VALIDATION OF MASONRY SYSTEMS FOR IN-PLANE LATERAL LOADING USING TRUSS REINFORCEMENT

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SUMMARY

The paper presents and describes the main issues related to two building systems for modern masonry structures using truss reinforcement, currently under development at University of Minho, one based on lightweight concrete blocks and another based on reinforced concrete block masonry. Details of the experimental and numerical work carried out are addressed, together with conclusions on the performance of the system for in-plane lateral loading.

INTRODUCTION

In Portugal, masonry is being mostly used as traditional in-fill material for reinforced concrete frames. Recently, modern engineered masonry is becoming popular as long horizontally reinforced non-load bearing walls in non-residential buildings (Lourenço, 2004). A major challenge that has to be faced by the 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, due to the moderate to high seismicity of the country.

This paper describes the current research carried out on two different modern masonry systems. The first wall system is co-sponsored by the lightweight concrete masonry block industry, where different possibilities of unreinforced and confined masonry walls are envisaged. The second system of masonry walls involves the hollow concrete block masonry industry and deals with the development of innovative systems for reinforced masonry walls. Besides the presentation of the main features of the different solutions for masonry walls systems, selected results on the cyclic behavior of the walls and validation using advanced non-linear finite elements are presented. 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 confined masonry solutions; (c) reinforced masonry systems based on vertical and horizontal truss reinforcement.

DESCRIPTION OF THE MASONRY SYSTEMS

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. Therefore, three different possibilities were adopted for the wall system: unreinforced, light horizontally reinforced and confined masonry.

Lightweight concrete masonry walls

The lightweight concrete blocks adopted in the testing program are regularly produced by the industry to comply with thermal regulations and have nominal dimensions of 400×320×200mm. A standard half block in terms of height and length was used in the tests. After cutting this half block in two pieces, the resulting half scale block has dimensions of 200×143×100mm, as shown in Figure 1. The adopted mortar is a pre-mixed mortar denoted MAXIT A M10, with 10 N/mm^2 of compressive strength. 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, which simplify the construction to a great extent, and reduces possible clearances.

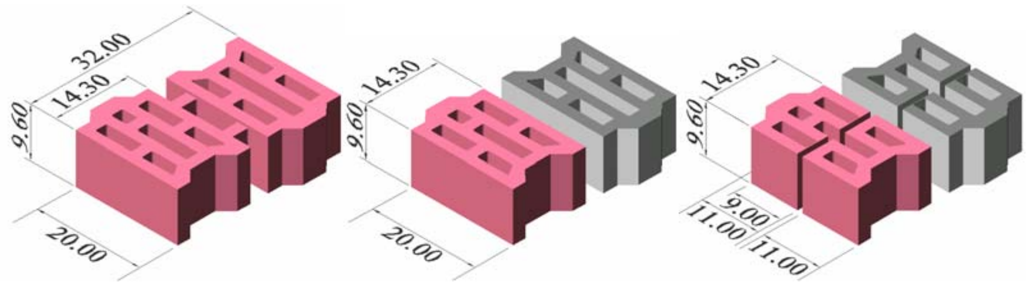


Figure 1. Half-scale and reduced-size of block

Reinforced walls are built by considering bed joint reinforcement of truss type, prefabricated truss type reinforcement Murfor® RND/Z, placed at the horizontal joints, see Figure 2. Note that the bed joint reinforcement is shown in the wall plan section. The horizontal reinforcement aims at increasing the ductility and lateral strength of the walls when submitted to cyclic horizontal loads. For confined masonry walls, lightly reinforced concrete elements are added vertically and horizontally. The bed joint reinforcement can be either connected or disconnected to confining vertical elements.

Hollow concrete masonry walls

Within the scope of this project, two distinct constructive systems are proposed for reinforced masonry solutions. Both constructive systems are based on concrete masonry units, whose geometry and mechanical properties have been adequately specified. Two and three hollow cell concrete masonry units were developed in order to accommodate vertical reinforcement. 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 units.

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 reinforcement is again 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 reinforcement, in agreement with the traditional techniques commonly used for the construction of unreinforced masonry walls. An important as-

pect 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, and an effective stress transfer mechanism exists between both materials. 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 in the constructive process are needed. It is noted that a possible alternative consists of placing the vertical reinforcement inside the hollow cells.

