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OUT-OF-PLANE LATERAL CAPACITY OF UNREINFORCED MASONRY WALLS: A PREDICTIVE ANALYSIS BEFORE EXPERIMENTATION

Scacco, Jacopo[1]; Silva, Luís C.[2]; Vasconcelos, Graça[3]; Milani, Gabriele[4] and Lourenço, Paulo B.[5]

ABSTRACT

The study addresses the mechanical analysis of unreinforced masonry (URM) walls through a numerical strategy based on a micro-modeling approach. The study includes the structural evaluation URM walls via quasi-static ('pushover') analyses. Masonry walls are made of clay brick units and weak mortar joints within an English-bond arrangement. The mechanical properties of the latter components try to give a fair representation of the ones found within the so-called 'placa' buildings. 'Placa' buildings have been mainly erected between the 1930s and 1960s and represent an important part of the Portuguese building. Its structure is characterized by being of a mixed type, i.e. composed of masonry walls and reinforced concrete (RC) slabs. The seismic response of this building type is affected by the increase of inertial loads – when compared to URM masonry buildings – due to the presence of concrete slabs. Hence it is important to draw strengthening solutions that are easy to implement and guarantee the required seismic capacity. With the view of future tests on reinforced structures, this work wants to provide a deep discussion about the best suitable experimental setup to design for the preliminary tests on the unreinforced scenario. Several hypotheses are explored on a URM scaled configuration representative of 'placa' buildings by changing the geometry, the boundary conditions and the load applied. Useful indications about the parameters governing the global behavior are provided to avoid at the experimental stage any rocking of the structures.

KEYWORDS: *'placa' buildings, out-of-plane, URM, strengthening, English-bond, pushover*

[1]Ph.D. Candidate, Politecnico di Milano, Department of Architecture Built Environment and Construction Engineering ABC, Piazza Leonardo da Vinci 32, 20133 Milan, Italy, jacopo.scacco@polimi.it
[2]Assistant Professor, ISISE, Faculty of Engineering, University Lusófona de Humanidades e Tecnologias, Campo Grande, 1749-024 Lisbon, Portugal, luis.silva@ulusofona.pt
[3]Assistant Professor, ISISE, Department of Civil Engineering, University of Minho, Azurém, 4800-058 Guimarães, Portugal, graca@civil.uminho.pt
[4]Full Professor, Politecnico di Milano, Department of Architecture Built Environment and Construction Engineering ABC, Piazza Leonardo da Vinci 32, 20133 Milan, Italy, gabriele.milani@polimi.it
[5]Full Professor, ISISE, Department of Civil Engineering, University of Minho, Azurém, 4800-058 Guimarães, Portugal, pbl@civil.uminho.pt

INTRODUCTION

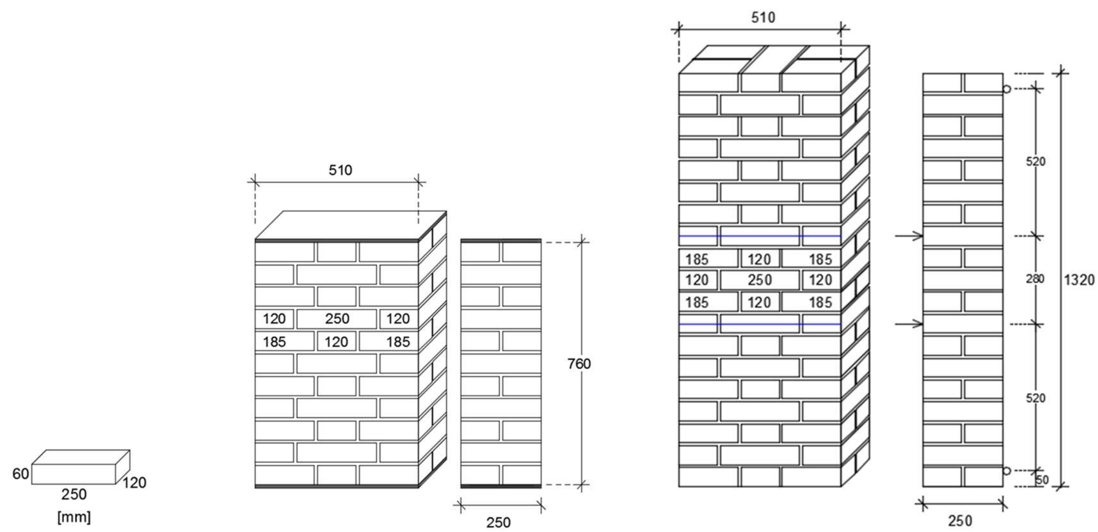
Brick Unreinforced Masonry (URM) structures are widely spread around the world city centers. URM structures have been typically designed to sustain gravity loads only hence tend to suffer moderate to severe damage when subjected to horizontal loads, such as earthquakes. This is certainly more relevant in countries with significant seismic exposition, which demands the evaluation of the seismic vulnerability of such buildings and the design of adequate and necessary strengthening measures. Great efforts have been already carried out by academia to better understand and better predict the out-of-plane capacity of masonry walls when subjected to destructive events. Stone walls have been tested and reported in [1,2], whereas experimentation on brick walls can be found in [3,4]. Several numerical analyses have been also conducted on unreinforced [5] and reinforced configurations [6,7].

