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THE BEHAVIOR OF PARTIALLY GROUTED MASONRY WALLS SUBJECTED TO OUT OF PLANE SEISMIC TYPE LOADS. LABORATORY MEASUREMENTS AND NUMERICAL SIMULATIONS

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Abstract

A number of ungrouted and grouted masonry walls were built at the laboratory of Strength of Materials and Structures of Aristotle University using an innovative clay unit vertically perforated. This vertically perforated clay unit was designed and produced with the proper holes in order to host the required horizontal and vertical reinforcing steel bars. At the same time the remaining holes are filled with expanded polystyrene parts capable to provide sufficient thermal insulation and drastically reduce the energy consumption. The specimens constructed with the thin mortar method using a high strength mortar and employing vertical reinforcing bars of different diameters. The measured behavior is depicted here in terms of horizontal applied load versus the horizontal displacement at mid height. Furthermore, numerical models were developed in order to simulate the observed behaviour of the tested specimens by modeling separately the masonry panels as homogenized material and linear beam elements representing the employed longitudinal (vertical) reinforcement. The numerically simulated behavior resembles the measured load-deformation response of the tested specimens and the observed actual damage at the end of the tests.

Keywords: Partially grouted masonry, out of plane bending, Laboratory measurements, Numerical Simulations.

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1 INTRODUCTION

The vulnerability of unreinforced masonry walls subjected to seismic loads was highlighted during past earthquake events [1, 2]. The employment of reinforcing bars to construct earthquake resistant partially grouted masonry structures with acceptable performance is one possible solution. The in-plane behavior of such structures has been widely investigated. Manos et al. [3, 4] tested partially reinforced piers with different reinforcing schemes under in plane cyclic loads. Recent studies investigate the in-plane behavior of reinforced masonry walls using new clay units with the appropriate thermal properties in an effort to improve the structures energy consumption [5, 6]. Over the literature there are both experimental and numerical investigations about the out of plane response of reinforced masonry walls focusing on the effect of the aspect ratio, boundary conditions, reinforcing ratio etc. [7, 8].

An ongoing research of Laboratory of Strength of Materials and Structures deals with partially grouted reinforced masonry walls constructed with a novel clay unit. A key issue in the construction of these walls is the masonry unit employed. The geometry of this new unit was defined using parametric numerical predictions taking into consideration not only the mechanical properties, but also parameters like thermal properties, production cost and ease of construction practice [9, 10]. In this paper the out of plane behavior of ungrouted and partially grouted masonry wallets is discussed. Results are presented from tests of unreinforced masonry wallets or reinforced with vertical rebars of different diameters, which are subjected to cyclic out of plane bending. The mechanical properties of all the employed materials are defined through testing. Following, numerical models were developed utilizing all the geometrical and mechanical properties in order to replicate the experimentally measured out of plane behaviour. All these results are presented and discussed focusing on the influence of the reinforcing arrangement in the overall in plane response.

2 SPECIMEN CONSTRUCTION AND MATERIAL PROPERTIES

The geometry of the employed clay unit is depicted in Figure 1. The basic mechanical properties of this unit were measured at the Laboratory. More specific, unit's compressive strength perpendicular to the bed joint and parallel to the bed joint are measured by compression test according to EN772-1 [11]. The proposed reinforced masonry system uses the construction technique of thin mortar joint. The mechanical properties of the mortar material used, were obtained by material testing according to EN1015-19 [12]. The same mortar is used as grout to fill the vertical holes when a rebar is placed. Additionally, tensile tests for the used reinforcing steel bars with diameter 10mm, 14mm and 16mm were conducted. The above mentioned propertied are listed at table 1 and table 2.

The used vertically perforated units with nominal dimensions length=210mm, height=240mm and thickness=300mm form a vertical hole between the units with dimensions about 75x75mm aiming to be used for the placement of the concentrated vertical reinforcing bar (figure 1).

