THE INFLUENCE OF MORTAR HEAD JOINTS ON THE IN-PLANE AND OUT-OF-PLANE SEISMIC STRENGTH OF BRICK MASONRY WALLS

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ABSTRACT :

A sound assessment of the in-plane shear and out-of-plane bending capacities of the load-bearing walls is imperative when conducting seismic assessment or seismic design of masonry buildings. The bulk of work on the subject so far has assumed uniform construction with the brick units connected to each other by mortar bed joints as well as head joints. However, in many construction practices, either for architectural purposes or for speeding up the construction process, the head joints are omitted. This omission may have a profound effect on the response and the strength capacities of the wall. In this paper, results of a number of tests carried out on half-scale brick wall panels, having different material properties, with head joints and without head joints are presented. The walls are subjected to in-plane, as well as out-of-plane pushover loads to failure and their load-displacement curves are established. It is found that, depending on the material properties and the modes of failure of the wall, the head joints contribute 40% to 50% to the in-plane shear capacity of the wall. The contribution of the head joints to the out-of-plane flexural strength of the wall is also found to be substantial.

KEYWORDS: masonry, brick walls, head joints, seismic strength, in-plane shear, pushover test

1. INTRODUCTION

The masonry shear walls are the main seismic load resisting elements in unreinfored masonry buildings. The in-plane shear resistance and the out-of-plane bending capacity of the walls are their main lines of defense against earthquake loads. The shear and bending capacities of brick walls are, on the other hand, dependant on the ability of the horizontal mortar joints (bed joints) and the vertical mortar joints (head joints) to transfer the loads through the brick units; they also depend on the mode of failure of the wall. A number of investigators have studied the behaviour of the mortar bed joints and head joints and their effects on the global strength and response of the wall. The prevalent view of the behaviour of the mortar joint, models the response on a Mohr-Columb shear failure mechanism assigning bond strength and friction for bed joints. In an earlier study, Stafford-Smith and Carter (1971) questioned this model and proposed that the failure of mortar bed joints occurs in tension and therefore it may be predicted more rationally by comparing the actual tensile stresses in the mortar layer with its tensile strength. El-Sakhawy, et-al (2002) also investigated the behaviour of mortar joints in masonry walls under shear. They conducted some tests on the brick mortar bed joints to verify the modified elasto-plastic joint model of Fishman and Desai (1987). They concluded that the modified elasto-plastic model predicts the shearing stress-displacement response reasonably well, although the prediction of the normal displacement field is not as good.

On the effects of the head joints on the strength and response of the masonry wall, very little is reported. Mojsilovic and Marti (1997) used a sandwich model to predict the strength of masonry wall elements subjected to combined in-plane forces and moments. Their model considered the force flow within and between masonry blocks using discontinuous stress fields and corresponding truss models. In their model the head joints only contributed to transferring the compressive stresses and no transfer of shear was assumed between the mortar bed joints and head joints. In another study, Schlegel and (2004) numerically evaluated the effects of the head joints on the failure pattern of stone masonry. According to them, due to shrinkage of the head joints and the subsequent loss of bond between the stone and mortar, their contribution to the shear transfer is far less than the bed joints. In one of the numerical models, they assumed no bed joints and obtained a different failure pattern to that of the model with full head joints. However, they did not elaborate on the effects of the head joints on the shear strength of stone wall. Considering the importance of being able to assess the real strength of brick walls constructed without head joints and the absence of sound information on the subject, in this paper, the effects of head joints on the in-plane shear and out-of-plane bending capacities of brick walls and their respective modes of failure are investigated experimentally.