This study addresses the so-called 'placa' buildings, which have been built especially in the region of Lisbon (Portugal) and during the period from 1930 until 1960. With the advent of reinforced concrete (RC), more traditional construction techniques were progressively adapted. Firstly, peripherical RC beams have been inserted within timber floors to increase both capacity and stiffness. RC frames, together with RC slabs, were given preference and timber-based solutions were gradually replaced. In fact, 'placa' is a local designation for this building type and stands for RC slab. Meaning that 'placa' buildings are a mixed unreinforced masonry-reinforced concrete structure that represents a transitory period between the typical URM structures and modern RC buildings [8]. Such building stock requires particular attention since Lisbon has a relevant seismic exposition.

"Placa" buildings are characterized by the presence of reinforced concrete slabs that causes a marked increase of inertial loads. An experimental campaign has been thus planned to investigate the out-of-plane capacity of such structures and enrich literature data. An ad-hoc setup has been designed and consists of a U-shaped configuration wall. The research plan includes experimentation on both unreinforced and reinforced configurations by applying a uniform out-of-plane pressure on the internal side of the wall. Whereas, to avoid stumbling into undesired failure mechanisms, a comprehensive set of numerical analyses have been carried out being herein presented and discussed. The main goal of this paper is the identification of key parameters that govern the typology of failures and lead to collapse. As final output one intends that different kind of strengthening solutions are applied. For that and to better identify the most effective designed solution, it is necessary that the damage mechanism of the unreinforced wall is governed by damage at the connection between the main wall and the two orthogonal walls. Rocking behavior needs, therefore, to be precluded or, at least, postponed. In such a way, the enhancement provided by the strengthening will be more noticeable. All the results are discussed by comparing damage patterns and load-displacement curves for the most significant outcomes.

EXPERIMENTAL PLAN: UNREINFORCED AND REINFORCED BRICK WALLS

Experimentation is still the natural source of knowledge when trying to better understand the behavior of URM structures. Although numerical and analytical strategies have become more and more powerful [9], experimental data is still paramount in such cases for validation purposes. The present experimental campaign intends to bring new data and enrich the literature on the behavior of URM structures in general. It may also provide a sound comparison between different strengthening solutions to improve the out-of-plane behavior of 'placa' buildings. In such a context, the experimental plan includes (a) material characterization tests and (b) larger-scale tests on un-strengthened and strengthened walls. At a material level, mortar characterization tests will be carried out following the European norm EN 1015-11 [10] aiming to obtain their compressive and flexural tensile strength values. These tests are performed even if a standardized M5 mortar will be used. Shear strength may be also evaluated [11]. Masonry characterization tests will include the determination of the compressive strength of masonry wallets within an English-bond arrangement and tested in compression following the direction perpendicular to the bed joints and diagonal compression tests (following recommendations given in EN 1052-1:1998 [12]). To characterize the out-of-plane behavior, vertical and horizontal flexural strengths of the masonry may be determined following EN 1052-2 [13].