All specimens were built by builders following the relevant prototype work conditions. The constructed specimens (length 970mm, height 1700mm and a thickness of 300mm) were tested under cyclic out of plane bending. Before the out of plane loading, all specimens where subjected to uniform compressive load equal to 4tn, which was kept constant during the out of plane loading sequence and was measured by a load cell. The horizontal load was applied at the mid height of each wallet by an actuator and was measured by a load cell. Displacement transducers were also used to measure the out of plane deflection of each specimen. All measurements were used to obtain the performance of each specimen in terms of out of plane load applied at mid-height versus the out of plane deflection, as it is showed below (section 3).

Brick unit	
mean compressive strength perpendicular to bed joints (f_b)	8.12 MPa
mean compressive strength parallel to bed joints ($f_{b,h}$)	2.73 MPa
Mortar	
compressive strength (f_m)	13.47 MPa
flexural strength (f_{mt})	2.80 MPa

Table 1: mechanical properties of masonry materials used.

steel bar's diameter	yield stress (MPa)	ultimate stress (MPa)	yield strain	ultimate strain
D10mm	580	680	2.9‰	10%
D14mm	540	670	2.7‰	12%
D16mm	530	640	2.6‰	11%

Table 2: mechanical properties of steel reinforcing bars

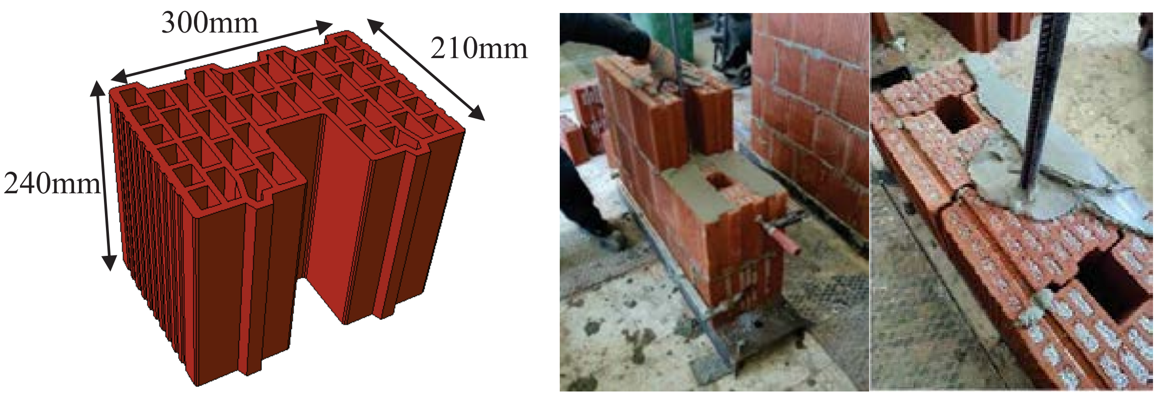

Figure 1: The geometry of the novel brick unit (left) and the employment of vertical bars (right)

