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RESPONSE OF CONCRETE BLOCK MASONRY WALLS SUBJECTED TO IN-PLANE SHEAR AND FLEXURAL LOADS

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ABSTRACT

This paper presents the results of a study onthe in-plane seismic performance of full-scale unreinforced concrete block masonry (URCBM) walls, commonly constructed in Iran, using numerical simulation. Considering limited studies in this field, an experimental research with the objective of investigating the behaviour of these walls under in-plane lateral loading, is first performed on small-scale masonry wall. The numerical modeling based on micro-modeling, is then developed and calibrated to present similar inelastic load-displacement response and failure mode to those of the tested specimens. After verifying the numerical model, a parametrical study is performed on 3D,full-scale dimensions URCBM wallshaving different aspect (height/length) ratios of 0.5, 0.75, 1, 1.5 and 2, and also with two different boundary conditions; cantilever (flexural behaviour) and fixed (purely shear behaviour). The nonlinear static (pushover) analyses results show that the walls boundary conditions have a profound effect on the lateral behaviour and mode of failure of masonry walls. The failure mechanism of fixed ends walls is predominantly shear, whereas, failure in cantilever walls is generally due to rocking.Also, the lateral capacity of walls decreases with increase of aspect ratio.

INTRODUCTION

Unreinforced concrete block masonry (URCBM) bearing wall building is currently the most common form of construction in southern regions of Iran. These buildings are commonly constructed by local masons without following any engineering design principles or seismic code recommendations. As a result, during recent earthquakes in south of Iran, such as Kaki and Borzjan earthquakes, URCBM bearing wall structures have suffered severe damage, in many occasions leading to collapse, and therefore resulting in significant loss of life and property.

The behaviour of Iranian type of brick walls under seismic loading has been the subject of many experimental and numerical works. Maheri et al. (2011) investigated the effect of mortar head joints and pre and post-construction moisture content of masonry units on the in-plane capacity of brick walls. Also, Najafgholipour et al. (2013) studied the in-plane shear and out-of-plane bending capacity interaction in brick walls.

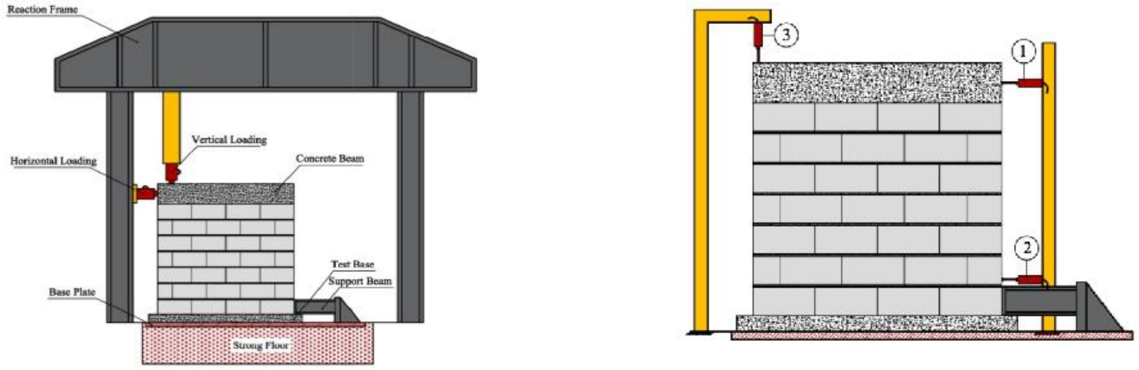
Generally, limited experimental studies on the behaviour of URCBM walls can be found in the literature. As one of the earliest experimental work, Drysdale et al.(1979) investigated the tensile strength of blockwork as the main parameter for concrete block wall in-plane failure and its relation to the angle between the load and the direction of the bed joints. Rahman and Subhash (1994) proposed failure criterion, with empirical Mohr-Coulomb relation, to calculate the modified values of shear bond strength for concrete block-mortar joints. They noted that important parameters other than the elastic moduli of the blocks and mortar, such as surface roughness, chemical composition, water content at the time of testing, gradation of mortar sand and block material, could play a significant role in the joint shear strength.Also, a cohesive interface model was formulated by Giambanco and Di Gati (1997) to simulate the behavior of mortar joints in masonry structures. The adopted yield surface is expressed by the classical bilinear Coulomb condition with tension cut-off and with a non-associated flow law. Miranda Diaz (2007) experimentally investigated the shear behaviour of masonry mortar joints and interface between masonry blocks and reinforced concrete beams and concluded that the properties of the referred joints are significant for the wall overall behaviour, and the inclusion of reinforcing elements in these joints may in some cases serve as a preventive measure and can determine positive implications on resistance and deformation behaviour. Wu and Hao (2008) derived the equivalent material properties of a three-dimensional basic cell of hollow concrete block masonry. In order to model the failure of mortar joint and concrete, a double scalar damage model based on the concept of continuum damage mechanics was applied. Memari et al. (2008) compared the structural behaviour of three types of masonry, concrete masonry unit (CMU), autoclaved aerated concrete (AAC), and adobe, in two different saturation levels, under in-plane shear and out-of-plane flexural tests. The CMU walls showed much more water penetration than the Adobe and the AAC.