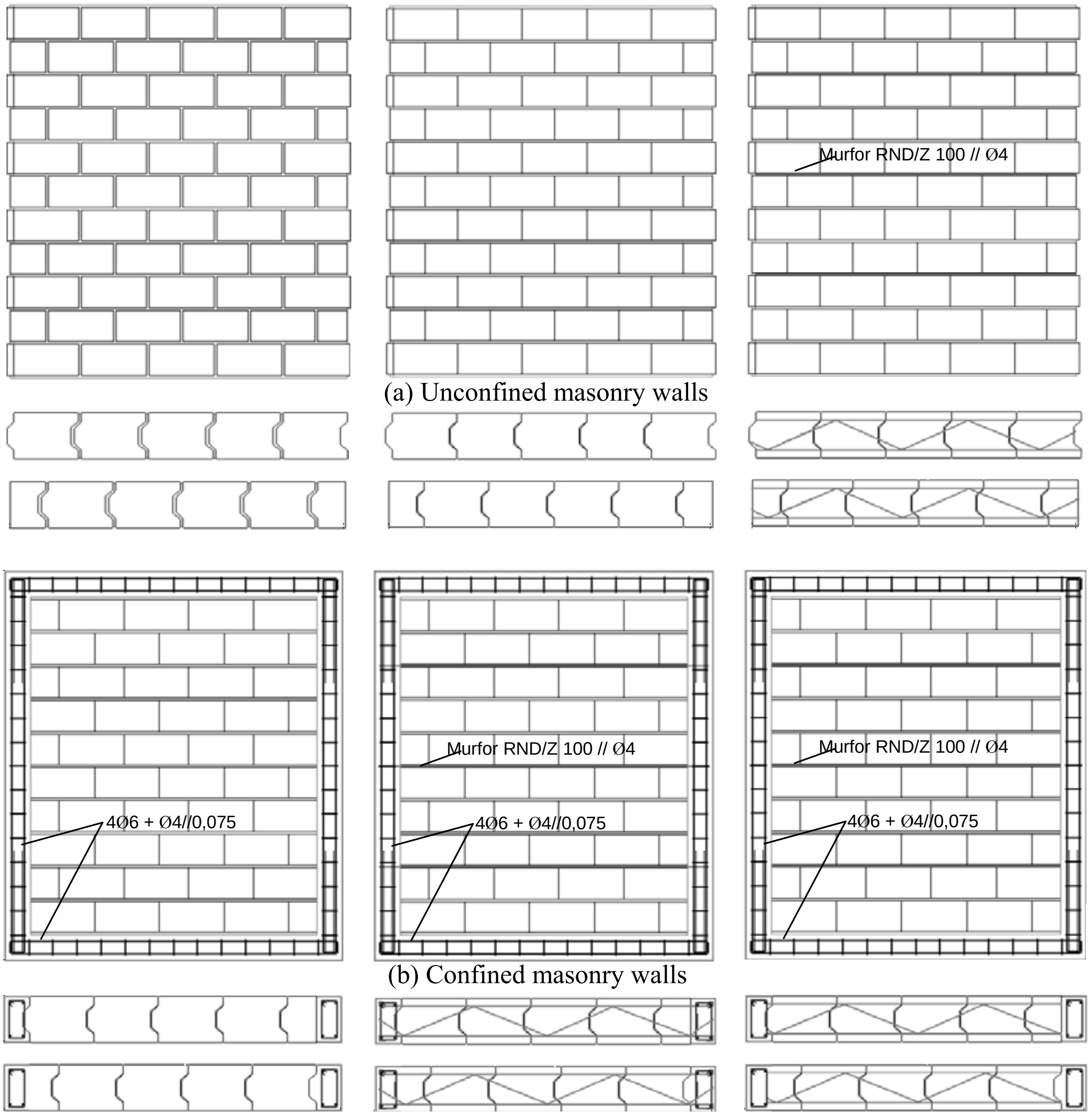
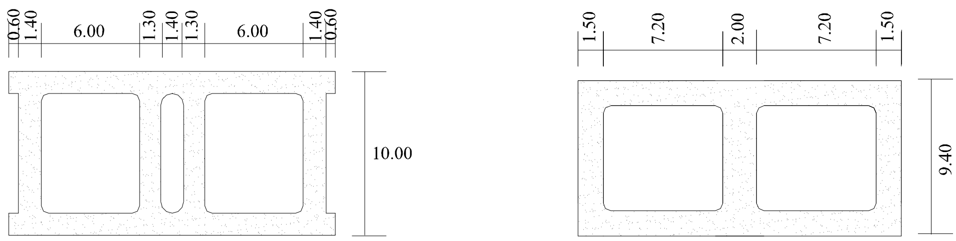


