COMBINED IN-PLANE/OUT-OF-PLANE EXPERIMENTAL BEHAVIOUR OF REINFORCED AND STRENGTHENED INFILL MASONRY WALLS

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ABSTRACT

This work presents experimental test results obtained on clay unit masonry infill walls for framed structures. The main aim of the tests is characterizing the out-of-plane behaviour of infill walls made with different types of masonry, under various levels of damage caused by in-plane deformation of the frame. Tests were carried out on one-bay, real scale reinforced concrete frames, by imposing in-plane cyclic displacements at the frame top beam until reaching pre-determined drift levels. Afterwards, the infill walls were tested out-of-plane, according to a non-standard procedure, which has been already adopted in the literature.
The results of seven tested frames are presented and discussed. One frame is a reference bare RC structure, without any infill wall. Four frames have thick (300 mm) clay unit masonry infill walls. Two of these specimens are made of unreinforced masonry, the other two are made of reinforced masonry, having both horizontal and vertical reinforcement. The remaining two frames have thin (120 mm) clay unit masonry infill walls with plaster layer, one of them is strengthened by means of a special quadriaxial net made by hybrid glass fibres, that is casted in an extra fibre-reinforced plaster layer.
In this work, the detailed analysis of experimental data is presented.

KEYWORDS: clay masonry infill walls, combined in-plane/out-of-plane behaviour, experimental tests

INTRODUCTION

As proven by recent earthquakes [1], when infill walls in reinforced concrete frames are not properly detailed and designed, they can be a cause of extensive economic losses and also a source of danger for human lives. Hence, it is necessary to reconsider the structural role of enclosures, in order to establish reliable analysis and design procedures and to update structural codes. The focus here is not on the effects of masonry enclosures on the structural system, for which already numerous studies and some code provisions exist [2, 3], but on the damage to the same enclosures and on the criteria to limit it, for which a lack of knowledge is felt.

A fundamental aspect related to the influence of frame behaviour on enclosure wall behaviour is that during an earthquake, enclosure walls are subjected not only to out-of-plane actions, but they are also concurrently subjected to in-plane actions provided by the frame displacements. Due to limited shear resistance of masonry, the damage caused by frame in-plane deformations causes also a reduction in the out-of-plane capacity of walls. Despite this aspect may seem obvious, the work carried out so far has never tackled it, coherently with the fact that out-of-plane behaviour of infill walls has been seldom taken into account e.g. [4]. Indeed, very few works have taken into account the definition of infill's limit states based on frame inter-storey drift [5], but in practice there is not systematic definition of to which extent the in-plane deformation of the frame cause a change/reduction of mechanical properties in the enclosure systems, and a change of out-of-plane behaviour of the enclosure systems [3-6]. For these reason, the project is aimed at studying these aspects.

MASONRY SYSTEMS

One of selected construction systems for infill walls, uses masonry made of clay units with vertical holes and special recesses for vertical reinforcing bars (unit dimension 195x240x300mm in height, length, thickness respectively). In these units (a) two webs can be removed forming an open "C" pocket that can be used to easily cast the vertical reinforcement bars (b). Four vertical reinforcement bars (Φ=8mm) anchored both on RC base and on the upper beam, were used. The stirrups (two Φ=6mm) used for horizontal reinforcement were placed starting from second mortar bed joint every three joints. The thickness of horizontal joints is about 10mm, while the tongue and groove units allow vertical joints to be unfilled (Figure 1). To check the performance of this reinforced masonry infill wall system (RM), two specimens were tested, and were compared to other two specimens (URM), made with plain (non-reinforced) masonry.

