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BEHAVIOR OF MASONRY INFILL PANELS IN RC FRAMES SUBJECTED TO IN PLANE AND OUT OF PLANE LOADS

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Abstract

The building envelope in Europe is usually made of masonry walls, with enclosure and infill functions. Masonry walls have a major economical importance and contribute significantly to the building performance. Even if infill walls have no load-bearing function, they contribute significantly to the seismic behavior of buildings. Therefore, their adequate structural performance is needed, avoiding the occurrence of severe in-plane damage, with very large economical losses, and the out-of-plane expulsion, which additionally represents a large risk for human life.

Recent earthquake codes in Europe require the safety assessment of non-structural elements (parapets, veneer masonry walls, infill walls, etc.), when their collapse entails risks for people or for the main structure. The Eurocode standards, entering the mandatory stage now, incorporate new requirements to be fulfilled by buildings or their parts. Such is the case of masonry infilled RC frames whose panels, according to Eurocode 8, are explicitly required to withstand the out-of-plane movement induced by earthquakes. Appropriate measures should be taken to avoid brittle failure and premature disintegration of the infill walls, as well as the partial or total out-of-plane collapse of slender masonry panels.

This paper presents the experimental work and results achieved by applying cyclic out-of-plane loads to damaged masonry infilled RC frames. The masonry panels were previously damaged by applying an in-plane cyclic load after which the cyclic out-of- plane loads were applied. The frames and panels tested follow the traditional Portuguese RC structure construction system to which different types of reinforcement have been introduced in the panels.

Keywords: Masonry Infill, RC frames, In-plane damage, Out-of-plane behavior

1. Introduction

The building envelope in Portugal is usually made by masonry walls, which have mainly enclosure and infill functions. Being one of the most important subsystems present in buildings, masonry walls allow a separation between indoor and outdoor environment and this is decisive for the buildings performance. Despite its undeniable importance, the masonry walls are usually neglected because of their properties as a constructive element, combined with a lack of tradition in research and teaching, and a lack of careful detailing masonry design. As a result, masonry infills are one of subsystems where there are more defects.

Although having no structural function, the masonry walls with enclosure and infill functions interact with the structure and contribute to the seismic behavior of buildings, requiring that these walls have adequate performance. In particular, it is necessary to avoid the occurrence of severe damage to the walls in their own plane (leading to serious economic losses) and the out-of-plane collapse of the walls (which could endanger human lives).

Much has been said in Portugal about the seismic vulnerability of buildings in recent years, due to insufficient resistance, selection of inadequate materials or construction techniques, changes to the original design and lack of maintenance. Although the concrete structures have appropriate normative to minimize such effects, masonry is having a legal framework in Portugal only with the appearance of EC6 [1] and EC8 [2].

Therefore, this work involves carrying out a series of tests on masonry specimens' under compression, flexural and shear in both directions, for the characterization and parameterization of the mechanical responses under different loading conditions. Tests were then performed also in masonry infill walls, subjected to combined in-plane and out-of-plane tests, as it occurs in real earthquakes. Firstly, cyclic in-plane tests were performed in the walls in order to introduce in-plane damage. Secondly, cyclic out-of-plane tests were performed in order to reach collapse.

2. Experimental program

2.1 Scope

The aim of this paper is to better understand the behavior of masonry infill panels in RC frames subjected to combined in-plane and out-of-plane loads.

2.2 Methodology

In the first phase of the work, a literature review and a preliminary modeling of the panels with mechanical data available in the literature were carried out. From this research, it was possible to definite the geometric characteristics, the sections of reinforced concrete elements and the displacements to be applied to specimens. The second phase of this work contemplated an extensive experimental program to define the masonry mechanical properties and the actual tests on masonry infills.

3. Specimens characterization

Four different types of masonry specimens were considered, with references: 1) PS – Unreinforced masonry specimen; 2) PRS – Masonry specimen with plaster; 3) PRA – Masonry specimen with external reinforcement in the plaster; 4) PJHA – Masonry specimen with bed joint reinforcement. All the specimens were made with clay hollow brick 300x200x150 mm and a M5 mortar.

3.1 Determination of compressive strength

The compressive strength test was performed according the European Standard EN 1052 – 1 [3] in specimens with 600x600x150 mm. The test campaign included tests in four types of masonry specimens given above, with five samples for each specimen type. Besides the compressive strength, also the Young Modulus E and Poisson coefficient ν were obtained. Table 1 provides a summary of the mechanical proprieties obtained during the determination of the compressive strength test. Here, c.o.v. is the coefficient of variation, f_{max} is the average compressive strength and f_k is the characteristic compressive strength.

Table 1: Mechanical properties of masonry specimens

Type of specimens	E N/mm²	E (c.o.v.)	f_{max} N/mm²	f_{max} (c.o.v.)	ν	ν (c.o.v.)	f_k N/mm²
PS	1577	10.3%	1.26	16.7%	0.092	65.3%	1.0
PRS	3603	27.6%	1.34	16.7%	0.213	38.7%	1.1
PRA	4296	4.4%	2.09	15.5%	0.186	32.7%	1.7
PJHA	2402	16.2%	1.66	21.1%	0.169	37.5%	1.4

The data given in Table 1 indicates that the specimens of unreinforced masonry are the ones with the lowest compressive strength. The specimens with higher results for the compressive strength were the masonry specimens with external reinforcement. These specimens exhibited a good behavior after peak load, as the rendering remained bonded to the masonry even when severely damaged.

3.2 Determination of flexural strength

The flexural strength test was performed according the European Standard EN 1052 – 2 [4]. Figure 1 shows the geometric properties of the specimens and the location of load application for the flexural strength test in two orthogonal directions.

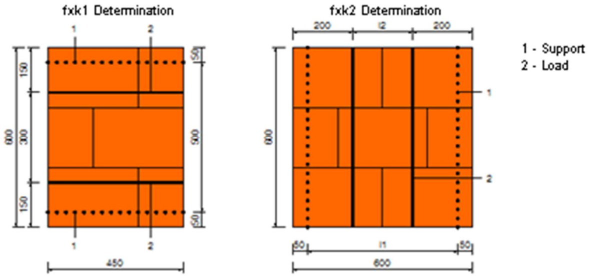


Figure 1: Geometric properties of specimens and location of load application

Table 2 provides a summary of the mechanical properties obtained from the flexural strength test. Here, f indicates strength, subscripts x1 and x2 indicates testing parallel and perpendicular to the bed joints, respectively, subscript ave indicates average and subscript k indicates characteristic.

Table 2: Flexural strength test in both directions

Type of specimens	Flexural strength				Characteristic flexural strength	
	$f_{x1,ave}$ (N/mm²)	$f_{x1,ave}$ (c.o.v.)	$f_{x2,ave}$ (N/mm²)	$f_{x2,ave}$ (c.o.v.)	f_{xk1} (N/mm²)	f_{xk2} (N/mm²)
PS	0.145	38.2%	0.501	23.6%	0.10	0.33
PRS	0.494	13.1%	0.740	16.3%	0.33	0.49
PRA	0.662	18.2%	1.848	10.5%	0.44	1.23
PJHA	0.540	16.0%	1.460	31.3%	0.36	0.97

The PRA specimens are the ones with higher values of flexural strength when the two directions of bending are considered. Besides higher strength, excellent ductility results, were obtained because the external mesh prevents the specimen from disintegration. This feature is especially noteworthy with respect to seismic behavior.

The PJHA specimens in the flexural strength test parallel to the bed joints had similar results to those obtained for PRS, since the bed joint reinforcement does not interfere directly in this loading direction.

3.3 Determination of shear strength

The shear strength test was performed according to European Standard EN 1052-3 [5]. Table 3 provides a summary of the mechanical properties obtained from the test in specimens with the 300x600x150 mm. Here, fv indicates the shear strength.