Figure 2. Lightweight concrete masonry walls; (a) unconfined walls; (b) confined walls



(a) (b)

Figure 3. Lightweight concrete masonry walls; (a) unconfined walls; (b) confined walls

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 recessed ends. Continuous and overlapped vertical reinforcement is possible, using half units or full units.

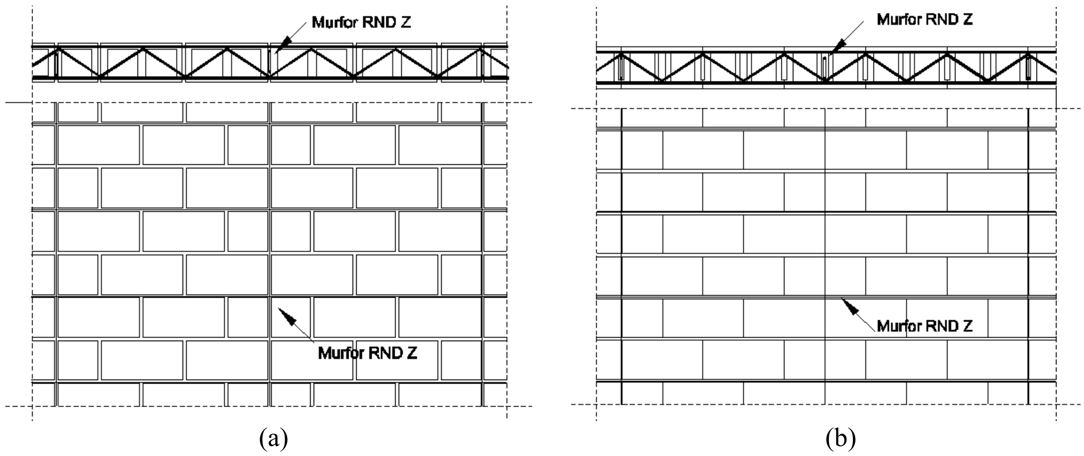


Figure 4. Constructive systems based on the use of concrete units; (a) two hollow cell concrete units, BS1; (b) three hollow cell concrete units, BS2

In both solutions above, proper filling of the vertical hollow cells is a major issue since it is intended to substitute grouting of the cells by general purpose mortar used for the bed joints, in order to simplify the constructive system. Therefore, a mortar with adequate workability and flow properties must be adopted, see Haach et al. (2007). Novel anchorage systems to fix the vertical reinforcement to the slabs to are under consideration.

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 (CEN, 2003) 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. The tests will be performed by following the traditional procedure commonly used on masonry walls under combined vertical-cyclic horizontal loading. The testing program for lightweight concrete masonry walls included 16 walls. 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. 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 with a compressive strength of 31.5N/mm^2, with a transverse section of 143×75mm^2 (vertical) and 143×80mm^2 (horizontal). The strength of reinforcing steel bars and reinforcement truss type is, respectively, 400 and 550N/mm^2.

The testing program for the hollow concrete masonry walls will include 11 walls, with a reference unreinforced masonry wall, models built according to systems BS1 and BS2 using different percentage of vertical and horizontal reinforcement, different location for the vertical reinforcement (in continuous vertical joints or also inside a hollow cell) and different vertical pre-compression loads. In the present stage, only 5 walls have been tested, using the three-cells block and different bond for the vertical reinforcement.

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 5. 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.

The vertical load was applied with an actuator designed to keep the vertical load constant. Therefore, vertical displacements are allowed in the top steel beam. The horizontal cyclic load was applied to the wall via controlled displacement. 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). In selected tests, the analysis of the contribution of the reinforcement to the global response and the evaluation of the bond strength was carried through strain gauges.

