Current experimental investigations on modern masonry at University of Minho

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ABSTRACT: The paper presents and describes the main issues related to two systems on modern masonry currently under development at University of Minho, one based on lightweight concrete blocks and another based on reinforced concrete block masonry. The details of the experimental work being carried out are addressed and preliminary test results obtained for lightweight concrete block masonry are provided.

1 INTRODUCTION

In Portugal, modern residential buildings are almost always constructed in reinforced concrete, being steel used also for industrial buildings. Masonry is being used almost exclusively as traditional infill material for reinforced concrete frames. Nevertheless, recently, modern engineered masonry is becoming increasingly popular as long horizontally reinforced non-load bearing walls in large non-residential buildings (Lourenço, 2006). Lack of knowledge about modern masonry technology and simple technology required by reinforced concrete are the main factors contributing to the reduced use of structural masonry.

Therefore, a major challenge that has to be faced by the Portuguese brick and block producers is the finding of an effective and attractive load bearing masonry system that is able to convince contractors and designers to use it in low and medium-rise buildings. The adoption of such a renewed building technology by contractors seems obvious due to the economical and technological advantages.

This paper describes the research that is being carried out at University of Minho on modern masonry aiming at filling a gap in structural masonry development at national level, namely increasing the knowledge about masonry mechanical performance under horizontal loads.

Two different modern masonry wall systems are analyzed. The first wall system is studied in the scope of a national project (SINALES) co-sponsored by the lightweight concrete masonry block industry, where different possibilities of unreinforced and reinforced masonry walls are envisaged. The second system of masonry walls represents a contribution to the European research project dealing with the development of innovative constructive systems for reinforced masonry walls (DISWall). The system addresses hollow concrete block masonry.

Besides the presentation of the main features of the different solutions for masonry walls systems, preliminary results on the cyclic behavior of lightweight concrete masonry walls are also provided here. The key aspects under discussion are: (a) the possibility of replacing the filling of the vertical joints by interlocking and horizontal bed joint reinforcement; (b) the need for filling vertical joints in standard unconfined masonry solutions.

2 DESCRIPTION OF THE MASONRY SYSTEMS

Portugal is a country with very different seismic risk zones, varying from low to moderately high seismicity. Thus, the wall systems should fit the requirements of strength to horizontal loads as the behavior of masonry shear walls is fundamental in the design of masonry buildings subjected to different horizontal actions. On the other hand, the masonry systems should not require major changes in the traditional workmanship.

2.1 Lightweight concrete masonry walls

The project aims at defining adequate structural solutions for regions of low to moderately high seismicity in Portugal to be used on low and medium rise residential buildings. Three different possibilities can be adopted for the wall system: unreinforced, light horizontally reinforced and confined masonry. The geometry of the lightweight concrete blocks is indicated in Figure 1.

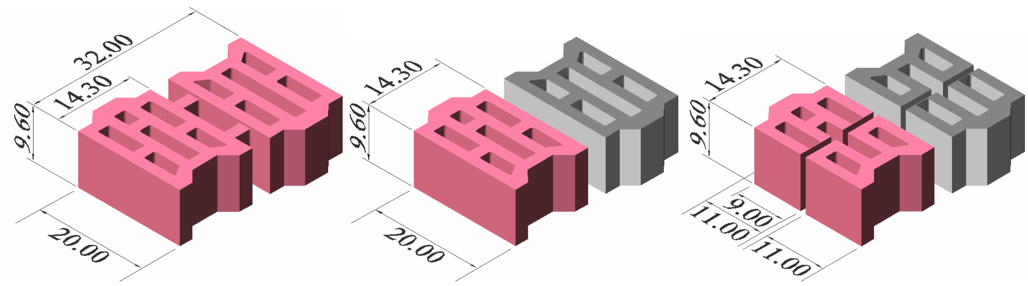


Figure 1: Half-scale and reduced-size of block

The blocks adopted in the testing program are regularly produced by the industry to comply with thermal regulations and have nominal dimensions of 200mm×320mm×100mm. This is a standard half block in terms of height and length, used normally for non load-bearing walls. After cutting this block in two pieces, the resulting half scale block has dimensions of 200mm×143mm×100mm, as shown in Figure 1. The adopted mortar is a pre-mixed mortar produced by the MAXIT Group. An important innovation of this constructive system is the possibility of having non-filled vertical joints, which can simplify the construction to a great extent. The shape of the block's ends enables an improvement on the contact surface in case of absence of the mortar in the vertical joints and thus reduces possible clearances.