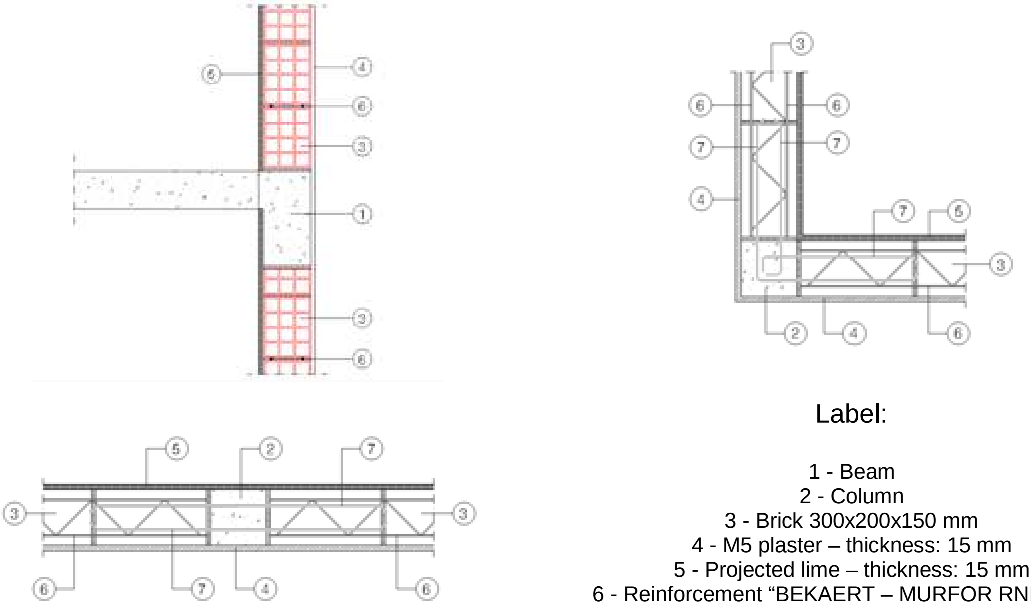
Table 3: Shear strength test

Type of specimens	Shear strength $f_{vo,ave}$ N/mm²	$f_{vo,ave}$ (c.o.v.)	Characteristic shear strength f_{vok} N/mm²
PS	0.09	11.3%	0.07
PRS	0.34	14.2%	0.27
PRA	0.50	27.4%	0.40
PJHA	0.26	51.2%	0.21

The PRA specimens had the highest shear strength and once again had a ductile experimental behavior. The PJHA specimens in the shear strength test parallel had similar results to those obtained for PRS, since the bed joint reinforcement does not interfere directly in this loading direction.

4. Characterization of the masonry panels

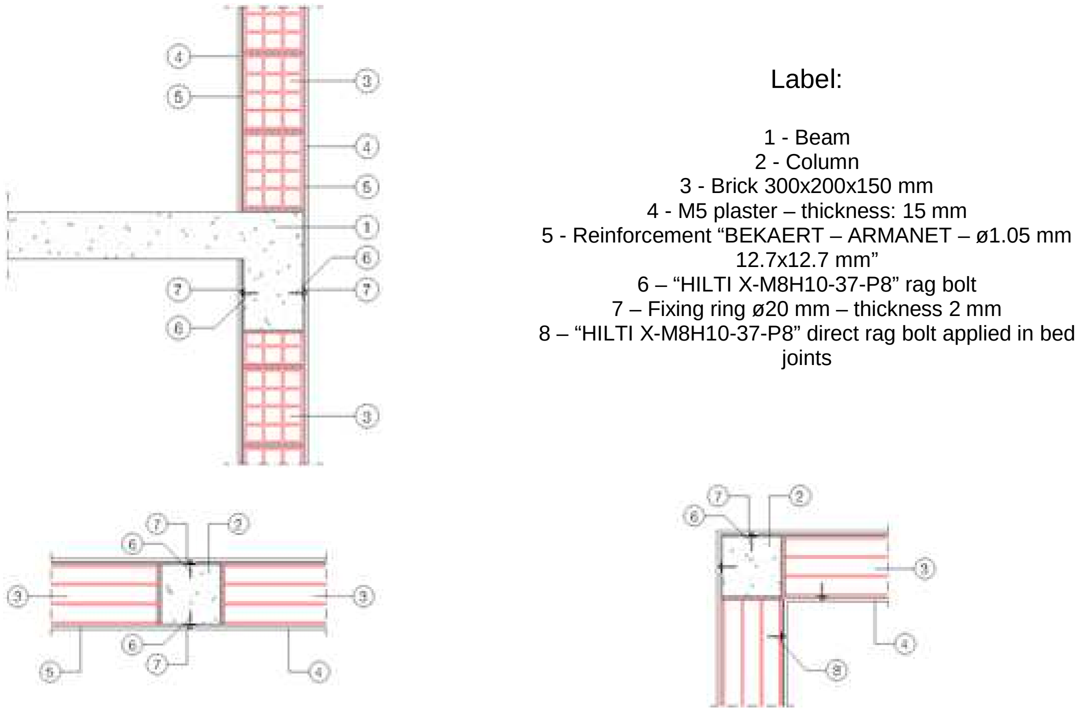
In this work, three types of masonry walls were studied. The references of these walls are: 1) WALL_REF – Reinforced concrete frame with infilled masonry; 2) WALL_JAR – Reinforced concrete frame with infilled masonry with bed joint reinforcement, Figure 2; 3) WALL_RAR – Reinforced concrete frame with masonry infilled with external reinforcement, Figure 3.



Label:

1 - Beam
2 - Column
3 - Brick 300x200x150 mm
4 - M5 plaster – thickness: 15 mm
5 - Projected lime – thickness: 15 mm
6 - Reinforcement “BEKAERT – MURFOR RND 4/100”
7 - ø6 mm reinforcement connected to the column before concreted

Figure 2: WALL_JAR reinforcement design

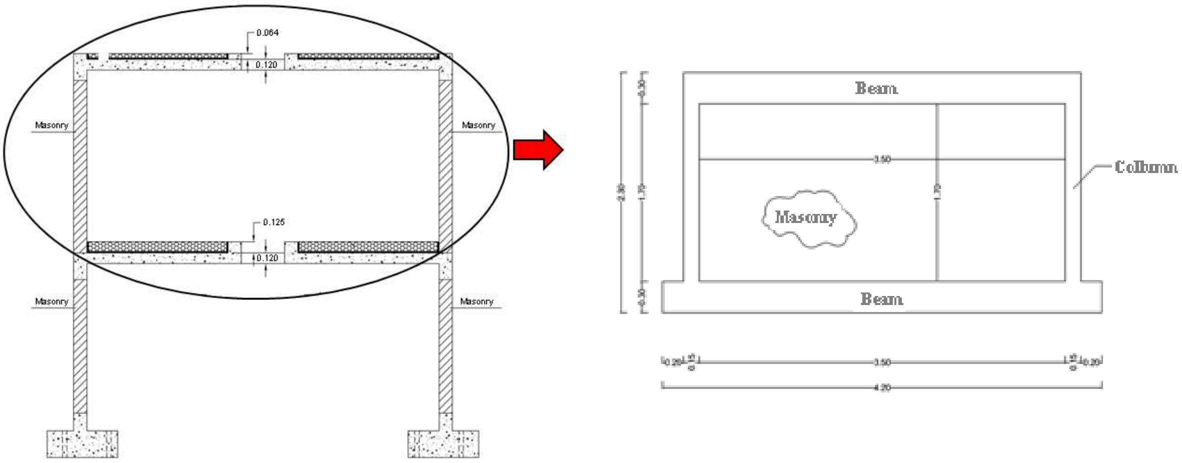


Label:

1 - Beam
2 - Column
3 - Brick 300x200x150 mm
4 - M5 plaster – thickness: 15 mm
5 - Reinforcement “BEKAERT – ARMANET – ø1.05 mm 12.7x12.7 mm”
6 – “HILTI X-M8H10-37-P8” rag bolt
7 – Fixing ring ø20 mm – thickness 2 mm
8 – “HILTI X-M8H10-37-P8” direct rag bolt applied in bed joints

Figure 3: WALL_RAR reinforcement design

The geometry of the masonry walls was defined taking into account a parallel testing program at a shaking table. From this study, a 1:1.5 scaled building model was defined. The panels considered in the present testing program are part of the building, so that the in-plane and out-of-plane mechanical response can be better understood. The resulting geometry, with the adaptations necessary to conduct the tests is presented in Figure 4.