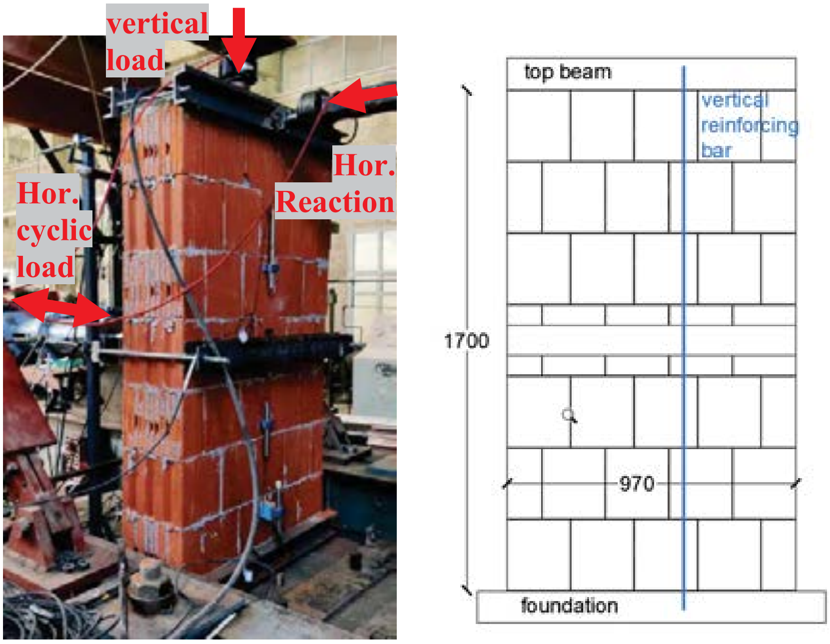

Figure 2: Experimental set-up (left) and the geometry of tested specimens (right)

3 EXPERIMENTALLY OBSERVED BEHAVIOR

The observed out of plane performance of the tested specimens with or without vertical reinforcing bars is presented and discussed in terms of the variation of the out of plane load applied at mid-height versus the out of plane deflection together with the observed damage. Firstly, the performance of the unreinforced wallet is given. Figure 3 (right) depicts the observed performance of the unreinforced masonry wallet without any reinforcement, which represents the control specimen. As can be seen a linear behavior is observed till the first cracking at the minimum load (-5.0KN). At this point the flexural failure of the bed joint develops and it is followed by a sudden decrease of bearing capacity. Following, for the next cycles the bearing capacity is almost constant (+2.3KN, -3.0KN). This performance can be characterized rather brittle. At the same figure (figure 4 left) the formation of horizontal cracking along the bed joint at mid height is depicted.

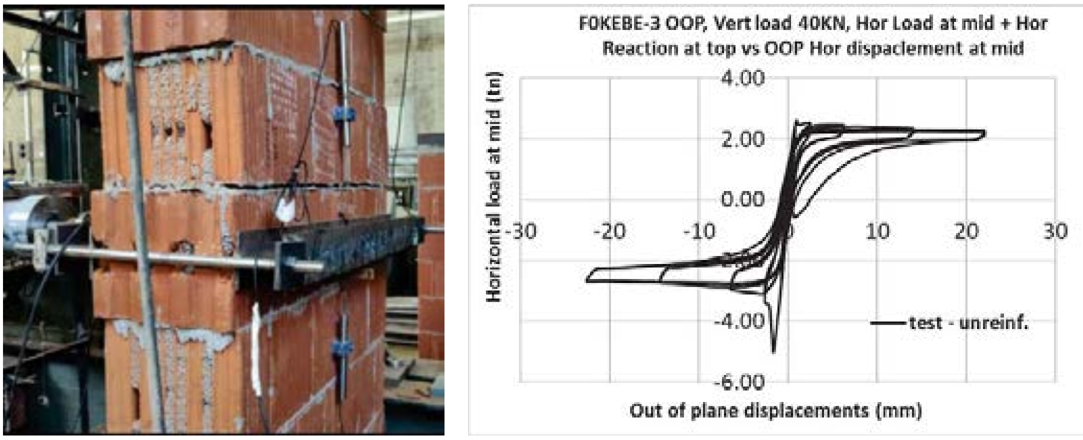

Figure 3: Damage pattern of bare wallet (left) and its response in terms load versus deflection (right)

Following, the response of the tested specimens with vertical reinforcing bars is presented. Figure 4 depicts the observed damage and the variation of the out of plane load applied at mid-height versus the out of plane deflection for a specimen with a vertical rebar of diameter 10mm placed at a vertical grouted hole. The bed joint failure develops again for a negative load about -5.0KN, but for the next cycles a ductile behavior is observed with maximum and minimum measured load +4.8KN and -6.0KN respectively. The formation of horizontal crack at the mid-height bed joint characterizes the observed mode of failure for this specimen.