Reinforced walls are built by considering bed joint reinforcement of truss type, Murfor® produced by Bekaert, placed at the horizontal joints, see Figure 2. The horizontal reinforcements aim at increasing the ductility and lateral strength of the walls when submitted to cyclic horizontal loads.

For confined masonry walls, self compacting concrete is foreseen to the confining concrete elements. The bed joint reinforcement can be either connected or disconnected to the infill wall. The connection between the wall and the confining elements is promoted by anchoring the horizontal reinforcements of the wall to the vertical reinforcement of the confining elements, see Figure 2b.

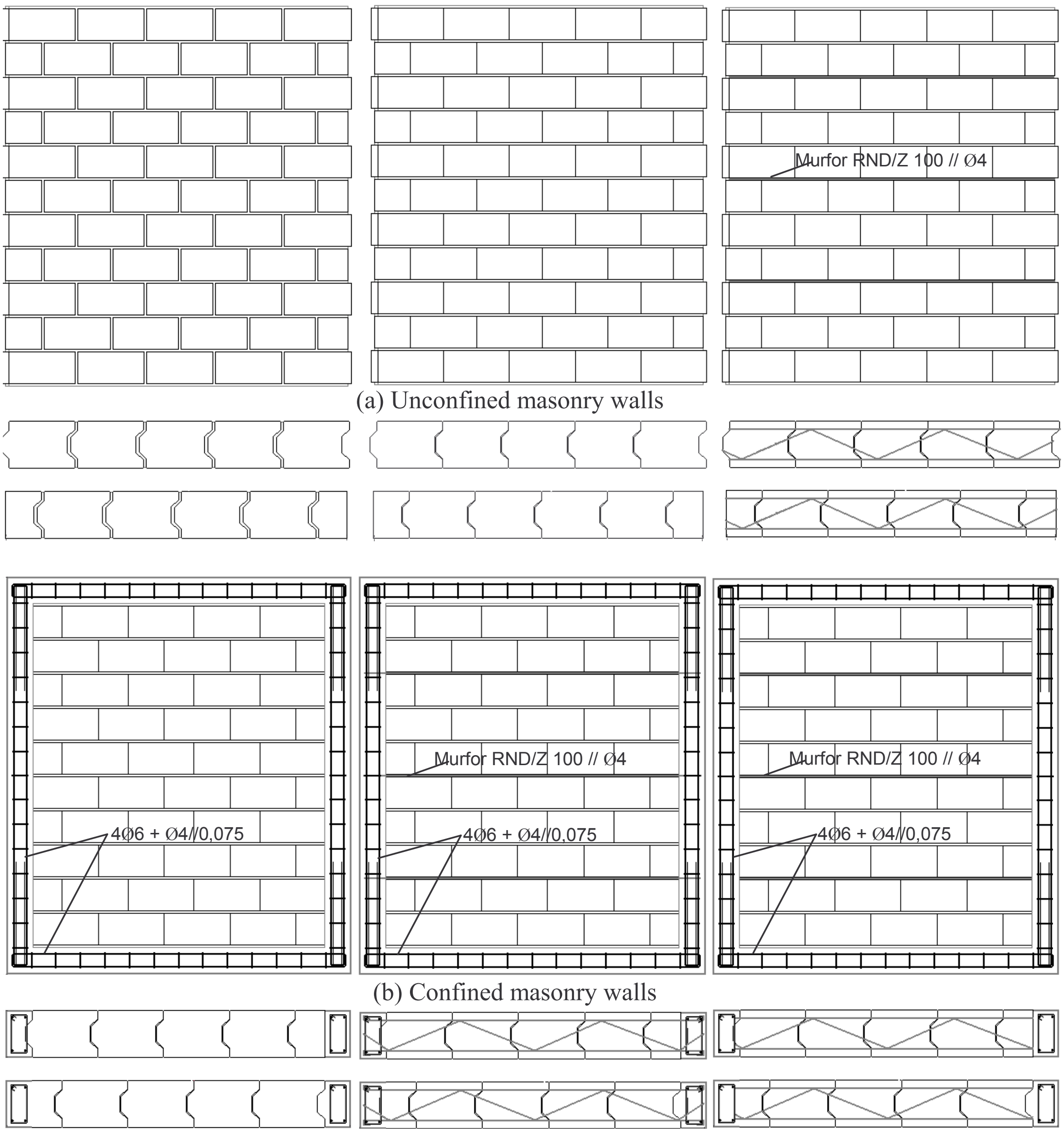
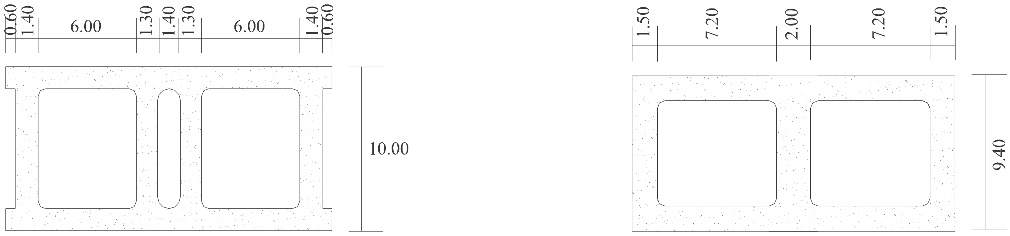