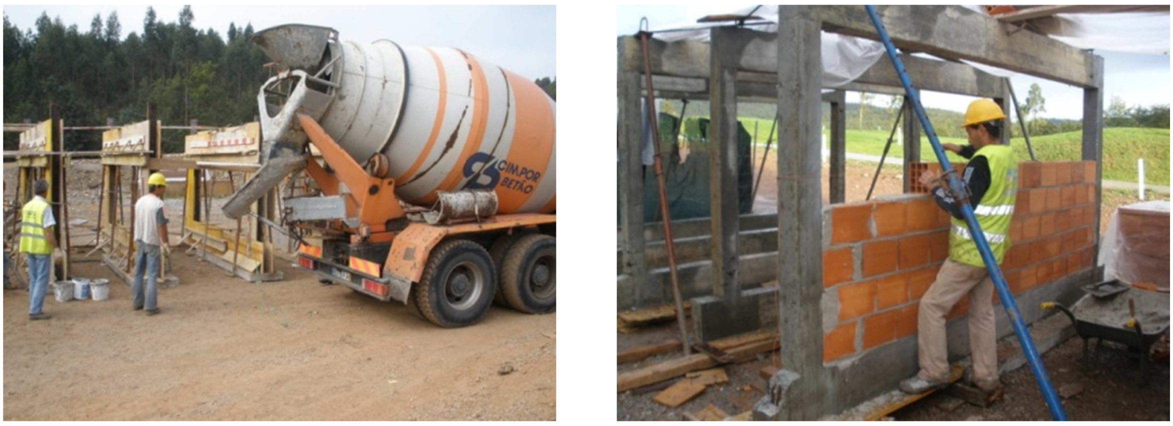


a) b)

Figure 4: Masonry panels characterization: a) storey; b) geometry

4.1 Construction process

The aim of the experimental campaign is to determine the behavior of masonry infill panels in RC frames, with and without reinforcement, constructed according to the traditional building process. The construction process of the walls consisted of the following steps: 1) construction of the concrete frames; 2) construction of masonry infill panel with or without reinforcement; 3) placement of plaster with or without reinforcement, as is briefly described in Figure 5. The construction process of the masonry walls is particularly important because it may result in different behavior. The placement of the masonry is done by successive horizontal rows, always from one of the pillars. At first masonry unit, mortar is applied on the bed and head faces. The unit is then pressed against bed and the column. The last unit in each horizontal row is usually cut due to dimensional compatibility. In situations where the panels geometry make the cut unreasonable (too small unit parts), the spaces are filled with mortar. The geometry of the panel led to a situation of this kind. In the last horizontal row units are cut so they can fit to the concrete frame geometry. The space between the unit and the beam is filled, possibly only partly due to execution difficulties, with mortar.



a) b)

Figure 5: Construction phases of the panels: a) frame concreting; b) wall construction

4.2 Preliminary modeling

In order to get a better idea of the influence of each displacement reference level, a nonlinear finite element model was developed to assess the performance of different reinforcement solutions. This preliminary model allowed the determination of the maximum stress expected for the different solutions of reinforcement as well the level of degradation of the panel for each displacement (drift) usually adopted in seismic testing. The finite element model provided, in addition to determining damage levels, an estimation of force levels associated with the test, which allowed the design of the support structure and choice of load equipment, as shown in Figure 6.

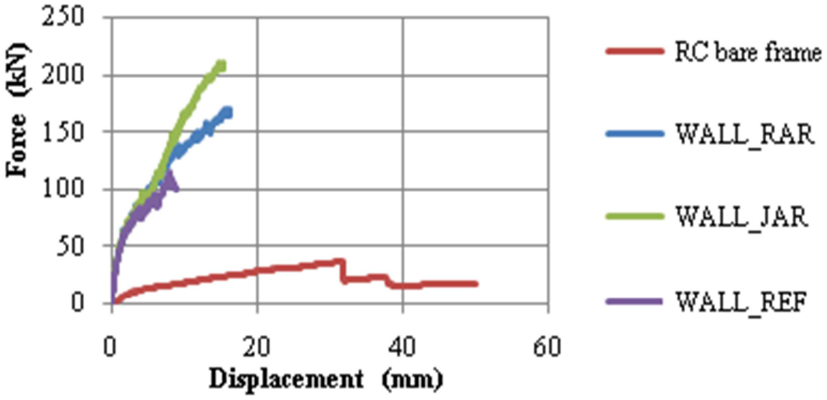


Figure 6: Preliminary modeling results

4.3 Test Setup

For the in-plane and out-of-plane tests, it was necessary to create a set-up that could apply displacements in both directions to the masonry panel, as shown in Figure 7 and Figure 8.

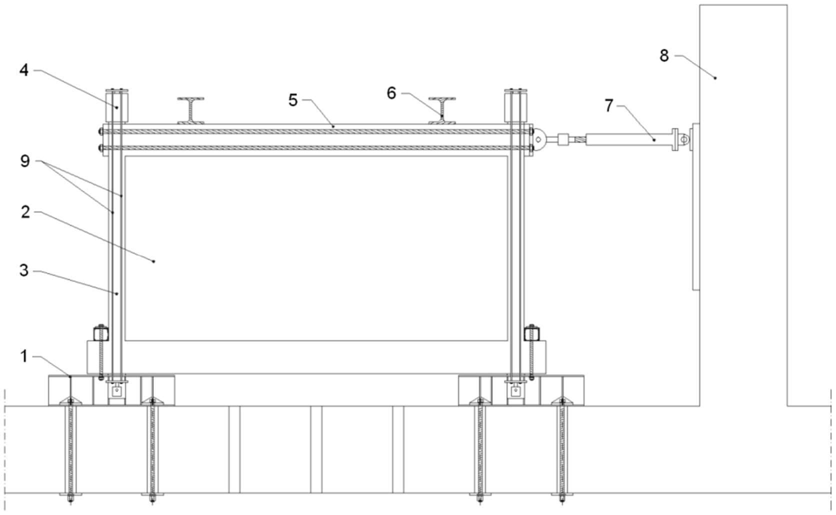


Figure 7: In plane setup. 1 – Metal support; 2 – Masonry panel; 3 – RC frame; 4 – Hydraulic jack which allows the transmission of the upper floor columns loads; 5 – Steel ties that allow the reversal of load; 6 – Cross beam to the RC frame; 7 – Horizontal actuator; 8 – Reaction wall; 9 – Reaction ties

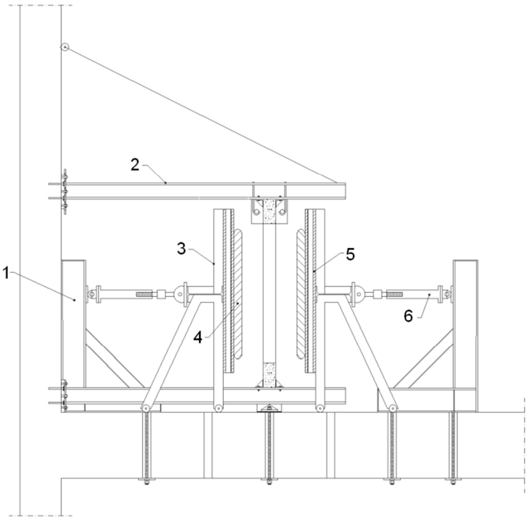
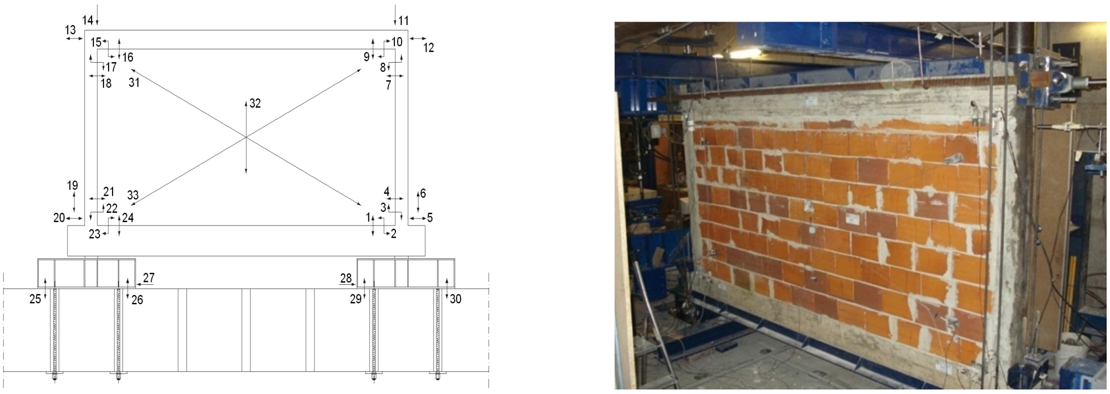


Figure 8: Out-of-plane setup: 1 – Reaction frame to the horizontal actuator; 2 – Cross beam to the RC frame; 3 – Structure of load application and airbags support; 4 – Airbags; 5 – Wood panel; 6 – Horizontal actuator

4.4 Test Procedure

4.4.1 In Plane

The in plane test is performed by applying cyclic horizontal displacements to the masonry panel until it reaches a predetermined value (0.5% drift). The tests were performed applying two vertical loads on the columns, to simulate the presence of the upper storeys. These loads were materialized on the form of two hydraulic jacks, each one on the top of each column. These hydraulic jacks have a tie system, which connect the hydraulic jack to the metallic base support. The total vertical load was then kept constant during the tests. In order to determine the contribution of each panel component for their behavior, the test load application in the horizontal plane was monitored using the scheme presented in Figure 9.