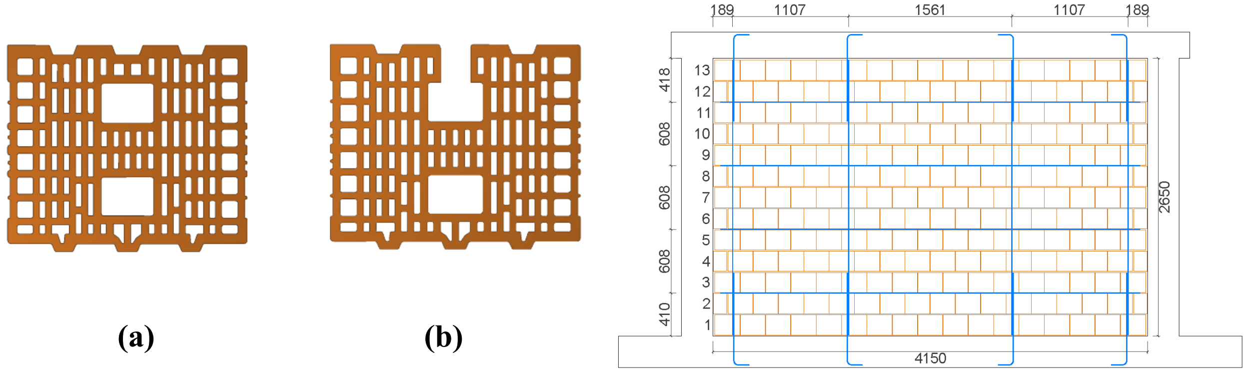

Figure 1. Unit and reinforced masonry system adopted in the experimental campaign.

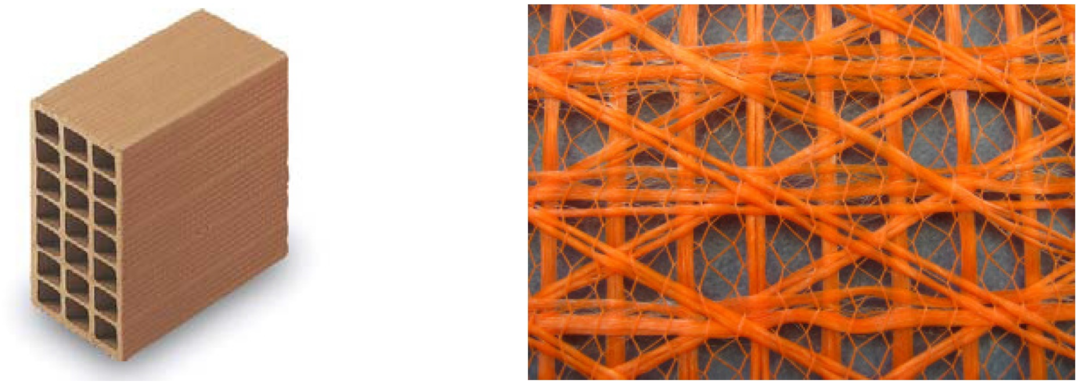

Figure 2. Unit (left) and net (right) used for the adopted strengthening masonry system.

Thin infill walls, representing typical light enclosure systems used from the Sixties until nowadays, are made of clay unit with horizontal holes and dimension of 250x250x120mm (height, length, thickness). One side is plastered with a layer of about 15mm (USM). One specimen of this kind is strengthened by means of a special quadriaxial net made by hybrid glass fibres, that is cast in an extra plaster layer of about 8mm using a fiber-reinforced plaster (SM). The thickness of horizontal joints is about 12mm, while vertical joints is about 9mm (Figure 2). The aim is checking the behaviour of infill walls that can be frequently found in existing buildings, and evaluating the effectiveness of strengthening them with fibre-reinforced plaster.

EXPERIMENTAL PROGRAM AND TEST SET-UP

The work is mainly aimed at evaluating the combined response of clay masonry infill walls under in-plane and out-of-plane actions, and in particular the behaviour under out-of-plane actions of walls characterized by different levels of damage, related to the in-plane drift of the frame. Other aims of the experimental campaign carried out are: comparing the response of plain (non-reinforced) and reinforced or strengthened types of infill wall; and evaluating the behaviour of infill walls when they fully fill the reinforced concrete frame or when they have openings (this part of the research is not described in this paper). A bare frame, with no infill wall, was also built and tested under in-plane cyclic loads until reaching ultimate displacements, for better evaluating the mutual infill/concrete frame behaviour under in plane loads. The experimental campaign also included mechanical tests on materials: masonry units, mortar, concrete, reinforcement bars, and on the infill walls, through compression and bending tests (Table 1).