Figure 2: Lightweight concrete masonry walls; (a) unconfined walls; (b) confined walls

2.2 Concrete masonry walls

Within the scope of the DISWall project, two distinct constructive systems are proposed for reinforced masonry solutions located in zones with moderate to high seismic hazard. Both constructive systems are based on concrete masonry units, whose geometry and mechanical properties have been adequately specified. It is foreseen that two and three hollow cell concrete masonry units are developed in order to accommodate vertical reinforcement. The concrete masonry block with two vertical hollow cells is standard in several countries, e.g. USA and Brazil. The concrete block with three hollow cells is designed to accommodate uniformly spaced vertical reinforcement, see Figure 3. In order to allow expedite and economical testing of a large number of masonry walls, it was decided to produce half scale concrete masonry units.

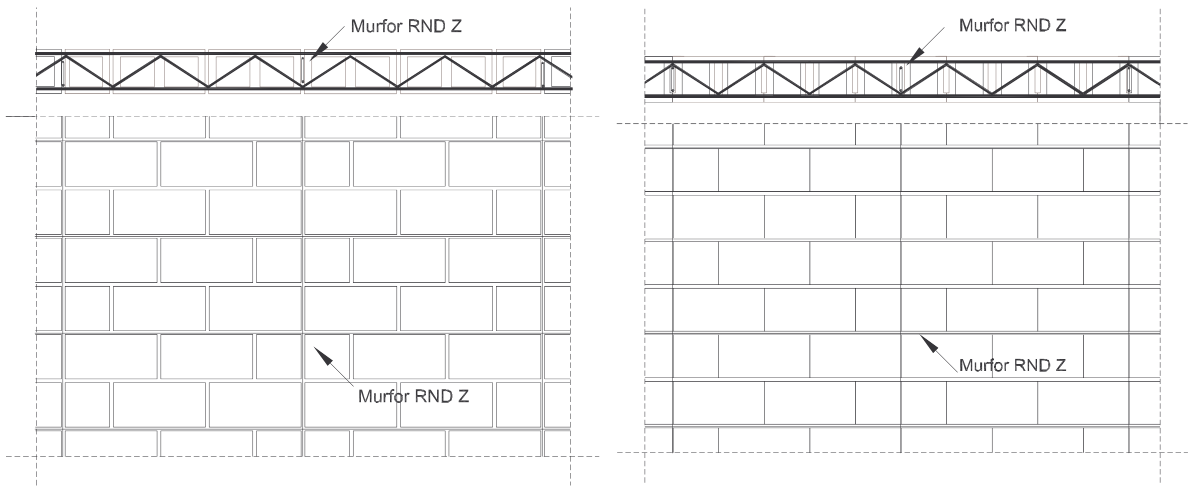


(a) (b)

Figure 3: Concrete blocks that will be used in masonry panels; (a) Block 1: two cells; (b) Block 2: 3 cells.

The first building system BS1 is composed by the two hollow cell concrete masonry units, where the vertical reinforcement is placed in a continuous vertical joint, by adopting the masonry bond indicated in Figure 4a, and the horizontal reinforcement is placed in the bed joints. Prefabricated truss type reinforcements (Murfor RND/Z) are used for the vertical and horizontal mortar joints. This system enables easy placing of full and half units on the wall after the positioning of the continuous vertical reinforcements, in a perfect agreement with the traditional techniques commonly used for the construction of unreinforced masonry walls. An important aspect to be taken into account during the construction is the appropriate filling of the vertical reinforced joints so that suitable bond strength between reinforcement and masonry can be reached, so that an effective stress transfer mechanism exists between both materials.

An alternative to this system consists of placing the vertical reinforcements inside the hollow cells. If on one hand, this can make the filling of the hollow cell easier, on the other hand, it implies a more difficult execution and an overlapping of the vertical reinforcements has to be made to keep the rules of traditional workmanship. Apart from the mechanical requirements of the blocks to be used on structural purposes, this system can be reasonably adopted by the Portuguese contractors since it uses well know masonry units and no additional changes on the constructive process are needed.



