# SEISMIC PERFORMANCE OF AAC INFILL AND BEARING WALLS WITH DIFFERENT REINFORCEMENT SOLUTIONS

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## SUMMARY

Code specifications for masonry elements have been often developed after experimental studies on construction materials and techniques. AAC walls can represent a very effective solution for thermal insulation purposes, lightness and workability both for structural masonry and infill panels. In this work their seismic behaviour has been assessed by cyclic testing of bearing walls and infilled frames: the performances of different solutions of slight reinforcements have been also compared and evaluated. Distributed horizontal reinforcements enhance strength, displacement capacity and energy dissipation in shear failure modes. The test results on masonry piers allow to perform first comparisons between different constructive technologies and to model and analyse the global seismic behaviour of AAC masonry buildings. The tests on infilled frames panels show that the AAC infill significantly contributes to the overall lateral capacity of the frame and, due to its high deformability, it can be considered effective up to the collapse limit state.

## INTRODUCTION

Autoclaved aerated concrete is a mixture of cement, lime, water and sand that expands by adding aluminium powder. The reaction between aluminium and concrete causes microscopic hydrogen bubbles to form, expanding the concrete to about five times its original volume. After evaporation of the hydrogen, the now highly closed-cell, aerated concrete is cut to size and form and it is steam-cured in a pressurized chamber, known as autoclave. Steam curing of specimens in these autoclaves at several times atmosphere pressure ensures that hydrothermal conditions are maintained. The curing process is termed autoclaving. The result is a non-organic, non-toxic, airtight material characterised by its fine cellular structure, with air pores ranging from 0.1 to 2 mm, a high strength/weight ratio and according to the manufacturers,

the production process generates no pollutants or hazardous waste. As a final remark and regarding the seismic behaviour of AAC buildings, the light weight of the material reduces the seismic inertia forces. In addition, the non-combustible and fire-resisting nature of AAC material is an advantage against fires commonly associated with earthquakes

## EXPERIMENTAL TEST CAMPAIGN ON LOAD BEARING WALLS

An experimental test campaign was performed with the aim of assessing the in-plane behaviour of AAC masonry piers. The test setup used was a cantilever system (fixed at the base and free at the top) with a constant vertical load applied at the top with hydraulic jacks. The horizontal load was applied by means of a displacement-controlled horizontal hydraulic actuator, performing three fully reversed cycles for each target displacement level. In Figure 1 it is possible to observe the test setup apparatus.

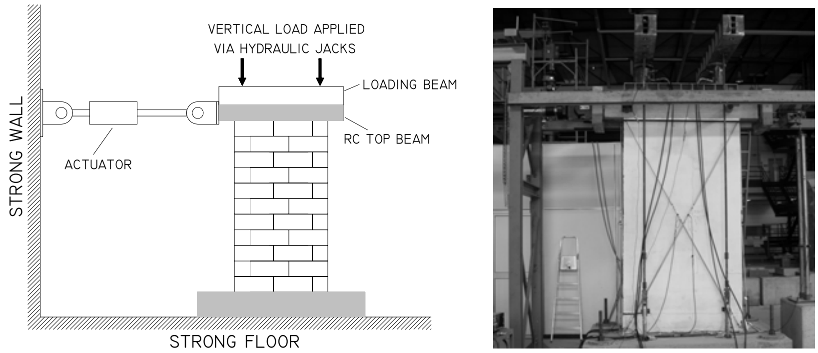



Figure 1. Scheme and picture of the test setup

Four unreinforced AAC masonry walls were tested to assess the in-plane behaviour of this type of masonry. Two walls with a length *l* of 1.5 meters, one of 3.0 meters and another of 4.5 meters, constituted by 625 x 300 x 250 $mm^3$ units were built, representative of different wall slenderness commonly found in modern buildings, with a thickness *t* of 0.30 m and a height *h* of 2.75 m. The mechanical properties of the masonry were measured experimentally with specific tests, performed on blocks, glue mortar and wallettes, according to the EN771-4, EN772, EN998 and EN1052 standards. A mean value of 2.2 MPa was found for the masonry compressive strength while the mean value of the Young modulus in compression was 1600 MPa. The specific weight of the blocks was 4.77 $kN/m^3$. In each wall a reinforced concrete top beam, with a cross section 0.30 x 0.25 m and four 16 mm longitudinal steel bars and 6 mm stirrups at 0.25 m spacing, was built with the aim of distributing better the applied loads. Two levels of vertical load were applied: 200 kN for the 1.5 meter long specimens, 300 kN for one unreinforced 1.5 meter long wall and the remaining specimens. Hence, these values resulted in a load ratio (ratio of average vertical compression to compressive strength) of 0.2 (200 kN) and 0.3, 0.15 and 0.1, respectively for the 1.5, 3.0 and 4.5 meters long specimens with 300 kN.