Table 1. Experimental program for mechanical tests on component materials

Material	Test	N° specimen
Block	⊥ to holes direction in the blocks: Compression strength + Elastic modulus & Poisson's Ratio	13 9
	|| to holes direction in the blocks: Compression strength + Elastic modulus & Poisson's Ratio	13 9
	Indirect tensile strength longitudinal	6
	Indirect tensile strength transversal	6
Mortar	Flexural strength	43
	Compression strength	86
	Elastic Modulus	16
Steel	Tensile strength	23
	Elastic Modulus	23

Tests were done on the mortar used in the thick infill and the three kinds of mortar used in thin infill walls. In particular, following [8] and [9] indications, they were tested for compression, tensile strength (by bending) and Young modulus. Other tests were done on masonry clay units, on both main directions, to determine compressive strengths [10], Young Moduli [9] and the indirect tensile strengths [11]. For the reinforced masonry system, reinforcement bars were tested for tensile strength and Young Modulus. Compression (8 URM specimens, see Table 2 for a summary of results) and bending (6 RM, 3 USM, 6 SM specimens, see Table 3 for a summary of results) tests were carried out on real scale masonry assemblages, on both principal directions, following [12] and [13] indications respectively (Figure 3).

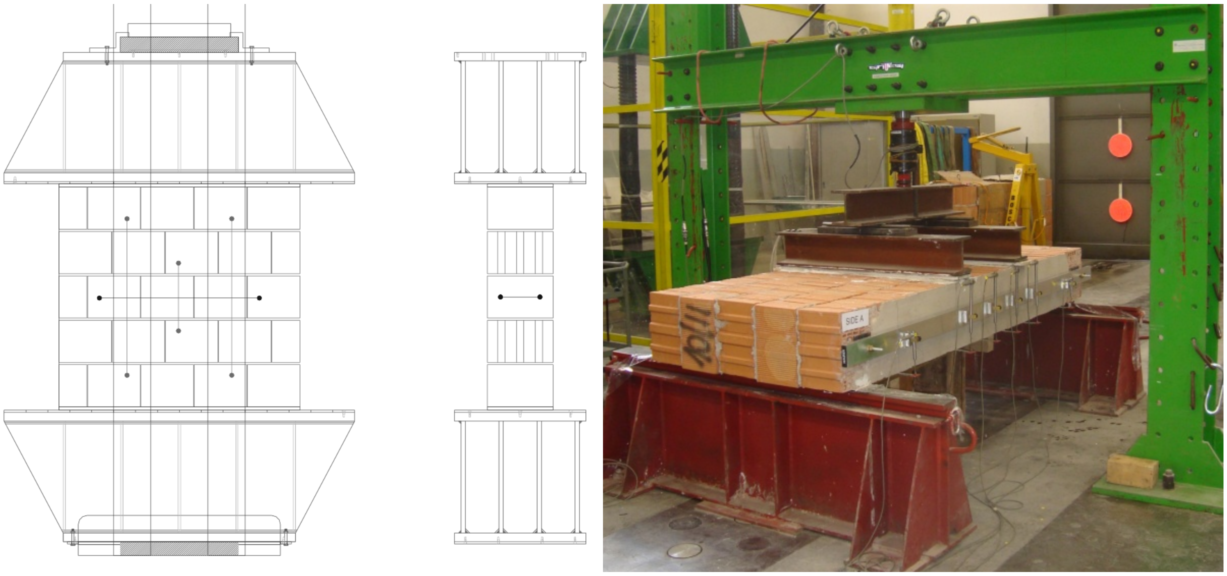

Figure 3. Examples of geometry and set-up of compression tests (parallel to unit holes, left) and bending tests (bed joints orthogonal to failure, right).

Table 2. Compression test, average results on thick masonry system

Specimens	**First crack** [MPa]	**Maximum Strength** [MPa]	**E** $_{(10 - 40\%)}$ [MPa]	**E** $_{(30 - 60\%)}$ [MPa]	**Poisson's ratio** $\upsilon(10 - 40\%)$	**Shear modulus** G(10 - 40%)
URM_V	4,25	6,00	4312	4384	0,24	1713
URM_H	0,85	1,19	1767	1095	0,13	788

Table 3. Bending test, average results

Specimen	**First Crack / Yielding**		**Maximum Strength**		**ULS**	**Type of Failure**
	Tot. Bending Mom. (Nm/m)	δ (mm)	Tot. Bending Mom.. (Nm/m)	δ (mm)	δ (mm)	
RM_V	3628	0.05	4682	6.72	-	Vertical reinf. slip
RM_H	5520 / 8390	0.75 / 4.11	8800	28.4	40	Combined failure
USM_H	571	0.02	1261	0.19	-	Tension in joint
SM_V	2242	1.69	3534	7.26	9.04	Bending/shear in units
SM_H	2093	0.85	4033	15.22	25.73	Tension in fibre