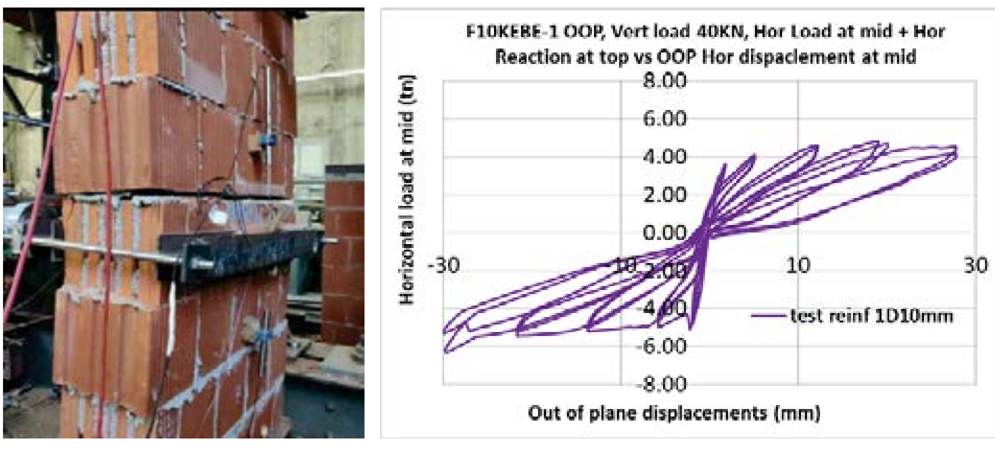

Figure 4: Damage pattern of reinforced wallet with D8mm reinforcing bars and its response in terms load versus deflection (right)

The response of the tested specimens with vertical reinforcing bars with diameter 14mm and 16mm is depicted in figures 5 and 6 in terms of variation of the out of plane load applied at mid-height versus the out of plane deflection and the observed damage pattern. In both cases, the bed joint failure develops again for a negative load about -5.0KN and for the next cycles a ductile behavior is observed with a maximum and minimum measured load +5.9KN/-6.1KN and +6.1KN/-6.2KN for the wallets with reinforcing bar with diameter 14mm and 16mm respectively. The formation of horizontal crack at the mid-height bed joint characterizes the observed mode of failure for these specimens. For the latter stages of the cyclic loading compressive failure of the outer face of bricks developed.

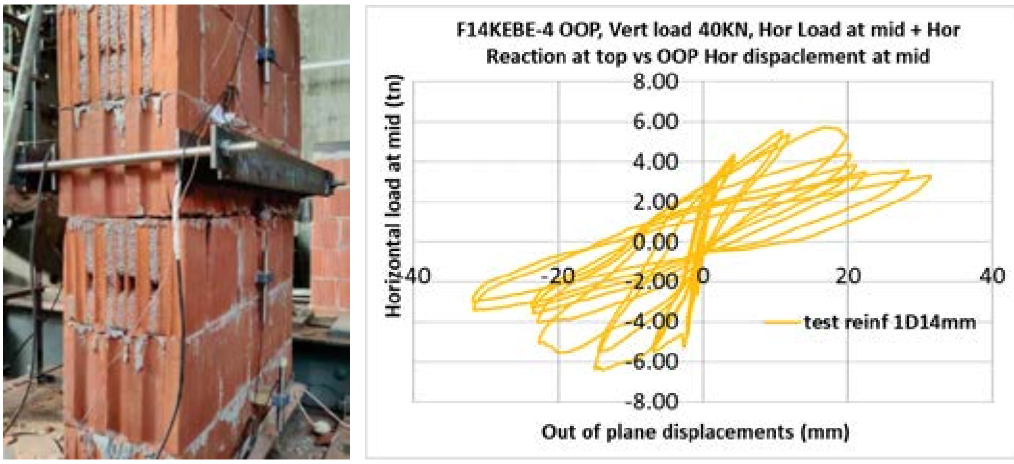

Figure 5: Damage pattern of reinforced wallet with D8mm reinforcing bars (left) and its response in terms of load versus deflection (right)

