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STRENGTHENING OF MASONRY SHEAR WALLS BASED ON METAL SOLUTIONS. PART I: EXPERIMENTAL INVESTIGATION

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Abstract. Due to the lack of resistance, to a small deformation capacity and to a low ductility, many masonry buildings in prone seismic areas may need structural interventions. Innovative interventions which will increase the wall capacity and ductility, without a major influence on its stiffness, may be valuable. A number of experiments attempting to establish the retrofitting technique efficiency will be detailed in the article. The proposed technique applies metallic plates as external reinforcing. They are connected by means of chemical anchors or pretension threaded rods, onto one or both sides of the wall. The solution can be applied to internal shear walls and on façades either on piers or spandrel. An important technique advantage may be the reversibility provided by dry steel connections. Limited damage occurs after uninstalling (except for the holes in the walls). Metal sheath reinforced masonry walls have complex behaviour and no analytic rules for design are available. Advanced numerical models confirmed by enlarged experimental tests are needed. All experimental tests were performed within the framework of the PROHITECH research project. Tests on component materials, in 500 x 500 mm and 1500 × 1500 mm retrofitted masonry elements, were done.

Key words: masonry, retrofitting techniques, experimental analysis, chemical anchors.

1. INTRODUCTION

1.1. Masonry behavior

An important and substantial task of the civil engineering community is to recover and keep existing buildings, both those with and those without historical or heritage value. The majority of the existing residential buildings are masonry and recently reinforced concrete structures.

In seismic areas, masonry buildings pose great vulnerability to earthquakes. Due to the inherent mechanical properties like the lack of resistance (small tensile resistance), small deformation capacity and low ductility, masonry structures fails are sudden and brittle. On the other hand, the resistance over the material own weight, and the small ratio make the masonry elements, massive with great mass and rigidity, attract high inertia forces. Retrofitting solutions which will increase the capacity and ductility of the elements, without a major influence on their stiffness, are useful.

1.2. Description of the innovative retrofitting technique

Within this paper, innovative retrofitting techniques are proposed, investigated and validated experimentally. The suggested solutions use sheathing plates: steel (SSP) or aluminium (ASP). Plates are applied either on both sides or on one side of the masonry wall. Plates are fixed either with pretension steel rods (PT) or by chemical anchors (CA) (Fig. 1). The proposed system provides added strength to the masonry element for both in-plane and out-of-plane failure mechanisms. Within the paper, the in-plane behaviour will be analysed considering that the out-of-plane benefits influence is obvious. The purpose of the intervention technique, besides strength improvement, is to enhance the deformation and energy dissipation capacity [1].

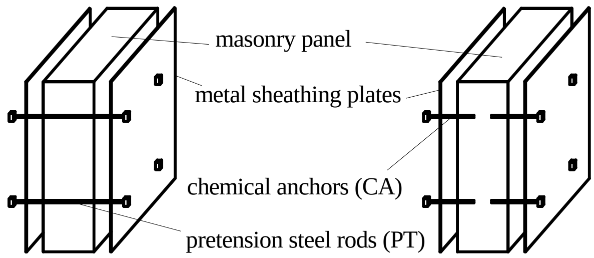

Fig. 1 – retrofitting techniques based on metal sheathing.

The connectors spacing, i.e. 200–250 mm, is imposed by the desire to make the connection in brick blocks, avoiding the mortar layer, for the sake of achieving safer behaviour. Likewise, the spacing of connectors must preclude the elastic buckling of metallic shear panels. It is considered that the desired failure mode of the strengthening system (metallic plates and connectors) should be yielding of the metallic plate and/or plastic deformations by the bearing of connectors.

Metallic plates should have comparative stiffness with the masonry wall if the metallic plates are designed so as to dissipate seismic energy through inelastic deformations. Due to the high in-plane stiffness of masonry walls, the suggested system will, most likely, not completely eliminate the damage to the masonry. A limited amount of masonry damage has to be allowed for. Considering this sheathing technique as a passive technique, it is obvious that some damage must be accepted until the system activation, and such technique is expected to work as “collapse prevention”.

