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INNOVATIVE SOLUTIONS FOR MASONRY STRUCTURES: CONCEPTION, TESTING AND APPLICATION

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Abstract

The evolution of structural masonry is briefly reviewed, from old thrust line behavior to modern global behavior using shear walls. For modern structural masonry, the use of unreinforced, confined and reinforced masonry is addressed, discussing the influence of seismic hazard and presenting different solutions adopted in developed countries. Finally, two building systems for modern masonry structures recently developed at University of Minho are presented, one based on lightweight concrete blocks and another based on normal concrete blocks. The experimental and numerical work carried out is addressed, together with conclusions on the performance of the system for in-plane lateral loading.

Keywords: Building technology, Structural masonry, Testing, Truss reinforcement.

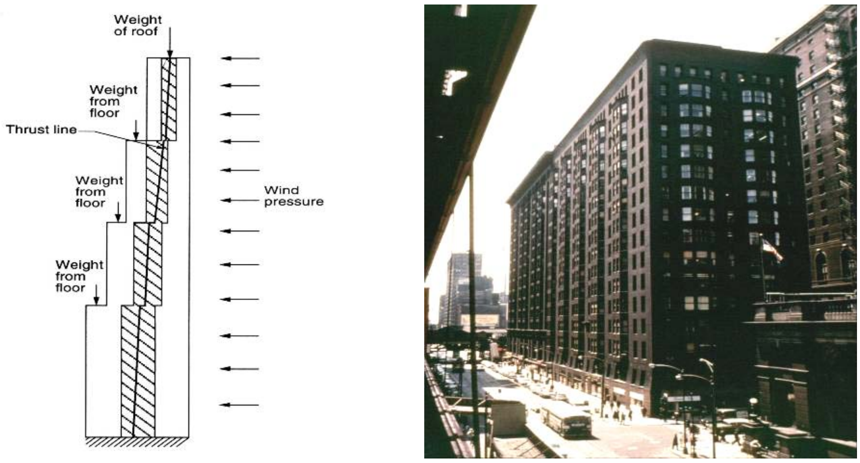
1. Introduction

The lack of masonry codes and norms, on top of technological and architectural motivations, has been until recently an important reason for the loss of market in structural masonry. Currently, unified European norms are available and the designers have adequate tools for structural masonry design.

The use of masonry in the last 10.000 years occurred with moderate innovation until the 20th century, based on the principle that masonry possesses a very low tensile strength. The resulting structural form consisted of thick masonry walls with floors made of timber or reinforced concrete (after the middle of the 20th century). Design based on graphical methods or simple calculations as cantilever walls, without shear walls, lead to increasing thickness from top to bottom. The famous Monadnock building in Chicago, USA, is the exponent of this structural typology with 16 floors and thickness in the base of 1.82m, see Figure 1.

Of course, structural masonry design has much evolved and modern design considers the combined behavior of floors and walls. In Portugal, masonry is being mostly used as traditional infill material for reinforced concrete frames. Recently, modern engineered masonry is becoming popular as long horizontally rein-forced non-load bearing walls in non-residential buildings [1]. 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.

The paper describes several modern structural systems and details the current research carried out on two innovative modern masonry systems. The first wall system is co-sponsored by the lightweight concrete masonry block industry, where different possibilities of 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.



(a) (b)

Figure 1 : Traditional (unreinforced) masonry designed for compressive loading: (a) possible actions in an external wall (self-weight, live floor load and wind) and associated thrust-line; (b) Monadnock building in Chicago, USA

2. Typical modern structural masonry solutions

A modern conception of masonry buildings based on shear walls, in which longitudinal walls, transverse walls and slabs resist together against horizontal actions, was introduced in several countries in the years 1950-60.The advantage of this principle is that the walls are used in compression and shear, being possible to make buildings with a high number of floors using unreinforced masonry and walls with moderate thickness, in zones of low seismic hazard. Design of such buildings has been supported by experimental research programs of large dimension and a solid structural analysis, similar to the approach adopted for reinforced or steel buildings. The buildings shown in Figure 2 have a height comparable with the Monadnock building but the thickness of the walls varies between 0.15 and 0.30m.

Due to the significant damage that occurred in large magnitude earthquakes, several "reinforced" masonry solutions were developed since centuries ago. In Portugal, the Lisbon earthquake in 1755 lead to large economical and human lives losses, and allowed to develop a timber-masonry composite system. With time, other solutions have been proposed, such as ties and iron cramps or dowels in the masonry units, aiming at increasing the performance of masonry when subjected to a large seismic demand. Earthquakes occur in several parts of the globe with a very long return period, which combined with the lack of technical and scientific knowledge, the financial restrictions of the buildings' owners, and the lack of codes and norms, kept on leading to devastating effects of the large magnitude earthquakes. In the early 20th century, three earthquakes of large magnitude, see Figure 3, contributed to the empirical assumption that masonry structures are unsafe in seismic regions and that the performance of reinforced and steel structures is better.

In several countries, e.g. USA, the solution found was to use unreinforced masonry only for low rise buildings and develop reinforced solutions for taller buildings, see Figure 4. Another solution is confined masonry, addressed below.

