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REINFORCED MASONRY PIERS BUILT WITH A NOVEL CLAY MASONRY UNITS UNDER SEISMIC-TYPE LOADS

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Abstract

The main features of a study dealing with partially grouted reinforced clay brick masonry wall specimens are summarized here. Results from an experimental campaign studying the in-plane behavior of such partially grouted wall specimens, built using novel clay bricks with vertical holes manufactured in Greece, are presented and discussed. All wall specimens were partially grouted at specific locations hosting vertical steel reinforcement. Horizontal (shear) steel reinforcement was also included at the mortar bed joints. These specimens were rigidly attached at a reaction frame and were subjected at their top to a constant vertical load together with a horizontal seismic-type in-plane cyclic load. A key issue in the construction of these wall specimens is the masonry unit which is employed. Due to the thermal insulation requirements as well as the revisions in the provisions of the Euro-Code relevant to the seismic design and construction of unreinforced and reinforced masonry, a novel masonry unit was designed and tested. The design was based on preliminary material tests and a series of numerical simulations. The thermal insulation properties of this new unit were also taken into account in its design as well as the accommodation of the transverse horizontal joint reinforcement that was to be accommodated in a thin layer mortar joint. Summary results of all these aspects in the design and construction of this new masonry unit are present and discussed.

Keywords: Partially reinforced masonry, clay bricks, in-plane behavior, seismic-type loads, Tests-numerical response

1 INTRODUCTION

The main objective of the present study is to validate the local materials and construction practices towards building earthquake resistant low-rise partially grouted reinforced clay brick masonry structures in areas of moderate seismicity of Greece (Manos et al [1-2]). The following summarizes the main features of the experimental program with partially grouted reinforced clay brick masonry wall specimens [1]. Extensive past research dealt with the performance of partially grouted reinforced masonry walls, when subjected to simulated

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seismic loads. Of particular interest is the in-plane seismic behavior. As was shown by Manos and co-workers (Manos [3], Gulkan [4-5]) for low-rise well-built masonry structures, the in-plane behavior can be studied separately from the out-of-plane behavior. When subjecting such masonry walls simultaneously to combined in-plane horizontal and vertical loads (Hidalgo et al. [6], Tomazevic et al. [7]), the most significant parameters that are usually examined are the type and strength of the mortar and masonry units, the geometry of the masonry walls and their reinforcing arrangement (in quantity and structural details), and the level of axial compression (Tasios [8]). Oan Shrive [9] examined the shear behavior of concrete masonry walls whereas Sandoval, C. et al. [10] investigated the in-plane cyclic response of partially grouted reinforced clay brick masonry walls in a way similar to the one employed in the present work. A very important aspect towards materializing this type of construction is the availability of a masonry unit which can accommodate the required partial reinforcement. There is a variety of such masonry units, made mainly either of clay or concrete, which are employed wordwide for reinforced masonry. Moreover, established building codes include the relevant design provisions and construction specifications. Eurocode 6 deals with masonry construction, including reinforced masonry, and Eurocode 8 details certain provisions relevant to designing and constructing reinforced masonry in seismic areas. The employed masonry unit and mortar, produced industrially, should conform to a series of specifications commencing with details of the geometry (Table 3.1 - Geometrical requirements for Grouping of Masonry Units, Eurocode 6), the various mechanical characteristics of the masonry units, the mortar, the resulting masonry, the grout, the used reinforcement and their interaction. Recent studies investigate the behaviour of reinforced masonry walls using novel clay units with the appropriate thermal properties in an effort to improve the structures energy consumption together with an acceptable structural performance [11, 12]. Again, the importance of the units' mechanical properties was noted as the deformation of these masonry walls appeared to be limited by the brittleness of the masonry units, because the crushing failure at the toes of these walls dominated their performance leading to low levels of energy dissipation [11, 12].