(a) (b)

Figure 4: Constructive systems based on the use of concrete units; (a) two hollow cell concrete units, BS1; (b) three hollow cell concrete units, BS2

The second building system BS2 uses the three hollow cell concrete units, see Figure 4b. If traditional masonry bond is used, vertical reinforcement (Murfor RND/Z) can be introduced both in the internal hollow cell and in the hollow cell formed by the frogged ends. In this case, continuous and overlapped vertical reinforcements are possible. If the masonry bond indicated in Figure 4b is adopted, the masonry units can be placed after the continuous vertical reinforcement has been positioned. Also in this constructive system, Murfor RND/Z bed joint reinforcement is foreseen.

In both solutions the proper filling of the vertical hollow cells is a major issue since it is intended to substitute the usual grout of the cells by the general purpose mortar used for the bed joints, in order to simplify the constructive system. This leads to the need of designing a mortar with adequate workable and flowable properties. With respect to this matter, an experimental study on the evaluation of the properties of fresh mortar, namely consistence and workability has been carried out. In both constructive systems, novel anchorage systems to fix the vertical reinforcements to the slabs to the traditional anchorage are under consideration.

3 EXPERIMENTAL PROGRAM

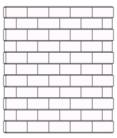
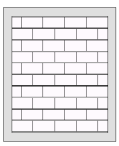
The behavior of masonry shear walls is fundamental in the design of masonry buildings subjected to different actions, namely of seismic nature. The usage of unreinforced, confined or reinforced masonry is currently subjected to a strong debate in Europe due to the new codes. In particular, the part of Eurocode 8 (Design of structures for earthquake resistance) related to masonry structures represents only a limited compromise for the different countries.

The performance of each constructive system to seismic actions will be evaluated by means of an enlarged experimental program based on in-plane cyclic tests. A large testing program was already started at University of Minho on lightweight concrete masonry walls (SINALES project). The aim is the clarification of different aspects regarding confinement of masonry and unfilled vertical joints. The performance of the wall system developed in the scope of the DISWall project to seismic actions will be also evaluated from the results of in-plane deformation controlled static cyclic tests. The objective is the comparison of the cyclic behavior of masonry panels with different bond patterns, distinct reinforcement arrangement and percentage of the vertical and horizontal reinforcements.

The tests will be performed by following the traditional procedure commonly used on masonry walls under combined vertical-cyclic horizontal loading, described in the next section. In both situations the walls have been designed before testing so that a shear failure mode or a mixed shear-flexural mode would occur.

The summary of the tests carried out on lightweight concrete masonry units is indicated in Table 1. Confined masonry is assumed as a hybrid material joining masonry with small section horizontal and vertical lightly reinforced concrete elements.

Table 1: Type and designation of specimens for lightweight concrete masonry walls

Type and designation of wall				n.º	Block	Mortar	Horizontal reinforcement			Confining elements
	unreinforced	standard unreinforced	W2.1	4	B1	✓				
			W2.2	3	B1	✓	✓			
		lightly horizontally reinforced	W2.3	2	B1	✓		✓		
	Confined		W2.5	3	B1	✓		✓		✓
			W2.6	2	B1	✓		✓	anchor	✓
		standard confined	W2.4	2	B1	✓				✓

The testing program included 16 walls, scaled 1:2, as shown in Figure 5a. Two unreinforced wall configurations have been considered, assuming filled and unfilled vertical joint. In the latter, the benefit of using bed joint reinforcement was analyzed. Such configurations have been tested again using confined masonry, always assuming unfilled vertical joints. In wall W6, the horizontal bed joint reinforcement is anchored to the reinforced concrete confining elements. The normalized compressive strength of the block is 5.7N/mm^2. The mortar adopted for the wall construction was a pre-mixed mortar, type MAXIT AM10 with a 10 N/mm^2 compressive strength. Confining concrete elements have been made using self compacting concrete (f_c=31.5N/mm^2) with a transverse section of 143mm×75mm (vertical elements) and 143mm×80mm (horizontal elements). The strength of reinforcing steel bars and reinforcement truss type is, respectively, f_{yk}=400N/mm^2, and f_{yk}=550N/mm^2.