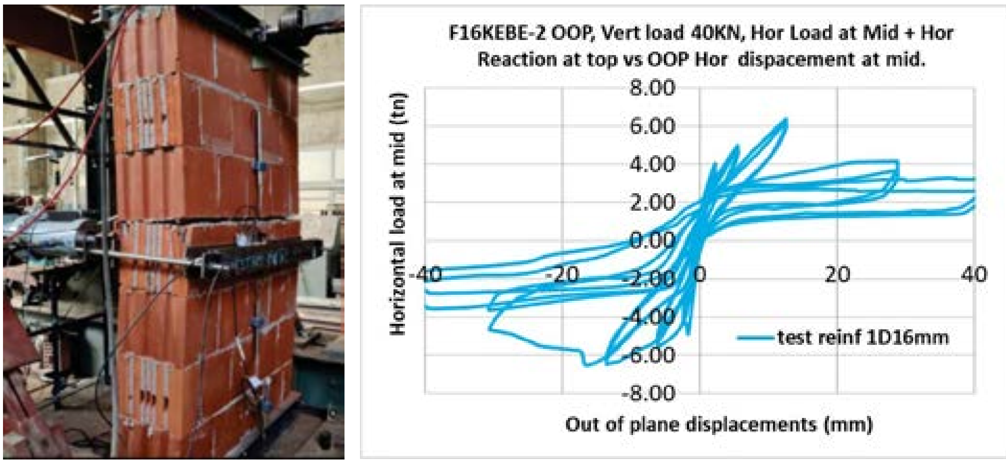

Figure 5: Damage pattern of reinforced wallet with D8mm reinforcing bars (left) and its response in terms of load versus deflection (right)

4 NUMERICAL MODELING

Three-dimensional finite element numerical models were formed, adopting a macro modeling approach with a homogenized material obeying the Concrete Damaged Plasticity (CDP) constitutive law for the masonry, that can satisfactorily represent the behaviour of brittle materials, like concrete or masonry, with different stress – strain laws for compression and tension. Two different material laws were formed resembling the ungrouted and grouted masonry parts. These two laws differ in the Youngs's Modulus and the compressive strength. The material properties assigned to material laws are listed in table 3 and they were obtained by material testing on prism masonry specimens according to corresponding EN Standrads [13,14]. The vertical reinforcing bars were simulated by wire elements given an elasto-plastic material law obtained by the laboratory measurements (see table 2). A perfect bond between masonry and reinforcing bars were assumed. The geometry and details of the numerical model are depicted in figure 6. The numerical predictions includes two monotonic pushover analysis for "negative" and "positive" deflection.

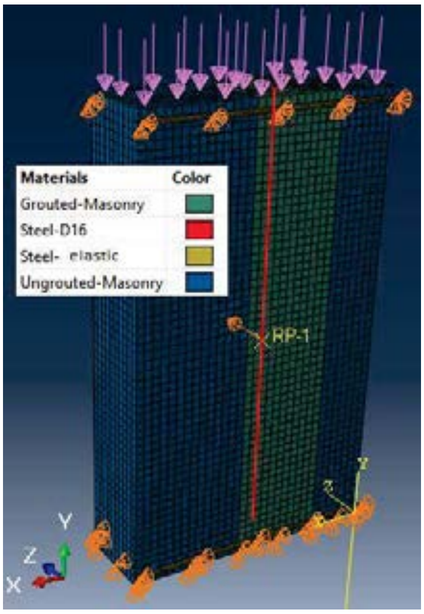

Figure 6: 3D view of the numerical model of the reinforced masonry wallet with a vertical D16mm reinforcing bar.