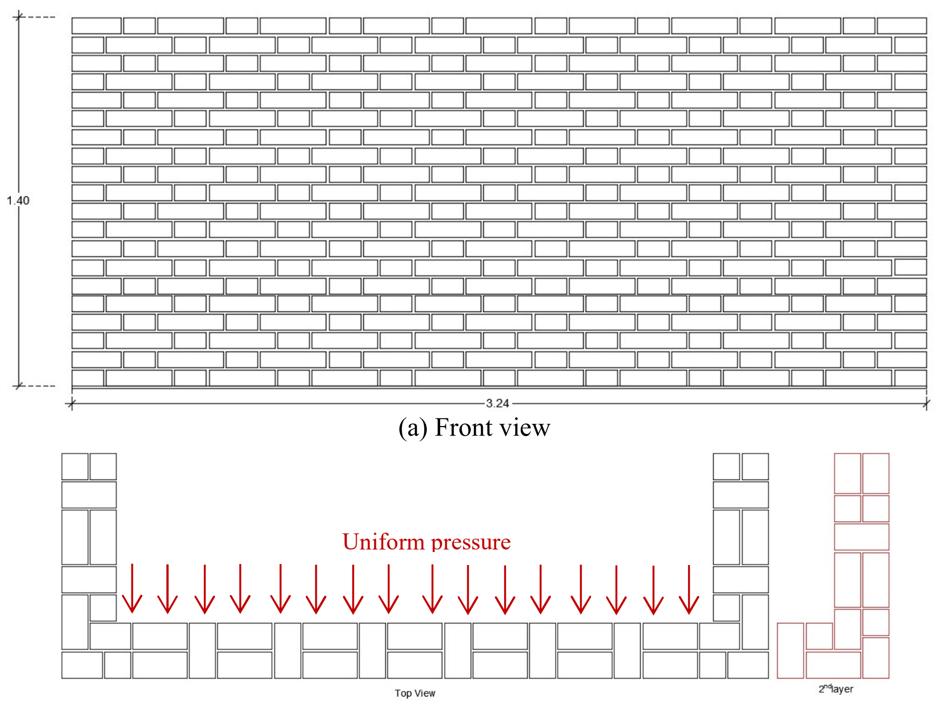


(a) Brick unit | (b) Vertical compression test | (c) Vertical flexural strength test

Figure 1. Geometric configuration for the material characterization tests.

At a larger scale, a total of four masonry walls are planned to be tested (one un-strengthened and three strengthened). Three main strengthening solutions are planned to be carried out: (1) textile reinforced mortar on the outer façade; (2) anchored system between façade and transversal walls; and (3) the so-called CAM system [14], a grid composed of mechanical anchors placed between mortar joints aiming active confinement of masonry. The masonry walls have a U-shape and try to represent a typical façade and corresponding transversal walls that constitute a 'placa' building, see Figure 2. The masonry follows an English-bond arrangement and the geometric dimensions that have been initially planned are given as follows: 3.24m of façade wall length, walls' height of 1.40m, transversal walls' length of 1.20m and thickness of 0.25m.

The RC slabs on 'placa' buildings are lightly reinforced, and typically show an absence of continuity between spans. Although the structural role of such RC slabs may be a contentious issue, especially in the case of an earthquake scenario, its self-weight may be considered. It is planned that an RC slab of 20 cm supported on the masonry walls. Its dead load will be accountable by direct application of representative load, meaning that no-continuity between spans is assumed. The main goal is to perform unidirectional out-of-plane tests to assess the out-of-plane capacity of the un-strengthened and strengthened walls. The out-of-plane load will be applied in the inner part of the façade wall through an airbag properly placed. Damage must be also collected. Results may provide important remarks on the most effective retrofitting technique concerning both strength (capacity) and damage control.



(a) Front view

(b) Top view

Figure 2 Initial planned configuration for the U-shaped URM masonry walls.

NUMERICAL STRATEGY: RESPONSE PREDICTION

The main objective of the study is to give a reasonable and detailed insight into the experimentation tests that will be carried out (briefly presented in the previous section). Such prediction is obtained through several numerical analyses that intend to supply valuable information that may influence the final set-up planning. In such a context, a numerical study has been developed to simulate the behavior of the U-shape English-bond walls. A detailed heterogeneous approach, the so-called micro-modeling, has been assumed. Brick units and mortar joints are explicitly represented. Although such a modeling approach is computationally demanding, especially for such preliminary analysis, the idealization of a composite material like masonry as a fictitious homogenous material can lead to inaccurate results. The latter is amplified in the case of strong-unit-weak-joint masonry, i.e. when brick units with good mechanical properties are assembled with mortar joints with relatively low tensile strength, as in the present case. A Finite Element (FE) based micro-model has been developed. FE mesh is discretized using solid 3D elements, in which at least one element has been assigned in the thickness direction within the mortar joints allowing to keep an average size around 10-20 mm.