Metallic plates and steel rods can be taken away from the masonry wall and replaced, so answering the reversibility demand [2]. Chemical anchors may be difficult to remove. The holes in the wall are the most intrusive effect of such techniques. In the case of threaded rods, local repair, such as the grouting of holes with mortar will be needed if the system is to be taken out completely. Metal plates can be hidden if plastering is applied, so preserving the aesthetical appearance. When the edifice façade needs an apparent look, the system can only be applied from the interior side.

This technique will be applied and tested like a reinforcing system onto the wall surface without any connection to the adjacent elements. Even if such a link could bring significant improvement of the behaviour, in most of the cases it is difficult or impossible to do. The chosen method of application will show the least expected improvement.

The applied technology is rather simple. Metallic plates, drilled before, are positioned onto the wall. Anchor holes are bored into the masonry wall through the plate holes. The debris is blown away from the holes. Epoxy resin is shot and the chemical anchors are fixed. Pretension rods are used similarly, but no resin is used. The threaded rods are tightened by using a torque control wrench.

2. EXPERIMENTAL TESTS AND RESULTS

2.1. Material characterization

The behaviour of the masonry material under lateral loads is different due to the higher non-homogeneity and composite nature of masonry components. The different mechanical properties of the masonry units and of the mortar and their interface make the masonry system behaviour difficult to predict by using simple hypotheses as adopted for other construction materials. The masonry mechanical behaviour can be established through experimental tests, which can be used for the calibration of numerical models needed in order to develop analytical formulas.

In addition to the pure masonry intricate response, metal sheath reinforced masonry walls have an even more complex behaviour. No analytic rules for design are available; therefore, advanced numerical models confirmed by experimental tests are needed. The experimental program carried out at the “Politehnica” University Timisoara, in the CEMSIG and CESMAST laboratories, is presented.

The experimental work included investigations on masonry prisms: for estimating masonry compressive strength (f_{mc}) and elastic Young modulus (E), besides tests on the composing materials, i.e.

brick units: for unit compression strength, mortar: for tensile and compression strength (f_m) (Fig 2). The most valuable is the test on wallets: for guess diagonal tension strength (f_t) and shear modulus (G).

Fig. 2 – Tests on masonry and components (mortar and brick).

2.2. Small specimen tests

A series of experimental tests were executed on small specimens in order to calibrate the proposed techniques. The tests on small specimens were carried out for the study of the connection behaviour and strengthening solution calibration. The small experimental specimens were 50 cm wide, 50 cm high and 25 cm thick. Wallets were built out of solid clay bricks with dimensions 6.3×24.0×11.5 cm and unit strength 9.0–10.0 N/mm^2 and cement based mortar (cement/sand ratio 1:1) with the strength of 30–50 N/mm2. These preliminary tests are summarized in Table 1 [1].

Table 1

Calibration experimental tests

Test type	Tested purpose		Number
Preliminary test	Masonry wallet		1
Connection push-test	Chemical anchor (CA)	ϕ8	3
		ϕ10	3
	Pretension rods (PT)	ϕ10 – 0%	3
		ϕ10 – 100 %	3
System diagonal tensile test	Steel shear panel (SSP) one side / both sides	Chemical anchor	6
		Pretension rods	6

Push-tests on connections were performed in order to select a reasonable connector diameter and to evaluate the influence of the pretension level of steel rods. The experimental set-up is presented in Fig. 3.