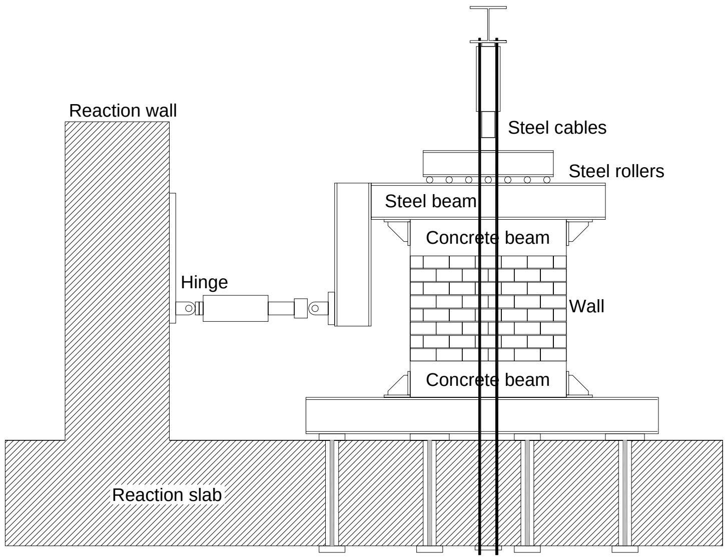


Figure 5. Front view of the test setup

Results for Lightweight Concrete Masonry Walls

Figure 6 illustrates typical failure modes obtained for the walls tested. In the walls without bed joint reinforcement, initially flexural behavior dominates with horizontal cracks appear-

ing 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 confined masonry walls, 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.

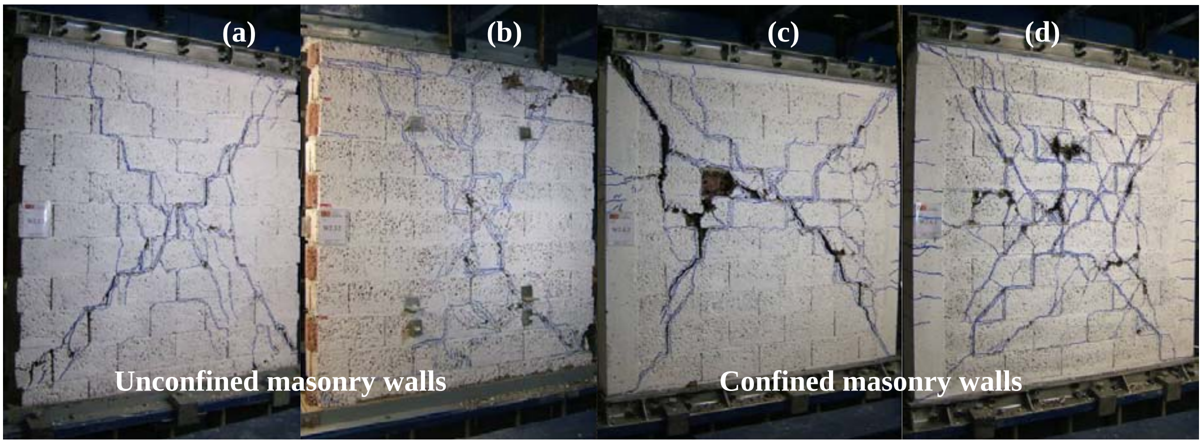


Figure 6. Typical failure modes for lightweight concrete masonry walls: (a) unreinforced; (b) lightly horizontally reinforced; (c) confined unreinforced; (d) confined and horizontally reinforced

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., 2003, Magenes, 1992). In order to obtain such reference values the bi-linear envelop of the force-displacement diagram was determined, see Figure 7. 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 d_u and the linear elastic displacement d_e. These values are obtained from the bi-linear diagram such that the area under the bilinear diagram equals the energy dissipated experimentally. Table 1 presents a comparative analysis of the results obtained from the bilinear envelops of all cyclic force-displacement diagrams, where in Figure 8 are displayed some examples.