For the combined tests on infill walls, the specimens are made of full-scale, one-bay, one-storey reinforced concrete frames. Besides one reference bare frame, tested until 3.4% drift (near ULS), the other frames are fully filled with masonry. The choice to adopt full-scale specimens was made to avoid eventual differences of frame to infill wall stiffness ratio, between the scaled specimens and the real situation. To design the specimens and the test setup, it was considered the ground level of a three-storey concrete frame building, regular in plan, with columns spaced 4.5m by 4.5m, and regular in height, with 3 m high storeys. The designed structure represents a typical Italian residential frame building structure (class of use II), and was designed according to Italian Building Code in ductility class "A" (higher ductility), considering a PGA=0.25g. In the design, the experimental conditions were also taken into account. Concrete frame cross-sections were designed to have ductile flexure failure and avoid shear failure. Frame beam-column nodes design permits plastic hinge formation in the beam. The infill wall design was carried out taking into account both the out of plane and the in-plane actions.

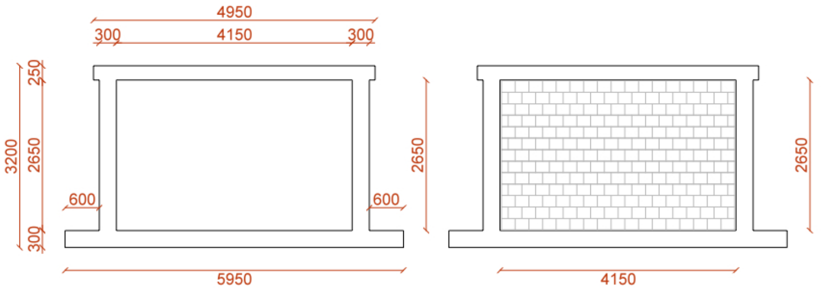

Figure 4. Different frame configurations adopted in the experimental campaign.

Experimental tests are subdivided in two steps: in-plane test and out-of-plane test.
In the first phase, after loading the columns to a constant level of axial load (400 kN each) to simulate the presence of the upper floors, an in-plane cyclic horizontal displacement is imposed at the level of the top beam. The displacement history is constituted of sinusoidal cycles, of increasing amplitudes and with peaks repeated three times for each displacement amplitude, applied with a quasi-static procedure, keeping displacement ratio always lower than 0.5 mm/s. The sequence of reference drifts corresponding to the applied top displacements is: +/-0.1%; +/-0.2%; +/-0.3%; +/-0.4%; +/-0.5%; +/-0.6%; +/-0.8%; +/-1.0%; +/-1.2%; +/-1.6%; +/-2.0%; +/-2.4%; +/-3.2%; +/-3.4% (maximum jack stroke).

After carrying out the in-plane tests, horizontal displacement is brought back to zero and, with vertical columns still axially loaded, the infill wall is monotonically loaded out-of-plane. Three level of target drift were identified to stop the in-plane test and start the out-of-plane test:

1. Drift 0.5% corresponding to damage limit state for fully filled frames (according to Italian building code [14]);
2. Drift 1.2% corresponding to a life safety limit state for the infill wall;

Drift of 3.4% was reached only in the case of the bare frame, to study its behaviour in the plastic phase, even though at that level of drift the bare frame did not yet reached a displacement corresponding to the ultimate limit state (Figure 4 and Table 4).

Table 4. Experimental program for combined in-plane and out-of-plane tests.

Type	Bare frame	URM		RM		USM	SM
Infill thickness	-	300mm	300mm	300mm	300mm	120mm	120mm
Reference		URM-D	URM-U	RM-D	RM-U	USM-U	SM-U
In-plane target drift	3.4%	0.5%	1.2%	0.5%	1.2%	1.2%	1.2%

Loads and displacements were imposed by means of servo-controlled hydraulic actuators both during the in-plane and out-of-plane phases. Two actuators placed on the beam-column nodes applied vertical loads through a self-locking rig, hinged to a reaction steel beam at the top of the actuator and connected by ball and socket joints at the RC frame bottom beam. The latter was bolted with ten threaded steel bars to the laboratory strong floor, to provide the required fixed condition. An actuator applied horizontal in-plane displacements in correspondence of the beam-column node. The actuator was connected by means of ball and socket joints to a self-locking. Hence, the loading system permitted the load reversal. Out-of-plane loads were applied as four point loads at the thirds of wall length and height (Figure 5).