The following structural solutions were considered:

- Unreinforced masonry;
- Confined masonry with horizontal truss-type bed joint reinforcement;
- Horizontally reinforced masonry, with flat truss steel reinforcement (Murfor) or rebar reinforcement placed in grooved blocks.

The chosen experimental configurations, for a total of nine specimens, are reported in the matrix in Figure 2.

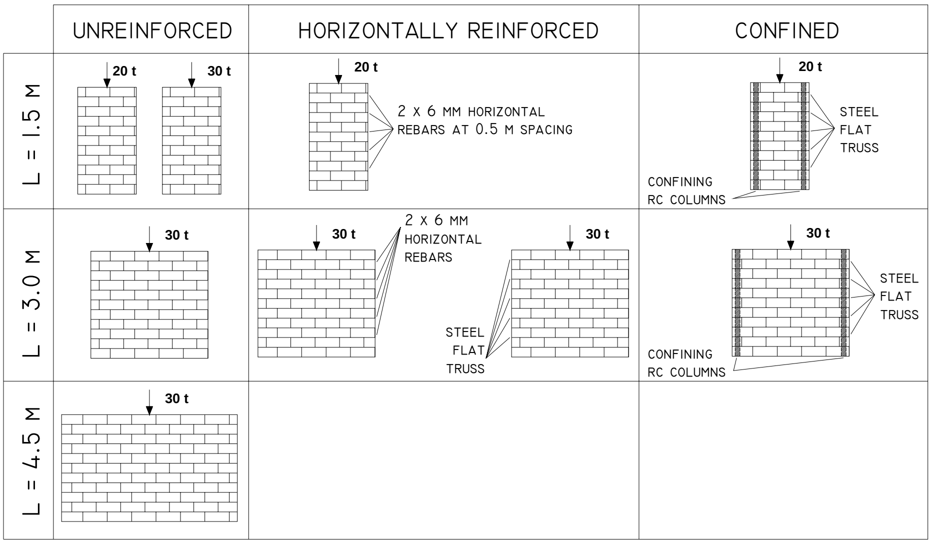



Figure 2. Matrix of the considered experimental schemes

The unreinforced specimens were built with thin (2-3 mm) mortar layers and filled head joints.
In Figure 3 the experimental force - displacement curves are reported for the four unreinforced specimens.

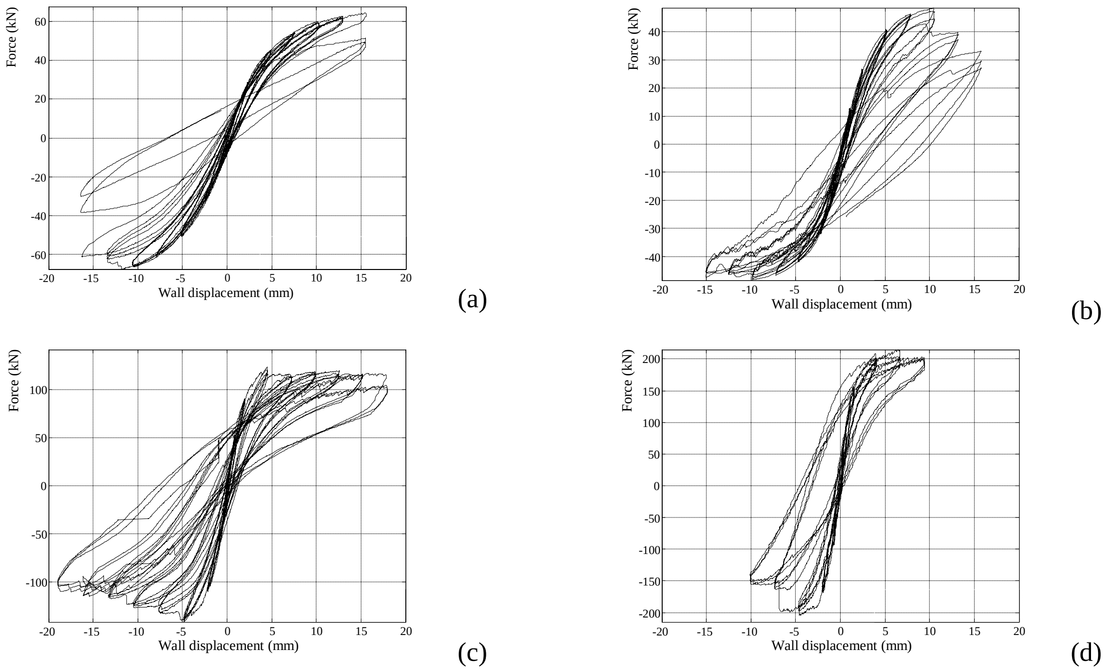
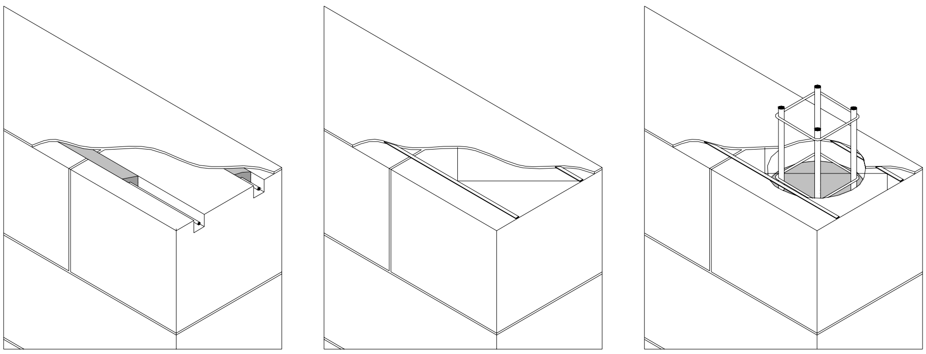