2 METHODOLOGY

Ongoing extensive research at the Laboratory of Strength of Materials and Structures (Aristotle University of Thessaloniki) deals with the development of a novel clay brick unit for the construction of load bearing partially reinforced masonry structures. This clay unit included a number of secondary vertical holes filled with expanded polystyrene EPS aiming to achieve proper thermal insulating properties. The main vertical hole is designed to host the desired longitudinal reinforcement. Additionally, two horizontal channels are formed aiming to host the horizontal reinforcing rebars. The final geometry of this brick unit and the configuration of the holes was designed utilizing extensive material testing combined with a series of numerical studies [13-17]. This work summarizes the most fundamental properties of the masonry unit which went though a preliminary design stage (section 3) in order to attain the desired characteristics before being produced industrially. Next, these industrially produced masonry units were extensively tested in order to measure the response of masonry wallets constructed using the novel clay unit under diagonal compression [17] and out of plane bending [16]. Due to space limitations these results are not presented here. However, the main conclusions of these experimental sequences are listed below:

- The shear strength, which was obtained by the diagonal compression tests, is highly affected by the clay unit's compressive strength as the diagonal cracking propagates through the clay units. This mode of failure is predicted in Eurocode 6 as the shear strength is prevailed by an upper limit of 0.065*fb (units' mean compressive strength).

- The horizontal reinforcing bars are not clearly increase masonry's shear strength, but they contribute for the increase on the ductility.
- The observed damage pattern of the diagonal cracking does not change when horizontal reinforcing bars are added and it is directly linked with the compressive strength of clay units used.
- All specimens, either unreinforced or reinforced, under out of plane bending exhibited the same mode of failure, that is 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.

Moreover, a number of masonry specimens were built with these industrially produced units and the selected mortar. These specimens were subjected to constant vertical load together with cyclic in plane load. The details and the results of this experimental procedure are discussed in section 4. Finally, numerical models were developed in an effort to numerically replicate the measured at the Laboratory behavior. The numerical predictions are presented in section 5.

3 DEVELOPMENT OF THE NOVEL CLAY UNIT

The methodology used to investigate the behavior of the new clay brick unit with vertical holes to be used for reinforced masonry low-rise buildings will be briefly presented here. First of all, an extensive experimental sequence was carried out focusing on monitoring basic properties of the ceramic material, that will be used to produce the new clay brick unit in the Laboratory of Strength of Materials and Structures, at Aristotle University. Specimens were subjected to either axial compression (figure 1, 2) or four-point-bending tests (figure 3, 4) in the laboratory, recording the brittle nature of their behavior together with the corresponding axial compression or flexural tensile strength. A 3-D non-linear finite element simulation of these tests was formed including all the geometrical, loading and support details, in an effort to numerically simulate the observed behavior. The numerical models captured successfully the measured brittle load-deformation response (figures 1-4). Moreover, the observed actual damage at the end of the tests resembles the distribution of the plastic strains after the ultimate load is reached, as predicted by these numerical simulations.

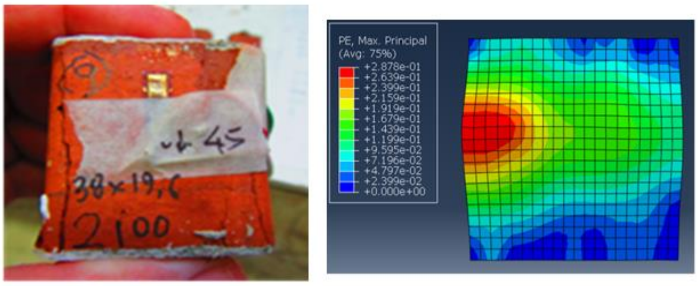

Figure 1: observed and numerically predicted damage ured patterns of the axial compression test,