a) b)

Figure 9: In plane instrumentation: a) Scheme; b) Overview

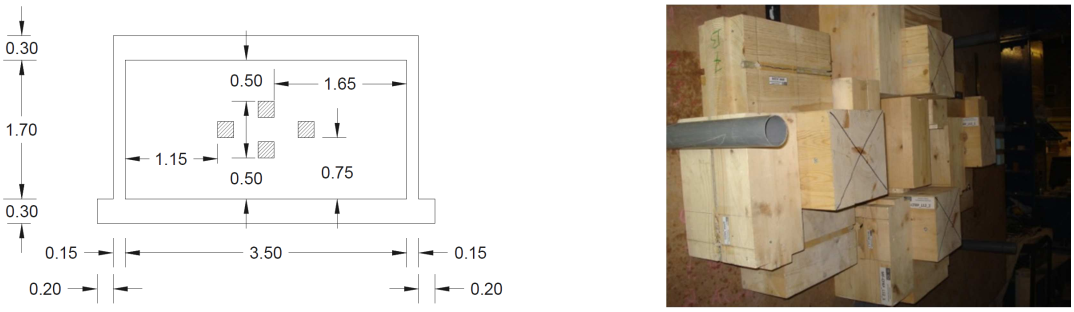
4.4.2 Out-of -Plane

The out-of-plane test consisted on applying displacements to the masonry panel in both directions. These displacements are transmitted to the panel by two actuators, one for each direction. These actuators transmitted the load to a structure with four airbags that did the final load transfer, Figure 10-a. The airbags were linked together via a hydraulic system, in order to have equal pressure and to allow a transmission of a distributed load to the masonry panel, Figure 10-b.

a) b)

Figure 10: Out-of-plane setup: a) Load transfer panel; b) Airbags

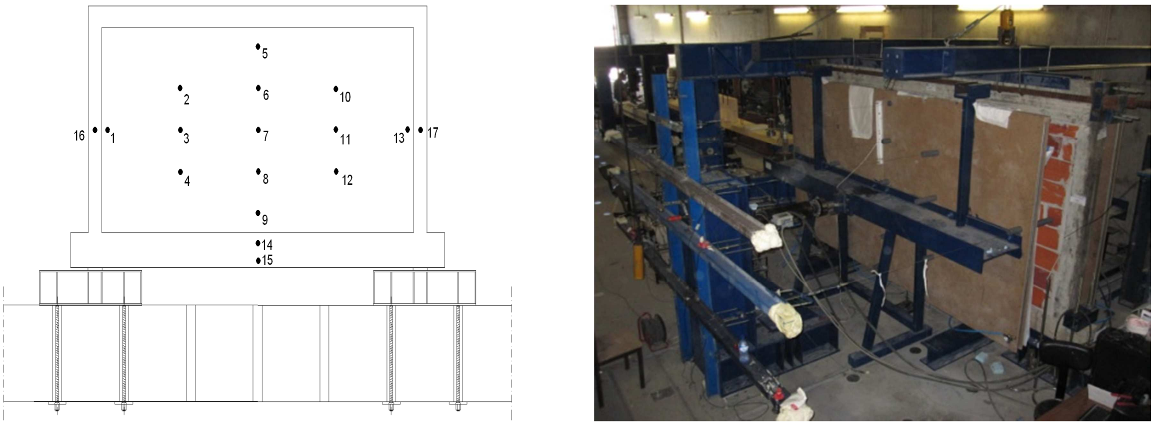
Since the airbags could not apply the intended displacement to the stronger masonry panel, a different out-of-plane test setup was also used, based on applying the displacements to the masonry panel through a concentrated rigid load system that works in a cyclic way as shown in Figure 11. This test consisted of three cycles namely 10 mm, 25 mm and 50 mm, with each cycle repeated twice, one for each direction. The displacements were applied to the panel at a speed of 0.100 m/s.



a) b)

Figure 11: Rigid load system: a) Geometry; b) Concentrated rigid loads

In order to perform the out-of-plane test, an instrumentation plan was created, Figure 12. The aim of the instrumentation is to know the displacements of various points of the panel in order to gather the most relevant data to the knowledge of the behavior of masonry wall when exposed to actions outside the plane.



a) b)

Figure 12: Out-of-plane instrumentation: a) Scheme; b) Overview

5. Results

5.1 In Plane test

5.1.1 Reference Wall

The masonry infill panels in reinforced concrete frames may respond in different ways when subjected to horizontal actions in their own plane, depending on the relationship between the mechanical properties of the frame, masonry and interface between two materials. Mehrabi et al [6] identified 25 failure modes related to the frame and masonry characteristics.

The Panel’s behavior until the conclusion of the test can be described in four phases, as identified in Figure 13.

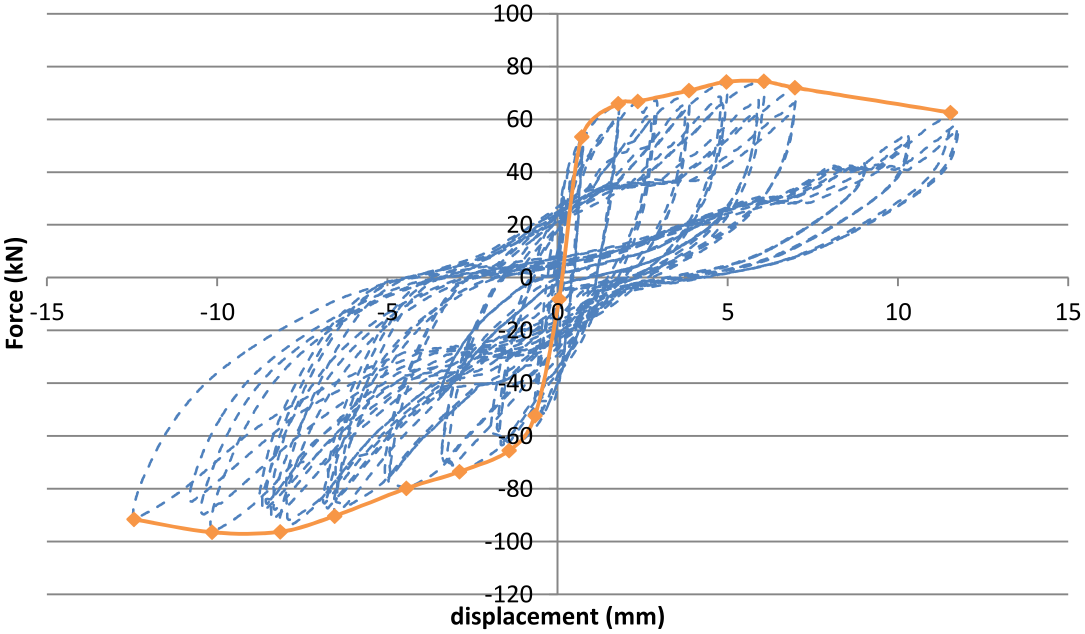


Figure 13: Results and experimental envelope of in plane test preformed to WALL_REF_01

In a first phase, all the panel’s elements work jointly (in an elastic way). Nonlinear phase starts to both directions to a relative displacement (drift) of 0.02-0.025%. This is related to: 1) slide by shearing in the vertical joints between the tops of columns and masonry; 2) detachment caused by tensile stressed between the top of columns and masonry; 3) sliding of the top joint between the upper beam and masonry; 4) beginning of crushing in the top joint corners, between top beam and masonry; 5) start of crack development; 6) development of a diagonal crack in the junction of the upper beam and the column, at the load application node. Maximum resistance is reached just before the interface or corner masonry crushes. Since this moment, there is a gradual loss of strength, as shown in Figure 13.

The load direction had direct influence in the maximum strength and drift (relative displacement). The maximum resistance is 96.1 kN and the minimum its 73.9 kN, for drifts of 0.37% and 0.19% respectively. The direction which has less resistance is related to the constructive process and matches the closing of the panel.

5.1.2 WALL_JAR

The relation between displacements and test force is depicted in Figure 14 for the bed joint reinforced horizontal wall.