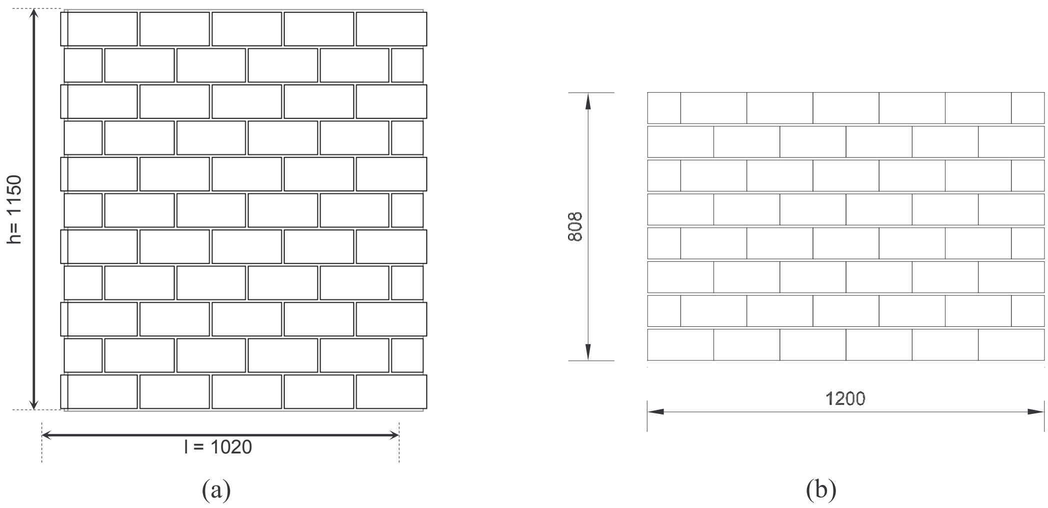


Figure 5: Geometry of the tested walls; (a) lightweight concrete masonry walls; (b) reinforced concrete masonry walls (dimensions in mm)

The geometry of the typical reinforced concrete masonry walls developed in the scope of the DISWall project is shown in Figure 5b. From the preliminary design, a height to length ratio of 0.67 was obtained, being the wall panels 808mm high and 1200mm long. A summary of the models of the masonry walls to be tested are displayed in Table 2.

Table 2: Type and designation of specimens for reinforced concrete masonry walls

Type and designation of wall	Description
Model 1	(unreinforced masonry wall)
Model 2 – CS1	ρ_v= 0.104% - ϕ_v=5mm; ρ_h= 0.132% - ϕ_h=4mm
Model 3 – CS1	ρ_v= 0.104% - ϕ_v=5mm; ρ_h= 0.132% - ϕ_h=4mm
Model 4 – CS2	ρ_v= 0.0982% - ϕ_v=5mm; ρ_h= 0.124% - ϕ_h=4mm
Model 5 – CS2	ρ_v= 0.0982% - ϕ_v=5mm; ρ_h= 0.124% - ϕ_h=4mm
Model 6 – CS2	ρ_v= 0.0982% - ϕ_v=5mm; ρ_h= 0.07% - ϕ_h=3mm
Model 7 – CS2	ρ_v= 0.0982% -ϕ_v=5mm; ρ_h= 0.194% -ϕ_h=5mm
Model 8 – CS2	ρ_v= 0.0628% -ϕ_v=4mm; ρ_h= 0.124% -ϕ_h=4mm
Model 9 – CS2	ρ_v=0.126% -ϕ_v=4mm; ρ_h= 0.124% -ϕ_h=4mm
Model 10 – CS2	ρ_v= 0.0%; ρ_h= 0.07%-ϕ_h=3mm)
Model 11– CS2	ρ_v= 0.0982% -ϕ_v=5mm; ρ_h= 0.0%)

Model 1 is a reference unreinforced masonry wall. Models 2 and 3 are masonry walls built according to the system BS1. In Model 2 a reinforced continuous vertical joint is considered. Alternatively, in model 3 the vertical reinforcement is placed in the vertical hollow cell. Models 4 and 5 are masonry walls constructed according to the system BS2 considering the vertical reinforcement both in the internal hollow cell and external recesses and exclusively in the external recesses respectively. The influence of the percentage of vertical and horizontal reinforcement is assessed through models 6 to 11, built with three hollow cell concrete masonry units. Models 10 and 11 only foresee horizontal and vertical reinforcements respectively.

3.1 Test setup and procedure

Apart from certain changes that have to be made in each system, the test setup used in the in-plane cyclic tests is displayed in Figure 6. The cantilever wall is fixed to a steel beam connected to the reaction slab through steel rods in order to preclude any movement. The pre-compression loading was applied by means of a vertical actuator with reaction in the slab given by the steel cables. A stiff steel beam is used for the distribution of the vertical loading and a set of steel rollers were added to allow relative displacement of the wall with respect to the vertical actuator. The seismic action is simulated by imposing increasing static lateral displacements by means of a hinged horizontal actuator appropriately connected to the reaction wall at mid-height of the specimen.