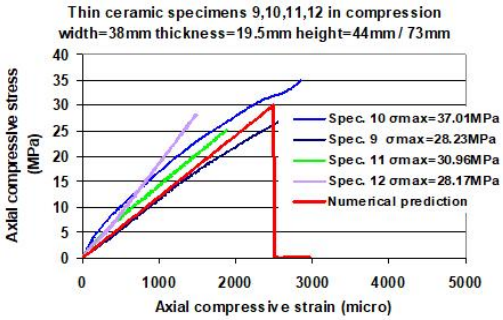

Figure 2: Stress-strain response meas- during the axial compression tests

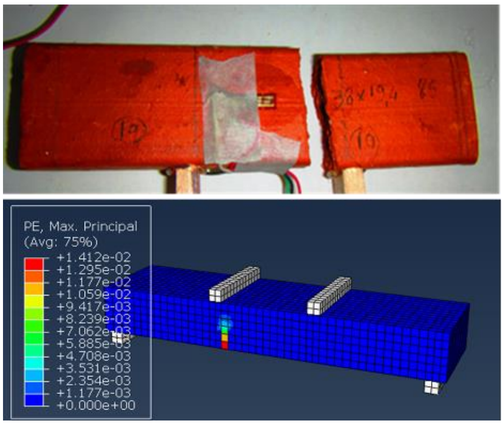

Figure 3: observed and numerically predicted damage patterns of the four-point bending test

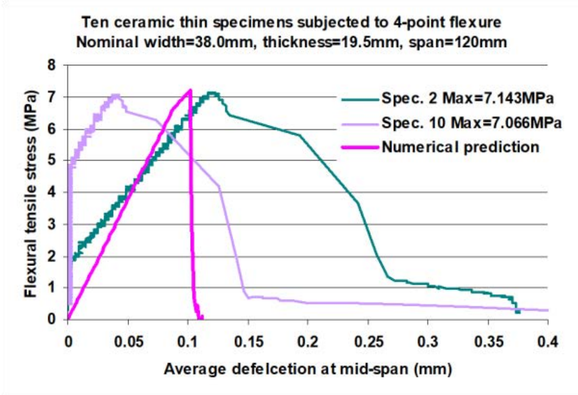

Figure 4: Stress-strain response measured during the four-point bending tests

Based on the numerical models developed before, an investigation about the specific geometrical properties (dimensions, shell thickness, arrangement of holes) of the new brick unit took place. The final geometry of the new brick is depicted in the picture below, figure 5. The numerical predictions of its compressive behavior parallel to the bed joint's direction is given in the diagram below, figure 5. The mean compressive strength of the new unit was predicted to 7.36 MPa according to EN 772-1 [20].

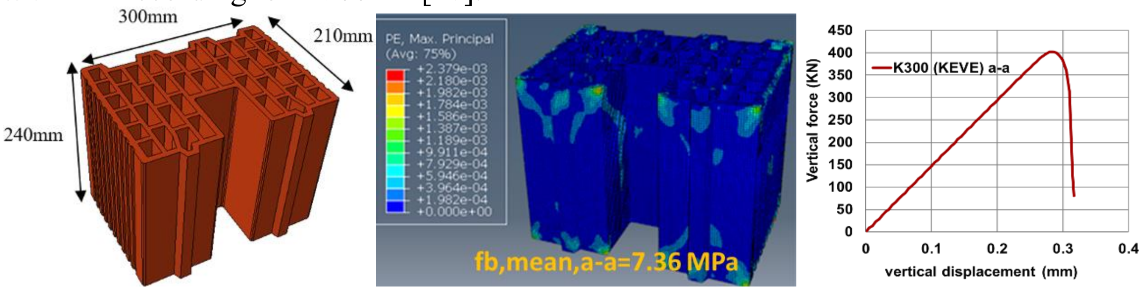

Figure 5. Parametric numerical investigation of the novel clay masonry unit being subjected to axial compression at the development stage.

A number of clay masonry units produced industrially were tested at the laboratory in axial compression. According to Eurocode 8 it is necessary to test the unit's compressive behaviour both in a direction either perpendicular (a-a) or parallel (b-b) to the horizontal (bed) joint of the masonry structural elements to be built with such units as indicated in figure 6 left and right, respectively.