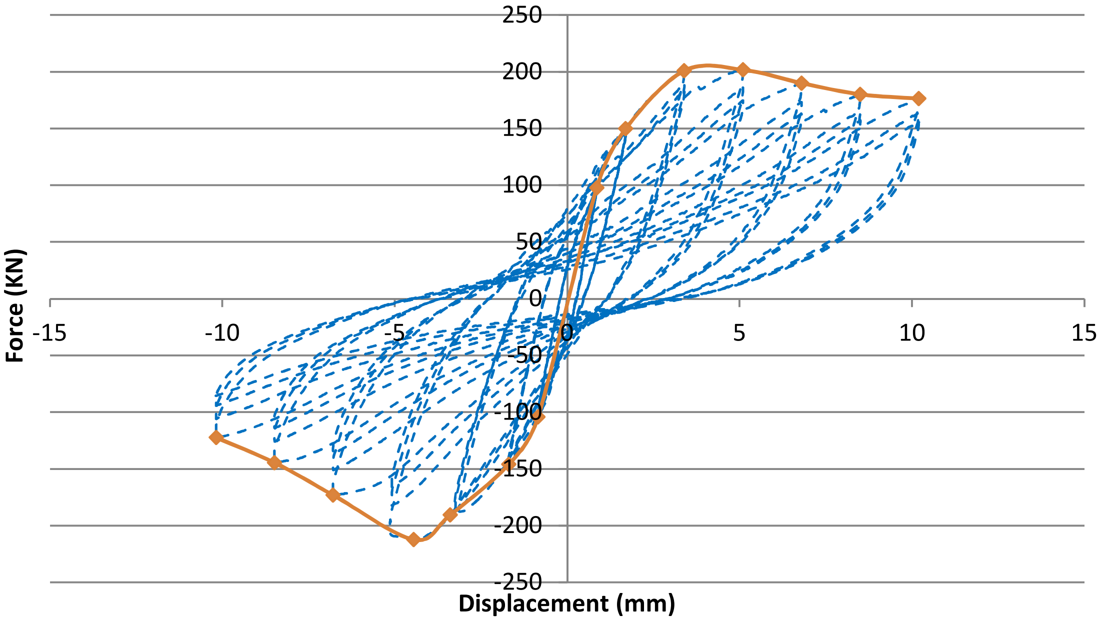


Figure 14: Results and experimental envelope of in plane test preformed to WALL_JAR_02

The behavior can be described in four phases as done for the reference wall. In the first phase, the elements that constitute the panel work together until a drift of 0,043%. Then there is a loss of stiffness so the wall enters a non-linear stage for a 0,085% drift. This loss of stiffness is associated with disruption of masonry connections to the RC frame, or by sliding friction or shearing loads, either by tension or crushing. The peak of resistance is reached at 201 kN (for a drift of 0.18%) in the positive test direction, and -212 kN (for a drift of 0.22%) in the negative test direction. The following cycles correspond to the materials deterioration and consequent loss of resistance. Figure 15 a) shows the interface masonry/RC frame rupture. Figure 15 b) presents the failure of the left column.

Figure 15: a) masonry/RC frame rupture; b) left column shearing failure

5.1.3 WALL_RAR

The instrumentation setup used to do this in plane test was similar to the one used in others walls. This wall behavior in the in-plane test is depicted in Figure 16.

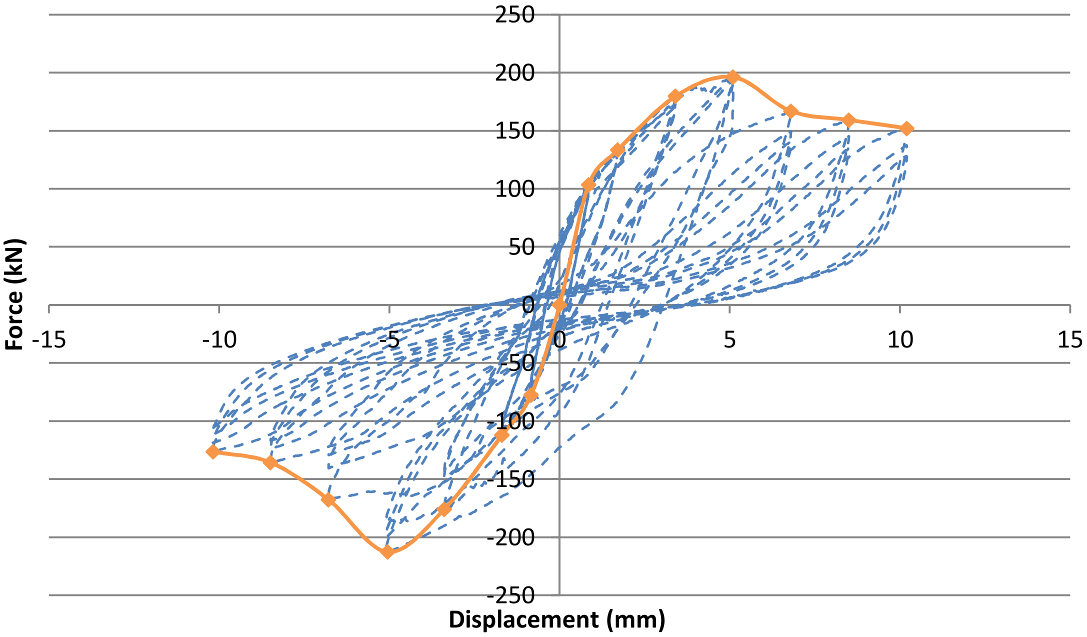


Figure 16: Results and experimental envelope of in plane test preformed to WALL_RAR_02

This experimental test can be divided into three distinct phases. During the first phase, the wall presents a linear behavior up to a drift of 0.04% for a load of 103.52 kN. In the second phase a stiffness reduction occurs due the start of crushing of the mortar from the upper interface. The maximum load of the wall with a value of 212.67 kN for a 0.25% drift at the end of second phase. The third phase is characterized by the rupture of the upper interface and by the rupture of the connection between the reinforced plaster and RC frame.

Figure 17 it shows the plaster condition at the end of the in-plane test. It is possible to observe that the rag bolts that connect the reinforced plaster to the RC frame does not work properly, as during the in-plane test the plaster detached from the concrete structure.

Figure 17: Plaster condition in the end of in-plane test

5.1.4 In-plane resume

The main results obtained from the in plane tests are summarized in Table 4. Figure 18 presents the envelope results of the walls tested in-plane.

Table 4: Summary of the in plane tests

Reinforcement	Force* (kN)	Displacement* (mm)	Drift* (%)	Stiffness* (kN/m)
WALL_REF	96.10	9.340	0.4670	10289
WALL_JAR_02	201.76	5.104	0.2552	39530
WALL_RAR_02	196.16	5.096	0.2548	38493

*All values are for the maximum force.

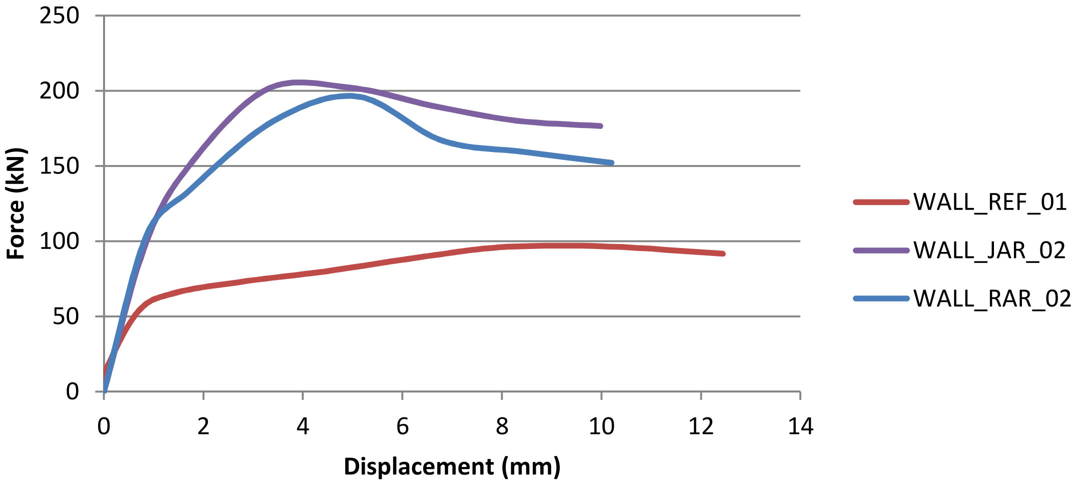


Figure 18: Comparison between all types of walls tested in plane

From the analysis of the graph, it can be conclude that the introduction of reinforcement in the walls is beneficial, in comparison to the non-reinforced solution. When comparing the two reinforcement situations, the solution that has a higher maximum load is the JAR solution; however the RAR solutions present higher ductility.