Figure 3. Horizontal force-displacement curves for unreinforced AAC walls: a) *l*=1.5 m with 300 kN, b) *l*=1.5 m with 200 kN, c) *l*=3.0 m with 300 kN, d) *l*=4.5 m with 300 kN.

The slender walls (*l*=1.5 m) developed flexural cracking in the initial stage of the test, followed by shear cracking at higher displacements, while the other two walls failed in prevailing shear. Moreover the slender specimens achieved equal maximum displacement, with a similar evidence of damage (significant hourglass type cracks) even with different vertical load. In this case, a reasonable design value of the ultimate drift, calculated as the ratio between the lateral displacement and the wall height, for flexural failure mode should not be assumed greater than 0.5% . The maximum ultimate drift for the 3.0 meters specimen,

estimated from entity and diffusion of cracks as well as separation of block portions, was 0.7%, and the longer one achieved 0.35% drift. The strength increased with the wall length, being the maximum strength of 221 kN obtained for the 4.5 meters wall.
Considering the results obtained in the experimental tests, and comparing those with the values proposed in [1], it is possible to infer that the suggested maximum ultimate drift of 0.3% seems to be very conservative for shorter walls failing in a mixed shear-rocking mode but rather appropriate for longer walls failing in shear.
In the horizontally reinforced walls a reinforced bed joint was present every second block layer (i.e. with a vertical spacing of 0.5 m). The walls reinforced with two horizontal 6 mm rebars were built using special grooved blocks for the reinforced layers and the grooves were fully grouted in order to achieve a good bonding between bars and blocks. The flat truss steel reinforcement consisted in a couple of thin longitudinal plates (2 x 1.5 x 8 $mm^2$) connected by a 1.5 mm wire.
In the confined specimens, in addition to the bed-joint reinforcement, a couple of r.c. columns was cast in place at the ends of the wall. The columns were built in special blocks with 150 mm diameter vertical holes with a reinforcement consisting of four 12 mm vertical rebars and 6 mm stirrups at 0.15 m spacing.
The reinforcement details adopted in the experimental campaign are represented in Figure 4.



(a) (b) (c)

Figure 4. Construction details of the reinforced specimens: (a) horizontal rebars lodged in grooved blocks; (b) flat truss bed-joint reinforcement; flat truss reinforcement and cast in place confining r.c. columns.

In Figure 5 a synthetic comparison of the experimental results, among the different reinforcement solutions, in terms of lateral force-displacement envelope curves is presented, for squat walls (3 m x 2.75 m) and slender walls (1.5 m x 2.75 m), respectively.