2. IN-PLANE SHEAR INVESTIGATIONS

2.1. Test Specimens and Setup

In total, four, single-layer brick wall panels were constructed for the in-plane shear experiments. The wall panels for these tests were 165cm wide, 145cm high and 11cm thick. Of the four panels, two were made with 'standard' materials and workmanship and two panels were constructed using 'non-standard' materials and workmanship. Also, in each pair of the standard and non-standard panels, one panel was constructed with mortar head joints and another without mortar head joints. In the latter type of construction, the space for the head joints were kept free from mortar by placing flexible poly-foam material in the gap between the bricks. The term; 'standard material' refers to brick units and mortar mixes compliant with internationally accepted norms for masonry construction. In constructing the standard walls, for uniformity of brick properties, compressed pavement brick units were used. Also, the mortar was made of ordinary Portland cement and fine sand (passing sieve # 20) with a weight ratio of 1:3. Also, the term 'standard workmanship', constitutes using the bricks in a state of saturated-surface dry, so that they do not drain the moisture of the mortar and curing the wall panels under polythene sheet for 28 days against loss of moisture. A number of samples were also made for the material and prism tests. These included; compressive and tensile tests on mortar, compressive and flexural tests on brick units, shear, compression and bending capacity tests of brickwork and determination of modulus of elasticity of mortar, brick units and brickwork.

The 'non-standard' wall panels were constructed with commonly used, non-engineered bricks and cement mortar. The traditionally fired bricks in Iran are generally weaker with a higher coefficient of variation. Also in making the cement mortar, instead of sand, fine aggregate is invariably used. In constructing the non-standard wall panels, a weight ratio of 1:4 was used for cement and fine aggregate (passing sieve # 4). Also, in accordance with common practice, in constructing the non-standard wall panels, the bricks were used in a dry state and no curing was performed on the constructed panels.

The test set-up is shown in Fig. 1. In this set-up, two hydraulic jacks, one placed horizontally and the other vertically at the loading end of the concrete beam, simultaneously exert equal loads on that corner of the wall. This loading arrangement would be equivalent to applying a single load on the diagonal of the wall. The loading step in all four tests was set at 3.0 kN. This loading step corresponded to 2% of the estimated ultimate capacity of the strongest panel. Four mechanical dial gauges were used to record the displacements of the wall specimens in each loading step. The positions of these gauges are also shown in Fig. 1.

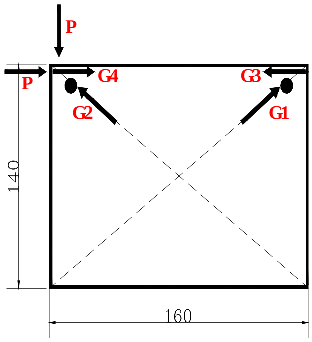


Figure 1. Test setup for the in-plane shear loading of wall panels

2.2. Test of Standard Wall with Head Joints (SWFS)

Considering the material properties and method of construction, the ultimate shear capacity of this wall was estimated as 150kN. The force-displacement pushover curve obtained for the drift (G_3) is plotted in Fig. 2.a. The force-displacement curves shown in Fig. 2 indicate a near linear response of the wall panel up to the 121 kN. A slight change in the slope of the curve beyond this load may correspond to the first cracking of the wall. However, during the test, no cracks became visible until the load of 140kN at which the sudden and explosive failure of the wall panel occurred on the compression diagonal (Fig. 2.b). The diagonal failure was primarily in the form of tensile failure of brick units and mortar joints with a major line crack and a number of smaller parallel cracks running through both materials. As it was expected, the brick-mortar bond slippage on the diagonal main crack was minimal. However, a small crushing zone developed near the loading corner of the wall. The drift measured at the load 121 kN is 0.83mm, giving a stiffness of 145.7kN/mm. Also, the drift at the ultimate load was recorded as 0.99mm.