Figure 2 : Modern (unreinforced) masonry in high rise buildings, designed for compression and shear

(a) (b) (c)

Figure 3 : Images of the devastating effects of earthquakes: (a) San Francisco, USA (1906); (b) Messina, Italy (1908); (c) Tokyo, Japan (1923)

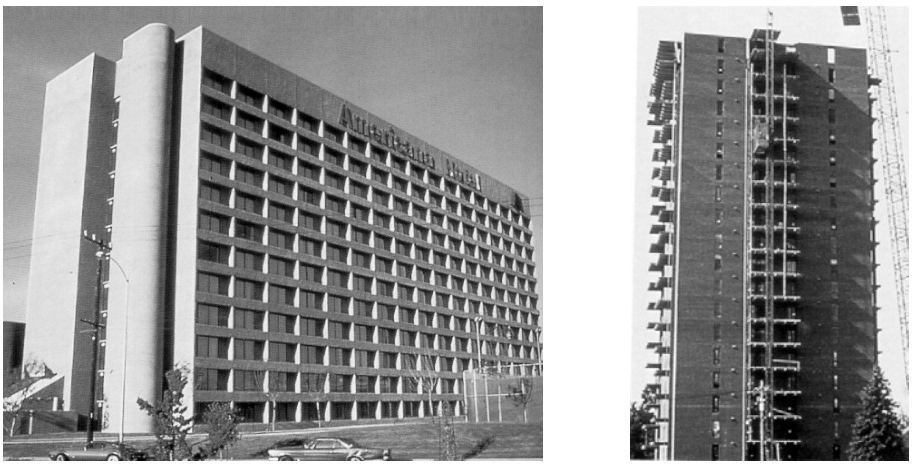


Figure 4 : Modern (reinforced) masonry in high rise buildings up to 30 storeys, designed for compression, shear and tension

2.1 Unreinforced masonry

In Europe, the building solutions using unreinforced structural masonry represent about 15 to more than 50% of the new housing construction, taking as reference countries with low seismicity (e.g. Germany, Netherlands or Norway) but also countries with high seismicity (e.g. Italy). A usual solution is the adoption of masonry units with large thickness in the building envelope, in order to fulfill thermal requirements, see Figure 5 for details. It is stressed that an integrated and complete building technology is needed, including units with different shapes and solutions for floors, see Figure 6.

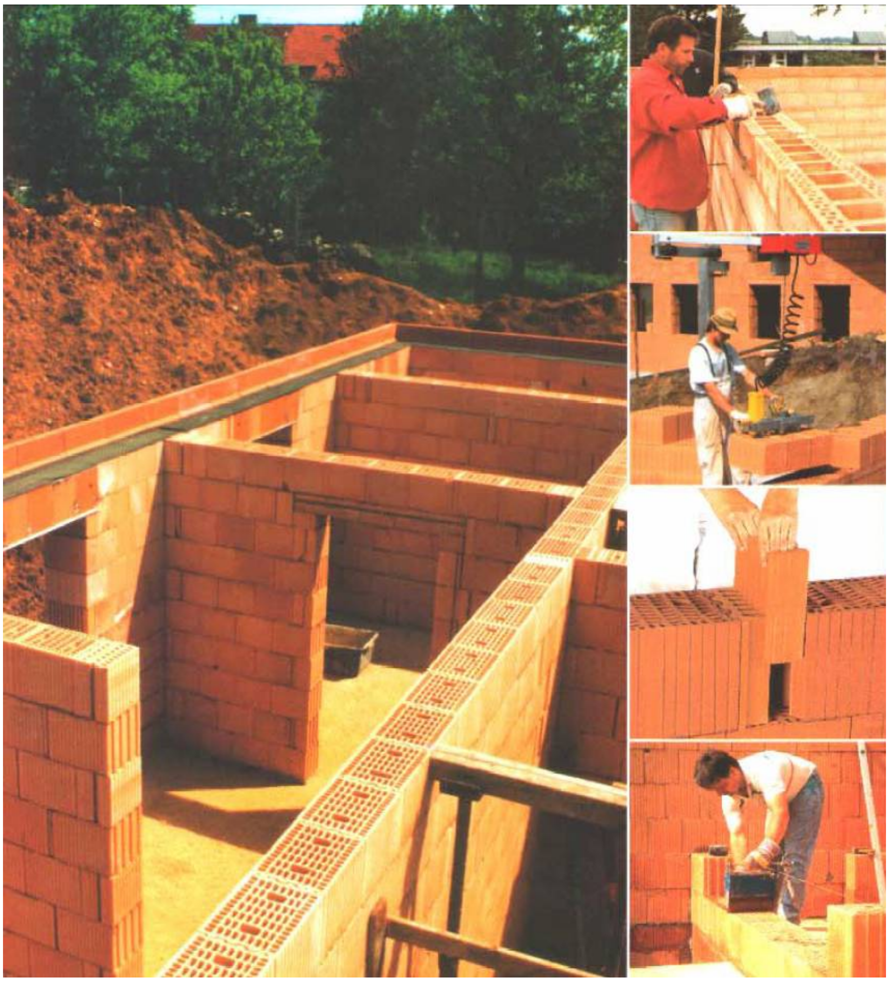
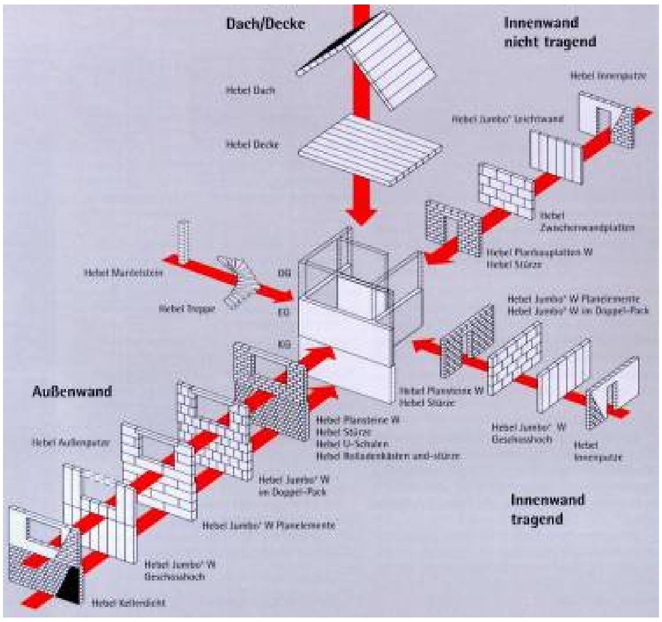