Concrete Damaged Plasticity – material model assigned to masonry panel		
	Ungrouted masonry	Grouted masonry
Young's Modulus (MPa)	4000 MPa	4700 MPa
Compressive strength (MPa)	3.6 MPa	4.30 MPa
Flexural strength (MPa)	0.2 MPa	0.2 MPa

Table 3: Parameters of CDP constitutive law for masonry material

The damaged pattern of the unreinforced wallet's numerical model is depicted in figure 7 together with the comparison of the variation of horizontal applied load with out of plane deflection response with the corresponding tested specimen. A very good agreement both in load – displacement curve and in the observed mode of failure.

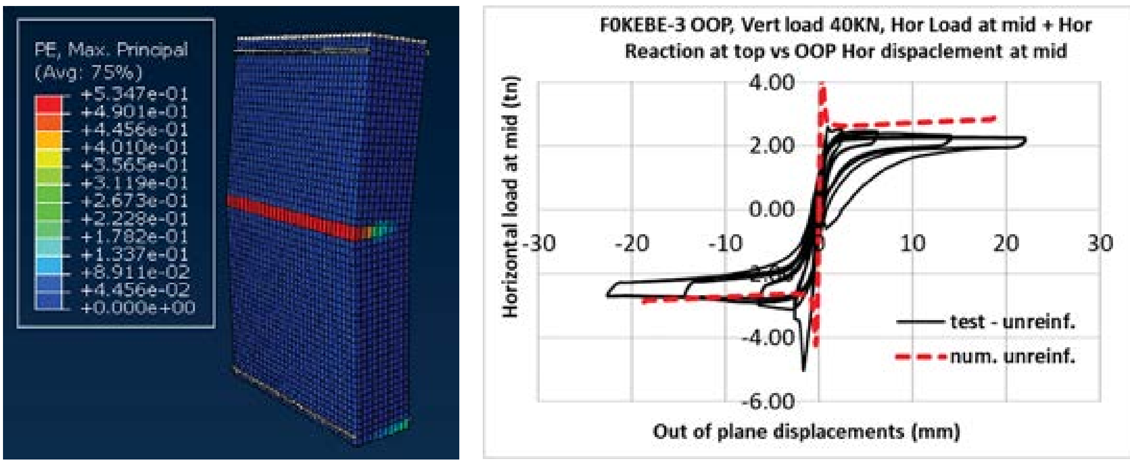

Figure 7: Plastic strains – damage pattern of unreinforced numerical model at the end of loading (left) and its response in terms horizontal applied load versus out of plane deflection (right)

Following, in the previous model a vertical reinforcing bar is added as shown in figure 6 with wire elements. The reinforcing bar is of diameter 10mm, 14mm or 16mm as in the tested specimens. Figures 8, 9, 10 depict a comparison between experimental results and the corresponding numerical predictions for the 3 above mentioned reinforced wallets. In general, a good agreement is observed both in the load – deflection response and in the damage pattern. Additionally, rebar's and masonry's panel plastic strains at the end of the analysis, for an out of plane displacement about 30mm are depicted. The reinforced wall with 1D10mm has relatively large plastic strains developed in the vertical rebars at the bottom and at the mid-height. On the other side, reinforced walls with 1D14mm and 1D16mm developed greatly smaller and no plastic strains at the rebar elements respectively. In these two models significant plastic strains are developed at the compressive zone at the mid-height cross-section indicating compressive failure.