Recently, several static cyclic and limited dynamic experimental tests have been carried out to investigate the in-plane behaviour of unreinforced masonry (URM) walls retrofitted using FRP. Mosallam and Banerjee (2011) experimentally and analytically evaluated the behaviour of URM walls with concrete units externally retrofitted with FRP composites.

The main scope of this article is to evaluate the in-plane seismic strength and performance of full-scale concrete block masonry walls commonly used in Iran. This objective is achieved in three phases: (i) considering limited previous study, an experimental study is conducted to investigate the seismic behaviour of such unreinforced walls, which were originally constructed as shear deficient walls, under in-plane loads, (ii) calibration of the numerical model against the experimental results, based on micro-modelling approach so that the resisting mechanism, mainly at the level of unit-mortar interfaces, could be acquired, and (iii) parametrical study based on numerical modeling of three dimensional full-scale URCBM having fivedifferent aspect (height to length) ratios of 0.5, 0.75, 1, 1.5, and 2, under lateral in-plane shear, with different boundary conditions (purely shear and flexural behaviour).

EXPERIMENTAL PROGRAM

Experimental study was performed in the Structural Engineering laboratory at Shiraz University to evaluate the in-plane shear capacity of unreinforced masonry walls. The main goal of the experimental research is to obtain failure mode and force-displacement curve. In this section a discussion on the adopted test specimen, set-up and instrumentation, procedure and results is presented.

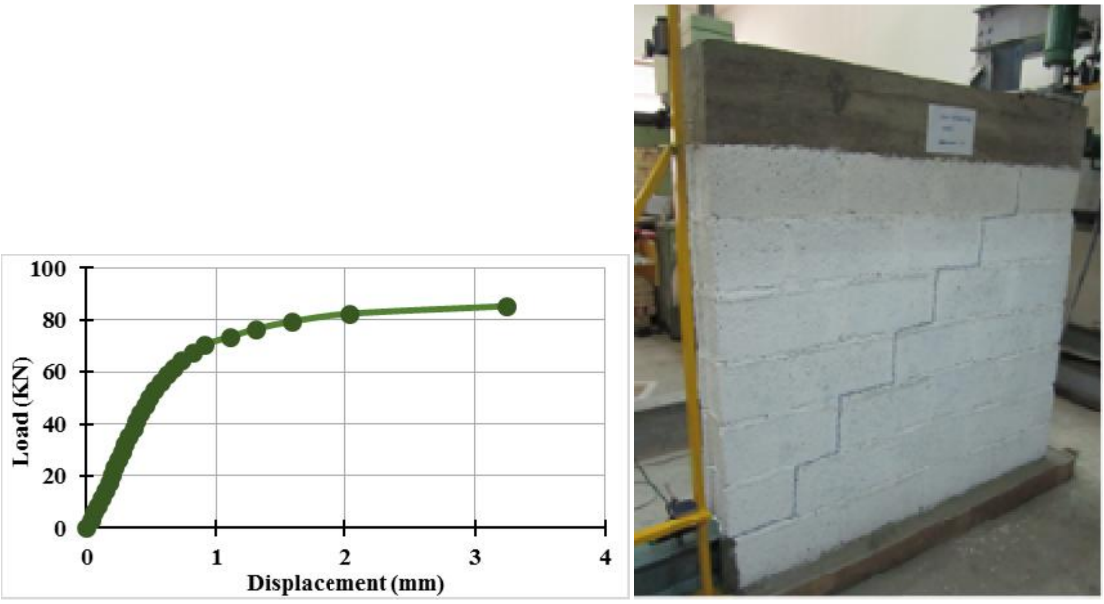


(a) (b)