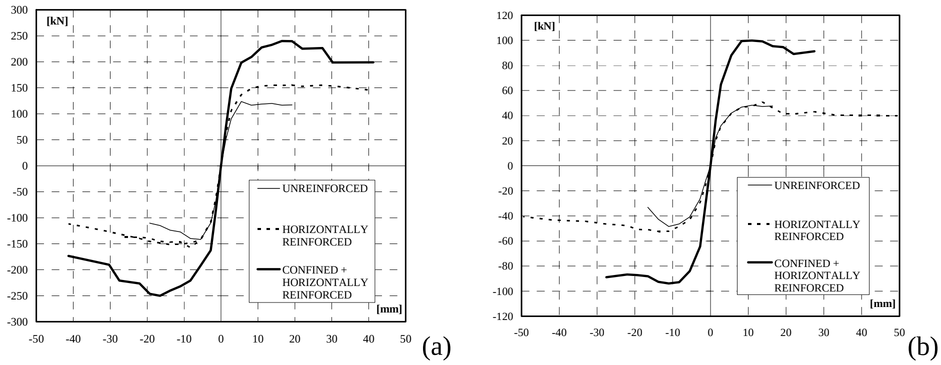



Figure 5. Force-displacement envelopes for the “squat”, (a), and “slender”, (b), AAC walls (thin line: unreinforced; thick line: confined and horizontally reinforced: dashed line: horizontally reinforced)

All the slender walls have shown a clear flexural behaviour. The confined masonry solution, compared to the unreinforced one, showed a significant increment of strength and stiffness and also an increase in the ultimate displacement capacity. In the case of the wall with bed joint reinforcement, the strength and stiffness has been not altered but, due to the reduction of vertical and diagonal cracking, the lateral displacement capacity has been highly increased.
The unreinforced squat wall has shown a clear shear failure, the horizontally reinforced one a flexural one and for the confined wall a mixed failure mode has been observed. The confined masonry solution provided, with respect to the unreinforced one, a significant increment of strength and displacement capacity. In the case of the bed joint reinforced wall, the stiffness has been not modified but, due to the prevention of the shear failure mode, the lateral strength has been slightly increased and the displacement capacity has been enlarged to the same level of the confined solution.

## EXPERIMENTAL TEST CAMPAIGN ON AAC INFILLED RC FRAMES

A second test campaign was performed on one-bay, one-storey full scale r.c. frames infilled with AAC panels, considering one single geometry and the same type of AAC units and glue-mortar. At different levels of in plane drifts, out of plane tests were performed to define strength domains as a function of in plane damage.
The overall dimensions were selected to be 4.5 × 3 (height) m. The concrete frame was designed as the lowest part of a four storey building, applying thoroughly the rules given by Eurocode 2 and Eurocode 8. The structure was designed according to the high ductility class of EC8, applying fully the capacity design rules. The plastic hinges were therefore supposed to form in the beams and all critical sections were well confined. All infill panels had identical geometry, with dimensions equal to 4200 × 2750 × 300 mm.
The frame reinforcement details are reported in Figure 6.

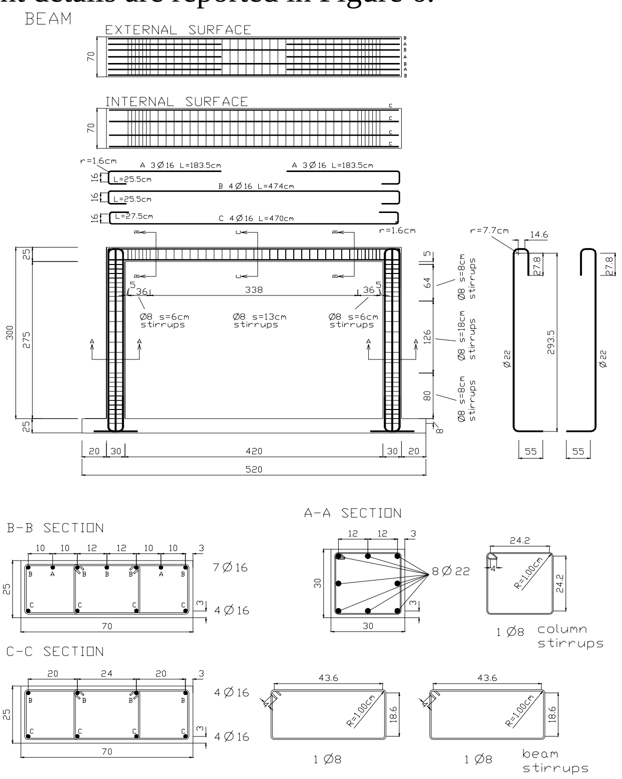



Figure 6. Reinforcement details of the tested frames (all dimensions are in cm)

All tests were performed applying first two vertical loads at the top of the columns, to simulate the presence of the upper storeys. No vertical load was placed on the beam, accepting this small difference from reality. The total vertical load was then kept constant during the tests, allowing the redistribution generated by the application of horizontal forces.