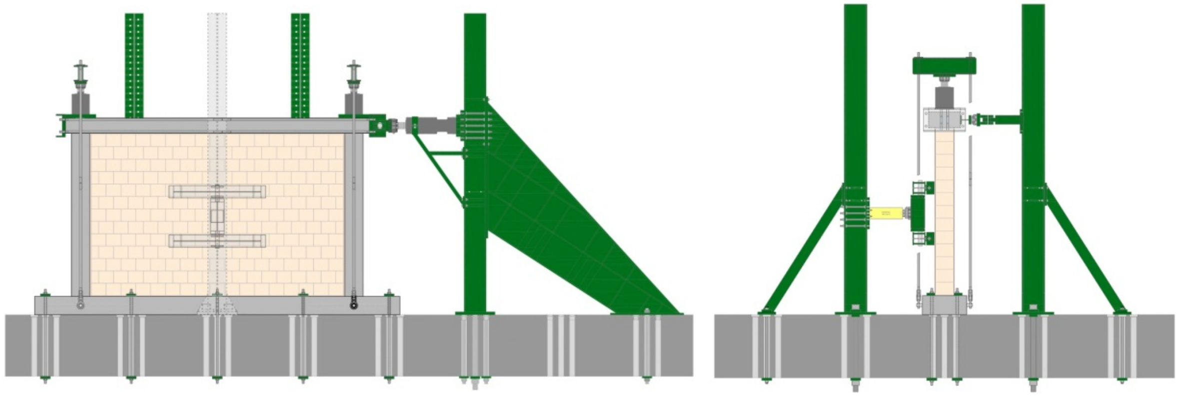

Figure 5. Tests set-up for in-plane (left) and out-of-plane (right).

The instrumentation set-up was designed to capture global and local deformation of the reinforced concrete frames; global in-plane deformation of infill walls and local strain on masonry related to the infill wall/RC frame interaction; global out-of-plane deflection shape of the infill walls; and to measure strain on some of the horizontal and vertical reinforcement bars used in the reinforced masonry walls. Linear (35) and draw wire (15) potentiometers and strain gauges (12) on the reinforcement bars were used at this aim.

COMBINED IN-PLANE/OUT-OF-PLANE TESTS RESULTS

During the in-plane tests (Figure 6 and Table 5), all the specimens with infill walls showed first nonlinearity from drift of 0.1%, detectable also by the change of stiffness (Figure 7). Indeed, even at this early stage, some visible crack between columns and walls are produced. For the following cycles, with increasing drift, thick and thin walls had different behaviour. The previous started developing cracks in joints in the central part of masonry panel for drift between 0.2% and 0.4%. Then, diagonal cracks, stepped through joints, developed from the upper corner towards the centre of the walls. The damage grew until drift of 0.8%÷1%, when these infill walls achieved their maximum strength. At this stage, even the upper frame nodes started to develop some cracks (minor cracks were already present in columns and beams from drift of 0.2%). In reinforced infill wall (RM-U) loads of 611kN were achieved, 17% higher than non-reinforced infill wall (URM-U). Diagonal cracks passing through horizontal joints and units were more spread in reinforced infill walls. In RM-U, after reaching the maximum strength, the units of the upper course, close to the nodes, started crushing.

Thin infill walls had different behaviour in terms of stiffness, strength and crack pattern, when compared to both thick panels, and in-between the strengthened and un-strengthened thin wall system (Figure 6 and Table 5). The latter (USM-U) had an initial stiffness of about one third that of the strengthened panel (Figure 7). After 0.1% of drift the USM-U stiffness decreased at values similar to those of the bare frame (RCF), until 1% of drift, when it achieved its maximum strength (211kN). The damage propagation mainly involved bed joints (sliding), due to poor quality of mortar and was concentrated at fourth and eighth joints from the base. The strengthened infill system (SM-U) had a very high initial stiffness, almost equal to that of the thick walls. At 0.3% of drift, a maximum strength of 306kN was achieved (+45% than USM-U). Starting from the level of drift equal to 0.6%, it can be noted that the average envelope curve of SM-U has a pattern similar to that of the un-strengthened infill wall. This may correspond to a loss of adhesion of the strengthening layer, after maximum strength achievement, although the presence of reinforcement is able to the wall to higher values of in-plane loads. The damage propagation started from 0.2% of drift, and involved both units and the external plaster layer in the central part of the panel, with mainly diagonal cracks.