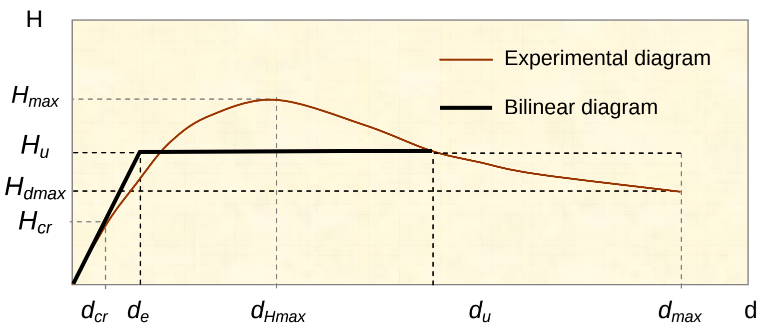


Figure 7. Envelope of experimental values and bilinear diagram

Table 1. 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 1st crack	lateral drift H_{max}
filled / unfilled vertical joints + bed joint reinforcement											
Unreinforced walls	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											
No bed joint reinforcement	1.14	**1.17**	1.14	1.15	1.11	**1.36**	1.43	1.30	**1.29**	1.06	**1.29**
Bed joint re-inforcement	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											
Unconfined walls	0.91	**1.15**	1.17	1.08	1.20	**2.07**	1.50	1.59	**0.98**	1.20	**2.07**
Confined walls	0.95	**1.20**	1.15	1.10	1.31	**1.76**	1.40	1.49	**0.88**	1.31	**1.76**
Confined + Anchor	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**

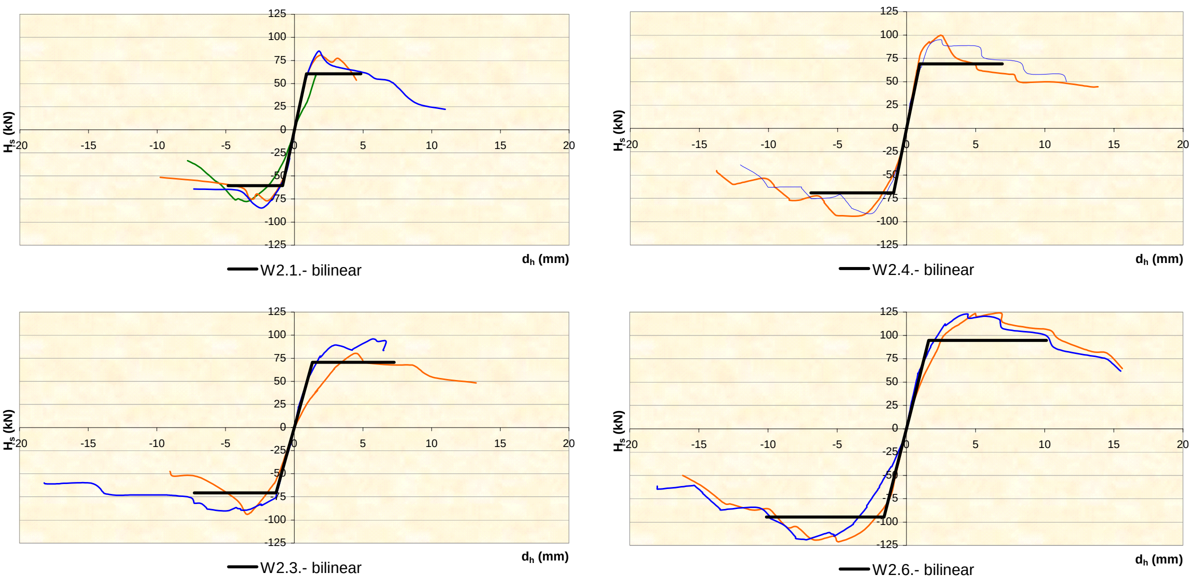
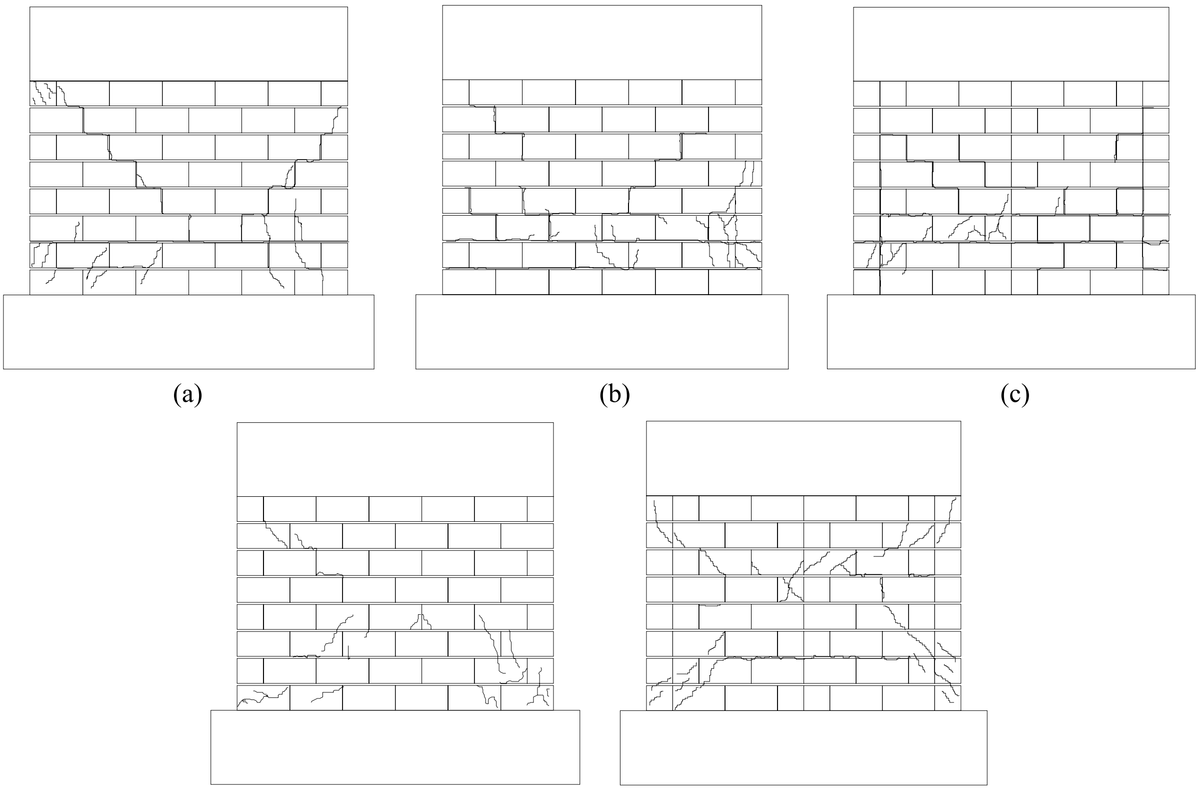