Numerical analyses are conducted with the FE-based software Abaqus. Non-linear mechanical properties are addressed taking advantage of the already implemented constitutive model Concrete Damage Plasticity (CDP). Although originally conceived for concrete-based material, it has been widely used with success for modeling masonry structures in both static and dynamic non-linear analyses [15]. CDP is an isotropic elastic-plastic constitutive model with damage and able to describe distinct behaviors in tension and compression regimes, in which exponential/linear and parabolic softening laws can be assigned, respectively. As it will be shown in the next sections, the authors assumed that material non-linearity is lumped on mortar joints only and brick units have a linear elastic behavior. Such consideration is valid for the present type of weak-joint masonry as damage onset tends to occur on mortar joints. Mechanical properties are gathered in Table 1. Tensile strength of 0.20 MPa has been assumed for mortar joints [16]. Mortar tensile softening behavior follows a linear law and fracture energy of 0.02 N/mm. In compression, a strength value given as 5 MPa is set, since the mortar planned to use in the experimental tests is a standardized M5 type, and fracture energy of 1.00 N/mm is assigned [16].

Table 1. Mechanical properties adopted for the masonry components.

	E [MPa]	**f_c [MPa]**	**f_t [MPa]**	**G_t [N/mm]**	**G_c [N/mm]**
Bricks	5000	-	-	-	
Mortar	1500	5	0.2	0.02	1.00

OUT-OF-PLANE NUMERICAL RESPONSE OF THE U-SHAPED URM WALL

Numerical analyses have been performed to evaluate the mechanical behavior of the English bond U-shape masonry wall. Parametric (sensitivity) analyses have been conducted and only for the unreinforced masonry case. This is a key and fundamental step as it will allow defining the correct set-up with the view of applying different strengthening techniques on the same configuration (in terms of geometry, pre-stress level and boundary conditions). Firstly, the initially planned geometric configuration given in Figure 2 has been analyzed. Quasi-static ('Pushover') analyses have been carried out to simulate the experimental airbag load. Note that a uniform pressure on the internal side of the U-shaped wall has been assumed. The analysis is conducted under load-control and with an arc-length algorithm to enable following the occurrence of any decrease in the capacity load. Fixed boundary conditions are applied at the base of the wall where a mortar layer (with the same mechanical properties used for the joints) is posed. Taking into advantage the symmetrical conditions only half wall is modelled, taking care of assigning the correct boundary conditions at the middle section. The final FE model has around 150,000 3D solid linear elements that allow a reasonable compromise between accuracy and computational time (Figure 3). Moreover, it is important again to highlight that the possibility of damage is lumped exclusively in the mortar joint, keeping the brick units working only under an elastic regime during all the load-history.

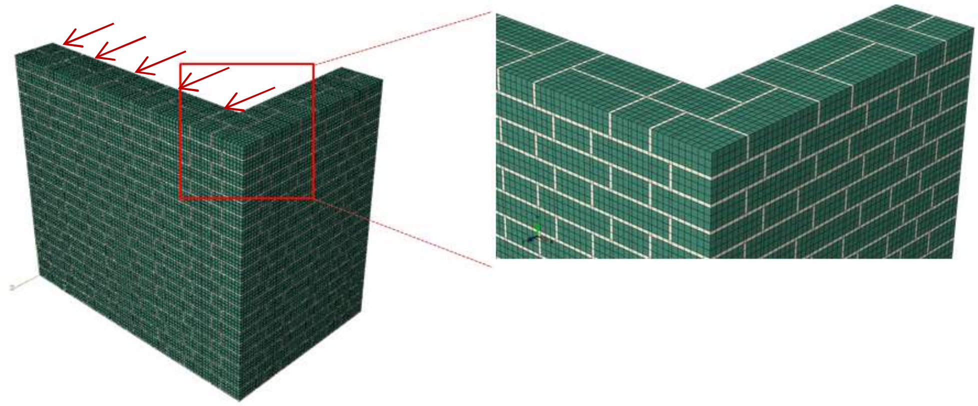
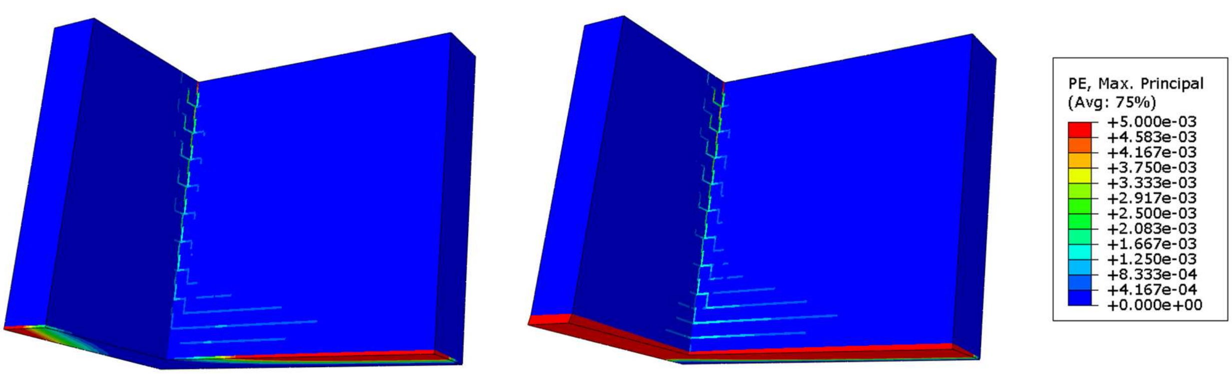