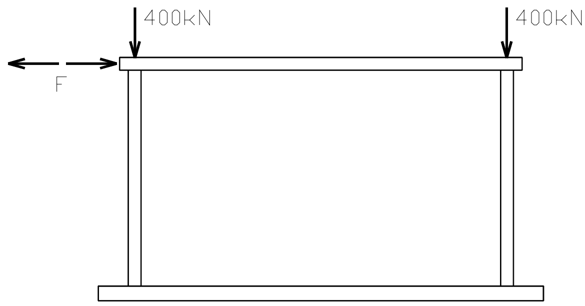



Figura 7. Scheme of the test setup adopted for the infilled frames

The in-plane tests were performed applying horizontal displacements cycles, according to pre-defined targets between 0.1 and 3.6 % drift. Three cycles were performed at each target displacement.
The force-displacement curve obtained from the bare frame is depicted in Figure 8.

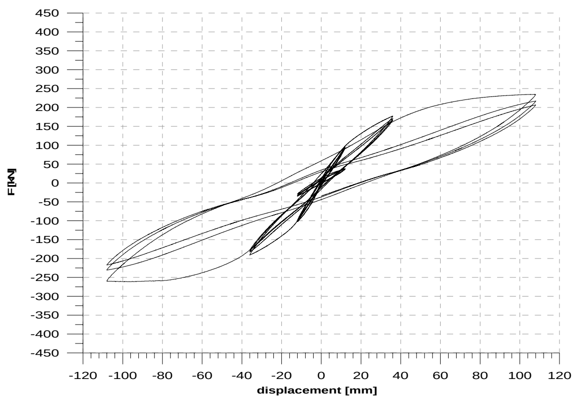



Figure 8. Experimental force-displacement response of the bare r.c. frame

The same frame geometry and testing conditions were adopted for the in plane cyclic tests of the infilled frames. In this case AAC blocks with thin mortar layer and filled vertical joints were used for all the infill panels with the different reinforcement solutions.
The experimental campaign on AAC masonry infilled r.c. frames included the following reinforcement techniques (Figure 9):

- Unreinforced AAC infill panel;
- AAC infill panel reinforced by horizontal bars lodged in special grooved blocks every second mortar layer (i.e. with a vertical spacing of 500 mm);
- AAC infill panel reinforced by a mid-height r.c. tie beam built using special U-shaped hollow blocks;
- AAC infill panel reinforced by flat truss reinforcement every second bed joint;
- AAC infill panel with a central opening (door) reinforced by flat truss reinforcement every second bed joint.