In the in-plane tests, it was possible to notice that the interfaces masonry/RC frame have lost their stiffness or got crushed specially in the upper interface, as it is shown in Figure 19. This fact is important as the out-of-plane test would not represent in the best way the seismic behavior without this previous damage, as it would neglected combined seismic effects.


a) b)

Figure 19: In-plane apparent state of damage: a) lateral interface; b) upper interface

5.2 Out-of-plane tests

5.2.1 WALL_REF

The damage introduced during the in plane test, in particular the cracking introduced along the interface between brick and concrete elements, substantially changed the support conditions of the masonry. The out-of-plane test was divided into four cycles of displacement. Each cycle i, was composed by two displacements procedures pre-defined, applied each one by one of the actuators, corresponding to the i and i+1 procedures. The rate of displacements increments during the test was 0.10 mm/s. The displacements targets for each cycle were 10 mm, 25 mm, 50 mm and 100 mm respectively for cycle 1, 2, 3 and 4. However due the limitations of the testing scheme, in particular the large airbag deformability and mechanism gaps, target values were not reached in all cycles. The displacements measurements due to the applied force at the midpoint of the masonry panel are shown in Figure 20, where it is possible to observe the different cycles that have characterized this test.

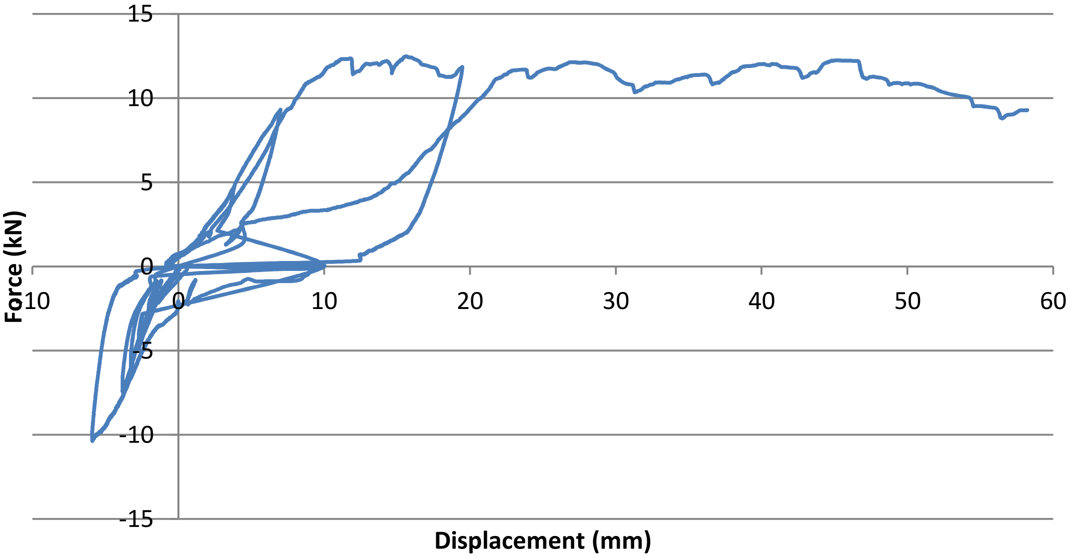


Figure 20: Force vs. Displacements results for out-of-plane test of WALL_REF_01

Elastic behavior can be identified in cycles 1 and 2, where in procedures 2 and 4 the displacements obtained are 3.83 mm and 7.02 mm, respectively. The force vs. displacement graph for procedure 4 is similar to procedure 2, concluding that there was not loss of stiffness.

In cycle 3 / procedure 6, plastic behavior is initiated, where the displacement is only recovered by the external action of the actuators, since it is a cyclic test in both directions. In the final procedure there is a large stiffness reduction, as can be verified by the graph slope, with a huge plastic behavior before the out-of-plane final collapse.

The top of the wall had a large percentage of units with total or partial collapse resulting from the fact that the wall was been expelled of the RC frame, see the intermediate phase in Figure 21 a) and final phase in Figure 21 b), where the complete expulsion of the masonry panel can be observed.


a) b)

Figure 21: Out-of-plane expulsion: a) an intermediate phase of the test; b) complete separation of the masonry panel from the RC frame

Figure 22 illustrates the crack pattern after the out-of-plane test performed in WALL_REF. As it can be observed the upper left corner is partly collapsed, the upper right corner is totally damaged and there is a crack 25cm above the lower beam, which indicates a cantilever type structural failure.

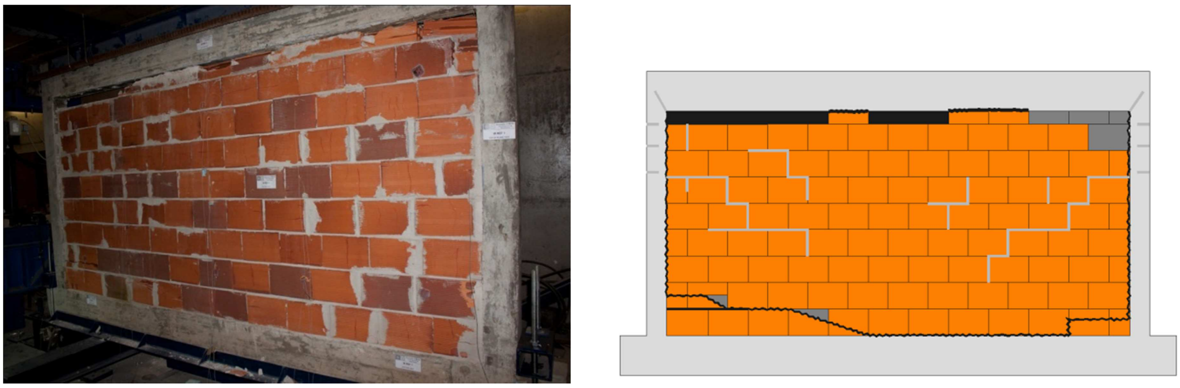

a) b)

Figure 22: Crack pattern after out-of-plane test: a) test result; b) scheme

5.2.2 WALL_JAR

The out-of-plane test of WALL_JAR_02 began according to the pre-established conditions, i.e. the wall had been subject to a 0.5% in plane drift.

When comparing the results obtained for WALL_JAR_01 and WALL_JAR_02, it can be noticed that the first one showed a lower failure load 44.95 kN against 51.1 kN obtained in the second test. This situation is explained by the fact that the WALL_JAR_01 was badly damaged in plane. Despite the moderate discrepancy in the failure loads, it is verified that the obtained failure drift was similar in both tests.

Figure 23 displays the force vs. displacements diagram for WALL_JAR_02, having as a measure point the center of the masonry panel. The graph shown in Figure 23 is substantially identical to the one obtained for the WALL_JAR_01. In this test, it is visible a stiffness loss between cycle 1 and 2. This effect is not so noticeable in WALL_JAR_01 since the initial stiffness of WALL_JAR_01 was lower than the WALL_JAR_02 stiffness. Figure 24 presents the condition of the masonry wall after the out-of-plane test in WALL_JAR_02. By the observation of Figure 24, it is noticeable that the upper interface is completely damaged, with the upper bricks totally destroyed. The lateral interface is cracked but there were not crushed bricks in this area. The lower interface presents a crack along all length. It is also emphasized that the top corners are badly damaged. This effect may be partly due to the in-plane test.

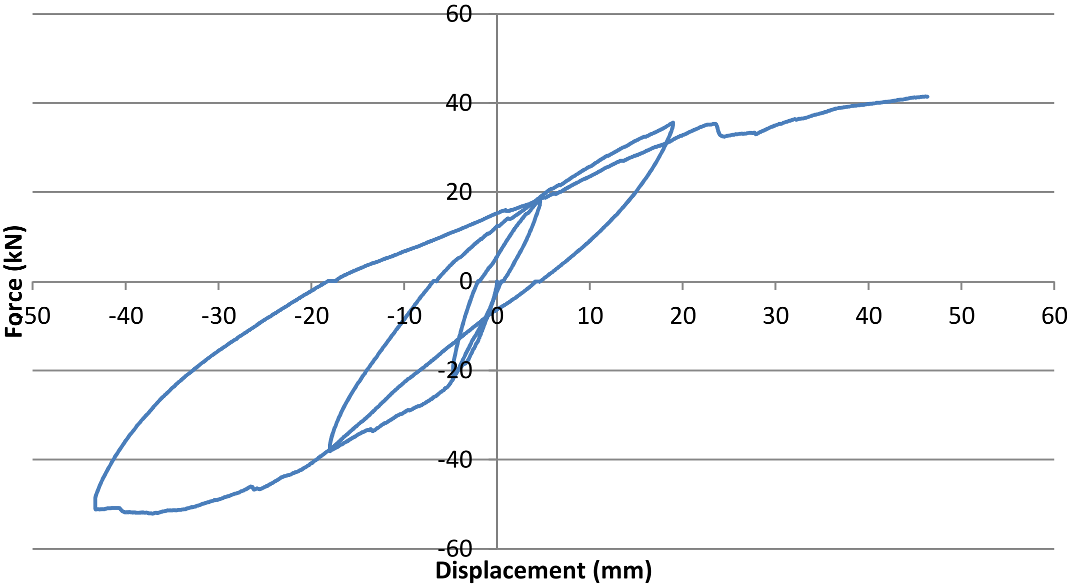


Figure 23: Force vs. Displacements results for out-of-plane test of WALL_JAR_02

Figure 24: Crack pattern after out-of-plane test

5.2.3 WALL_RAR

The experimental results obtained can be observed in Figure 25.

