EXPERIMENTAL BEHAVIOUR OF NEWLY DEVELOPED SYSTEM FOR LOAD BEARING REINFORCED MASONRY WALLS

F. MOSELE[1], F. da PORTO[2], M. DALLA BENETTA[3], C. MODENA[4]

[1]PhD Student; [2]Assistant Professor; [3]Engineer; [4]Full Professor
Dept. of Structural and Transportation Engineering
University of Padova
Via Marzolo 9, 35131 Padova, Italy

SUMMARY

In the framework of a research project funded by the European Commission, innovative construction systems for load and non-load-bearing reinforced masonry walls are being developed. In particular, a new reinforced masonry system made with perforated clay units, purposely developed for low-rise residential buildings to withstand in-plane actions, based on the use of horizontally perforated clay units and concentrated vertical reinforcement, is under study for the application in areas characterized by low to high seismic hazard. This contribution presents the description of this construction system and the first experimental results obtained.

INTRODUCTION

Reinforced and confined masonry have been developed in order to exploit the strength potential of masonry and solve its lack of tensile strength, improving significantly not only the resistance, but also the ductility and the energy dissipation capacity, that is the seismic behaviour, of the masonry walls (Tomaževič 1999, Tassios 1988). In the last decades, a large variety of reinforced and confined masonry techniques have been developed. The different masonry systems depend on many parameters: geometric shape and material of the units, composition of the mortar and/or grout, quantity and layout of the reinforcement (Tomaževič 1999).

In the framework of the DISWall research project, funded by the European Commission, four innovative construction systems for load and non-load-bearing reinforced masonry walls are being developed. Two systems are based on the use of large hollow clay unit for concrete infill and on the use of concrete units with mortar bedding and filling, the other two are based on the use of perforated clay units, assembled with mortar. A complete description of the construction systems and their objects of investigation can be found in (Mosele et al., 2006).

Reinforced masonry made with horizontally perforated clay units

One of the two latter reinforced masonry systems is based on the use of concentrated reinforcement, almost similar to a confined masonry system. Special clay units are placed in the masonry panel with horizontal holes and they present recesses for the placement of the horizontal reinforcement (see Figure 1). The units width is 300 mm and they are developed in order to be laid also with vertical holes in the

masonry columns and simplify the site procedures in future. Currently, ordinary commercial units are used for the confinement columns. For the vertical reinforcement steel rebars are used, whereas for the horizontal reinforcement, both steel rebars and prefabricated steel trusses can be adopted. The mortar has been expressly developed for this reinforced masonry system, in particular for what concern the properties of consistence, plasticity, and workability, to allow for a proper bed joint and recess filling and at the same time, also for a proper filling of the reinforced vertical cavities.

The main advantages of the system are that all the problems related to cover of bars and mortar shrinkage are overcome, due to the fact that there is a special recess to place the reinforcement, and it is possible to have the un-coupling of the reinforcement. Furthermore, this system preserves a construction technique (masonry made with horizontal holes) which is very traditional for the countries facing the Mediterranean basin, as it allows reaching very good thermal and acoustic insulation.

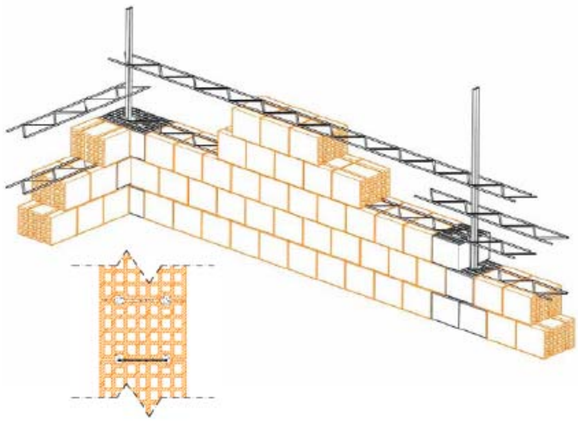


Figure 1. Construction systems based on the use of horizontally perforated clay units.

Experimental program

For this kind of reinforced masonry wall system, the main objective of the testing program was to assess the behaviour under in-plane cyclic actions. The tests were repeated on two series of specimens, with different horizontal reinforcement. One series was built with usual steel rebars (specimens named SR), the other with prefabricated truss reinforcement (specimens named TR). In all of the specimens, the horizontal reinforcement was distributed on the specimens each other course.