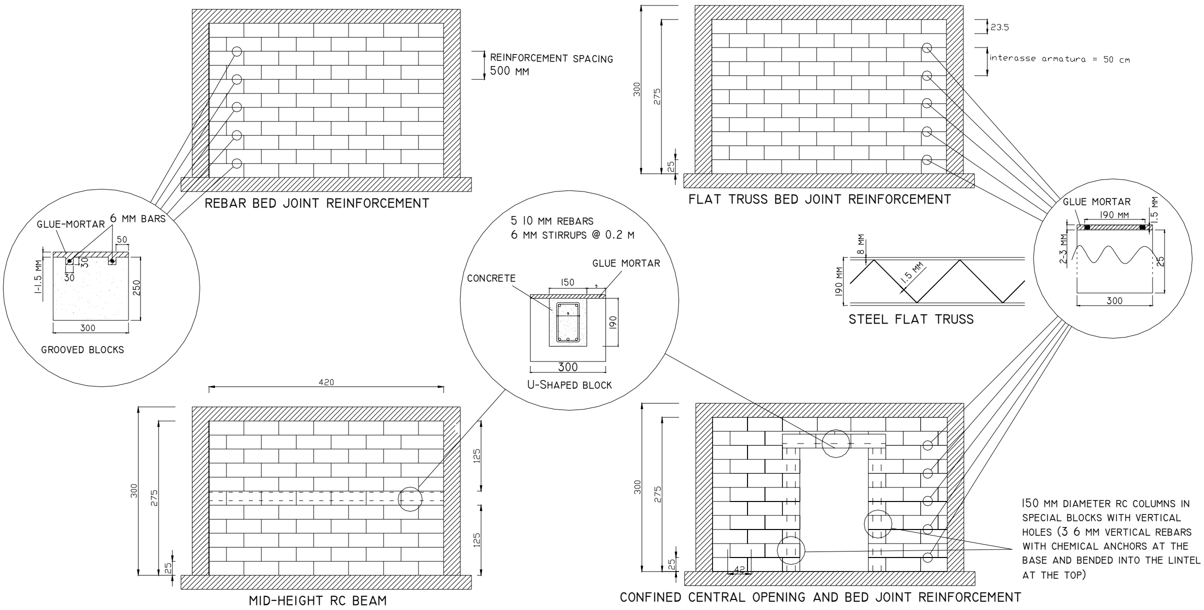
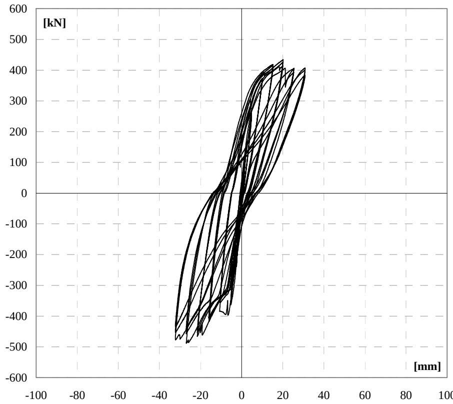
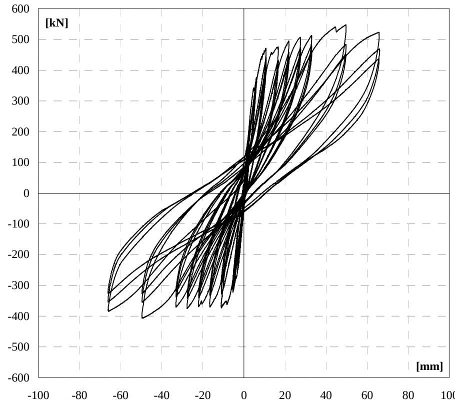



Figure 9. Structural details of the reinforced infill panels

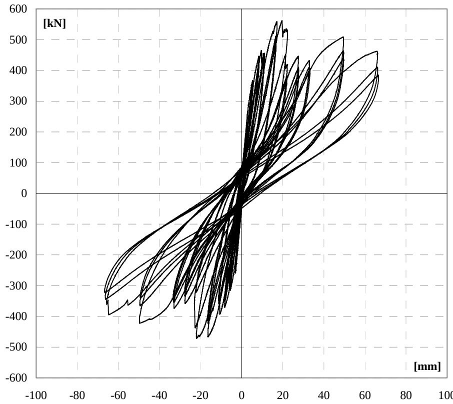
U-shaped blocks and blocks with circular vertical holes (150 mm diameter) were used to cast in place the r.c. light frame surrounding the door in the last specimen. No mechanical devices were placed at the interfaces between the frame structure and the infill panel.
The in-plane cyclic force-displacement response of the first four configurations is represented in Figure 10.



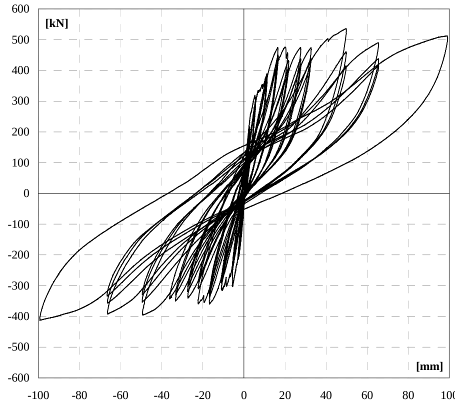
(a)



(b)



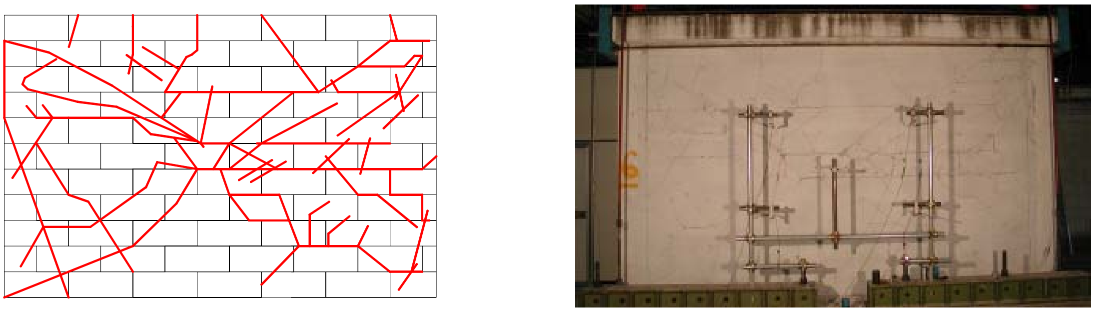
(c)