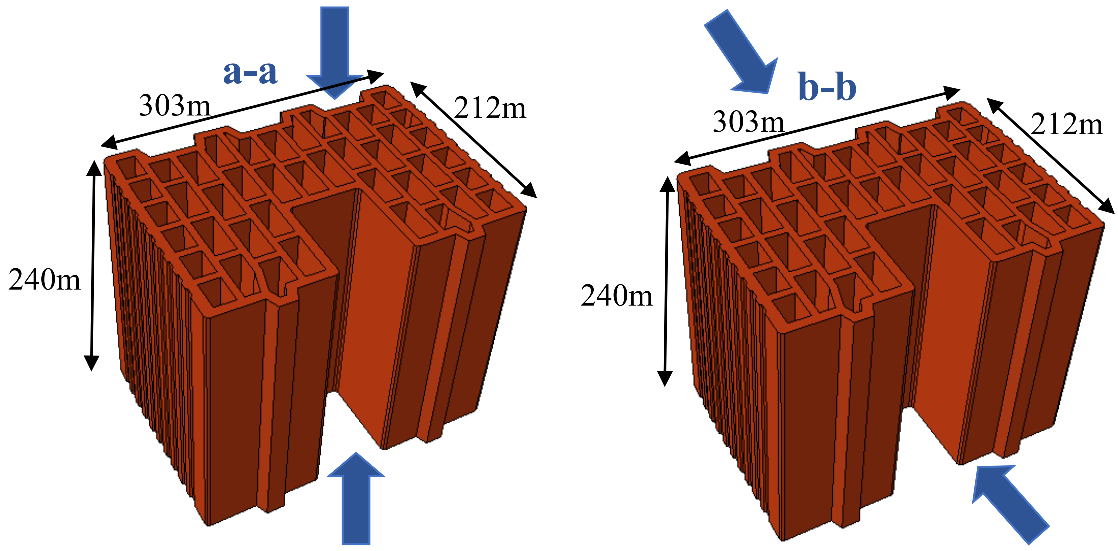

Figure 6. The novel clay masonry unit being subjected to a series of compressive tests at the laboratory.

Table 1 lists the mean compressive strength of the masonry unit either in the a-a or in the b-b direction. Together with the clay masonry units the mortar to be used in the masonry construction was also tested according to Eurocode 6 specifications in either axial compression or tensile flexure [21]. The relevant results are also listed in table 1. For thermal insulation purposes the novel unit was investigated having all the secondary holes filled either with or without expanded polystyrene foam. The distribution of the heat flow from one side (internal) to the other side (external) of a wall built with these units is depicted in figure 7. The main vertical hole which is to host the longitudinal reinforcement was studied in this parametric study being filled with grout or being left unfilled. As it was expected, the filling of the secondary holes with the thermo-insulating material improved substantially the thermal-insulation capacity of the clay unit.

Table 1: mechanical properties of masonry materials used.

Brick unit	
mean compressive strength perpendicular to bed joints (fb1)	8.12 MPa
Characteristic compressive strength perpendicular to bed joints (fb2)	7.14MPa
mean compressive strength parallel to bed joints (fb,h)	2.73 MPa
Mortar	
compressive strength (fm)	13.47 MPa
flexural strength (fmt)	2.80 MPa

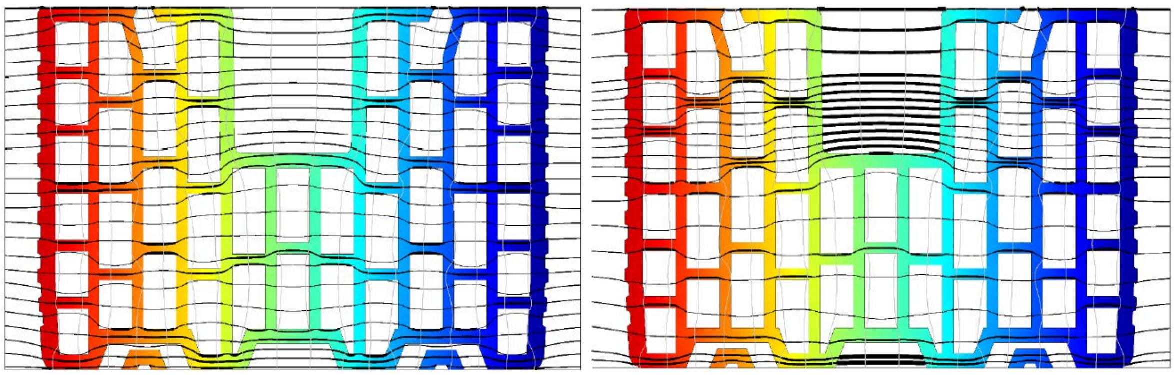

Figure 7. Thermo-insulating study - thermal flow under constant temperature difference with the main vertical hole being unfilled (left) and filled with grout (right).