Figure 1. (a) Test set-up for in-plane shear loading (b) LVDT sensors location

A single-layer URCBMwall was constructed, with ‘non-standard’ workmanship, for the in-plane shear experiment. The term non-standard workmanship refers to using dry blocks that drain the moisture of the mortar, Iranian fine aggregate-cement mortar (ratio of 1:4) and no specimen curing. The wall panel dimension for this test, which were built without mortar head joints, were 1560 mm length by 1330 mm height. Concrete hollow block units having average dimensionsof 390 mm length, 180 mm width and 180 mm height with compressive strength of 14.9 MPa, were used. A 180 mm width and 250 mm hight rigid reinforced concrete (RC) beam, here referred to as the RC loading beam, was constructed over the top of the wall specimen to transmit the shear load and simulate a flooring diaphragm.

The test set-up used in this study and shown in Fig. 1, conforms to one of a number of test set-ups presented by Mayes and Clough (1975) in their state of the art reports and also Maheri et al.(2011)regarding the in-plane shear tests on masonry walls. In this set-up, two hydraulic jacks, one horizontally and the other vertically installed at the end of the concrete beam, simultaneously exert equal loads on one corner of the wall. Meanwhile, the top of the wall is allowed to rotate. The loading step in the test was set at 3.0 kN. In each load step, the wall displacements were measured with displacement transducer and recorded with a digital data logger. Three LVDTs were used to record displacements of the specimen in each loading step (Fig. 1-b). LVDTs were installed on a frame independent of the loading frame to ensure a fixed reference for measurement.



(a) (b)

Figure 2. Experimental results, (a) Force-displacement curve (b) Mode of failure at the end of loading

Since the URCBM failure force was a large number, there was a chance for slippage of specimen over the foundation. Consequently, a support steel beam with high rigidity attached to the strong floor, was located in front of the specimen to prevent possible slippage. The pushover force-displacement curve presented in Fig. 2, shows a linear response at the beginning with an elastic stiffness of 106.2 KN/mm. By increasing the load, the main crack in the form of a stepwise bond failure on the compression diagonal appeared at the load of 85.4 KN. Also, the specimen failed in diagonal tensile mode with cracks passing through the mortar joints (Fig. 2).

NUMERICAL MODELLING

Due to the presence of a vast range of geometrical and structural configurations of masonry, use of physical models to investigate masonry is costly and difficult. As a result finite element method (FEM) has been widely used in the analysis of masonry structures and, various models have been developed to simulate the behavior of masonry. The numerical model applied to study URCBM wall under in-plane loading was defined using the software ABAQUS.

Generally, three approaches exist to model masonry walls using the FEM; detailed micro-modelling, simplified micro-modelling and macro-modelling (Lourenco, 1996).In the present study,considering the lack of detailed information about the mechanical properties of URCBM required to carry out a detailed micro-modelling approach, it was decided to adopt the simplified micro-modelling.

Concrete Damage Plasticity (CDP) model in ABAQUS library was used to simulate the inelastic behaviour of masonry as a quasi-brittle material. This model uses a yield condition based on the yield function proposed by Lubliner et al. (1989) and incorporates the modification proposed by Lee and Fenves (1998) to account for different evolution of strength under tension and compression.Typical yield surfaces for plane stress state is shown in Fig. 3.