Specimens of the entire reinforced masonry system (RM system) and the single components of the system itself (i.e., the confining columns, named "C", and the masonry panels without the confining columns, named "H") were tested under uniaxial compression. In order to understand the influence of the column slenderness on the test results (deformability of the inner mortar core and buckling effects of the vertical reinforcement), the confining columns were built and tested with 3 rows of units (specimens named "C3") and with 5 rows (specimens named "C5").

Following, specimens built with the entire RM system and masonry panels without the confining columns ("H") were tested under in-plane cyclic shear compression tests. One test was carried out on a specimen ("HSa") with no vertical or horizontal reinforcement, in order to check the behaviour of the plain masonry. The shear compression tests on the entire reinforced masonry system were carried out on specimens characterized by two slenderness ratios, in order to force the shear behaviour (slenderness ratio "a" equal to 1.09) and the flexural behaviour (slenderness ratio "b" equal to 1.64).

For these specimens, the vertical reinforcement was constituted by two rebars with diameter equal to Φ16 mm at each masonry edge (squat specimen "a") and by one rebar with diameter equal to Φ16 mm at each masonry edge (slender specimens "b"). The main tests carried out on small and large masonry specimens are summarized in Table 1.

Table 1. Test matrix

Type of Test Type of Specimen	Reference standard	Horizontal Reinf.	Dimensions (mm)	n° of tests	Name
Uniaxial Compression Test Confining Column	ASTM E 477-97	-	380x300x670 380x300x1070	4 4	C3 C5
Uniaxial Compression Test Wallettes – no confining columns	EN 1052-1	Single Rebar	1030x300x1080	3	SRHC
		Murfor	1030x300x1080	3	TRHC
Uniaxial Compression Test Wallettes – entire RM system	EN 1052-1	Single Rebar	1550x300x1690	1	SRCa
		Murfor	1550x300x1690	1	TRCa
Cyclic Shear Compression Test Wallettes – no confining columns	RILEM TC 76-LUM C3	-	1550x300x1690	2	HSa
		Single Rebar	1550x300x1690	2	SRHSa
		Murfor	1550x300x1690	2	TRHSa
Cyclic Shear Compression Test Wallettes – entire RM system	RILEM TC 76-LUM C3	Single Rebar	1550x300x1690	2	SRSa
		Murfor	1550x300x1690	2	TRSa
Cyclic Shear Compression Test Wallettes – entire RM system	RILEM TC 76-LUM C3	Single Rebar	1030x300x1690	2	SRSb
		Murfor	1030x300x1690	2	TRSb

BASIC MATERIAL CHARACTERIZATION

Before the specimens construction, the unit geometry and mechanical properties and the mortar composition and physical properties were developed. In particular, during the mortar development, a large variety of physical and chemical tests were carried out, in order to check the workability, the bleeding properties, the bulk density, the air content, the workable life, the mechanical properties. The mechanical tests included 54 tests on mortars and 52 on the units.

Development of units and mortar

The horizontally perforated units were developed in order to optimize the behaviour under in-plane actions of the RM system, following the concept of "robustness" that is mentioned in the Eurocode 8 (EN 1998-1-1, 2004) and is recalled also by (Tomaževič et al. 2006). The developed unit is characterized by thick webs and shells (about 12mm) with rectilinear and continuous webs and high curvature radius in the webs connections (
Figure 2a). The percentage of holes is less than 45%. The mean nominal dimensions are 250x300x200 mm (length x width x height). Two compositions of raw materials were proposed for the production. The first contained a percentage of tuff equal to 15% and was affected by shrinkage during the drying process; the second a percentage of tuff equal to 20%, which improved the plastic behaviour of the unit but reduced its compressive strength (see Table 2).

The main objective for the development of the mortar was to use a single mortar, adequate for both the placement of horizontally perforated units and for the filling out of the cavities for vertical reinforcement. The mortar requirements, needed for the development of the construction system, were: compressive strength higher than 10 N/mm^2 (as suggested by the Eurocode 8), high workability and plasticity, high adhesion to the clay units and to the steel reinforcement. Starting from a general purpose M10 mortar, with hydraulic binder and aggregates with maximum thickness of 4 mm, two different modified mortars were made, by including a plasticizer additive or a powdered dispersion to increase the adhesion characteristics. Since the loss of mechanical strength of the modified mortars was high, a further modification regarded the additives and the binder and inert dosage (see Table 3).