4 EXPERIMENTAL PROCEDURE

A number of walls were constructed, with thin mortar joints, and tested at the Laboratory of Experimental Strength of Materials and Structures (figure 8). These specimens, with dimensions 1935 x 1400 x 300 mm3 (length x width x thickness), were partially grouted at specific locations hosting vertical steel reinforcement. The details of the specimens are depicted below (figure 9). Particularly, the 1st specimen called SW2, is reinforced with 2 vertical steel rebars with a diameter of 16mm, placed at the two vertical holes at the edges of specimen. The 2nd specimen, called SW1, has an additional vertical rebar with a diameter of 10mm almost at the center of the specimen. The last specimen, called SW9, apart from the 2 vertical rebars, is reinforced with 2 horizontal rebars per bed joint with diameter 8mm. Specimens were tested under constant vertical load equal to 20KN and cyclic horizontal load. The experimental set up includes the rigid support of the specimens at bottom of the wall, simple support at the top edge of the wall in both directions, where load cells are placed in order to record the reaction forces and the hydraulic jack, together with a load, at the mid height of the specimen where the horizontal cyclic load is applied. Displacement transducers were used, as depicted at the figure below, to capture the variation of the deformation of each specimen during the experimental procedure. The experimental results discussed here are presented in terms of shear force at the base of each specimen versus the horizontal in plane displacement at the mid-height.

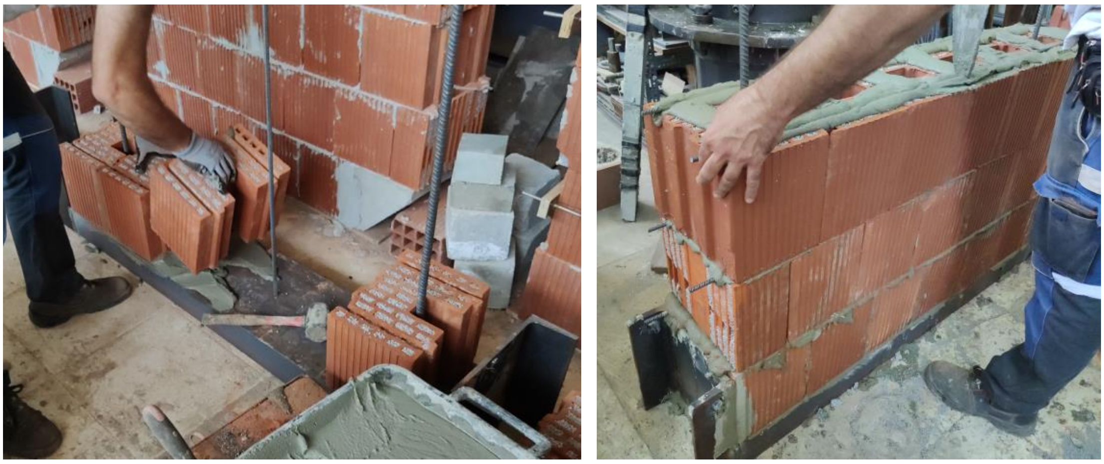

Figure 7. Construction of specimen SW1 with 3 vertical reinforcing bars (left). Placement of horizontal rebars for the SW9 specimen (right).

