per le
567 Costruzioni” (in Italian), 2018.
- 568 Liu, X.L., Guo, C., Wang, X.B., 2011. Discussion on Crack of Aerated Concrete Block
569 Wall, in: Applied Mechanics and Materials. Trans Tech Publ, Switzerland, pp.
570 1805–1809.
- 571 Lönhoff, M., Sadegh- Azar, H., 2018. Seismic out- of- plane behavior of unreinforced
572 masonry walls, in: Ce/Papers- Proc. of the 6th Int. Conf. on AAC (ICAAC),
573 Potsdam. Wiley Online Library, pp. 291–299. <https://doi.org/10.1002/cepa.844>
- 574 Miccoli, L., 2018. Seismic performances of AAC masonry: a review of experimental and
575 numerical approaches, in: Ce/Papers- Proc. of the 6th Int. Conf. on AAC (ICAAC),
576 Potsdam. Wiley Online Library, pp. 301–309. <https://doi.org/10.1002/cepa.878>
- 577 Mollaioli, F., AlShawa, O., Liberatore, L., Liberatore, D., Sorrentino, L., 2018. Seismic
578 demand of the 2016-2017 Central Italy earthquakes. Bull. Earthq. Eng.
579 <https://doi.org/10.1007/s10518-018-0449-y>
- 580 Penna, A., Mandirola, M., Rota, M., Magenes, G., 2015. Experimental assessment of the
581 in-plane lateral capacity of autoclaved aerated concrete (AAC) masonry walls with
582 flat-truss bed-joint reinforcement. Constr. Build. Mater. 82, 155–166.
- 583 Penna, A., Morandi, P., Rota, M., Manzini, C.F., da Porto, F., Magenes, G., 2014.
584 Performance of masonry buildings during the Emilia 2012 earthquake. Bull. Earthq.
585 Eng. 12, 2255–2273. <https://doi.org/10.1007/s10518-013-9496-6>
- 586 Piekarczyk, A., 2018. Reinforced and unreinforced AAC masonry walls supported on
587 deflecting structure, in: Ce/Papers - Proc. of the 6th Int. Conf. on AAC (ICAAC) ,
588 Potsdam. Wiley Online Library, pp. 377–387. <https://doi.org/10.1002/cepa.861>
- 589 Pongiluppi, N., Barbieri, L., Botti, F., Mosele, F., 2015. Miglioramento sismico con
590 l’impiego di muratura armata di un fabbricato produttivo-residenziale sito a San
591 Possidonio (MO), danneggiato dagli eventi sismici dell’Emilia 2012 (in Italian).
592 Progett. Sismica 139–152.
- 593 RAN, 2016. www.protezionecivile.gov.it/jcms/it/ran.wp.
- 594 Rosti, A., Penna, A., Rota, M., Magenes, G., 2016. In-plane cyclic response of low-
595 density AAC URM walls. Mater. Struct. 49, 4785–4798.
596 <https://doi.org/10.1617/s11527-016-0825-5>
- 597 Savoia, M., Buratti, N., Vincenzi, L., 2017. Damage and collapses in industrial precast
598 buildings after the 2012 Emilia earthquake. Eng. Struct. 137, 162–180.
- 599 Schiavi, A., Di Bella, A., Semprini, G., Astolfi, A., Tarizzo, P., Luison, L., Barbaresi, L.,
600 Pontarollo, C.M., 2010. Proposal for a reference floor for hollow brick and concrete
601 slabs based on Italian experiences, in: Proceedings of the 20 Th International
602 Congress on Acoustics, Sidney.
- 603 Shakemap Working Group, 2016. Shakemap homepage.
604 <http://shakemap.rm.ingv.it/shake/index.html>.
- 605 Sorrentino, L., Cattari, S., da Porto, F., Magenes, G., Penna, A., 2018. Seismic behaviour
606 of ordinary masonry buildings during the 2016 central Italy earthquakes. Bull.
607 Earthq. Eng. <https://doi.org/10.1007/s10518-018-0370-4>
- 608 Tanner, J.E., Varela, J.L., Klingner, R.E., Brightman, M.J., Cancino, U., 2005. Seismic
609 testing of autoclaved aerated concrete shearwalls: a comprehensive review. ACI
610 Struct. J. 102, 374–382.
- 611 Tomažević, M., Gams, M., 2012. Shaking table study and modelling of seismic behaviour

D. Ferretti et al.

- 612 of confined AAC masonry buildings. *Bull. Earthq. Eng.* 10, 863–893.
613 <https://doi.org/10.1007/s10518-011-9331-x>
614 Ugurlu, K., Demir, C., Ilki, A., 2013. Seismic assessment of a school building constructed
615 with AAC panels and experienced 1999 Kocaeli earthquake, in: *Proc. SMAR 2013*
616 *2nd Conference on Smart Monitoring Assessment and Rehabilitation of Civil*
617 *Structures*.
618 USGS, 2019. Shake maps.
619 <https://earthquake.usgs.gov/earthquakes/eventpage/usp000jkn8/shakemap/intensity>
620 (Accessed April 2019).
621
622