Experimental testing of unit, mortar and reinforcement

The main mechanical properties of the horizontally perforated units are reported in Table 2, together with the main properties of the units with vertical holes adopted to create the confining columns of the RM system. Table 2 gives: average and normalized compressive strength of the units loaded orthogonally to the bed face ($f_{b,m}$ and f_b) and parallel to the bed face in the plane of the wall ($f_{bh,m}$ and f_{bh}); elastic modulus and Poisson's ratio of the units loaded orthogonally to the bed face (E_b and ν_b) and parallel to the bed face in the plane of the wall (E_{bh} and ν_{bh}).

Table 3 summarizes the main physical and mechanical properties for the employed mortar, respectively bulk density, bleeding, air content, plunger penetration, and flexural strength f_{mt}, compressive strength f_m (see
Figure 2b), elastic modulus E_m and Poisson's ratio ν_m. The mechanical properties were measured at 28 days and 60 days of curing. Table 3 gives an average of the two test series, as the samples were obtained from different batches and thus the differences in the test results were due to the mortar variability more than the curing period.

The vertical reinforcement was constituted by usual ribbed rebars, with diameter Φ16mm, made of FeB44k hot-drawn steel. The horizontal reinforcement was constituted by single rebars with diameter Φ6, made of FeB44k hot-rolled steel, or by a prefabricated truss reinforcement, composed by zinc coated steel wires with diameter Φ5 mm (Murfor RND/Z-5-150, see
Figure 2c). Table 4 summarizes the main mechanical properties of the adopted reinforcement: yielding stress f_y, tensile strength f_u and elastic modulus E.

Table 2. Mechanical properties of units

Units	$f_{b,m}$	f_b	E_b	ν_b	$f_{bh,m}$	f_{bh}	E_{bh}	ν_{bh}
	N/mm^2	N/mm^2	N/mm^2		N/mm^2	N/mm^2	N/mm^2	
Hor. holes, 15% tuff	9.45	10.40	7175	-	17.87	20.55	8638	-
Hor. holes, 20% tuff	9.26	10.18	7896	-0.18	13.24	15.23	12789	-0.15
Vertical holes	21.61	24.10	13627	-	-	-	-	-

Table 3. Mortar T300 M10 DISWall properties

Mortar curing period	Bulk density	Bleeding	Air content	Plunger	$f_{m,t}$	f_m	E_m	ν_m
	Kg/m^3	mm	%	mm	N/mm^2	N/mm^2	N/mm^2	

Fresh	2040	162÷161	8,2	26	//	//	//	//
Cured	2081	//	//	//	4.27	14.07	12553	-0.17

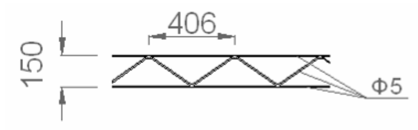
Table 4. Mechanical properties of reinforcement

Property	Horizontal Reinf.		Vertical Reinf.
	Φ6	Murfor	Φ16
f_y (N/mm^2)	515	378	463
f_u (N/mm^2)	614	678	620
E (N/mm^2)	204460	202060	193760

Figure 2. (a) Horizontally perforated unit during the uniaxial compression test under load orthogonal to the bed face; (b) mortar sample after compression test; (c) Murfor RND/Z-5-150

(a)

(b)



(c)

UNIAXIAL COMPRESSION TESTS

The uniaxial compression tests were carried out by means of an Amsler machine whose maximum load is 10000 kN. Two layers of Teflon were placed between each end of the specimens and the loading plates, in order to minimize friction at the ends and create a uniaxial stress state. The tests were carried out under monotonic loading, with a load increment rate of about 0.5 kN/s (EN 1052-1, 1998). A preload equal to 5kN, 10kN and 15kN, equal to 1% of the foreseen maximum load, was respectively applied to the columns, the wallettes without vertical reinforcement and the specimens of the entire RM system. After reaching the maximum load, the load was maintained until the 80% of the peak value, when possible, in order to check the load decrease caused by the propagation of damage.

The specimens were instrumented with potentiometric displacement transducer (±50 mm), LVDTs (±10 mm) and strain transducers (±2.5 mm) in order to measure the horizontal, vertical and transversal deformation of the specimens. The instruments placed on the specimens of the entire RM system partially reproduced the instruments scheme adopted for the specimens without vertical columns HC and the five unit courses columns C5, in order to study the behaviour of the components, and were partially placed across the entire specimen, in order to catch the global behaviour of the RM system.