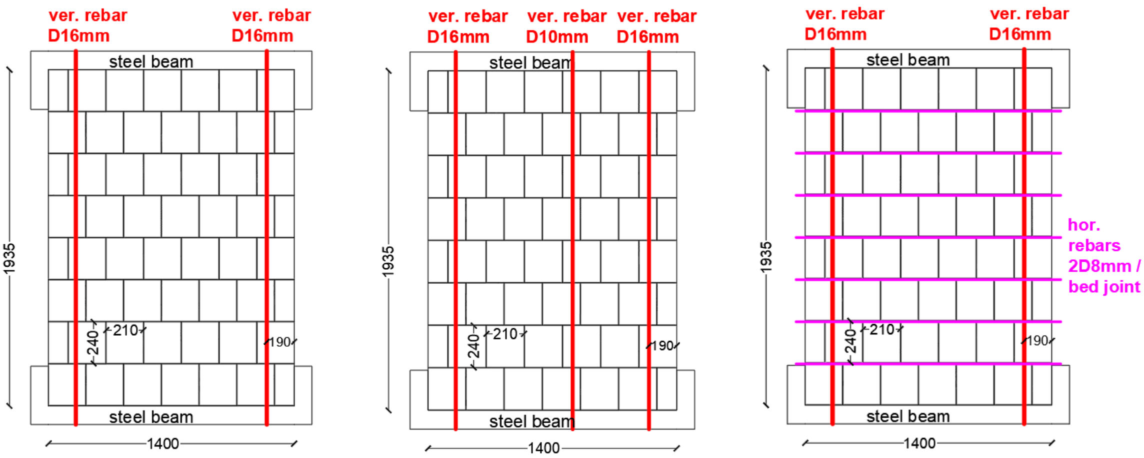

Figure 8. Reinforcing details of the tested at the Laboratory specimens

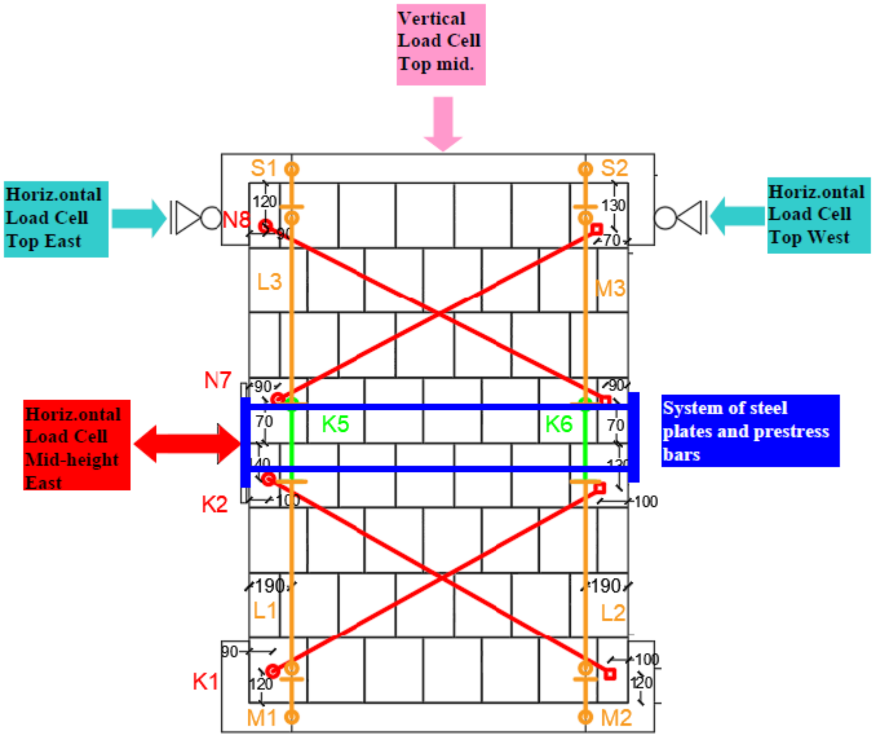

Figure 9. Experimental set up and instrumentation of the discussed experimental campaign.

Figure 10 depicts the variation of the base shear force versus the mid height deflection of specimen SW2. The maximum recorded shear force equals to 274KN, while the average maximum and minimum recorded load equals to 238KN. After the maximum load, the formation of diagonal cracking of clay units appeared, on the lower part of the specimen, while its bearing capacity decreases. For the next cycles of loading, disintegration of the outer face of the clay units, followed by failure of whole bricks.