Figure 8. Comparison of the envelope of experimental values and bilinear diagram between unconfined and confined walls

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 of the experimental results, the following observations can be made: (a) 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%; (b) The theoretical resistance (using the bilinear diagram) is about 75% of the maximum experimental resistance.

Results for Hollow Concrete Masonry Walls

Figure 9 illustrates failure modes obtained for the walls tested. All walls presented a well distributed cracking pattern, with crushing of masonry in the compressed toes. No significant differences are found between the cracking in walls with reinforcement placed inside the hollow cells or in a continuous vertical joint. The influence of the amount of vertical load was clear, as higher vertical loads delayed cracking, which appear very close to peak load in this case. Comparing the behavior of the unreinforced masonry with the reinforced walls, it is possible to observe that the reinforcement makes masonry a more homogeneous material. Only the unreinforced masonry walls exhibited localized cracks with considerable opening, which divided the specimen into two parts. After the crack opening, the stress transfer between both parts is achieved almost exclusively at the bottom corners where compressive stresses concentrate.



(a) (b) (c)

(d) (e)

Figure 9. Failure modes for hollow concrete masonry walls with low vertical load: (a) unreinforced; (b) vertically reinforced inside masonry cells; (c) vertically reinforced in the joints; and with high vertical load: (d) vertically reinforced inside masonry cells; (e) vertically reinforced in the joints

Figure 10 presents the load-displacement diagrams, where it is possible to observe that the reinforcement increases the wall strength and peak displacement. The increase in vertical load leads to a more brittle response. No significant differences in terms of load-displacement diagrams are found between the walls with reinforcement placed inside the hollow cells or in a continuous vertical joint.

NUMERICAL ANALYSIS

Numerical simulations of the experimental programs aim at carrying out parametric studies that allow the definition of design rules appropriate to be included in the codes. The first step

in the numerical simulations includes the validation of the modeling strategy adopted. For this purpose different material models included in DIANA® finite element code were considered, see Diswall (2007) for details. Figure 11 illustrates typical results of the numerical analyses, which comparison with experimental results and parametric studies taking into account the aspect ratio of the walls, the level of vertical pre-compression and the amount of reinforcement. Currently, a proposal for an adequate design approach is being validated, in order to allow practitioners to adopt the masonry systems developed.