For the lightweight concrete masonry walls, the vertical load was applied with an actuator of 350kN capacity, designed to keep the vertical load constant. Therefore, vertical displacements are allowed in the top steel beam. The horizontal cyclic load was applied using a 250 kN actuator.

The tests were carried out with constant vertical stress, at a constant level of about 30% of the masonry strength. The horizontal action is applied to the wall via controlled displacement at a rate of 60μmm/s. Two full displacement cycles were programmed for each amplitude increment, aiming at strength and degradation assessment (Calvi et al., 1996; Tomaževic et al., 1996; Vasconcelos, 2005).

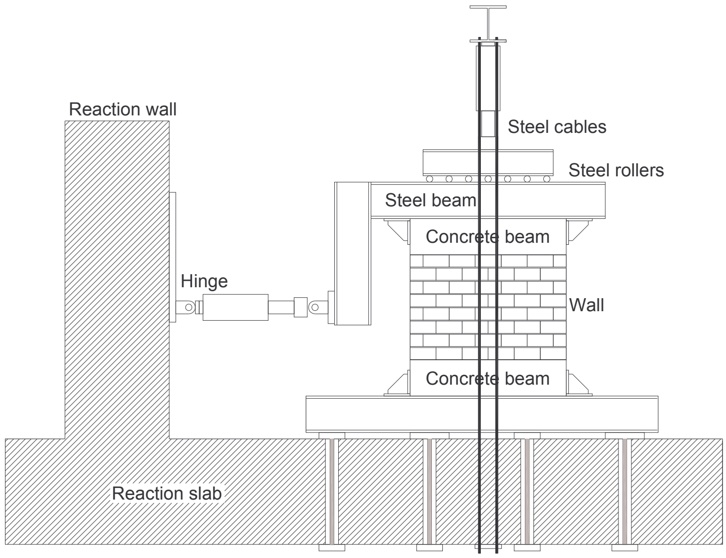


Figure 6: Front view of the test setup

In the reinforced concrete masonry walls the analysis of the contribution of the reinforcements to the global response of the masonry walls as well as the evaluation of the bond strength will be carried through a careful monitoring of their strain by means of strain gauges.

The out-of-plane behavior of concrete masonry walls will be studied from monotonic four-point bending tests. The influence of the in-plane damage on the out-of-plane performance of masonry walls is to be analyzed by means of combined in-plane and out-of-plane tests.

4 PRELIMINARY RESULTS

The results of the in-plane cyclic tests carried out on lightweight concrete masonry walls are presented in this section. Besides the failure modes, an analysis of the force-displacements diagrams based on the bilinear envelop is pointed out.

4.1 Failure Mechanisms

Figure 7 illustrates some typical failure modes obtained for the walls tested. In the walls without bed joint reinforcement (W2.1 and W2.4), initially flexural behavior dominates with horizontal cracks appearing at the bottom and top of the walls. With increasing application of horizontal displacement, a diagonal shear crack appears, usually well defined and with sudden occurrence for a given orientation of the loading. With the load increase and inversion of load direction, additional diagonal cracks appear.

In the walls with light bed joint reinforcement, the strength deterioration is slow and more distributed cracking occurs (Zepeda et al., 2000). At ultimate stage, cracking is much more severe as the ultimate displacement is much larger. In walls W2.5 and W2.6, the steel bars of the confining elements are severely stressed, with considerable cracking of these elements. In these walls, masonry crushing was also observed at final stage due to the larger number of cycles applied. In the unreinforced masonry wall (only with light bed joint reinforcement), a higher maximum load could be reached but the test was terminated due to danger of damaging the test set-up with an uncontrolled failure.