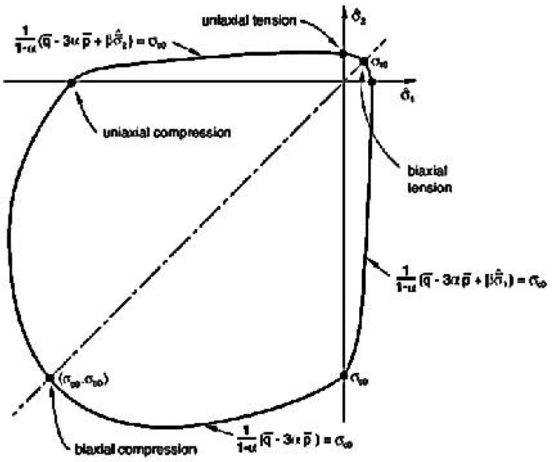


Figure3. Yield surface in plane stress space (Lee and Fenves, 1998)

MODEL VERIFICATION

In this study, the explicit finite element analysis technique was chosen as a suitable method to represent the non-linear behaviour of the wall. The geometry of the walls considered was the same as that used in the experimental test, and the concrete blocks were modeled as perforated units. Also, because of high rigidity of foundation, a rigid plate is used to represent the base.

In terms of boundary conditions, the rigid plate is completely fixed, and the bottom of the wall was assumed to be constrained to the rigid plate. The other boundary conditions are also the same as those in the experimental test.Also, eight-node linear brick, reduced integration, hourglass control (C3D8R) meshes are used to simulate concrete blocks.

The concrete beam is considered to behave linear and elastic, as no damage was observed in that part. The mechanical properties used for masonryare summerized in Table 1. In this table,f'_{tm} and f'_{cm} are the tensile and compressive strengths of masonryobtained from tests, respectively.

As mentioned before, a simplified micro-modelling was developed to conduct nonlinear pushover analysis of the wall. The interface between mortar and units is modeled using coulomb failure criterion, which is based on maximum shear and normal stress applied to the interfaces. The applied contact behaviour parameters to unit-mortar interfaces, are presented in Table 2. In this Table,f_n andf_s are normal bond strength and shear bond strength of interfaces, respectively. Likewise, the coefficients μ_h and μ_v are the friction coefficients of horizontal and vertical joints, respectively. The shear behaviour of dry vertical joints was modeled, with null cohesion and friction coefficient that was appliedto the dry contact between two vertical contact surfaces of units. Defining the surface element allowing the blocks slide on or separate from the other blocks.

Table 1.Verified masonry parameters in numerical model

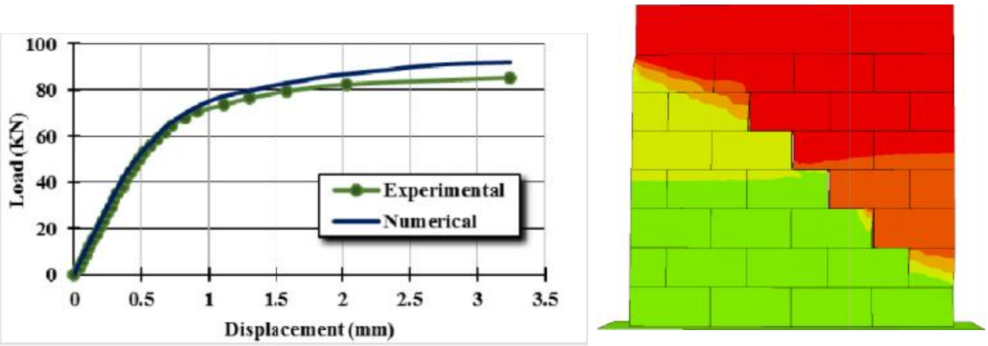
E (Mpa)	υ	Dilation angle	f'_{tm}(MPa)	f'_{cm}(MPa)
7000	0.15	25	1.5	8.5

Table 2.Verified interface parameters in numerical model

μ_v	μ_h	f_n(MPa)	f_s (MPa)
0.75	0.95	0.41	0.58

NUMERICAL RESULTS

The pushover load-displacement curve and crack pattern obtained from the numerical analysis of the URCBM wall under in-plane loading is compared with that obtained from the experiment in Fig. 4. It is observed that the numerical curve matches the experimental curve very well, both in term of elastic stiffness and the maximum lateral strength; the differences being below 10%. Also, the failure pattern of this wall, completely resembles the experimental failure.It can therefore be deduced that the proposed numerical model is capable of detecting the major features of the experimental behaviour of the wall.