Table 5 presents the results in terms of maximum compressive stress σ_{max} (maximum applied load divided by the horizontal cross sectional area), compressive stress at which the out-of-plane buckling of the specimens started (σ_{inv}) and their ratio. The elastic modulus, E, determined between 10-40% and 30-60% of the ultimate load and Poisson's ratio, ν, evaluated on the first linear branch of the curve

between the 10-40% of the ultimate load, vertical and horizontal strain ($\varepsilon_{v\sigma inv}$, $\varepsilon_{h\sigma inv}$) and their ratio at the load at which the out-of-plane buckling of the specimens started, are also shown in Table 5. The results are presented as mean values of the tested specimens except for the specimens of the entire RM system, for which just one test has been carried out for each type of horizontal reinforcement (Table 1).
The 3 rows confining columns showed a behaviour governed by vertically oriented cracks formed in correspondence of the vertical mortar joints, distributed all around the specimens. After the attainment of the maximum load, some out-of-plane deformations of the units occurred. The effect of the transversal deformation of the inner mortar core appeared to be more evident on the 5 rows columns, on which the vertical cracks were concentrated in correspondence of the vertical joint. The experimental evidence was confirmed also by the stress-strain diagrams, which showed a decrease of the elastic modulus and an increase of the Poisson ratio.

The failure mode of the wallettes made with horizontally perforated units corresponded, to a certain extent, to the typical behaviour of masonry made with vertically perforated units. The first crack appeared at 60% of the ultimate load. The cracks were vertically oriented following the discontinuity of the head joints. These cracks corresponded to the loss of linearity in the stress-strain diagram (Figure 4a). Only after the propagation of the vertical cracks, the spalling of the units with horizontal holes started. At a load level equal to 95% of the ultimate load, the specimens showed an out of plane deformation, due to the unit spalling and to the development of other cracks on the transversal sections. The trend of the displacement measured by the vertical transducers inverted, measuring lengthening (negative values) instead of shortening (positive values). The two adopted horizontal reinforcement did not influence significantly the behaviour of the specimens in terms of strength and elastic deformation (see Table 5 and Figure 4a). However, the presence of the truss reinforcement allowed a more uniform stress distribution on the wallettes, avoiding local failures and guaranteeing a higher stability in the cracked and post peak phases (Figure 3 (a)).

Table 5. Uniaxial compression tests results

Specimen	σ_{max}	σ_{inv}	$\sigma_{inv}/\sigma_{max}$	$E_{10-40\%}$	$E_{30-60\%}$	$\nu_{\sigma max}$	$\varepsilon_{v\sigma inv}$	$\varepsilon_{h\sigma inv}$	$\varepsilon_{h\sigma inv}/\varepsilon_{v\sigma inv}$
	N/mm^2	N/mm^2	%	N/mm^2	N/mm^2	‰	‰	‰	‰
C3	5.44	-	-	8110	7528	-0.18	-	-	-
C5	5.73	-	-	7473	6504	-0.22	-	-	-
SRHC	2.94	2.83	96	4225	3375	-0.18	0.96	-0.81	-0.84
TRHC	2.48	2.32	94	4427	3522	-0.21	0.79	-0.67	-0.85
SRCa	4.11	3.72	90	6492	6040	-0.10	0.69	-0.15	-0.22
TRCa	3.69	3.25	88	5231	5635	-0.12	0.61	-0.28	-0.46