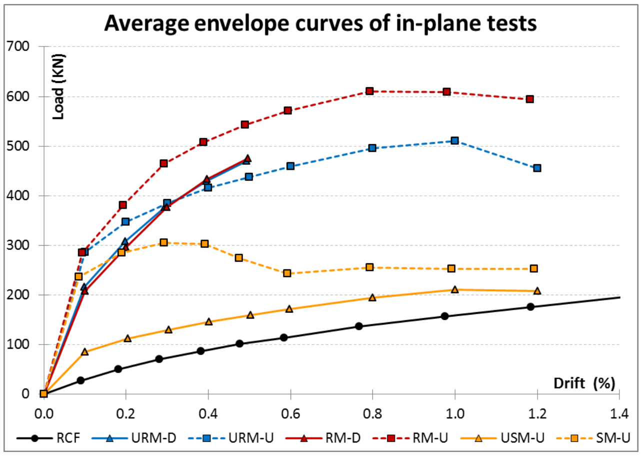

Figure 6. Average envelope curves of in-plane tests (thin and thick walls).

Table 5. In-plane results on masonry systems

LEGEND: Ψ = Drift F= Strength d= Displacement	Non cracked-phase			Maximum strength			Maximum displacement		
	Ψ_y [%]	F_y [kN]	d_y [mm]	Ψ_{Fmax} [%]	F_{max} [kN]	d_{Fmax} [mm]	Ψ_u [%]	F_{du} [kN]	d_u [mm]
RCF	0.1	28	2.5	3.0	271	88.0	3.4	249	94.1
URM-D	0.1	217	2.7	0.5	470	13.6	-	-	-
URM-U	0.1	281	2.5	1.0	520	28.5	1.2	447	33.2
RM-D	0.1	208	2.7	0.5	476	13.7	-	-	-
RM-U	0.1	285	2.6	0.8	611	22.0	1.2	593	32.8
USM-U	0.1	86	2.8	1.0	211	27.7	1.2	208	33.1
SM-U	0.1	237	2.4	0.3	306	8.1	1.2	252	33.1

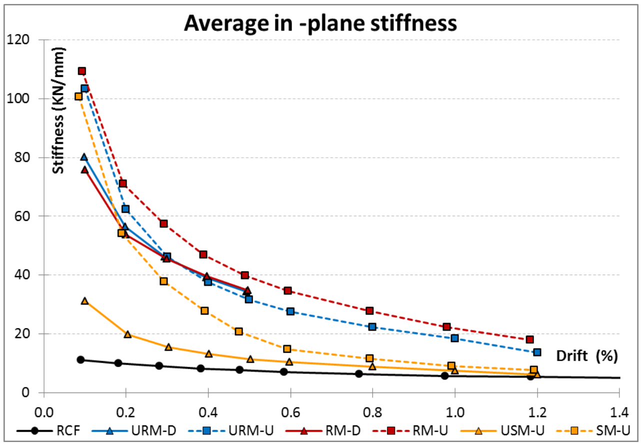

Figure 7. Average secant stiffness variation during in-plane tests (thin and thick walls).

After the application of cyclic in-plane drift, the infill panels were subjected to out-of-plane loads, applied monotonically until collapse. Displacements were measured in thirteen positions. Figure 8 and Table 6 refer to the central out-of-plane displacement of the walls.