(a) (b)

Figure4. Comparison between experimental and numerical of URCBM wall;
(a) Force-displacement diagram (b) Ultimate crack pattern

FULL-SCALE NUMERICAL MODELLING

After verifying the numerical model, parametric analysis of the wall was performed for the assessment of the influences of different parameters on the in-plane behaviour of full size unreinforced concrete block masonry walls. Fivedifferent walls with dimensions of 3 m × 6 m, 3 m × 4.5 m, 3 m × 3 m, 3 m × 2 m and 3 m × 1.5 m, respectively, corresponding to aspect (height/length) ratios of 0.5, 0.75, 1, 1.5 and 2 are investigated. Similar to the concrete block panels, the full-scale walls were one concrete block thick. The wall specimens are subjected to a combination of vertical and in-plane lateral loads, to better represent the seismic action. First, a pre-compression load in the form of vertical stress equal to 0.2 MPa was applied to the top of the RC beam, and was kept constant during the analyses. Then, the nonlinear analyses were carried out under displacement controlled scheme by imposing horizontal displacement to the top of the wall. The bottom edge of the wall was fully restrained. The concrete beam was completely connected to the wall.

In this section, the effects of two possible boundary conditions on the in-plane behaviour of unreinforced concrete block masonry walls are investigated. These boundary conditions include: (i) one endfixed (cantilever), whereby, the wall is allowed to rock and lift up at its heel exhibiting a flexural behaviour, and(ii) both ends fixed, in which, the wall is constrained against rotation at base and at top, hence simulating a pure shear behaviour. Meanwhile, the out-of-plane degrees of freedom of the walls were restrained but they were free to move in the in-plane direction.

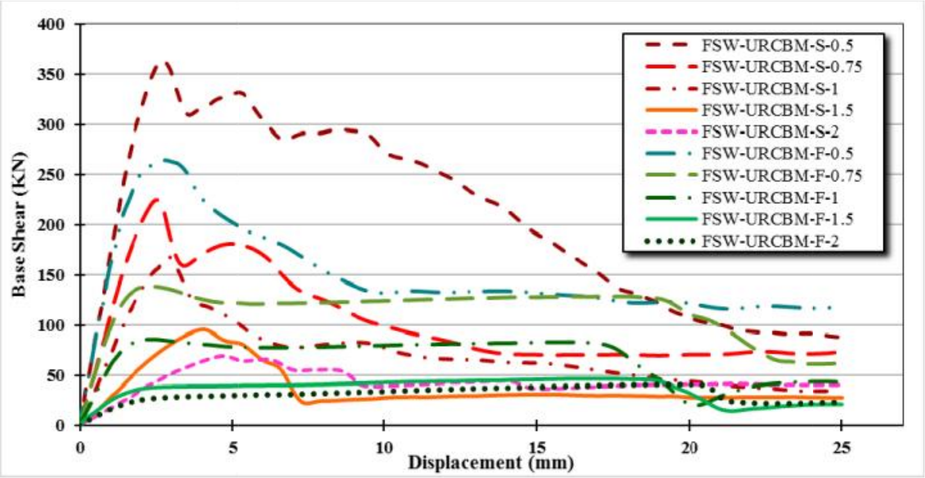
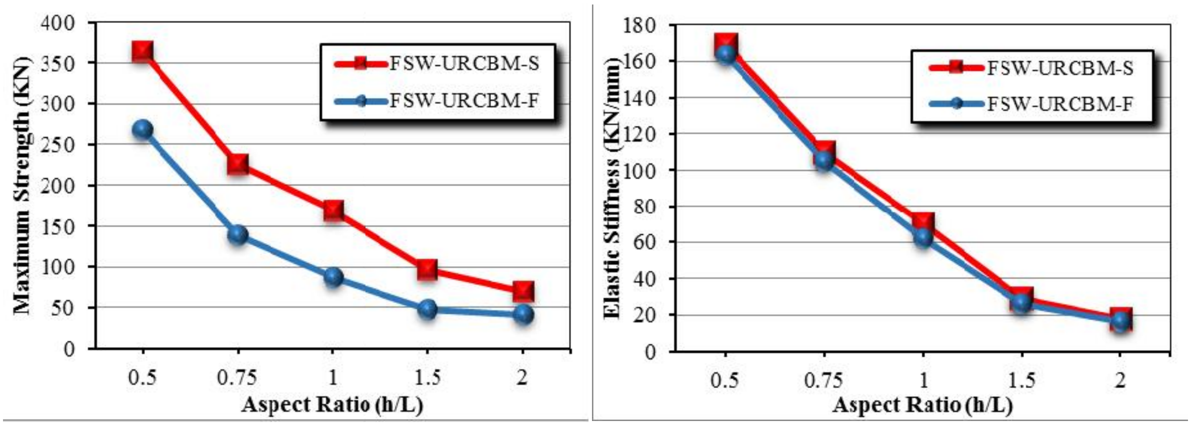