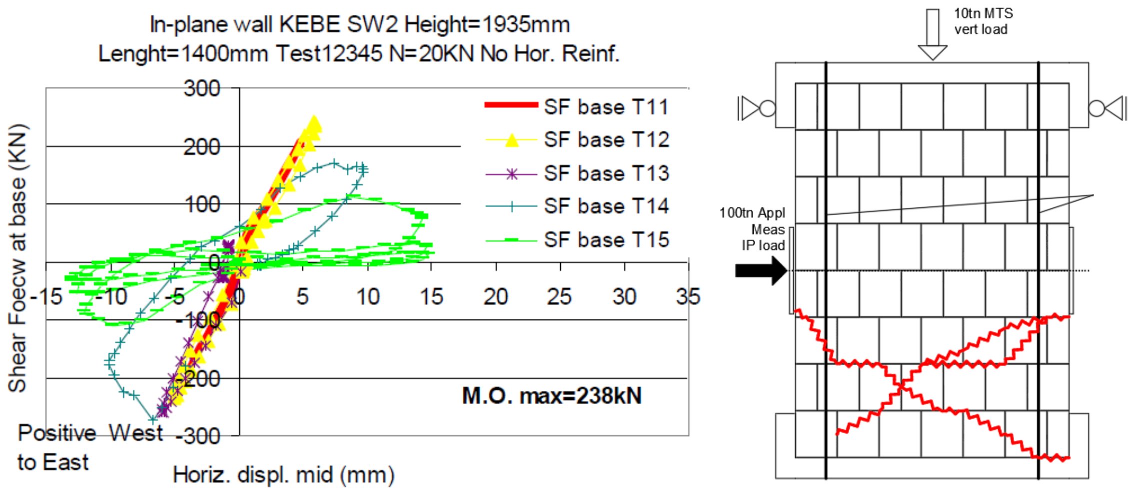

Figure 10. Response of specimen SW2 in terms of shear force at the base versus the horizontal displacement at the mid height (left). Mode of failure after test 4 (right).

Figure 11 depicts the variation of the base shear force versus the mid height deflection of specimen SW1. The maximum recorded shear force equals to 237KN, while the average maximum and minimum recorded load equals to 221KN. After the maximum load, the formation of diagonal cracking of clay units appeared, on the lower part of the specimen, while its bearing capacity decreases. For the next cycles of loading, disintegration of the outer face of the clay units, followed by failure of whole bricks.

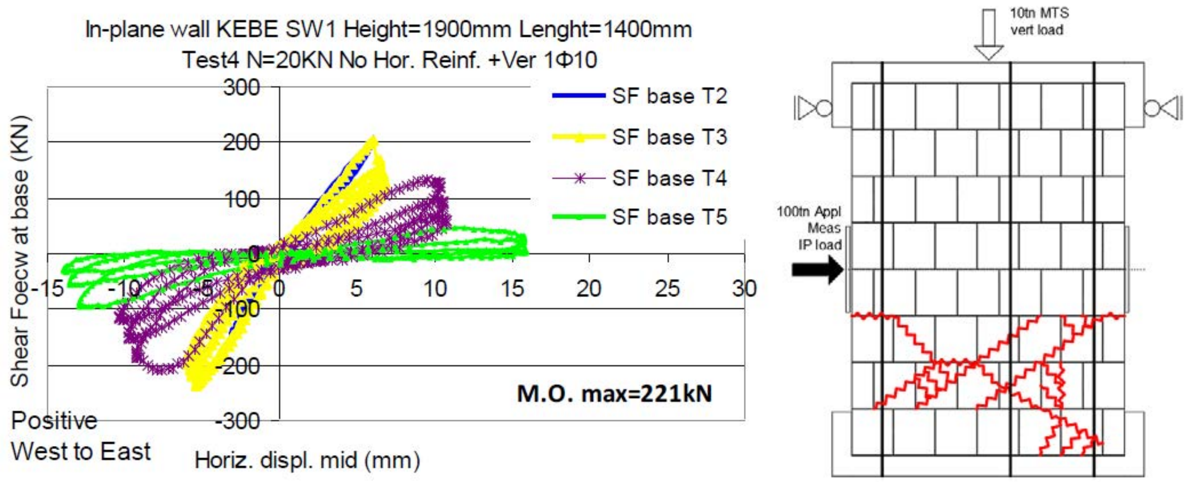

Figure 11. Response of specimen SW1 in terms of shear force at the base versus the horizontal displacement at the mid height (left). Mode of failure after all conducted tests.