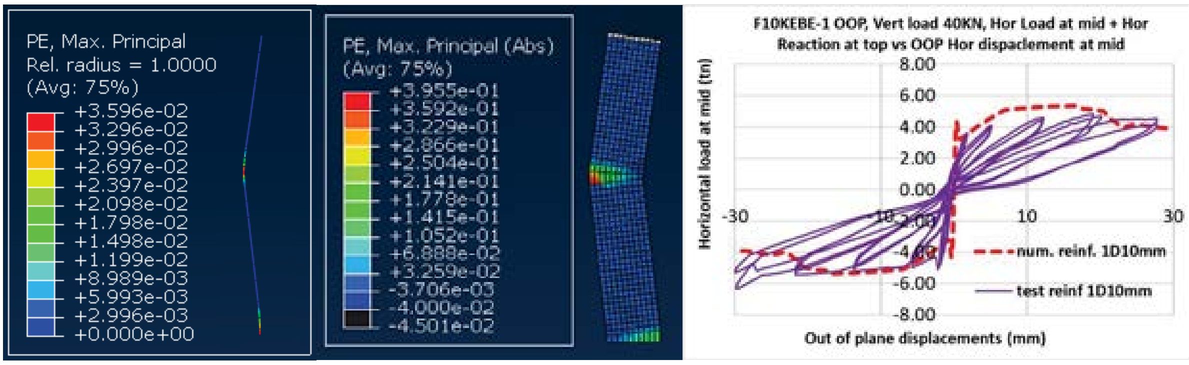

Figure 8: Plastic stains at rebar and masonry panel (left) and horizontal applied load versus out of plane deflection response of numerical model with 1D10mm vertical reinforcing bar, compared with the corresponding experimental measurements (right).

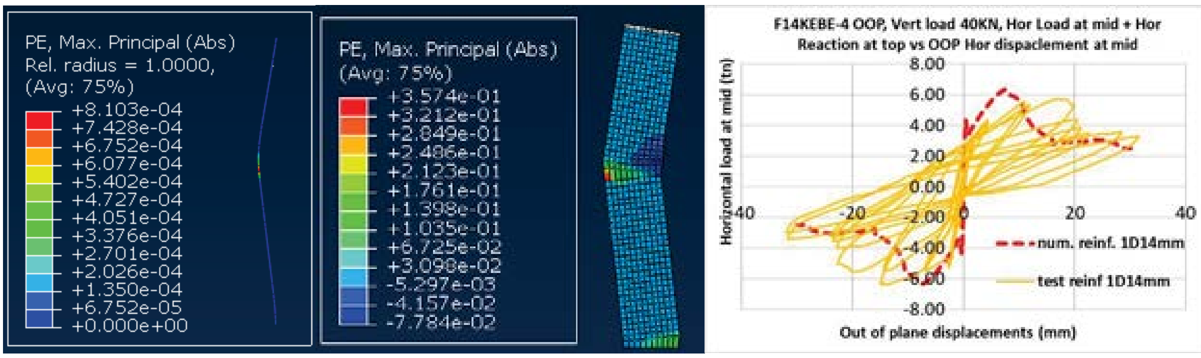

Figure 9: Plastic stains at rebar and masonry panel (left) and horizontal applied load versus out of plane deflection response of numerical model with 1D14mm vertical reinforcing bar, compared with the corresponding experimental measurements (right).