Figure5. Force-displacement curve of unreinforced masonry walls

The force-displacement curves of the specimens, obtained from different analyses, are illustrated in Fig. 5. In this figure, the unreinforced specimens are denoted by *FSW-URCBM-x-y* where, *FSW-URCBM* stands for *full-scale wall-unreinforced concrete block masonry, x* indicates the purely shear (S) or flexural behaviour (F) and y represents the specimen aspect ratio, respectively.Also, the results of the numerical analyses in terms of the maximum strength and elastic (initial) stiffnessare presented in Fig. 6. From the results, it can be concluded that the relation between maximum strength and elastic stiffness is well-described by a power functioninversely proportional to aspect ratio and is independent from the boundary conditions. As the aspect ratio increases, walls maximum strength decreases. It is also observed that the fixed boundary condition enhances the maximum lateral strength from 37% up to 95%. The same is true for the effective elastic (initial) stiffness, fixed boundary condition increasing the effective stiffness up to 14% compared to the cantileverwalls. On the other hand, the both ends fixed boundarycondition decreases the ductility of the wall,and mode of failure becomes more brittle. However, the influence of different boundary conditions on ductility of the wall with aspect ratio 0.5 is almost negligible.

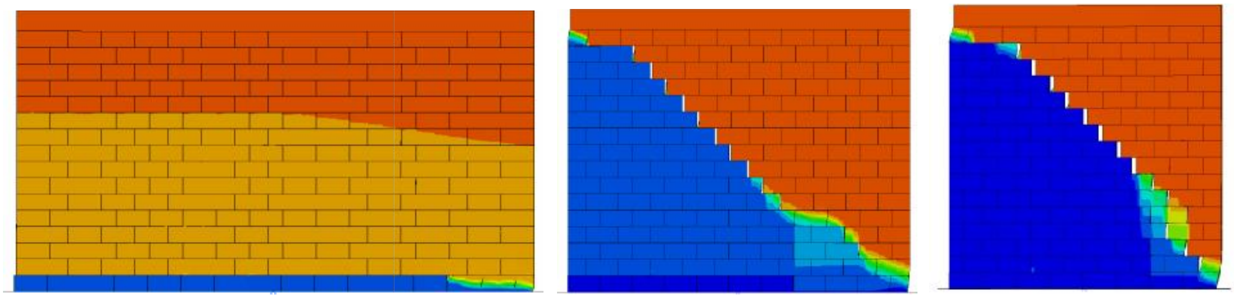


(a) (b)

Figure 6. Influence of boundary conditions on URCBM walls: (a) Maximum Strength, (b) Elastic Stiffness