Figure 5 : Details of modern construction in Germany using structural clay masonry

The solutions shown, typical of countries with low seismicity, are also used in Italy with several additional requirements, namely with respect to robustness of the masonry units (minimum strength and moderate percentage of holes) and the presence of ring-beams at floor level. Figure 7 illustrates examples of Italian design, where the combination of structural walls (thicker) with partition walls (thinner) can be observed. It is stressed that the design of unreinforced masonry structures under seismic loading has not yet received general consensus at European level. In particular, the use of elastic design methods and the behavior factors in Eurocode 8 lead, usually, to results different from the ones in the simplified methods and from the results obtained in shaking table tests, see [2] for details.



(a)

(b) (c)

(d) (e)

Figure 6 : Modern unreinforced masonry: (a) integrated building systems; (b) aerated autoclaved concrete units; (c) calcium-silicate units; (d) clay units; (e) lightweight concrete units.

2.2 Reinforced masonry

Reinforced masonry was developed in different countries as a response to the lower performance of unreinforced masonry buildings under large horizontal loading, but no unified solution was found. Below selected solutions with different levels of success are shown, together with recent innovative solutions. It is common practice to combine prefabricated slabs with load resisting walls, so that formwork, scaffolding and execution times can be significantly reduced.

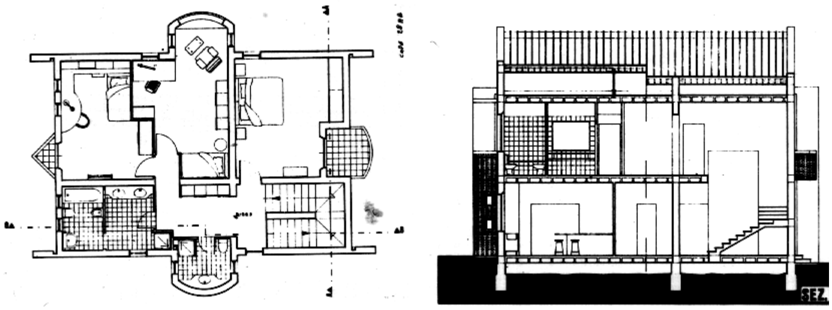
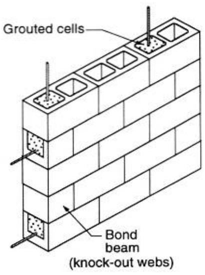


Figure 7 : Unreinforced modern masonry: Design example in Italy

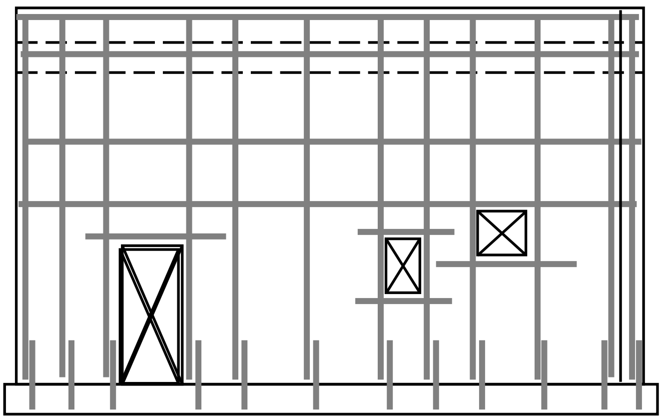
In USA, in the last 30 to 40 years, reinforced masonry became an attractive and efficient solution from a perspective of cost-benefit analysis for buildings in regions of low to high seismicity, including e.g. hotels, residential buildings, office buildings, schools, commercial buildings or warehouses. The standard solution includes reinforced concrete horizontal bond beams, two-cell blocks filled with grout and vertical reinforcement, see Figure 8.