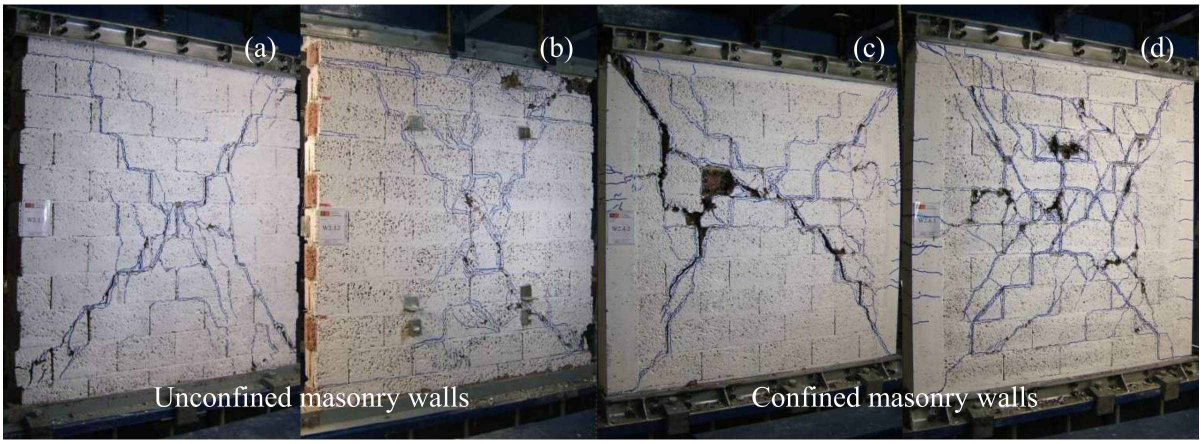


Figure 7: Failure modes: (a) unreinforced wall W2.1; (b) light horizontally reinforced wall W2.3; (c) confined unreinforced wall W2.4; (d) confined and horizontally reinforced W2.6

4.2 Experimental envelops

The cyclic behavior of masonry walls is characterized by key parameters, typically, maximum shear resistance, horizontal displacements at selected load levels, ductility and energy dissipation (Bosiljkov et al., 1988, Magenes, 1992). In order to obtain such reference values the bilinear envelop of the force-displacement diagram was determined, see Figure 8.

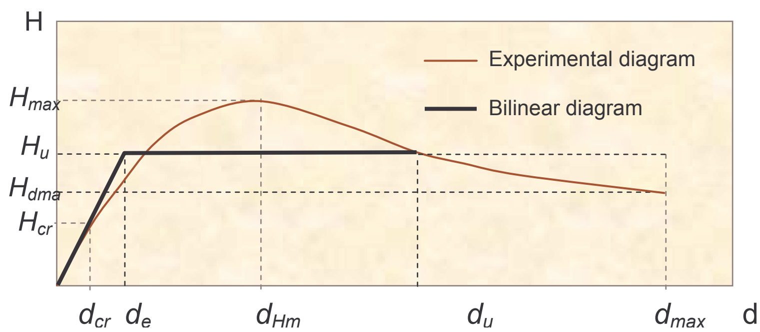


Figure 8: Envelope of experimental values and bilinear diagram

Characteristic points of the diagram include the occurrence of the first crack d_{cr}, the maximum shear load H_{max} and the corresponding lateral displacement d_{max}. The elastic wall stiffness (K_e) is defined using the early load values, where the response is linear, whereas the stiffness K_{Hmax} is the secant stiffness corresponding to the occurrence of the maximum lateral load. The deformation capacity is assessed in terms of horizontal displacement achieved and ductility. Here, ductility is defined as the relation between the maximum theoretical displacement du and the linear elastic displacement de. These values are obtained from the bi-linear diagram shown in where the area under the bilinear diagram is calculated so that the energy dissipated experimentally is replicated.

4.3 Lateral Resistance and Deformability

Table 3 presents a comparative analysis of the results obtained from the bilinear envelops of all cyclic force-displacement diagrams, where in Figure 9 are displayed some examples.