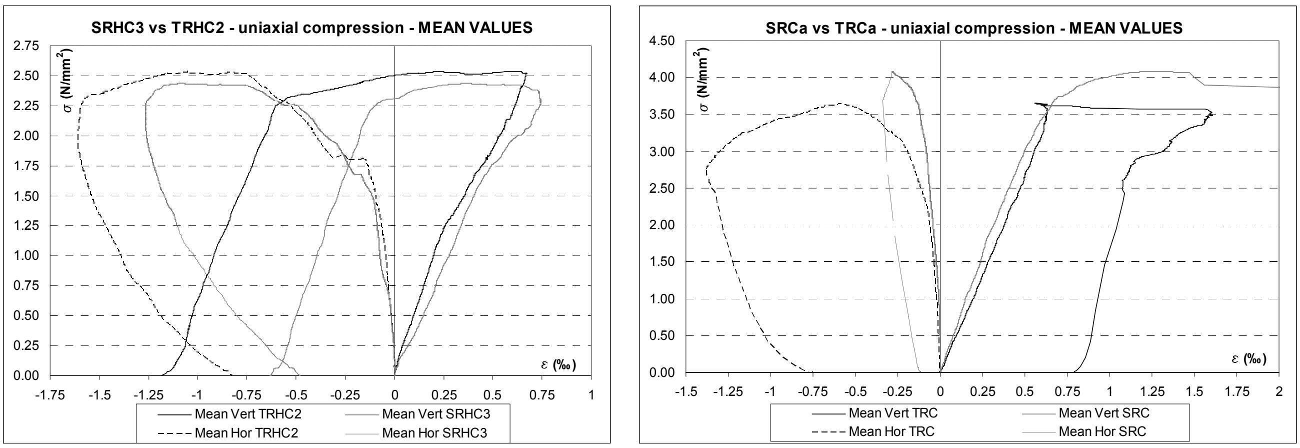
For the specimens of the entire RM system the first cracks appeared between 30%-60% of the ultimate load, at the interface between the confining columns and the masonry panel made with horizontally perforated units. The behaviour of the masonry walls was still linear after the opening of these cracks (Figure 4b), but varied for the specimens SRCa and TRCa. The first presented new vertical cracks following the interface, until a load level equal to about 90% of the ultimate load. At that point, vertical and horizontal cracks opened on the two upper rows of horizontally perforated units, with intense spalling. On the contrary, the specimen TRCa presented a distribution of vertical cracks on the entire masonry wall, both on the façades and on the transversal sections. The spalling of the units, which occurred on the three upper rows of the specimen, and the out of plane deformation of the specimens, still started at about 90% of the ultimate load (Figure 3 (b)).

The difference in the mechanical properties between SRCa and TRCa, reported by Table 5, has to be evaluated taking into account that just one specimen for masonry type was tested. It can be said that the presence of the vertical columns induced a modification on the behaviour of the masonry made with horizontally perforated units. It also caused an increase of the compressive strength of about 44%, an increase of the elastic modulus of about 35%, and a decrease of the Poisson ratio of about 44%.

Figure 3. Deformation in transverse direction of the murfor truss reinforcement: (a) TRHC2 side L (b) TRC side A

(a) (b)

Figure 4. Stress-Strain diagrams: (a) comparison SRHC3-TRHC2 (b) comparison SRCa-TRCa



(a) (b)

IN-PLANE CYCLIC SHEAR-COMPRESSION TESTS

The specimens were tested with cantilever type boundary condition, with fixed base and top end free to rotate, by applying a centred and constant vertical load equal to 11% and 16% of the measured

maximum compressive strength of the RM system walls, and corresponding to 15% and 22% of the measured maximum compressive strength of the wallettes without confining columns. The corresponding compressive stress levels (0.4 N/mm^2 for the lower pre-compression rate, 0.6 N/mm^2 for the higher one) are adequate to represent the typical vertical loads for two up to four-storey height buildings. Each series reported in Table 6 is constituted by two specimens, one for each pre-compression level.

The specimens were instrumented with 24 potentiometers to measure the deformation of the masonry specimens and to verify the displacements between the wall and the top and the bottom bond beam and 4 strain gages to measure strains in the reinforcement at characteristic sections of the wall. Horizontal cyclic displacements, with increasing amplitude and with peaks repeated three times for each displacement amplitude, were applied at a frequency of 0.004 Hz. The displacement history was determined by fixing a reference critical displacement δ_{cr}=3 mm (interstorey drift equal to 0.17%) and considering that the first non linearity is expected for displacements equal to 1÷1.5mm (interstorey drift between 0.05%-0.08%).

Table 6. Test series and type of reinforcement for shear compression walls

Series	Dimensions (mm)	Vertical Reinf.	Vertical Renf. ratio	Horizontal Reinf.	Horizontal Renf. ratio
SRHSa	1550x300x1690	-	-	2Φ6/400mm	0.045%
TRHSa	1550x300x1690	-	-	1murfor/400mm	0.040%
SRSa	1550x300x1690	4Φ16	4x0.043%	2Φ6/400mm	0.045%
TRSa	1550x300x1690	4Φ16	4x0.043%	1murfor/400mm	0.040%
SRSb	1030x300x1690	2Φ16	2x0.065%	2Φ6/400mm	0.045%
TRSb	1030x300x1690	2Φ16	2x0.065%	1murfor/400mm	0.040%