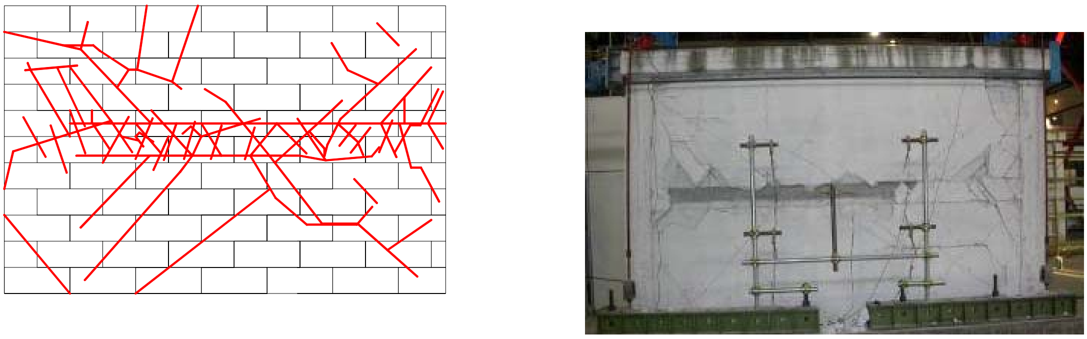
(d)

Figure 10. Experimental force-displacement curves of the in-plane cyclic test of the four configurations: (a) unreinforced; (b) mid-height r.c. tie beam cast in U-shaped blocks; (c) bed-joint reinforcement with bars in special grooved blocks; (d) bed-joint reinforced with flat truss reinforcement.

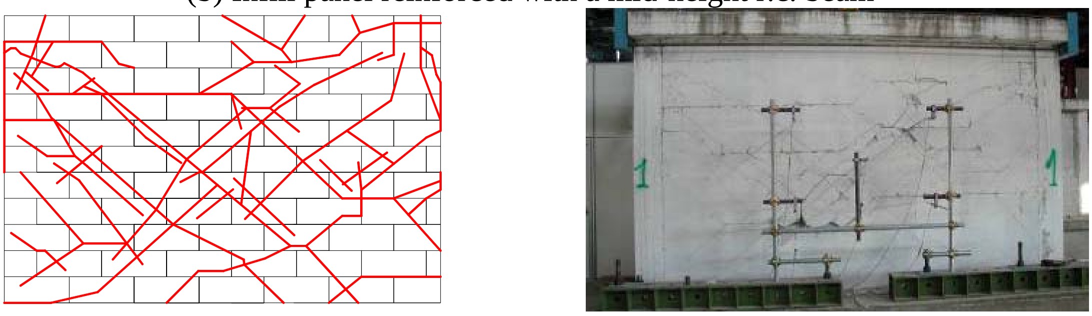
With respect to the bare frame, the lateral strength is more than doubled, the initial stiffness significantly increased and the hysteresis cycles enlarged in all cases. The tests have been carried out up to 1.2 % drift for the unreinforced infill panel, 2.4 % drift for the rebar reinforced infill panel and the first panel with the mid-height tie beam and 3.6 % for both the flat truss reinforced panel and the second panel with the mid-height tie beam.
The maximum lateral strength of such infilled frames is comparable. The flat truss reinforcement solution, however, has shown a rather stable response governed by sliding mechanism, with friction, in the unreinforced horizontal mortar joints.
The final cracking patterns of the four experimental configurations is reported in Figure 11.