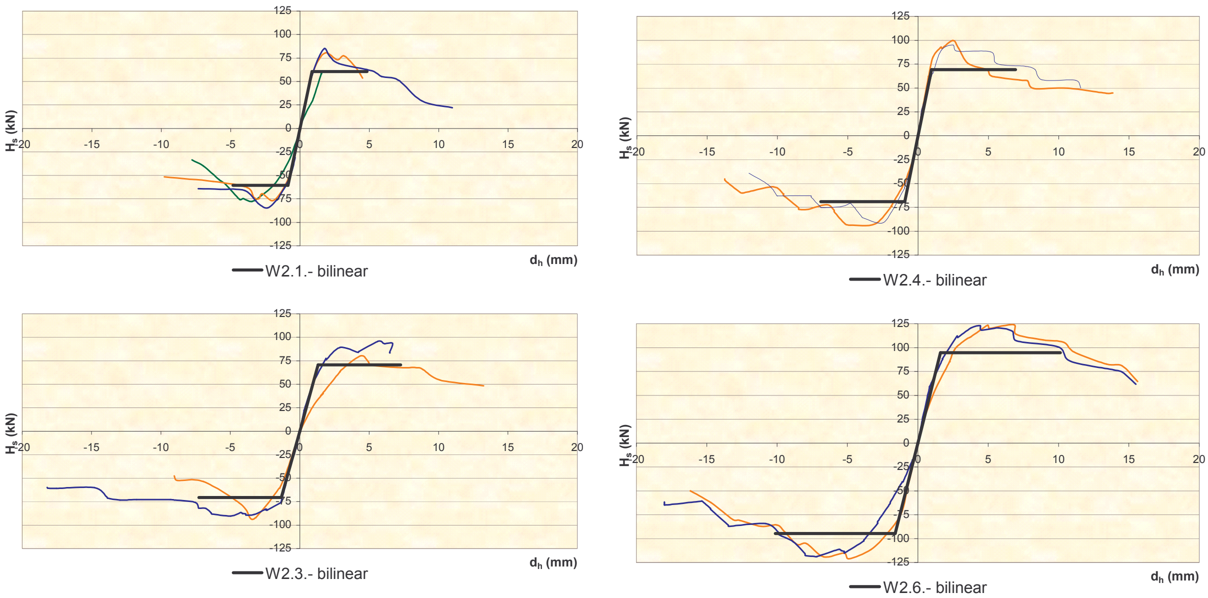


Figure 9: Comparison of the envelope of experimental values and bilinear diagram between unconfined and confined walls

Table 3: Comparison lateral resistance and deformability

Comparison between wall groups	H_{cr} (−)	H_{max} (−)	H_u (−)	$H_{average}$	d_{cr} (−)	d_{Hmax} (−)	d_u (−)	$d_{average}$	μ	*lateral drift* $1_{st\ crack}$	*lateral drift* H_{max}
filled / unfilled vertical joints											
W2.2/W2.1	1.27	**1.10**	1.05	1.14	1.15	**1.16**	1.09	1.13	**1.14**	1.15	**1.16**
confined wall / unreinforced wall											
W2.4/W2.1	1.14	**1.17**	1.14	1.15	1.11	**1.36**	1.43	1.30	**1.29**	1.06	**1.29**
W2.5/W2.3	1.19	**1.22**	1.12	1.18	1.22	**1.15**	1.33	1.23	**1.16**	1.15	**1.10**
average	1.17	**1.20**	1.13	1.17	1.16	**1.26**	1.38	1.27	**1.23**	1.11	**1.19**
effect of bed joint reinforcement											
W2.3/W2.1	0.91	**1.15**	1.17	1.08	1.20	**2.07**	1.50	1.59	**0.98**	1.20	**2.07**
W2.5/W2.4	0.95	**1.20**	1.15	1.10	1.31	**1.76**	1.40	1.49	**0.88**	1.31	**1.76**
W2.6/W2.4	1.08	**1.28**	1.37	1.24	1.33	**1.89**	1.46	1.56	**0.86**	1.33	**1.89**
average	0.98	**1.21**	1.23	1.14	1.28	**1.90**	1.45	1.55	**0.91**	1.28	**1.90**

The comparison focus on the differences between filled vs. unfilled vertical joints, confined vs. unreinforced masonry walls, and the effect of including bed joint reinforcement. From the analysis, the following observations can be made:

- The addition of bed joint reinforcement in standard unreinforced masonry contributes to a very low increase of the shear resistance (5 to 10%). The horizontal displacements are also increased marginally, with a typical lateral drift at peak of 0.21% The addition of bed joint reinforcement in confined masonry contributes to a moderate increase of the shear resistance (about 20%).Confined masonry walls have a shear strength increase of about 20%, when compared to unreinforced masonry. The horizontal displacements increase also, leading to a ductility about 20% larger than unreinforced walls. The typical drift at peak is about 0.45%.
- The theoretical resistance (using the bilinear diagram) is about 75% of the maximum experimental resistance.

5 CONCLUDING REMARKS

This paper presents the main experimental research on modern masonry that has been carried out at University of Minho. Different technological systems have been proposed aiming at stimulating the use of modern masonry as an effective alternative to reinforced concrete structures: lightweight concrete masonry and reinforced hollow concrete masonry. Both proposed systems are characterized by yielding minimal changes on the traditional workmanship.

The results that were already obtained on lightweight concrete masonry walls allowed the assessment of the relevance of vertical joint filling, confining masonry elements and bed joint reinforcement. The difference in terms of strength was very moderate for the different configurations tested. In terms of deformation capacity and energy dissipation, the addition of confining elements and / or bed joint reinforcement represents a significant advantage. These two aspects are much more relevant that the usage of filled / unfilled vertical joints.

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