During the in-plane cyclic tests the attainment of four main limit states, which can be used to idealize the masonry wall behaviour, can be observed. These states are related to the occurrence of the flexural cracking on the horizontal joints (flexural cracking limit, H_f, δ_f), to the appearance of the first significant diagonally oriented shear crack (crack limit, H_{cr}, δ_{cr}), to the attainment of the maximum resistance H_{max} at a corresponding displacement level δ_{Hmax}, and, finally, to the attainment of the maximum displacement δ_{max}, to which a consequent value of residual lateral resistance $H_{\delta max}$ corresponds. This idealization is developed on purpose for plain masonry (Abrams, 2001), and with some adaptations could be applied to the tested specimens. All the specimens presented the first non-linearity related to the opening of flexural cracks at the base of the wall for a displacement of about 1÷2mm, independently by the applied pre-load and by typology of the specimens. The evaluation of the shear cracking limit was evident for the specimens designed to fail in shear (SRSa and TRSa), whereas for the specimens designed to fail in flexure (SRSb and TRSb), this limit state was identified with the appearance of the second non-linearity in the envelope of the hysteresis loops.

For the first type of specimens, having a slenderness equal to 1.09, the first diagonal oriented shear crack was visible at a displacement amplitude of 5÷6.25 mm and 2.5÷4.5 mm respectively, according to the level of applied pre-stress (0.4 N/mm^2 or 0.6 N/mm^2). This crack was mainly characterized by a stepped pattern. The attainment of the maximum lateral load, for the specimens loaded with 0.6 N/mm^2, was characterized by a well defined diagonal compression strut, with cracks passing through the joints and the units and falling out of the unit shells. It was also possible to notice the buckling of

the vertical rebars. The collapse was reached at the imposed displacement amplitude immediately following the δ_{Hmax} (Figure 5b). In the case of the specimens loaded with 0.4 N/mm^2, it was still possible to observe the crack pattern following the diagonal compressed struts; however, the deterioration of the compressive toe due to the buckling of the vertical rebars was worsened. In this case, the collapse was reached four displacement cycles after the δ_{Hmax}. These specimens thus showed less marked shear behaviour and higher ductility. The specimens with slenderness equal to 1.64 were characterized by a crack pattern with damage concentrated at the bottom of the wall and on the compressed toes. The maximum load was attained at displacement of about 25÷35 mm and 20 mm respectively, according to the level of applied pre-stress (0.4 N/mm^2 or 0.6 N/mm^2). The specimens TRSb, with the horizontal prefabricated reinforcement, were characterized by higher maximum displacement (Table 7 and Figure 5c). The failure occurred with crushing of the toe at the higher pre-compression level, whereas it occurred with yielding, and subsequent failure, of the vertical reinforcing bars, at the lower pre-compression level. The specimens of the HS series (without the vertical reinforcement) developed a rocking type of mechanism, as commonly observed for unreinforced masonry, with damage concentrated at the bottom of the specimen (Figure 5a). Table 7 summarizes the values of lateral load and correspondent displacement at the previous characteristic limit states.

Figure 5. Cyclic shear compression specimens under test: (a) SRHS2 (b) TRSa1 (c) SRSb1