(a)

(b)

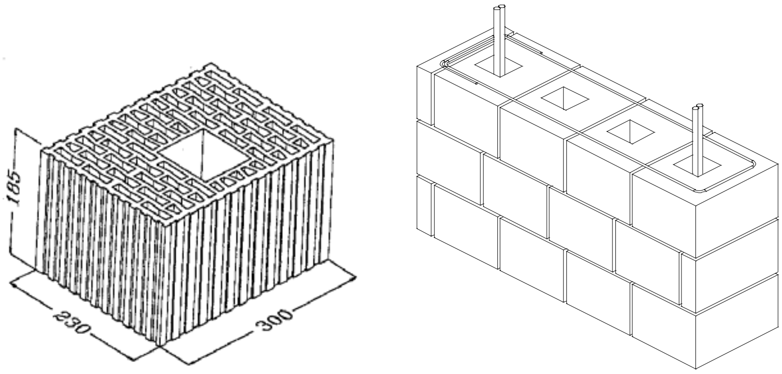
(c)



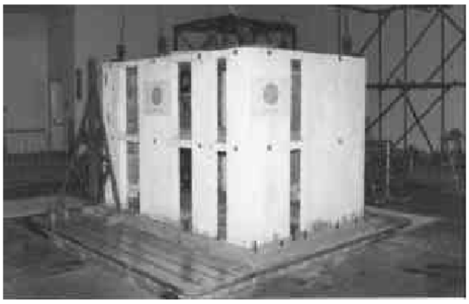
(d)

Figure 8 : Modern reinforced masonry (typical American solution). Details: (a) reinforcement and units; (b) wall execution; (c) completed building; (d) reinforcement lay-out.

In Italy, in the last 20 to 30 years, a reinforced masonry system was developed incorporating blocks with a large hole for placement of vertical reinforcement and horizontal hoop bars, using the same mortar for the bed joints and for filling the hole, see Figure 9. A prototype building for comparison with a reinforced concrete solution (with masonry infills) was made and several models were tested in a shaking table. The adequacy of the proposed system was demonstrated by tests and prototype but this reinforced masonry solution received moderate success in Italy, in comparison to the still used unreinforced masonry solutions for low rise buildings. One of the critical aspects of the system seems to be the quality control of the hole filling, and associated bond and durability problems.



(a)



(b) (c)

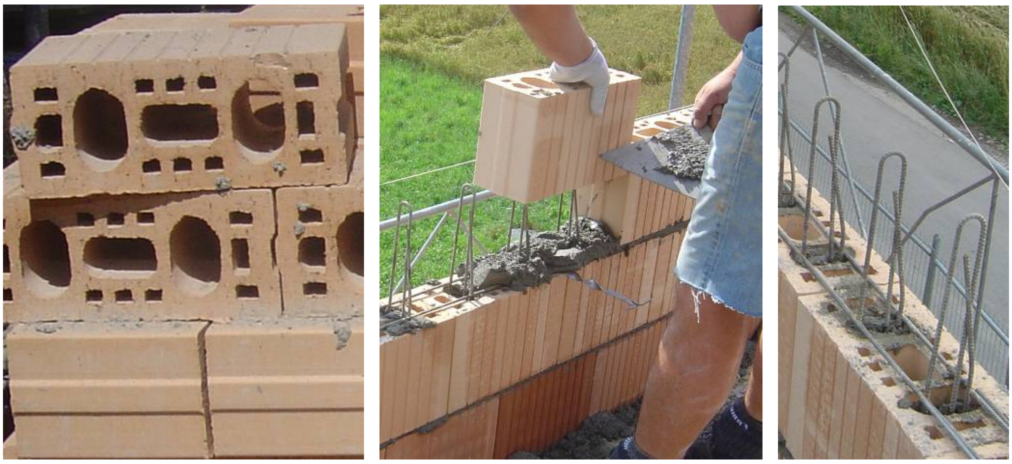
Figure 9 : Modern reinforced masonry (typical Italian solution). Examples of: (a) units and reinforcement; (b) prototype building; (c) shaking table test [3].

In Switzerland, in the last 15 to 20 years, a reinforced masonry system was developed incorporating blocks with two holes of large size, for placement of a complex 3D reinforcement that is corrosion protected and simultaneously acts as vertical and horizontal reinforcement, see Figure 10. The same mortar is again used in the bed joints and in filling the holes. The system is used frequently for all types of buildings, up to 4 or 5 storeys.

In Spain, in the last 15 to 20 years, a reinforced masonry system was also developed incorporating truss reinforcement protected against corrosion, horizontally and vertically [4]. This system was originally developed as an alternative to the traditional solution for non-loadbearing walls of large size, see Figure 11, with horizontal bond beams and vertical elements, made with reinforced concrete. Presently, a similar system is under validation in Portugal, as shown below in the paper. Finally, a recent system is being developed in Germany to respond to the increase in seismic action in the code, see Figure 12. The solution considers two-cell clay blocks, to be filled with self compacting concrete, and vertical and horizontal reinforcement, allowing to cast the slab and walls simultaneously, see [5] for details.