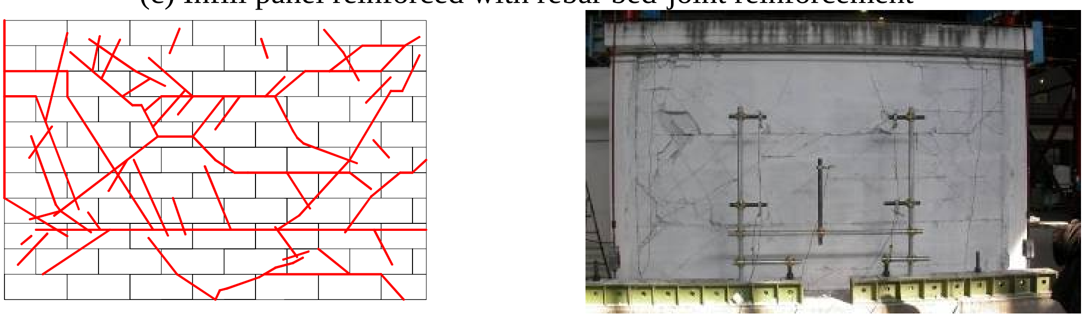
(a) Unreinforced infill panel



(b) Infill panel reinforced with a mid-height r.c. beam



(c) Infill panel reinforced with rebar bed-joint reinforcement



(d) Infill panel reinforced with flat truss bed-joint reinforcement

Figure 11. Final cracking patterns and pictures of the specimens at the end of the in-plane tests

The initial stiffness for all the specimens is approximately the same and therefore not affected significantly by the presence or absence of the reinforcement. The reinforcement on the other hand increases the displacement and ductility capacity. All the reinforced specimens have demonstrated the capacity, due to the high deformability of the AAC material (Young modulus in compression equal to 1600 MPa), of undergoing in-plane deformations up to high drift values for the frame structure (1.2 %) with moderate damage.
In such cases the contribution of the infill panel to lateral strength of the structure can be taken into account up to the development of the ultimate strength of the frame.
Figure 11 shows the significant differences in the damage distribution to the infill panels. In the case of the cast in place mid-height tie beam the cracks are mostly concentrated along the r.c. beam and, as shown in Figure 12, cracks also occur in the frame columns.

Figure 12. Damage to the frame columns induced by the mid-height r.c. beam

Figure 13 shows the force-displacement curve and the final damage pattern obtained for the horizontally reinforced AAC infilled frame with a central door opening. Although the lateral strength is obviously reduced, it is anyhow significantly larger than for the bare frame, and the displacement capacity is comparable to the cases without opening. The presence of the bed joint reinforcement is again beneficial in controlling the damage to the infill panel.

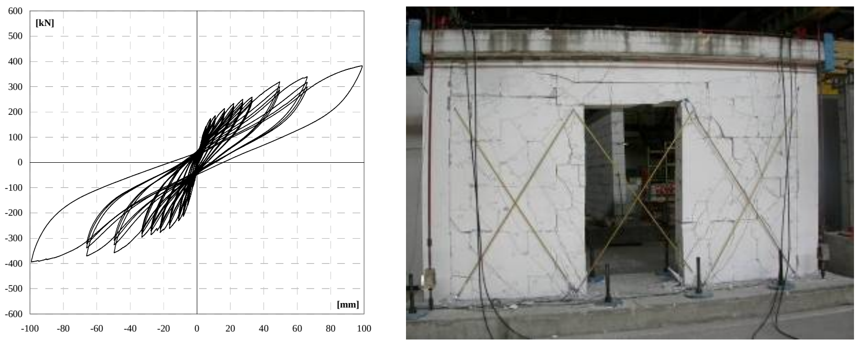



Figure 13. Hysteretic curve and final damage to the infilled frame with a central opening and horizontal flat truss reinforcement

## CONCLUSIONS

This comprehensive testing campaign on AAC loadbearing masonry piers and infill panels showed the potential in seismic design applications of AAC masonry, both for structural and non-structural elements.

The test results on unreinforced AAC piers suggest the adoption of ultimate drift values lower than 0.5 % for flexural failure modes and confirm the maximum drift of 0.3 % for unreinforced long shear walls. The drift capacity of relatively short walls failing in shear can be higher than 0.5 % and therefore, from a seismic design viewpoint, a limitation to the maximum wall length could make sense.
The tested distributed reinforcement solutions, in particular in the case of flat truss reinforcement which requires a shorter anchorage length, have shown a high effectiveness in cracking control and hence enhancing ductility and displacement capacity. The presence of only horizontal reinforcement has been effective for the tested configurations in preventing shear failure modes and significantly improving the displacement capacity in bending failure modes (preventing the activation of shear damage at higher drift values).
The presence of AAC infill walls strongly influences the seismic response of structural frames, increasing stiffness and strength without reducing the frame displacement capacity. Apart from the mid height beam, the tested reinforcement solutions have shown a considerable effectiveness in reducing the seismic damage both to the infill panel and to the frame structure.

## ACKNOWLEDGEMENTS

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