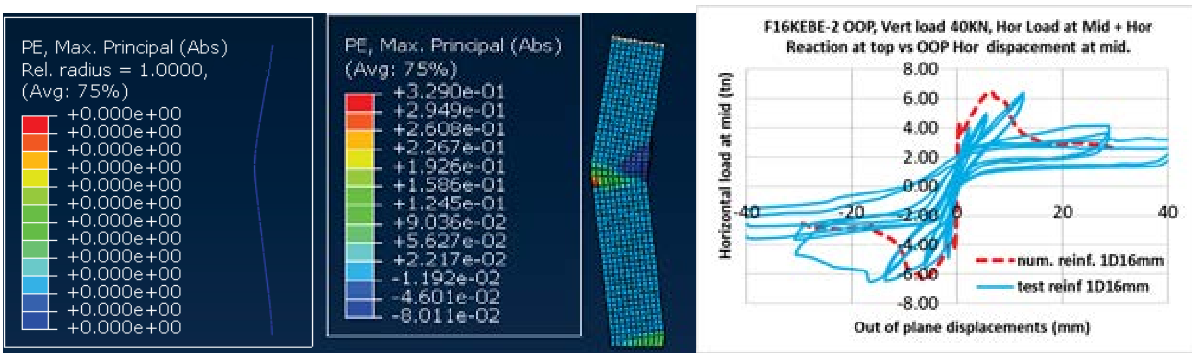

Figure 10: Plastic stains at rebar and masonry panel (left) and horizontal applied load versus out of plane deflection response of numerical model with 1D16mm vertical reinforcing bar, compared with the corresponding experimental measurements (right).

5 DISCUSSION

Figure 3 depicts the response of the unreinforced masonry wall. The applied load is increasing till the bed joints failure starts followed by a sudden drop of the applied load, which from this point and for greater out of plane displacements remains almost constant. As it is showed in figures 4, 5, 6 the existence of a vertical reinforcing bar leads to a further increase of the applied load after the bed joint's failure and as the out of plane deflection is increased. The table below includes the maximum / minimum load for each specimen and the corresponding deflections. For all specimens the mode of failure was the same and was characterized by the bed joints cracking at the mid-height section.

Apart from the bearing capacity increase, the existence of vertical reinforcing bars contributes to relatively fat hysteresis loops under the cyclic loading compared to the unreinforced specimen's performance. This fact indicates that the reinforcing rebars have exceeded their yield limit and developed plastic strains contributing in that way to a much more ductile response for the reinforced specimens. Vertical rebar's yield is also confirmed by the numerical predictions. Figures 8, 9, 10 depicts the developed plastic strains of reinforcing bars for an out of plane imposed deflection about 30mm.

	Experimental measurements		Numerical predictions	
Specimen detail	Minimum load (corresponding displacement)	Maximum load (corresponding displacement)	Minimum load (corresponding displacement)	Maximum load (corresponding displacement)
Unreinforced	-5.04 tn (-1.63mm)	2.59 tn (0.94mm)	-4.23tn (-0.38mm)	4.23tn (0.38mm)
Reinforced 1D10mm	-6.31 tn (-30.20mm)	4.85 tn (22.63mm)	-5.35 tn (-16.62mm)	5.35 tn (16.62mm)
Reinforced 1D14mm	-6.40 tn (-10.92mm)	5.72 tn (22.62mm)	-6.31 tn (-7.31mm)	6.31 tn (7.31mm)
Reinforced 1D16mm	-6.54 tn (-16.50mm)	6.37 tn (12.54mm)	-6.43 tn (-6.25mm)	6.43 tn (6.25mm)

Table 2: Summary results of all tested and numerically simulated wallets. Maximum/minimum load is given together with the corresponding displacement

6 CONCLUSIONS

The behavior of reinforced masonry wallets under out of plane bending is discussed here, mainly focusing on the contribution of the vertical reinforcing bars in the overall wallet's response. Apart from the experimental observations, numerical models were developed using all the available information about the mechanical properties of the materials used and the geometrical details in an effort to numerically reproduce the behavior observed at the laboratory. The main conclusions are listed below:

- The observed mode of failure of all specimens was the cracking along the bed joint at mid-height joint
- The existence of reinforcing bar, placed vertically at a grouted hole, contributed in an increase of maximum load measured, proportional to the rebar's cross section.
- The unreinforced masonry wallet exhibited a rather brittle performance, as after the bed joint's crack a sudden loss of the applied load occurred. On the contrary, reinforced masonry walls performed much more ductile exhibiting an "elastic – plastic" response.

- The vertical rebar of diameter 14mm and 16mm, while leading to a further increase of maximum load, exhibit a less ductile behavior compared to the reinforced wall with 1D10mm vertical rebar, due to the failure of the compressive zone at the mid height.
- The developed numerical models discussed here can satisfactorily capture the observed mode of failure, the maximum load measured and up to a point the force – deflection curves.

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