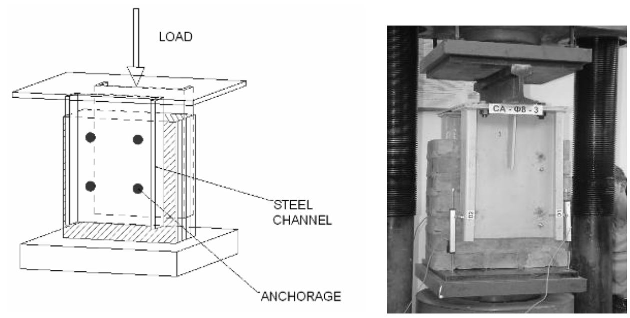

Fig. 3 Experimental set-up and testing machine for connectors

The objective was to consider the bond characteristic and to harmonize the crushing resistance of the matrix (masonry and epoxy resin) and shear of the steel connector and to ensure the masonry element integrity as much as possible. The testing device was made of two back-to-back cold-formed channel profiles (f_y = 350 N/mm^2) with 3 mm thickness of the walls. The connectors spacing was 200 × 225 mm, imposed by the brick masonry texture. The total force and relative displacement of the bottom part of the wall to the level of the last connector's row were recorded and plotted.

Chemical anchors of ø8 and ø10 diameters gr.5.8 have been tested. The anchor hollow depth in brick was 85 mm. The failure mode for ø8 was the connector shear, showing a weak connector and for ø10 the shear of connector and crushing of masonry (Fig. 4). Starting from chemical anchors results on ø10 steel rod were chosen by 0% and 100% pretension level (M_t = 35 Nm) applied. For full thickness penetrating rods, due to loads spread on the entire thickness and the absence of the prying forces inside masonry wall, only threaded rod failure was obtained.

Fig. 4 – Failure modes for chemical anchor (CA) and steel rods (PT) connections.

It was noted that the pretension level has slightly increased the resistance and initial rigidity of the interface (Table 2), due to the masonry confinement. For the large specimen tests, an ø10 connector fully pretensioned was chosen, due to efficient behaviour and resistance (Table 2). In comparison with chemical anchors, steel rod connections (Fig. 5) are more resistant and more rigid [1].

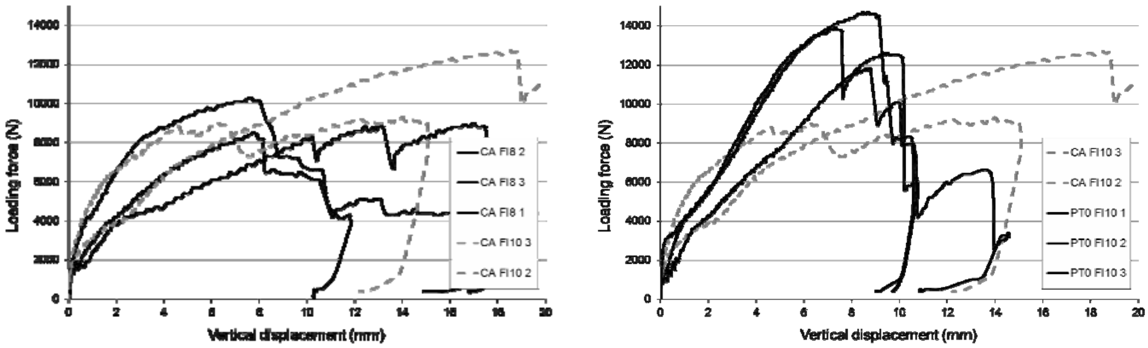

Fig. 5 – Comparative slip-force experimental behavior law between CA ϕ8 and ϕ 10, and CA and PT ϕ 10.

The failure of the rods, either snug tightened or fully pretensioned, shown two distinct zones. The first one is a masonry embedded zone, slightly bent at the ends and undistorted in the middle, and the second one is a shear interaction zone. The last one governs the connection capacity and the deformability. The steel rods initial internal force doesn't seem to affect the shear capacity. Obviously, in the case of large specimens, will improve the panel local behavior acting as a restriction. Because no bearing or plastic deformation of the testing channel holes were noticed, one may conclude that the obtained experimental results represent the slip-shear law of the interface. An average load capacity F_m on the connections is presented in Table 2.