Figure 3. The perspective of the FE Model and detail of the adopted FE mesh.

The analyses conducted on the initially planned configuration revealed a marked predisposition of all the structure to rock without leading to evident damage at the orthogonal connection that is the point of main interest (especially for future comparison between strengthening solutions). As it can be appreciated from Figure 5, the softening branch is mainly caused by the progressive occurrence of damage at the base of the sidewall that consequently leads to the rocking of all the U-shaped wall. In such a way, the sidewalls do not provide an adequate constraint for limiting the rotation of the main wall.

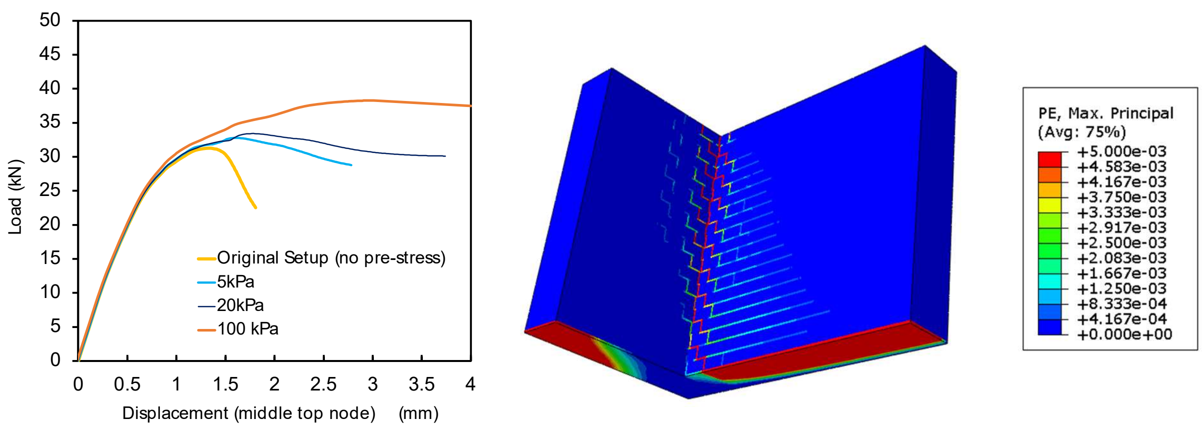


(a) Damage at the peak load (b) Damage at the end of softening branch

Figure 4. Damage pattern found for the initially planned configuration of the U-shaped URM wall.

Parametric analysis: vertical pre-stress level

Following the undesired rocking response expected when assuming the initial planned geometric configuration for the URM U-shape wall, a parametric analysis has been performed. The first parameter that has been analyzed is the relative importance of the vertical pre-stress that acts on the sidewalls and represents the RC slab of 'placa' buildings. Three different values have been considered, namely 5 kPa, 20 kPa and 100 kPa. As can be appreciated from Figure 5a, the imposition of a vertical pre-stress reduces the softening behavior of the global response. Yet, the rocking of the wall is only delayed and the damage at the connection remains lower than the desired one (always in view of future tests on strengthened configurations). The application of a pre-stress equal to 100 kPa is the only one that ensures a marked increase of the peak load and visible damage even at the connection (Figure 5b).