2.3 Confined masonry

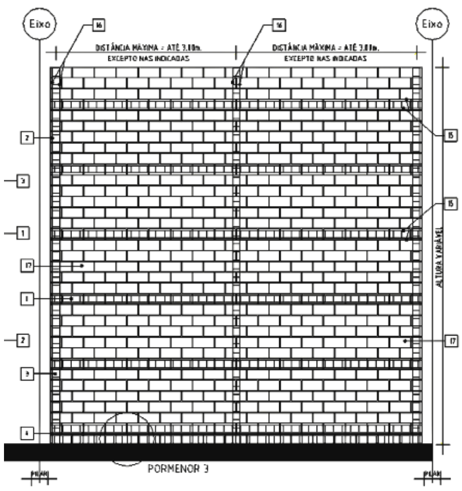
Confined masonry is a system in which vertical and horizontal reinforced concrete elements of small section are included in the masonry, see Figure 13. These elements aim at providing an increase of shear and flexural strength, together with a larger energy dissipation capacity and larger ductility with respect to horizontal actions. The system is often used in developing countries, as the changes with respect to unreinforced masonry construction are small. As the system received limited attention from the research community, it is further discussed below in the paper.



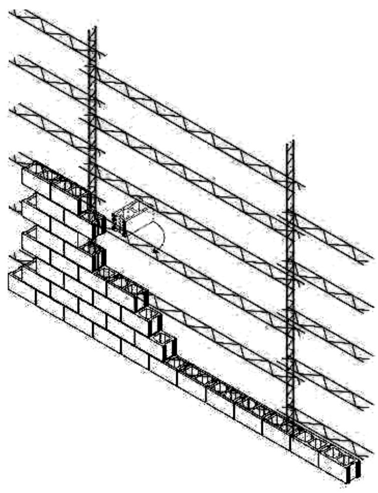
(a)

(b)

Figure 10 : Modern reinforced masonry (typical Switzerland solution, with Murfor RE®). Examples of: (a) on site execution; (b) small and medium size buildings

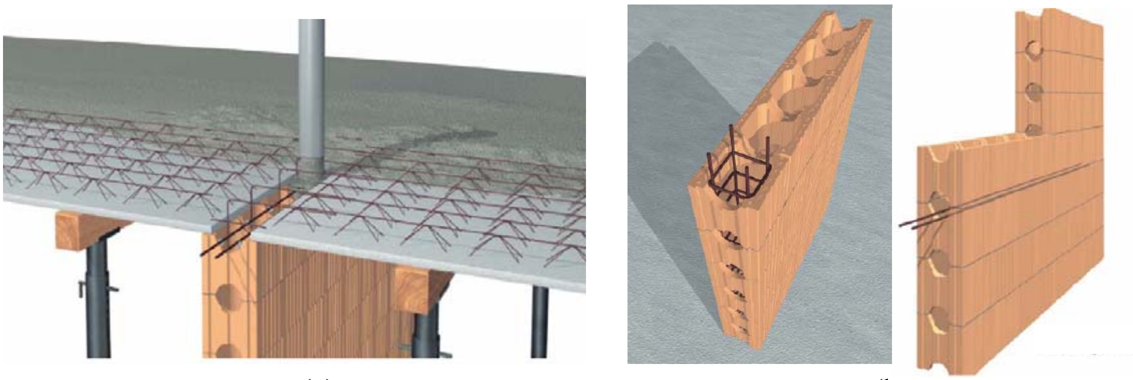


(a)



(b)

Figure 11 : Modern reinforced masonry (typical Spanish solution, with Murfor ® and Allwall Systems®) for non-load bearing walls. Examples of: (a) wall with bond beams and vertical elements; (b) alternative wall with vertical and horizontal truss reinforcement [4].



(a) (b)

Figure 12 : Modern reinforced masonry (German solution under development). Examples of: (a) slab and wall to be cast simultaneously with self compacting concrete; (b) reinforcement details [5].

Figure 13 : Example of modern confined masonry under construction.

3. Innovation in masonry systems using truss reinforcement

Next, a research carried out on two different modern masonry systems is addressed. 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.

The proposed 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, two different possibilities were adopted for the wall system: combined vertical and horizontal truss reinforcement and confined masonry.

3.1 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 14. 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.

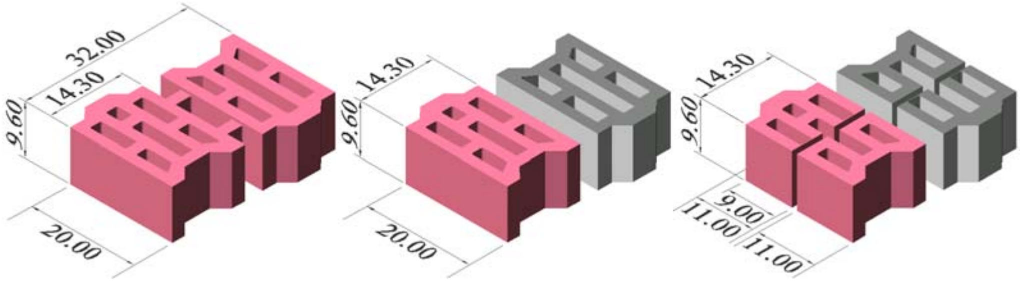


Figure 14 : Half-scale and reduced-size of block.