An interface made with steel rods may ensure better compatibility through a better shear connection and interaction degree between the masonry panel and reinforcing element. The experimental results are very important in order to establish a law for the connection behaviour, to be used in the case of an advanced numerical simulation, otherwise impossible to be precise numerically replicated accounting for all the complex interaction phenomena.

Table 2

Experimental results on masonry-metal sheath connections

Connector diameter	Sp.	F (ton)	D (mm)	F_m (ton)	Connector diameter	Sp.	F (ton)	D (mm)	F_m (ton)
Chemical anchor 8 mm	1	10.1	8.02	1.15	**Pretension rods 10 mm snug tightened**	1	11.8	8.78	1.35
	2	8.8	12.5			2	13.9	7.35	
	3	8.5	7.87			3	14.7	8.7	
Chemical anchor 10 mm	1	10.1	11.37	1.68	**Pretension rods 10 mm full pretension**	1	14.8	6.92	1.75
	2	9.3	14.07			2	13.6	10	
	3	12.6	18.02			3	13.7	8.46	

A preliminary test was carried out on the unreinforced masonry panel (Fig. 6) in order to obtain reference values for the virgin specimen. Tests on retrofitting systems were carried out in order to confirm the analytical assumption [3] about the shear plate behaviour. The experimental scheme on 12 small specimens and a sample test on the unreinforced masonry panel are presented (Fig. 6). The maximum load capacity of the unreinforced panel was 8 t.

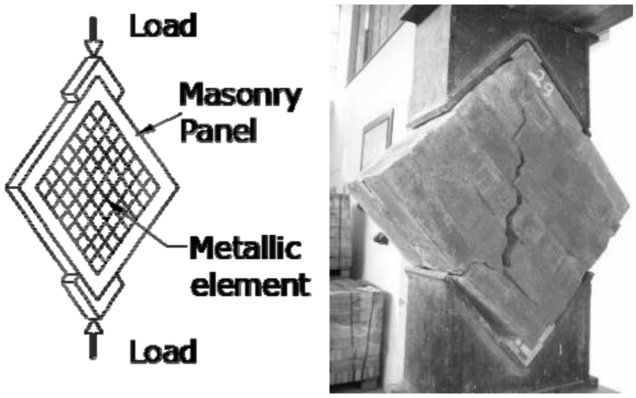

Fig. 6 –Testing set-up for diagonal tensile test and reference specimen failure mode.

Three masonry wallets equipped with steel shear plates S235 grade of 2 mm thickness on both sides and 3 mm thickness on one side, connected by means of chemical anchors (CA) and pretension rods (PT) were tested for each case. Figures 7 and 8 present the failure modes for reinforced specimens, with CA and PT, on one side and on both sides [1, 3].

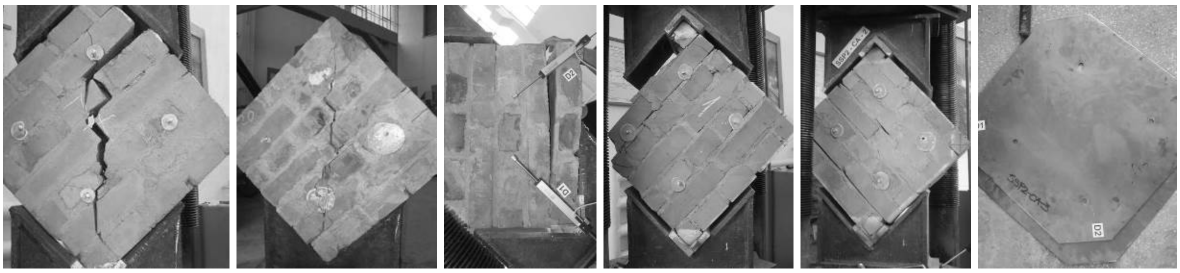

Fig. 7 – Failure modes of chemical anchors (CA) applied on one side and both sides.