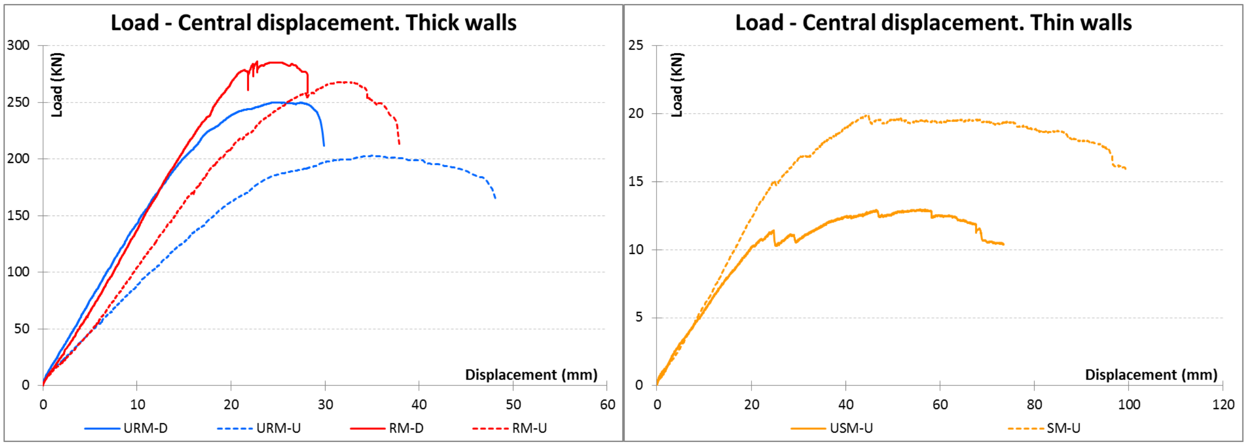

Figure 8. Out-of-plane tests. Load vs Central displ. of: thick (right) and thin (left) walls.

Table 6. Out-of-plane results on masonry systems

LEGEND: F = Strength d = Displacement	Pseudo-elastic phase		Maximum strength		Ultimate displacement	
	F_y [kN]	d_y [mm]	F_{max} [kN]	d_{Fmax} [mm]	F_{du} [kN]	d_u [mm]
URM-D	201	15.0	250	24.1	212	29.9
URM-U	159	19.4	203	34.9	162	48.2
RM-D	272	20.4	286	24.3	259	28.2
RM-U	195	18.2	268	31.6	214	38.0
USM-U	10	20.3	13	56.8	10	73.5
SM-U	15	24.9	20	44.3	16	99.6

Thick infill walls developed an arch mechanism, mainly in the vertical direction. The stiffness degradation can be related to crushing of units due to compression for arch mechanism development. The set-up for out-of-plane loading, consisting in a four-point bending test, with loads concentrated at third of panel height and width, hence different load distribution when compared to real inertia forces, caused local collapses, although those occurred only after the achievement of the maximum out-of-plane capacity. The reinforcement bars (both vertical and horizontal) were able to hold effectively the out-of-plane expulsion of masonry wall portions until collapse. Out-of-plane strength of reinforced infill walls were higher than that of unreinforced walls, in particular for higher in-plane damage or drift (+32% at ULS and +14% at DLS). Strength decay due to increase of in plane drift (or damage) was smaller in RM (-6%) than in URM (-23%). Similar considerations can be done with out-of-plane stiffness.

Out-of-plane tests for thin masonry systems had a linear initial load-displacement phase related to the development of a resistant mechanism (Figure 8 and Table 6). In the following phase, the un-strengthened infill wall (USM-U) had a sudden stiffness degradation and then collapse was due to bending with failure parallel to bed joint (in particular 1st, 4th and 8th from the base). The strengthened SM-U infill wall did not collapse, thanks to the restraint effect of the fiber-reinforced plaster that guaranteed a bending resistant mechanism in both principal directions. The out-of-plane strength of the strengthened wall was +54% (20kN) higher than that of the un-strengthened wall (13kN). The displacement achieved at 20% strength decay was +35% higher for SM-U: 99.6mm versus 73.5mm.

EFFECTIVENESS OF REINFORCEMENT AND STRENGTHENING TECHNIQUES

The ratio between dissipated and input energy during the in-plane tests (calculated from hysteresis cycles) was very high compared to bare frame and about constant from 0.5% of drift, respectively around 40% and 20%. The equivalent damping (calculated from hysteresis cycles) goes from about 6% when frame was filled with thick masonry, to less than 3.5% for the bare frame (Figure 9). For un-strengthened thin masonry system, the energy ratio had the same behaviour of thick infill walls until 0.5% of drift. Subsequently, it decreased from 40% to 30% at 1.2% of drift, and this is reflected in the equivalent damping that, even though starting from values that are twice those of thick infill walls, decreased to values similar to those of the bare frame at 1.2% of drift. The strengthened thin infill wall had a slightly different behaviour, both in terms of energy ratio and in terms of damping (Figure 9). Indeed, the energy ratio was around 60% until 0.5% of drift, to decrease at 45% at the end of the in-plane test. Similarly, the equivalent damping was over 10% until 0.5% of drift, and then decreased to 5% at 1.2% of drift.