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 15. 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.

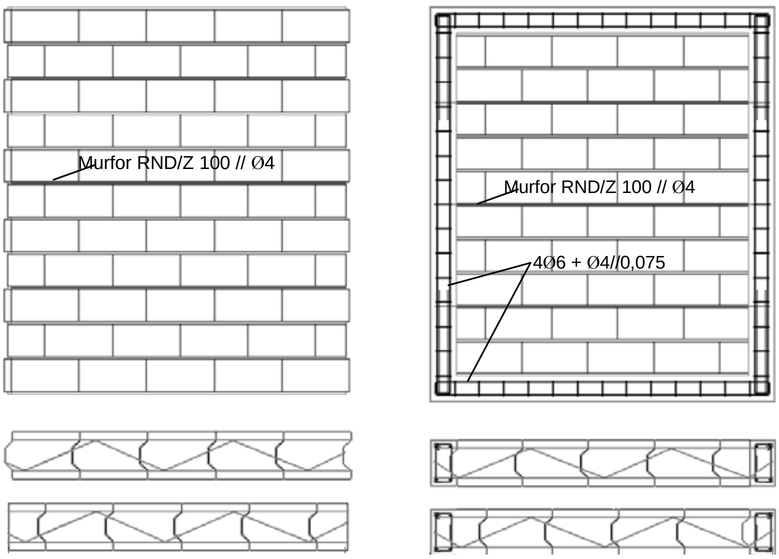


Figure 15 : Examples of unconfined and confined lightweight concrete masonry walls.

3.2 Hollow concrete masonry walls

Within the scope of this project, two distinct building systems are proposed for reinforced masonry solutions. Both 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 16. In order to allow expedite and economical testing of a large number of masonry walls, it was decided to produce half scale units.

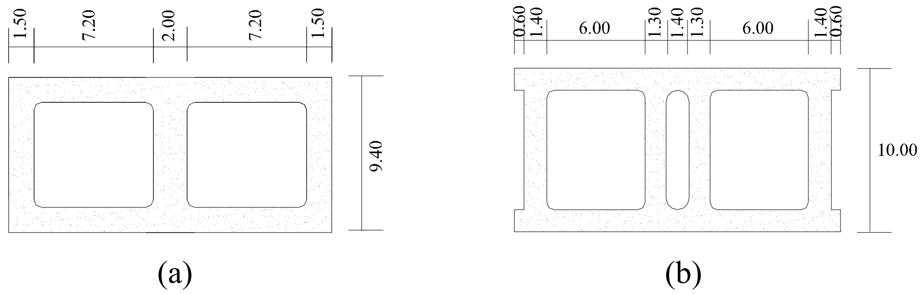


Figure 16 : Half scale concrete blocks: (a) two-cells; (b) with reinforcement pocket.

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 17a, 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 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, 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 building process are needed. It is noted that a possible alternative consists of placing the vertical reinforcement inside the hollow cells.

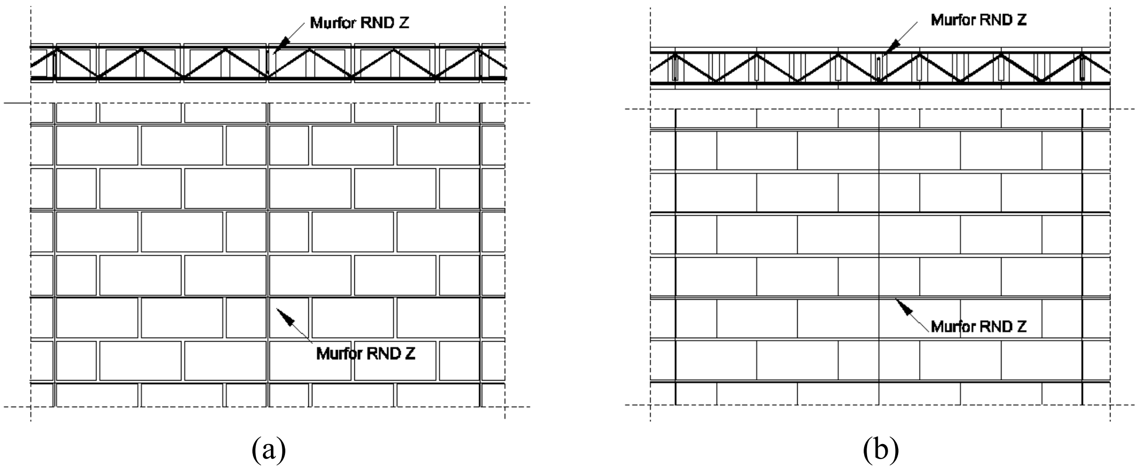


Figure 17 : Systems based on the use of concrete units; (a) two hollow cell concrete units, BS1; (b) three hollow cell concrete units, BS2.