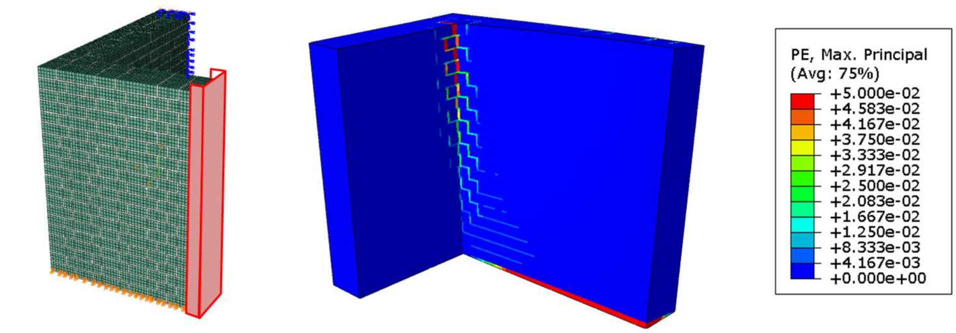
(a) Capacity ('pushover') curve (b) damage configuration for a pre-stress level of 100 kPa

Figure 5. Results for the original geometric configuration.

Parametric analysis: boundary conditions

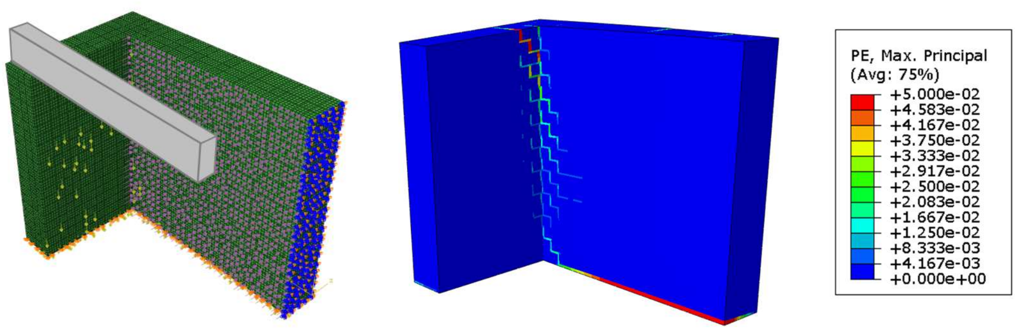
Another possibility that can change the hierarchy of strengths, i.e. to postpone the rocking mechanism, is to further constrain the side walls to ensure an almost undamaged orthogonal connection. Two different approaches can be followed: (i) constrain the back face of the side walls (Figure 6a). This can be done, for instance, by embedding them in U-shaped steel beams connected to a steel frame (as done in [4]); and (ii) constrain the top back corner of the side walls by locating a steel beam between the wall and steel frame (Figure 7a) by avoiding any unplanned rotation (a similar setup can be found in [17]). Numerical results found from the damage pattern (Fig. 6b-7b) show that, in such a way, the rocking of the system is precluded and the main damage spreads at the base of the main wall (as in any hypothesis) and after at the connection. Although these strategies can solve the postponing of the rocking response and prove an apparent efficiency, their effective realization in laboratory may be difficult since the controlling of the load being transferred to the constraints is hard to collect. Another possibility could be ensuring the constrain of the side walls base and of the first layer of brick and mortar (again embedding them in a U-shaped steel beam as in Figure 8a). However, such strategy ensures only a marked delay in the occurring of the rocking at the level of the second layer as can be seen in Figure 8b.

Changing the boundary conditions might be operated also by involving the main façade wall. For instance, by considering its base to be simply supported (a layer of sand between the first layer of the wall and the floor) rather than fixed, as presented in Figure 9a. In this case, a single curvature due to vertical bending moment would be induced. However, this option has been dismissed as it seems to avoid the rocking but leads to a damage pattern that is concentrated mainly at the connection base between walls (Figure 9b).



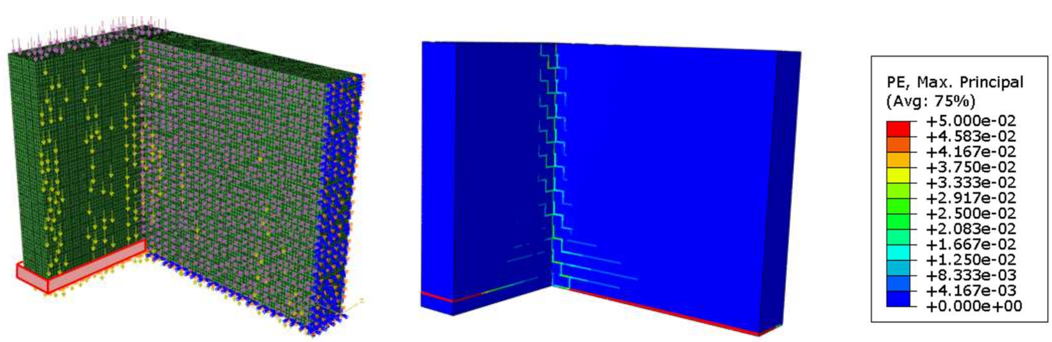
(a) Boundary conditions (b) related damage pattern

Figure 6. Parametric analysis conducted on the effect of boundary condition change at the back face of sidewalls.