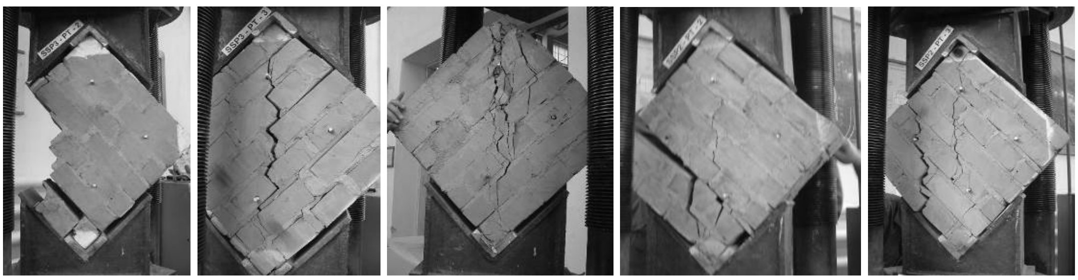

Fig. 8 Failure modes of pretension rods (PT) applied on one side and both sides

The failure modes confirm the beneficial action of the sheath reinforcing but show a large scatter of the results (Table 3). Better results, both in terms of strength and post-crack deformation capability of the composite system, were evident when a two side metal sheath was applied. Table 3 presents the maximum force attained by each experimental specimen and the corresponding vertical and horizontal deformation of the masonry wallets.

Table 3

Experimental results on reinforced masonry wallets

Connection types	One Side	*F* (ton)	*V* (mm)	*H* (mm)	Both sides	*F* (ton)	*V* (mm)	*H* (mm)
Chemical anchor CA	1	16.6	4.0	0	1	18.2	3.6	0.2
	2	14.1	3.4	0	2	10.8	0.8	0
	3	10.5	0.3	0.6	3	25	2.8	0
Pretension rods PT	1	12.4	2.4	0	1	35.9	4.8	0
	2	15.2	1.5	0	2	12.5	2.5	0.3
	3	9	0.5	0	3	13.3	5.4	0.4

The diagonal tensile failure mode and accidental sliding of the mortar layer were observed without any local damage of the connection areas. This proves that the concentrated forces introduced by the retrofitting system are successfully overtaken by the masonry wallet surrounding the connection area and the expected global failure mechanics is activated. Once the allowable maximum principal tensile stress is reached in the masonry wallet, it will quite suddenly crack at very small horizontal elongation and the forces will continue to be sustained by the metal sheath. The force drops up to two-thirds of the maximum load (Fig. 9), and the remnant load bearing capacity accompanied by significant displacements shows the reinforcing system activation.

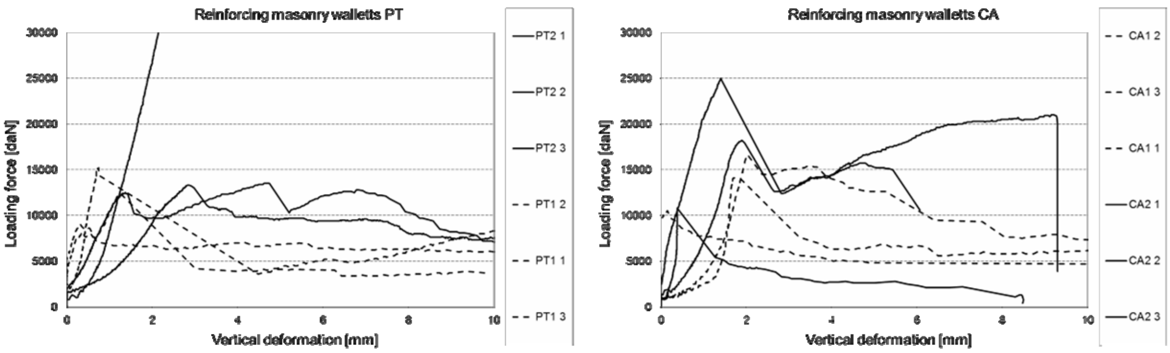

Fig. 9 – Load-elongation diagrams for the experimental specimens.