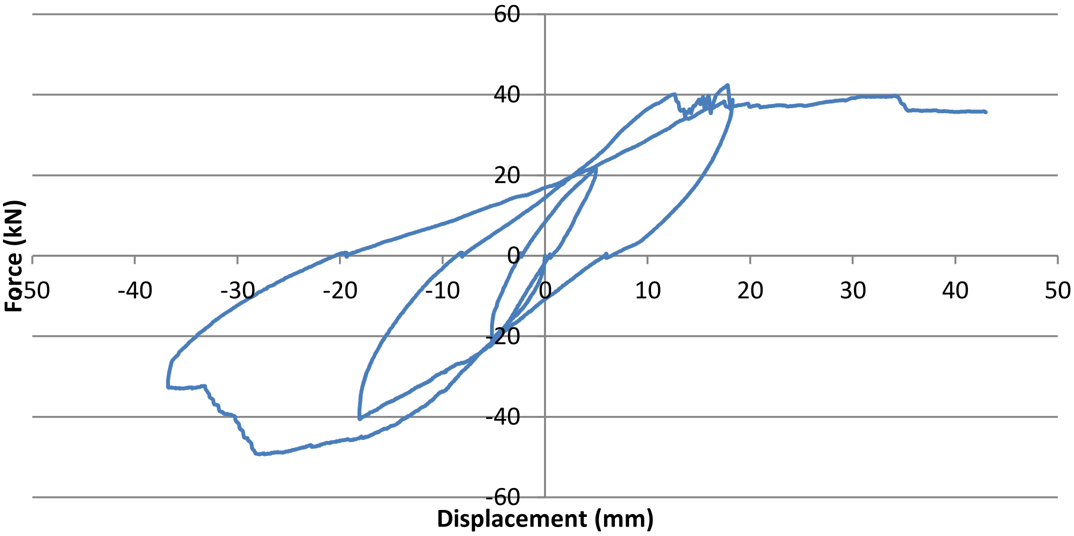


Figure 25: Force vs. Displacements results for out-of-plane test of WALL_RAR_02

The graph in Figure 25 represents WALL_RAR_02 behavior during the out-of-plane test. For each load cycle a stiffness reduction of the masonry panel is noticeable. The maximum load is 49.34 kN for a displacement of 27.85 mm in the center of the panel. Figure 26 presents the crack pattern after the out-of-plane test was done.

Figure 26: Crack pattern after out-of-plane test

5.2.4 Out-of-plane summary

Figure 27 presents the envelope results of the five walls tested out-of-plane.

From the analysis of Figure 27 we can verify that the reinforced solutions present the best out-of-plane behavior when compared with the non-reinforced solution. The main results obtained from the out-of-plane test are summarized in Table 5.

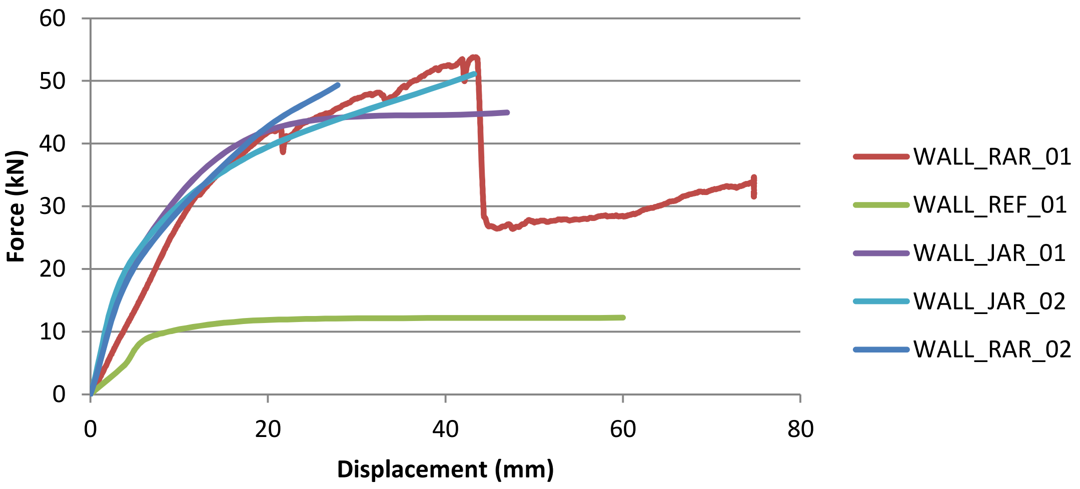


Figure 27: Comparison between all types of walls tested out-of-plane

Table 5: Summary of the out-of-plane tests

Reinforcement	Force (kN)	Displacement (mm)	Drift (%)	PGA (g)	Stiffness (kN/m)
WALL_REF	11.84	19.48	0.974	0.710	608
WALL_JAR_01	38.76	18.07	0.903	2.324	2145
WALL_RAR_01	48.13	32.30	1.615	2.886	1490
WALL_JAR_02	41.41	16.36	0.818	2.483	2531
WALL_RAR_02	49.34	27.86	1.393	2.959	1771

6. Numerical simulations

After the in plane and out-of-plane tests were done, a numerical simulation was made using a finite element model. The software used was Autodesk Robot Structural Analysis Professional 2011.

In the models that represent the in plane test, two loads of 50 kN were placed on top of each column in order to simulate the upper floor and a variable lateral load was applied at the center of the upper beam in order to introduce the in plane damage. The interfaces between the masonry panel and the RC frame were defined by “compatible nodes” which were calibrated according to the stiffness of these interfaces for certain levels of load in xx direction. The materials proprieties used were established for strength, flexural and shear tests made to some specimens. The next figures (Figure 28, Figure 29 and Figure 30) depict the numerical results of the in-plane simulation.