Figure 12 depicts the variation of the base shear force versus the mid height deflection of specimen SW1. The maximum recorded shear force equals to 210KN, while the average maximum and minimum recorded load equals to 210KN. After the maximum load, the formation of diagonal cracking of clay units appeared, on the lower part of the specimen, while its bearing capacity decreases. For the next cycles of loading, disintegration of the outer face of the clay units. The horizontal rebars limits up to a point the decrease of bearing capacity, while preventing the complete failure of the clay units.

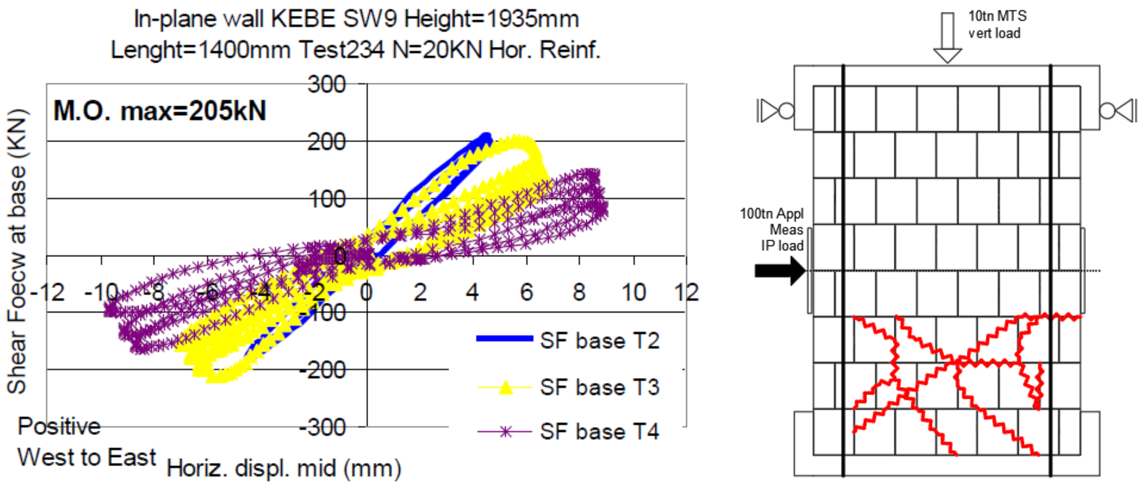

Figure 12. Response of specimen SW9 in terms of shear force at the base versus the horizontal displacement at the mid height (left). Mode of failure after all conducted tests.

CONCLUSIONS

A summary of the methodology used for the design, development and testing of a novel masonry unit with vertical holes capable to host longitudinal steel reinforcement has been presented. This unit was produced towards constructing seismically resistant and energy efficient low-rise partially reinforced masonry housing in Greece. The actual mechanical behaviour of the clay masonry units, industrially produced in Greece, was confirmed by extensive subsequent testing of the produced unit.

The used numerical simulations together with the constituent laws established from basic material testing was successful in the development stage so that the industrially produced clay masonry unit exhibit mechanical behaviour fulfilling the set objectives.

The tested walls under vertical and horizontal loads, in all cases exhibited similar response. The addition of vertical and horizontal reinforcing bars did not increase masonry's shear strength. The observed damage pattern of the diagonal cracking does not change, as it was observed in all specimens and it is directly linked with the compressive strength of clay units used. After the diagonal cracking all specimens exhibited decrease of their bearing capacity, followed with disintegration of the outer face of the clay units and failure of whole bricks. The addition of horizontal reinforcing bars prohibited the failure of whole bricks and improved up to a point the declining branch of the bearing capacity.

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