The increase of the loading force proves that the masonry wallet works together with the steel plate and they share the internal forces in the middle of the wallet where the maximum principal tensile stress appears. Moreover, the confining effect would improve the masonry material behaviour. The horizontal tensile and vertical compression bands appearance in the plates between two diagonal positioned anchors is proved by the bearing of the steel plate around connectors (Fig 10).

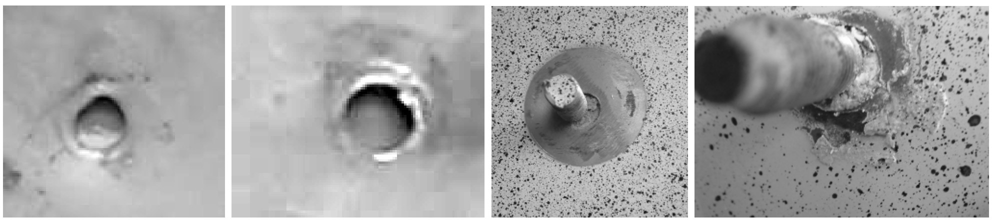

Fig. 10 – Bearing of steel plates applied on both sides.

2.2. Large specimen tests

After the calibration tests, tests on large specimens were carried out [1] [3]. Two different experimental frames have been set up, one for monotonic loading (Fig. 11a), in the CESMAST Laboratory, and one for cyclic loading (Fig. 11b), in the CEMSIG Laboratory, both within the “Politehnica” University of Timisoara.

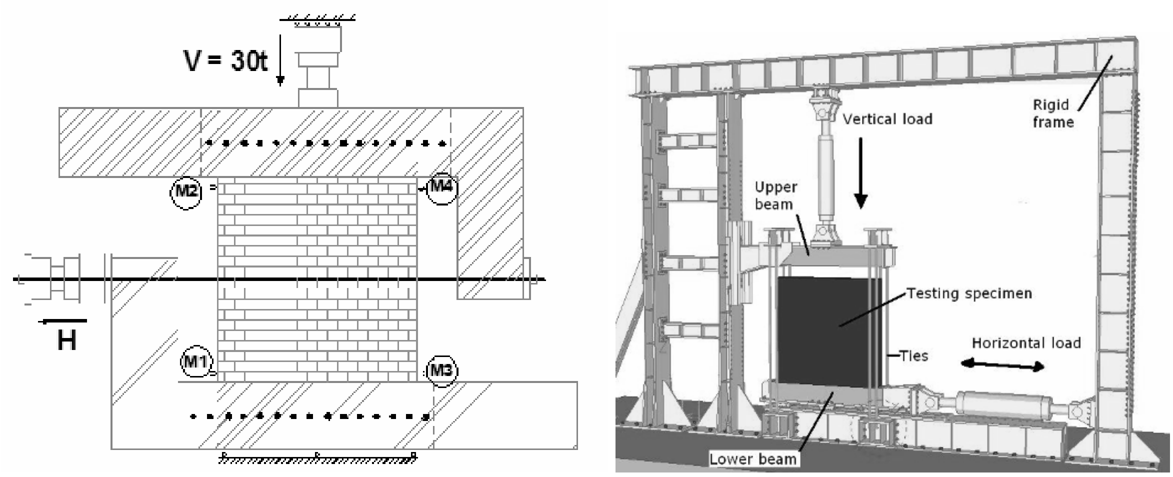

Fig. 11 – Testing frames and set-up for monotonic and cyclic loading.

The real scale experimental specimens were 150 cm wide, 150 cm high and 25 cm thick. The dimensions of the tested wall were chosen so as to respect the test set-up capabilities and to correspond to a commonly used wall pier. No scaling process was intended. The retrofitting systems were applied to undamaged masonry panel. For specimens sheathed on both sides a 2 mm thickness S235 steel plate was used, and for one side specimens 3 mm thickness. The connectors (either chemical anchors or pretension rods) spacing is the same as for wallets specimens.