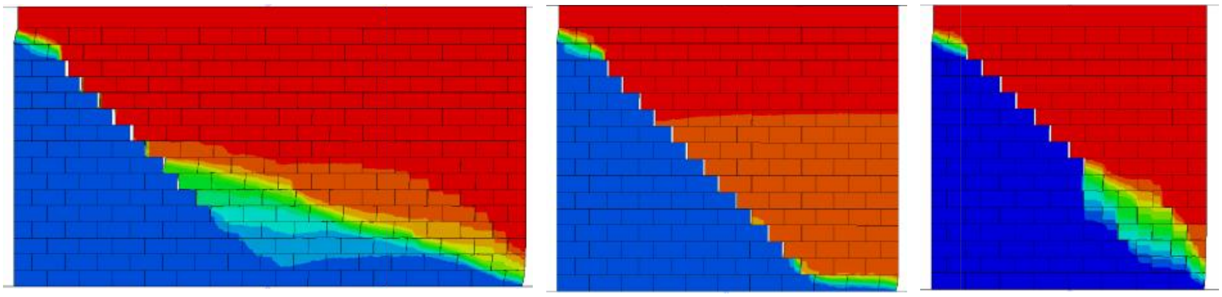
The results also indicate that boundary conditions have a major effect on the walls behaviour and failure mode of the walls. In rocking (cantilever)walls, flexural mechanism governs (Fig. 7, Fig. 9-a, and Fig. 9-b). In all walls failure began with rotation around the toe, while a horizontal crack opened at the base.The aspect ratio has also a significant influence on the mode of failure. By increasing the applied load,wall with aspect ratio 0.5 failed in bed-joint slippage and toe crushing due to the concentration of high compressive stresses,whereas, in more slender wallsdiagonal cracking appeared in the form of stepped crack along the unit mortar interfaces, and through unit-mortar interfaces and masonry units.

On the other hand,with fixed-ends boundary, walls had shear responses, as it is indicated in Fig. 8, Fig. 9-c and Fig. 9-d. All failures began with diagonal cracking. Walls with aspect ratios 0.5 and 0.75 failed in diagonal cracking followed by wall slippage. More slender walls (h/L=1 to h/L=2) had diagonal cracking. However, second diagonal crack appeared in the wall with aspect ratio of 2 joining the first one through vertical cracking due to block failure under applied stresses, as shown in Fig. 9-d.



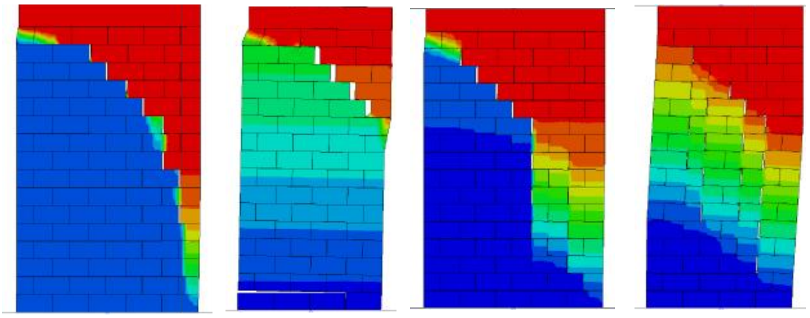
(a) (b) (c)

Figure7.Modes of failure of cantilever URCBM walls (at maximum displacement);
(a) FSW-URCBM-F-0.5, (b) FSW-URCBM-F-0.75, (c) FSW-URCBM-F-1



(a) (b) (c)

Figure8.Modes of failure of fixed end URCBM walls (at maximum displacement);
(a) FSW-URCBM-S-0.5, (b) FSW-URCBM-S-0.75, (c) FSW-URCBM-S-1



(a) (b) (c) (d)

Figure9. Modes of failure of cantilever and fixed end URCBM walls (at maximum displacement); (a) FSW-URCBM-F-1.5, (b) FSW-URCBM-F-2, (c) FSW-URCBM-S-1.5, (d) FSW-URCBM-S-2

CONCLUSIONS

This paper reported on experimental and numerical evaluation of thein-plane response of concrete block masonry walls. A parametric investigation was performed aiming at assessing the influence of the aspect ratio and different boundary conditions on the in-plane responseof full-scale unreinforced concrete block walls. Based on the results presented in this paper the following conclusions can be drawn:

(a) In general, by increasing thewall aspect ratio, shear capacity and elastic (initial) stiffness of the walls decreases. This indicates prominence of flexural response in higher wall aspect ratios.

(b) Boundary conditionsplay a central role on seismic behaviour of URCBM walls under in-plane loading. It was observed that in cantilever walls flexural rocking mechanism is predominant,whereas in fixed end walls shear failure mode prevails. Thus, cantilever walls have less shear capacity but more ductile capacity. However, there is no significantdifference between the elastic (initial) stiffness of these two kinds of wallshaving the same aspect ratio.

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