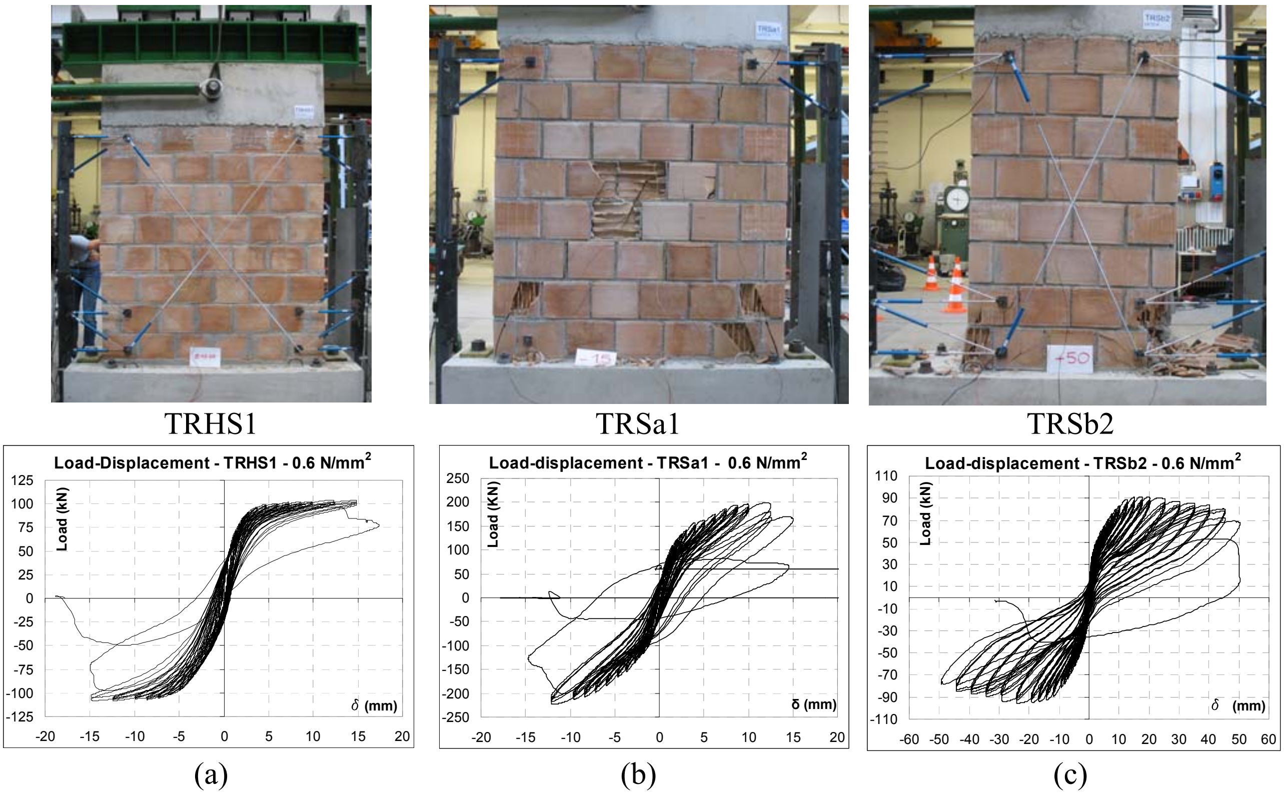


Table 7. Test results: lateral load and lateral displacement at four limit state of hysteretic envelopes

Specimen	H_f kN	δ_f mm	H_{cr} kN	δ_{cr} mm	H_{max} kN	δ_{Hmax} mm	H_{dmax} kN	δ_{max} mm	Failure Mode
σ_0= 0,6 N/mm²									
TRHS1	60	1.51	94	4.01	104	13.75	40	17.97	Flex
SRHS1	50	1.00	91	4.52	113	23.74	72	34.99	Flex
TRSa1	104	1.51	170	5.13	207	12.51	145	15.00	Shear
SRSa2	88	1.26	160	5.13	217	12.50	182	17.50	Shear
TRSb2	40	1.51	86	11.25	93	21.25	72	49.99	Flex
SRSb2	41	1.26	80	8.76	89	20.00	70	30.00	Flex
σ_0= 0,4 N/mm²									
TRHS2	47	1.25	73	5.63	78	25.00	46	69.98	Flex
SRHS2	45	0.99	72	4.75	81	37.47	24	64.96	Flex
TRSa2	82	1.12	117	2.71	199	11.67	105	24.67	Shear/Flex
SRSa1	81	1.49	120	3.50	200	17.49	139	24.98	Shear/Flex
TRSb1	32	1.66	74	12.04	77	36.99	29	79.85	Flex
SRSb1	30	1.31	67	8.82	78	24.24	32	64.68	Flex

CONCLUSIONS

The experimental research investigated the in-plane behaviour of a newly developed reinforced masonry system, based on the use of horizontally perforated clay units. The RM system mainly presented a brittle behaviour in the case of shear failure, whereas the reinforcement provided a more stable and ductile behaviour in flexure, characterized by a good energy dissipation capacity. The influence of different types of horizontal reinforcement was also investigated. The truss reinforcement, compared to usual rebars, was able to provide an increased stability and a more diffused crack pattern in compression. Under in-plane cyclic shear compression tests, the truss reinforcement was able to increase the displacement capacity of the specimens designed to fail in flexure. The test results are still being analyzed, and are being used as reference data for modelling the hysteretic behaviour of the envisaged reinforced masonry system.

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