The second building system BS2 uses the three hollow cell concrete units, see Figure 17b. 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.

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 system. Therefore, a mortar with adequate workability and flow properties must be adopted [6].

3.3 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 [7] related to masonry structures is a compromise for the different countries.

The performance of each system to seismic actions was evaluated by means of an enlarged experimental program based on in-plane cyclic tests. The tests were performed by following the traditional procedure commonly used on masonry walls under combined vertical-cyclic horizontal loading. Two unreinforced lightweight concrete masonry 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. Confining concrete elements have been made using self compacting concrete.

The testing program for the hollow concrete masonry walls included walls 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.

3.3.1 Test setup and procedure

The typical test setup used in the in-plane cyclic tests is displayed in Figure 18. 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.

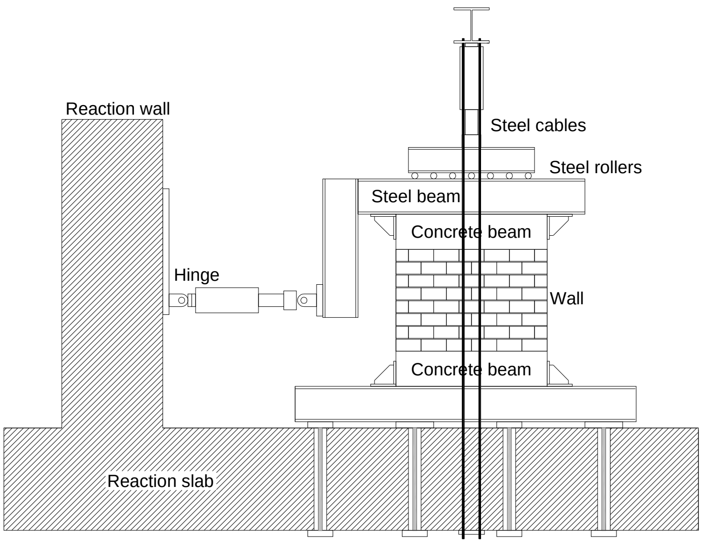


Figure 18 : Front view of the test setup.

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 [8]. 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.

3.3.2 Results for lightweight concrete masonry walls

Figure 19 illustrates typical failure modes obtained for the walls tested. In the walls without bed joint reinforcement, 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. 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.

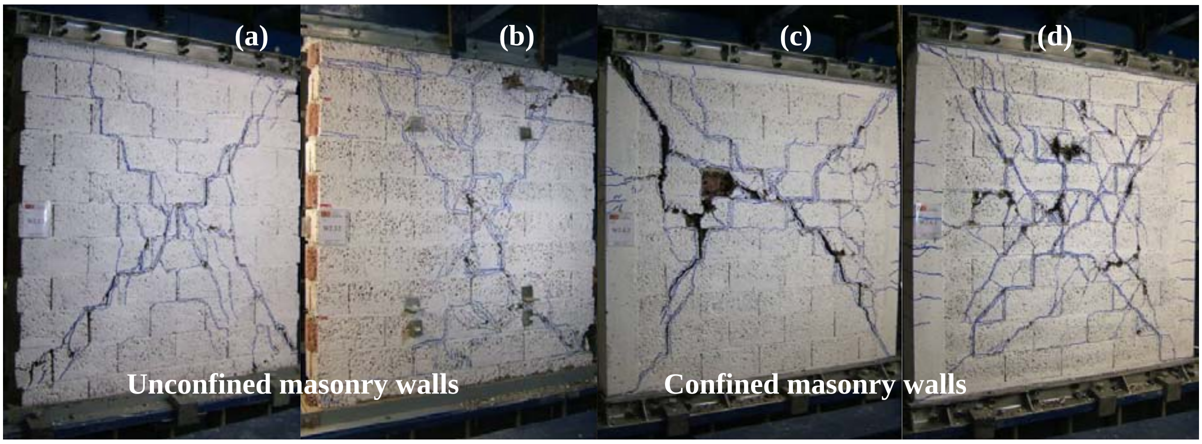


Figure 19 : Typical failure modes for lightweight concrete masonry walls: (a) unreinforced; (b) lightly horizontally reinforced; (c) confined unreinforced; (d) confined and horizontally reinforced.

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.

3.3.3 Results for hollow concrete masonry walls

Figure 20 illustrates typical failure modes obtained for hollow concrete masonry walls. All walls presented a well distributed cracking pattern, with crushing of masonry in the compressed toes. 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.

Figure 21 presents the experimental load-displacement diagrams, where it is possible to observe that the reinforcement increases the wall strength and peak displacement. Also, 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.

3.3.4 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 [9] for details. Figure 22 illustrates typical results of the numerical analyses, which includes 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. A proposal for an adequate design approach and design charts have also been prepared, in order to allow practitioners to adopt the masonry systems developed.