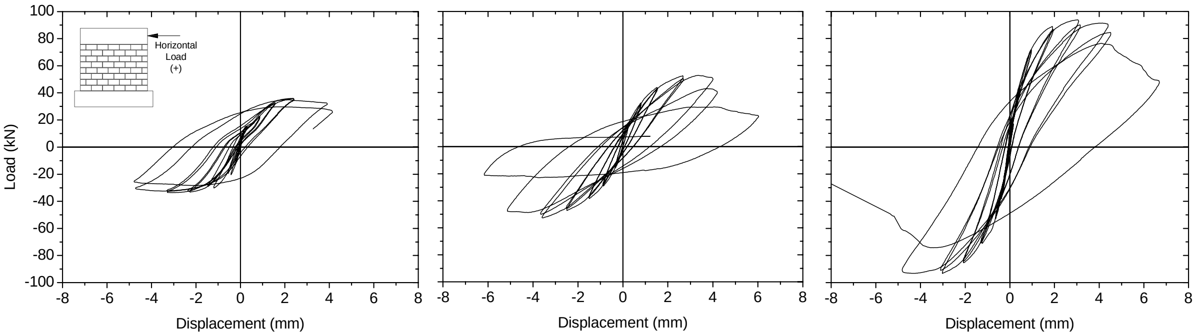


Figure 10. Load-displacement diagrams: (a) unreinforced; (b) reinforced with low vertical load: (c) reinforced with high vertical load

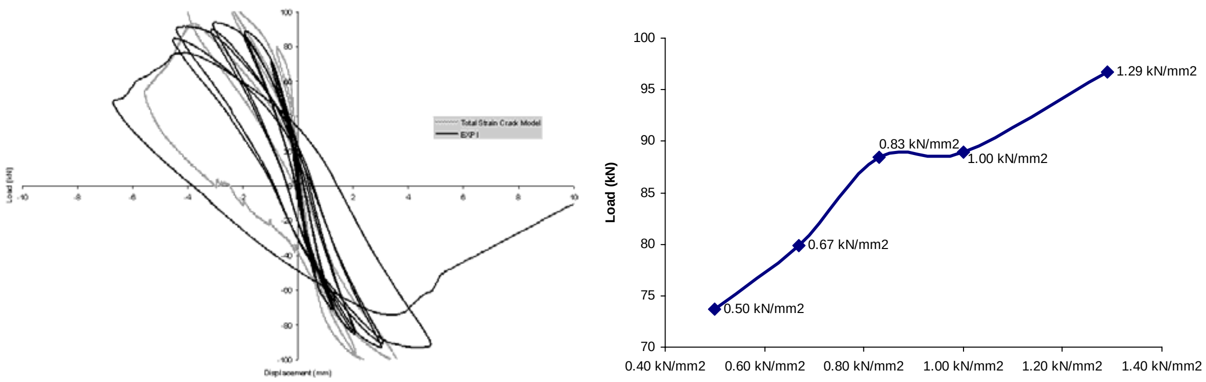


Figure 11. Typical results for non-linear analysis: (a) validation of modelling through comparison with experimental results; (b) influence of a given parameter in the results (in this case the vertical pre-compression)

CONCLUSIONS

This paper presents an overview of two research projects on modern masonry carried out in University of Minho, Portugal, and co-sponsored by the masonry industry. Different technological systems have been proposed aiming at stimulating the use of modern masonry as an effective alternative to reinforced concrete structures: confined lightweight concrete masonry and novel reinforced hollow concrete masonry. Both proposed systems are characterized by minimal changes on the traditional workmanship.

The results obtained on confined masonry walls shear walls aimed at studying 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.

The results obtained on reinforced masonry walls shear walls composed of vertical and horizontal truss reinforcement aimed at studying the relevance of bonding in vertical elements (either inside a masonry cell or on a continuous vertical joints) and the performance of the system. It was found that the masonry bond did not influence the behaviour of the reinforced masonry walls and the reinforcement system is appropriate to increase the lateral strength, energy dissipation and masonry homogeneity.

Numerical simulations have been carried out validating the available non-linear constitutive models. Parametric studies taking into account the aspect ratio of the walls, the level of vertical pre-compression, the amount of reinforcement and the characteristics of the confining elements have been carried out. Currently, a proposal for an adequate design approach is being validated, in order to allow practitioners to adopt the masonry systems developed.

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