The load was applied in two steps. A 300 kN vertical compression loads, corresponding to a 8 kg/cm^2 compression stress, was applied, followed by a horizontal load applied until the specimens failure. In the case of monotonic loading, the deformations of the wall were measured by linear displacement transducers (M1-4, see Fig. 11a). These devices were placed along the height of the wall, on both sides, and measured the horizontal displacement of the specimen in the first and the last mortar bed joints.

The diagonal failure mode was observed in all specimens (Fig. 12), both under monotonic and cyclic loading. There were observed some horizontal hairline cracks in the bed joints at the heel of the wall, along with the crushing of wall corners. Out-of-plane movement at the top and the bottom parts have been recorded, mainly at the specimens retrofitted on one side. All these failure mechanisms presented above prove that the retrofitting systems have forced the masonry wall to activate most of its strength and deformation capacity. A significant improvement of the ultimate displacement (that shows significant improvement in ductility), and the increase in strength, at almost the same stiffness, were recorded (Fig. 13). The ultimate displacement of the steel shear plates connected with chemical anchors specimens tested under monotonic loading conditions, increased more than 5 times, reaching over 20 mm [4].

Fig. 12 – Failure modes for cyclic specimens reinforced with CA and PT on one and both sides.

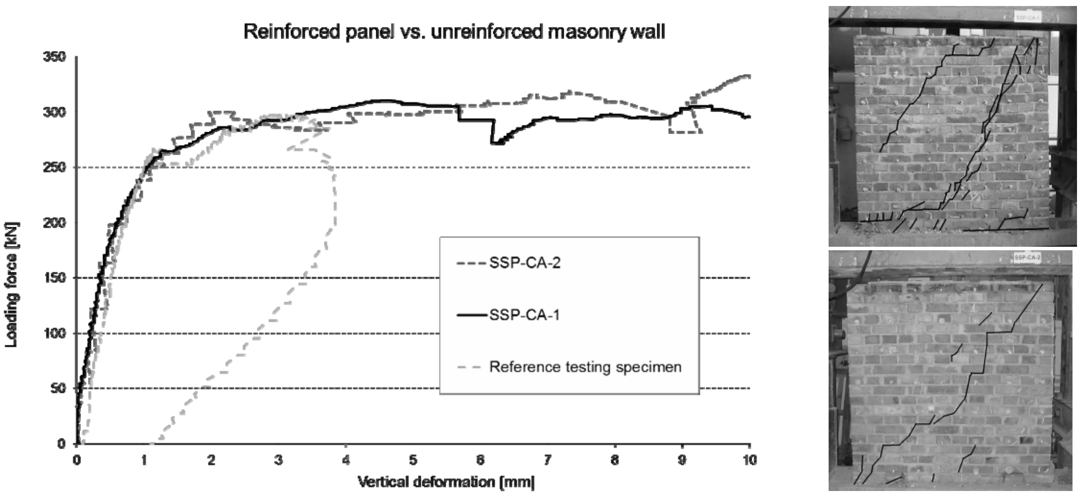

Fig. 13 – Monotonic experimental curves and failure mode for reinforced walls by means of steel plates fixed with CA.

3. CONCLUSION

The proposed strengthening solutions, based on metal sheathing masonry walls fixed by means of chemical anchors or pretension threaded rods, proved their efficiency, being an alternative at existing retrofitting techniques, enabling to get a ductile increase of strength without a significant increase of the stiffness of the wall. It can be concluded that metal shear plates mainly increase the ductility. It is expected that these strengthening solutions could be applied successfully in the case of weakly reinforced concrete diaphragms.

Nowadays, there are no analytical calculation procedures for the application of these strengthening solutions and the only available ways to design the composite masonry-connector-plate system, besides experimentally based design, are the ones relying on advanced numerical simulation. The experimental program presented in this paper would be used for the calibration of a finite element model able to replicate the positive effect of the retrofitting solutions. The experimental calibration of such an advanced numerical model will be presented in the second part of the paper.

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