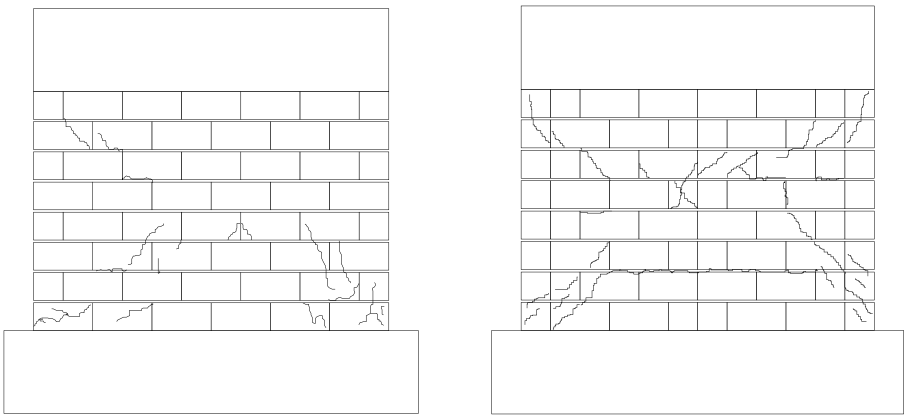
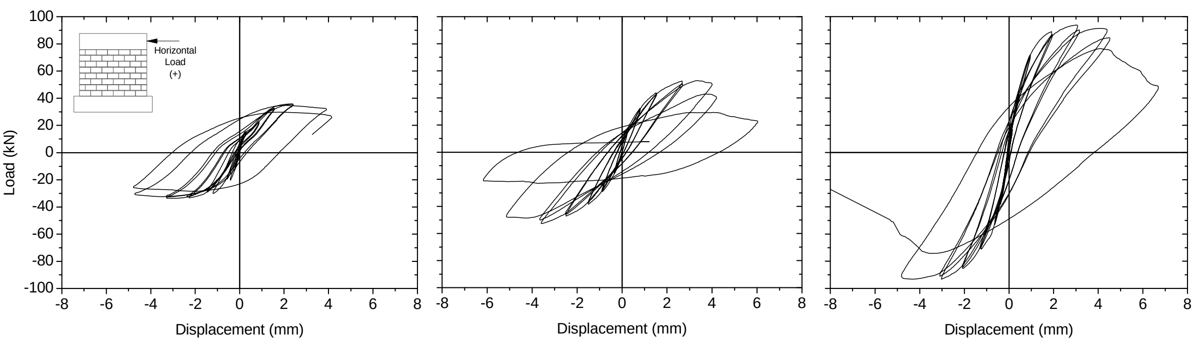
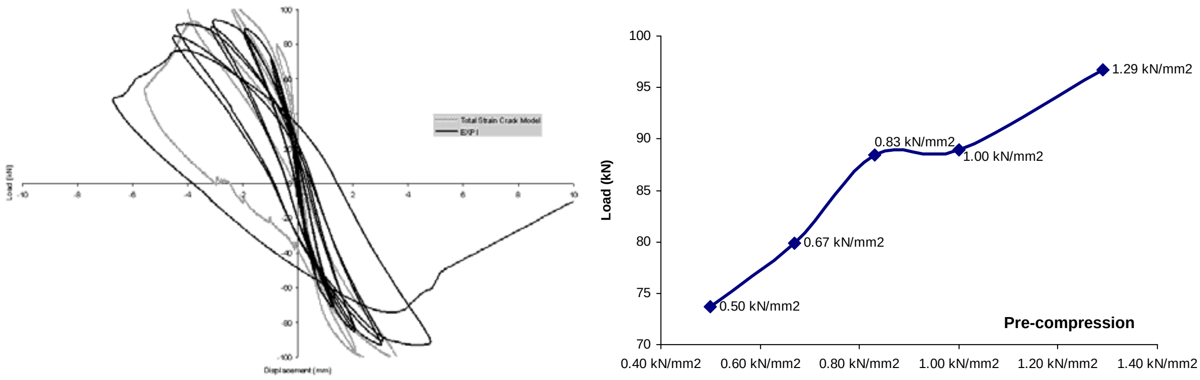


Figure 20 : Typical failure modes for hollow concrete masonry walls with horizontal reinforcement, and vertical reinforced inside masonry cells or in vertical joints.



(a) (b) (c)

Figure 21 : Load-displacement diagrams: (a) unreinforced; (b) reinforced with low vertical load: (c) reinforced with high vertical load.



(a) (b)

Figure 22 : Typical results for non-linear analysis: (a) validation of modeling through comparison with experimental results; (b) influence of a given parameter in the results (in this case, the vertical pre-compression)

4. Conclusions

Even if structural masonry is used for thousands of years, its use has gradually decreased and new approaches seem necessary in moderate to high seismicity countries. Confined and reinforced masonry solutions coexist but, in the first case, the amount of information seems limited and, in the second case, no unified solution could be found for developed countries. The local practices for reinforced masonry have very different levels of success with respect to market share.

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 a novel reinforced hollow concrete masonry. Both proposed systems are characterized by minimal changes to 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. A proposal for an adequate design approach and design charts has been proposed, in order to allow practitioners to adopt the masonry systems developed.

5. Acknowledgements

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