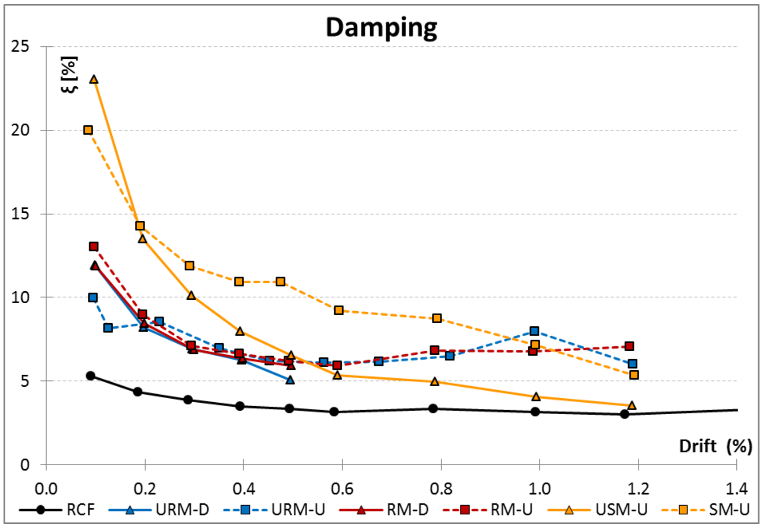

Figure 9. Average damping variation of in-plane tests (thin and thick walls).

The effectiveness of the reinforced system can be evaluated also through the analysis of strain-gauges (SGs) measurements. The position of SGs attached to vertical bars was intended to catch out-of-plane deformation (placed at half-height of the wall), therefore the measured strains underestimate the greatest expected strains during in-plane tests (yielding strain ≈ 3.1‰). Conversely, the crack pattern of unreinforced thick infill walls confirms that SGs on horizontal reinforcements were placed (at 5th and 8th horizontal joint from base, in-between vertical bars) where principal cracks developed. The central vertical bars reached their maximum measured strain (between 2‰ and 2.5‰) at 0.3% of drift, and after remained almost constant. Strains on vertical bars placed near RC columns started to develop from 0.5% of drift and reached, in average, the same maximum value around 0.8-1% of drift. The measured strains on horizontal reinforcement bars were generally lower than those of vertical bars (only a few amount over 1‰), but in certain cases (SG at the 5th joint) reached even 2‰.

During the out-of-plane tests the vertical bars started to deform significantly after an out-of-plane displacement of about 5mm in the centre of the panel. This is related to the barycentric position of vertical bars in the cross-section of wall (initial contribution to out-of-plane bending moment is null). After that, an almost linear relation between strain of vertical bars and out-of-plane displacement can be found. At maximum load, the central bars reach 1.7‰ and 2.5‰ respectively for RM-D and RM-U specimens, conversely, bars near to RC columns had smaller strain (< 1‰), in agreement with the analyses of deformed shape of panels. The SGs, applied to horizontal reinforcements on the loaded side of the infill walls, reached about 0.7‰ in compression, following the out-of-plane load trend. The SGs applied on the opposite side started in tension until 10÷15mm, where strains were about 0.5‰, after they decreased achieving 0.6‰ in compression at maximum load.

CONCLUSIONS

A non-standard set-up for combined tests under in-plane cyclic and out-of-plane loads was designed and used to test four types of masonry infill walls, made with different perforated clay units and different types of reinforcements or strengthening systems. The main mechanical parameters were extracted by common tests on masonry panels (such as monotonic compression and bending tests) or on constitutive materials (such as clay units, mortars and steel reinforcement). The designed test procedure could highlight the influence of in-plane damage level on the out-of-plane behaviour of the infill walls. In particular, the out-of-plane strength of thick masonry infill walls was evaluated after the application of two levels of maximum drift under in-plane cyclic tests, corresponding to two levels of damage for the infill walls.

The thick masonry systems tested (both reinforced and unreinforced) presented high of out-of-plane strength, due to the development of an arch mechanism, even for high values of attained in-plane drift. Conversely, thin masonry systems, even when strengthened, developed a bending out-of-plane failure that somehow limits the strength of the wall, with respect to the previous failure mode. The strengthening/reinforcing techniques were demonstrated to be effective in preventing out-of plane expulsion of masonry portions. The in-plane damage mechanisms were affected by the presence of strengthening or reinforcing systems and, in particular, they tended to reduce the global damage, although it was more spread over the infill walls. On the basis of the issues discussed above, it seems that limitation of in-plane drift at 0.5%, to prevent excessive damage to non-structural elements, given by the Italian building code [14], is adequate for the studied thick masonry systems, but it is overestimated for thin infill walls.

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