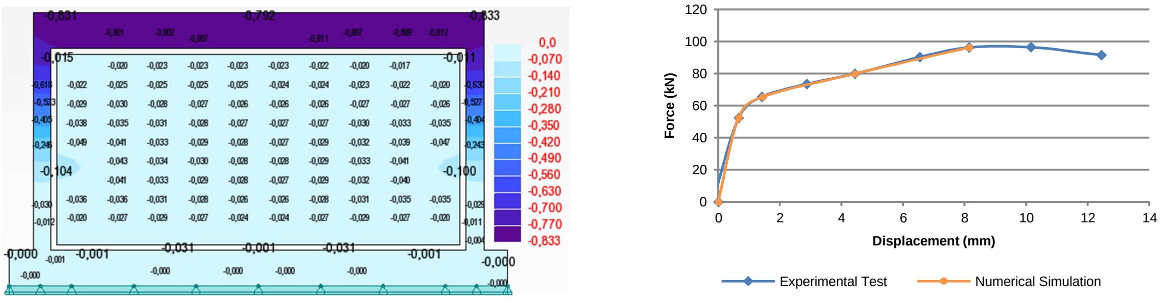


Figure 28: Numerical Simulation WALL_REF_01

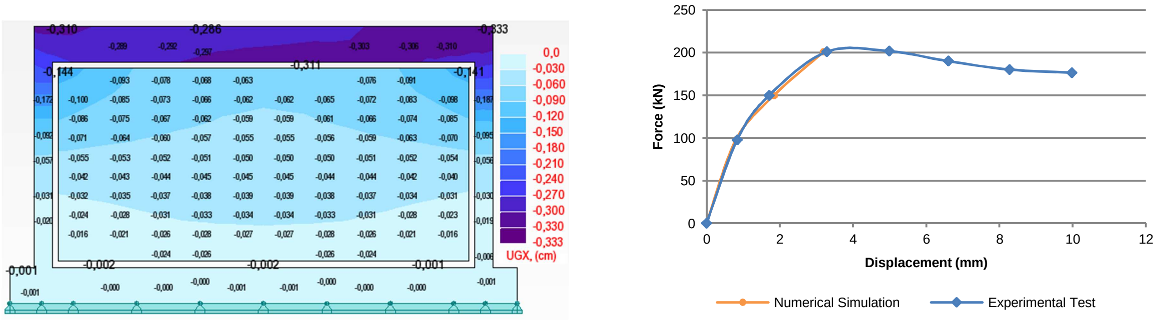


Figure 29: Numerical Simulation WALL_JAR_02

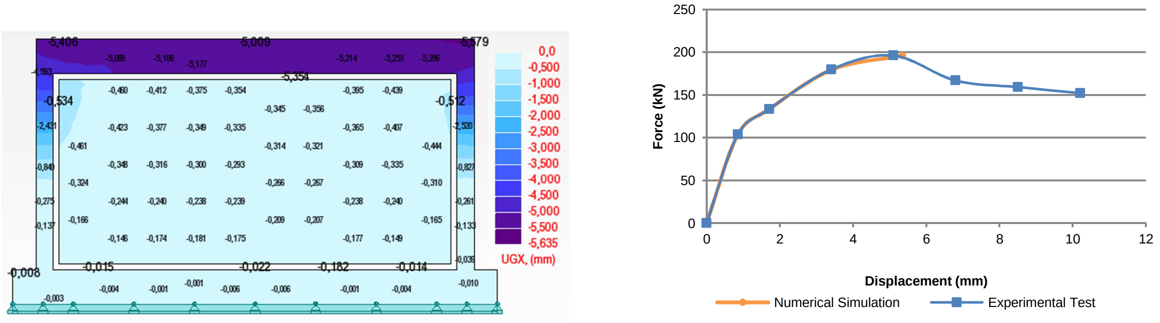


Figure 30: Numerical Simulation WALL_RAR_02

In finite element models that represent the out-of-plane test, “compatible nodes” to define the interface were used. These were calibrated according to the stiffness that the interface displayed in the yy direction for different load levels. In order to simulate the out-of-plane test four loads were applied on the masonry model, placed geometrically as in the experimental test. The next figures (Figure 31, Figure 32 and Figure 33) depict the numerical results of the out-of-plane test simulation.

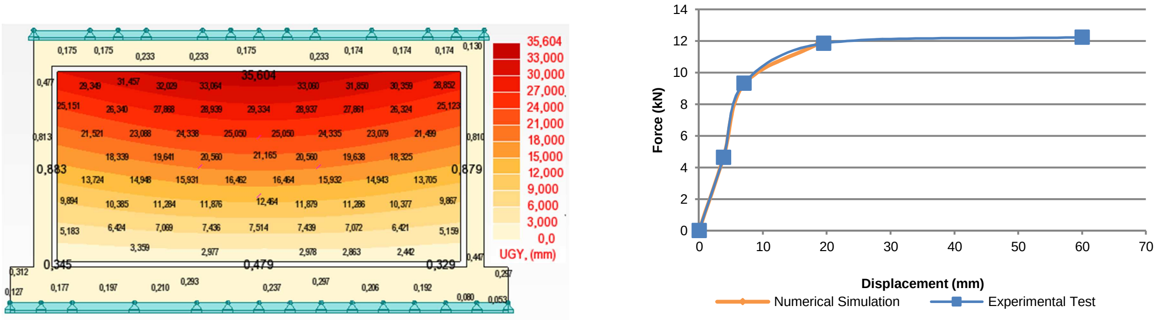


Figure 31: Numerical Simulation WALL_REF_01 out-of-plane test

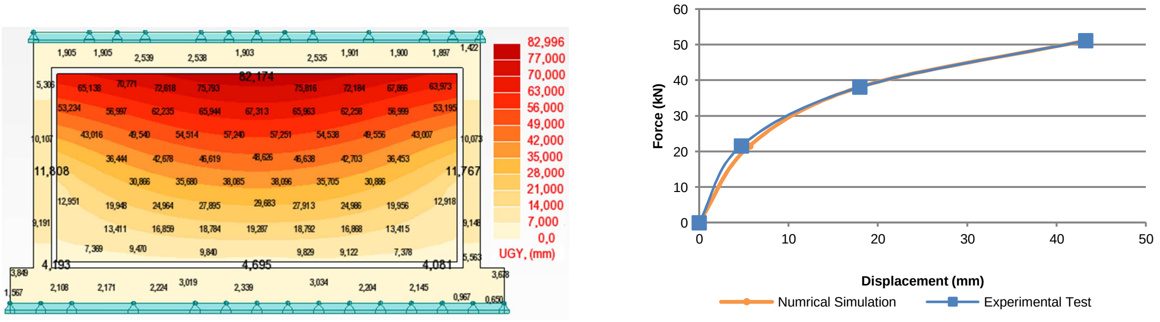


Figure 32: Numerical Simulation WALL_JAR_02 out-of-plane test

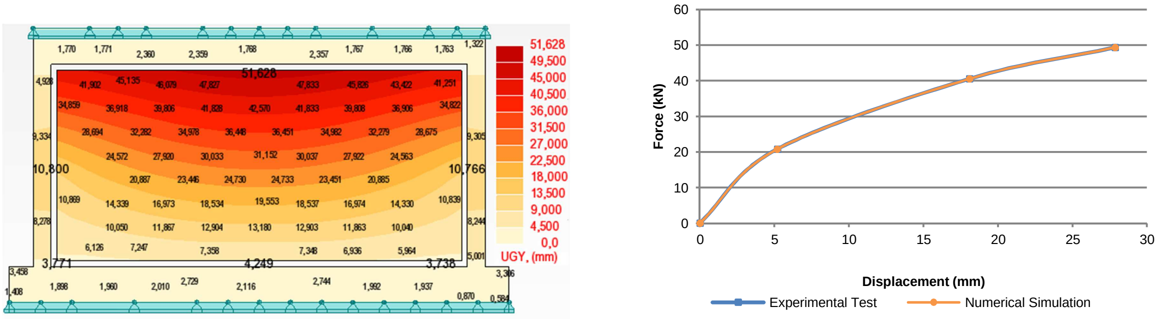


Figure 33: Numerical Simulation WALL_RAR_02 out-of-plane test

7. Conclusions

For the four types of specimens studied it was verified that the unreinforced masonry specimens are the ones with the lowest resistance, even if they represent the typical masonry adopted in Portugal construction. From the studied solutions, the best behavior of the specimens occurs with reinforced plaster. This type of specimens presented compressive strength 1.7 higher than the PS specimens, flexural strength 4.4 and 3.7 higher when comparing to PS in parallel and perpendicular directions respectively and according to shear strength the PRA specimens present 5.7 higher than the PS specimens. Also PRA specimens maintained structural integrity preventing the structure collapse. These types of solution are very useful when applied to a masonry panel because it makes them capable of supporting actions arising from seismic occurrence.

The construction process, besides the own mechanical characteristics of the materials included in the panel, lead to significant differences in the level of strength and ductility of the panels.

For the in-plane test, in all the different solutions the interfaces are primarily responsible for the non-linear stage. The results shows that the relevance of masonry for the frame stiffness, thus to the level of drift under the influence of Eurocode 8 [2] masonry is still significant, giving the panel a stiffness much higher than the bare frame.

According to the values presented in table 4, it is notable that both reinforced masonry walls (JAR and RAR) have approximately 4 times higher stiffness than the reference wall.

For the out-plane-test, it is important to notice that the previous in-plane damage change the failure mode of the panel due the substantially change of support conditions of the masonry. Therefore, the upper interface no longer exists, so WALL_JAR and WALL_REF present a failure mode typical in cantilever structures. The reinforced plaster wall (WALL_RAR) shows a typical slab failure mode, because of as happened in the specimens, the plaster hold the masonry preventing the wall failure and masonry expulsion which is important to prevent the danger to humans lives. According to the values presented in table 5, WALL_JAR presents the higher stiffiness comparing to the reference wall (2.5 times higher), thus the WALL_RAR presents the best behavior in what it takes to drift (2 times higher than the WALL_REF).

WALL_JAR has an excellent performance in both in-plane and out-of-plane tests. At the end of the tests this wall has visible damaged that allows to have the perception of the stiffness reduction which does not happen in the reinforced plaster.

As result of previously induced in-plane damage, the panels resist a lower out-of-plane load. It is also important to notice that all the reinforced solutions used have structural benefits, so the reinforced plaster or the reinforced bed joints tend to increase the stiffness of the structures.

The infill masonry panel in RC frame is able to mobilize a higher resistance to horizontal loads than the bare frame and to the expected drift present in Eurocode 8 [2]. Infilled masonry still plays an important role, giving the panel a higher stiffness than the bare frame. This last fact is in opposition to the current design practice, which ignores the masonry, and its contribution to the structure resistance and to the vibration buildings period in seismic analysis. If neglecting the resistance can be conservative, the higher stiffness and consequently the reduction of vibration period can give a lower demand for the seismic building design.

8. References

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