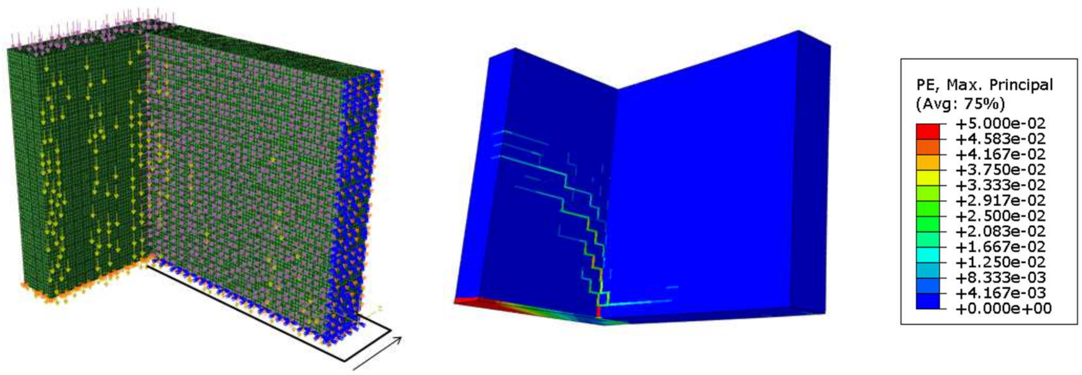
(a) Boundary conditions (b) related damage pattern

Figure 7. Parametric analysis conducted on the effect of boundary condition change at the top face of sidewalls.



(a) Boundary conditions (b) related damage pattern

Figure 8. Parametric analysis was conducted on the effect of fixing the first two layers of brick units.



(a) Boundary conditions (b) related damage pattern

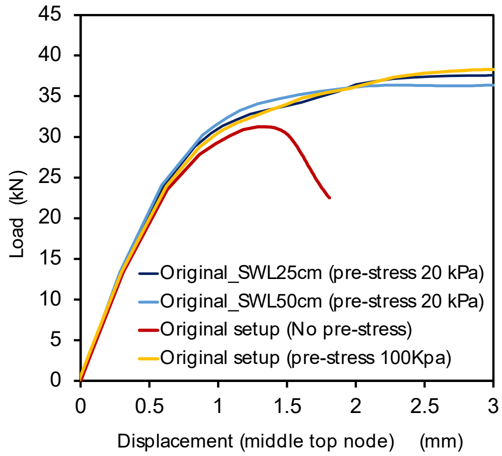
Figure 9. Parametric analysis was conducted on the effect of releasing the bottom face of the main wall.

Parametric analysis on the geometric configuration

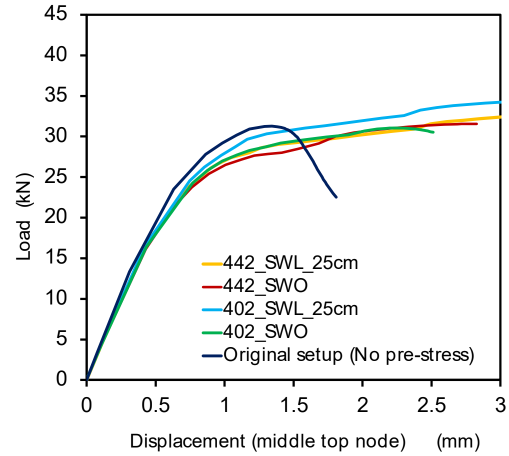
Following the previous conclusions, further parametric analyses have been conducted by varying the original geometric configuration (Figure 11). An increase in the length of the side walls has been considered, for instance, by 25 cm (model 'SWL_25 cm') and 50 cm (model 'SWL_50cm'). For the main façade wall, a length increment of around 80 cm (402_SWO and 402_SWL_25cm) and 120 cm (442_SWO and 442_SWL_25cm) have been assumed. It is important to address that 'O' stands for original configuration and 'L' stands for longer configuration. By comparing the damage patterns and the capacity curves (out-of-plane load vs displacement at the central node of the façade wall), it is interesting to highlight how the increase of the length of the side walls has a much more significant influence than the longitudinal dimension of the main wall. It is enough to extend the sidewalls of around 25 cm to obtain an enhancement of the global behavior and a strong reduction of rocking. Additionally, it can be pointed out that, at the unreinforced stage, it seems that adding another supplementary 25 cm seems irrelevant. Yet, the latter might be relevant when exploring strengthening scenarios. A vertical pre-stress of 20 kPa was imposed on the top of the sidewalls, an amount that eventually can be increased to prevent any rocking in the last stages of lab tests. It is also interesting to notice that such a small increase of the side walls provides capacity curves that resemble the one obtained by imposing 100 kPa on the originally planned geometry (Figure 10a). The load-displacement curves related to the increase of the main wall-length are shown in Figure 10b.

In this case, the softening branch that characterized the original setup is avoided, but at the same time, the rocking is only delayed. An increase of the main wall requires more material for the effective realization and involves a reduction of both the global stiffness and of out-of-plane capacity. Figure 10b also provides the comparison of the accounted geometry variations, namely: (i) main wall extended up to 4.02 m with the original sidewall and the extended sidewall; and (ii) main wall extended up to 4.42 m with the original sidewall and the extended sidewall (Figure

11c). These results are useful to understand if a variation of the geometry is desirable and, if so, to optimally address the resource usage.

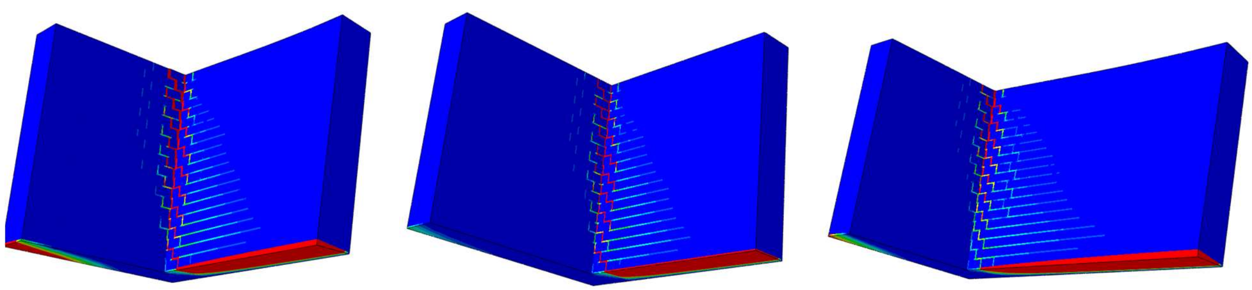


(a) increase the length of the side walls



(b) increase the length of both main and side walls

Figure 10. Capacity curves (load-displacement curves) related to the original geometric configuration.



(a) model SWL_25cm (b) model SWL_50cm (c) model 442_SWL_25cm

Figure 11. Damage patterns found with the numerical simulations.

FINAL REMARKS

Parametric analyses based on numerical FE micro-models have been performed to assess the out-of-plane behavior of a U-shaped English-bond masonry wall. Numerical results provide valuable information concerning different ways of conceiving the experimental setup for upcoming tests that will be carried out at the University of Minho. Such experimental tests intend to investigate the seismic vulnerability of the so-called 'placa' buildings and to better draw effective strengthening solutions. To such an end, particular care needs to be addressed in the final definition of the unreinforced wall set-up. Geometry, pre-stress level and boundary conditions significantly affect the overall behavior of URM structures. Hence different scenarios were explored that allowed putting in evidence the parameters with more relative influence on the global behavior of the wall when subjected to an out-of-plane load. Results have shown the need to adapt the initially planned configuration to avoid a rocking mechanism of the structure. Several alternatives have been found. Note that such a type of failure mechanism is undesirable as it precludes the exploration of energy dissipation at the connection between transversal walls, which will the point of major interest when defining the planned strengthening solutions. By means of such preliminary analyses, the final setup has been defined: i) the side walls with a length of 1.55 m; ii) the main wall with a length in the range of 3.24 m; iii) a pre-compression applied on the top of the side walls equal to 0.2 MPa; iv) a fixed support at the base of wall.

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