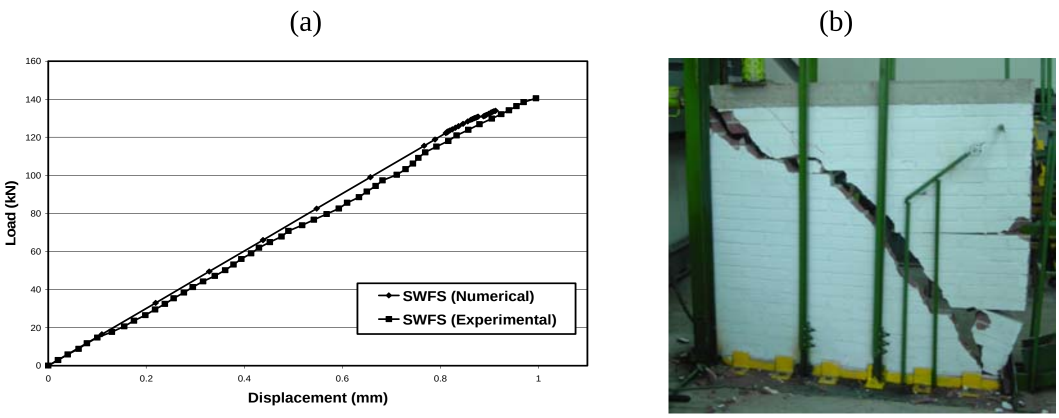


Figure 2. (a) Experimental and numerical pushover curves for wall SWFS and (b) mode of failure of the wall

2.3. Test of Standard Wall without Head Joints (SWES)

The incremental pushover curve for drift measured for this wall during the in-plane shear test is plotted in Fig. 3.a. Similar to the response of the wall with head joints, an almost linear force-drift relation can be observed for this wall. The slope of the curve, however, changes markedly beyond 74 kN load, indicating some form of yielding of the wall panel. However, no cracking could be seen at this load. At 85.5 kN load, the failure of the wall occurred somewhat similar to that of the wall SWFS, with a sudden and explosive cracking on the compression diagonal (Fig. 3.b). In this wall, the crushing zones extended to both ends of the compression diagonal. The main form of failure was, however, parallel diagonal tensile cracks through the bricks and mortar joints with very small sections of bond slippage.

(a) (b)

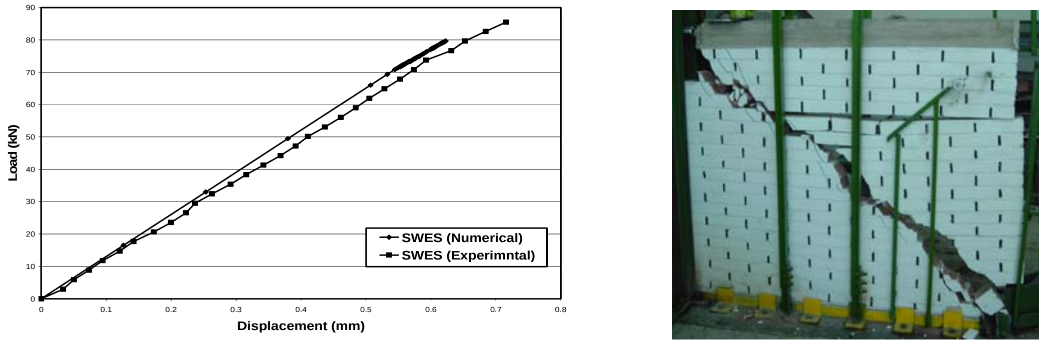


Figure 3. (a) Experimental and numerical pushover curves for wall SWES and (b) mode of failure of the wall

The slope of the drift pushover curve, up to 74 kN provides a stiffness of 125.4 kN/mm for this wall. This stiffness is 13.2% less than the stiffness measured for the wall SWFS, indicating the stiffening effects of the head joints. By comparing the ultimate loads measured for the two walls, it becomes evident that the bed joints had a 39% contribution to the in-plane shear capacity of the wall SWFS.

2.4. Test of Non-standard Wall with Head Joints (NWFS)

The force-displacement curves for the non-standard wall with head joints (NWFS) are plotted in Fig. 4.a. The first crack in the wall appeared at the load of 25 kN. This crack developed horizontally at the joint between the bed mortar and the bricks, one brick layer below the concrete beam. The ultimate failure of the wall, at 31 kN load, was sudden. However, contrary to the failure of the standard walls it was not explosive. The main crack followed, more or less, the compression diagonal in a combination of horizontal and stepwise bond slippage (Fig. 4.b). Small sections of tensile brick and mortar failure beyond the main line of bond failure indicate local flaws in the non-uniform brick units. The stiffness of this wall is calculated as 104.1 kN/mm. This is well below the stiffness of the standard wall SWFS.

(a) (b)

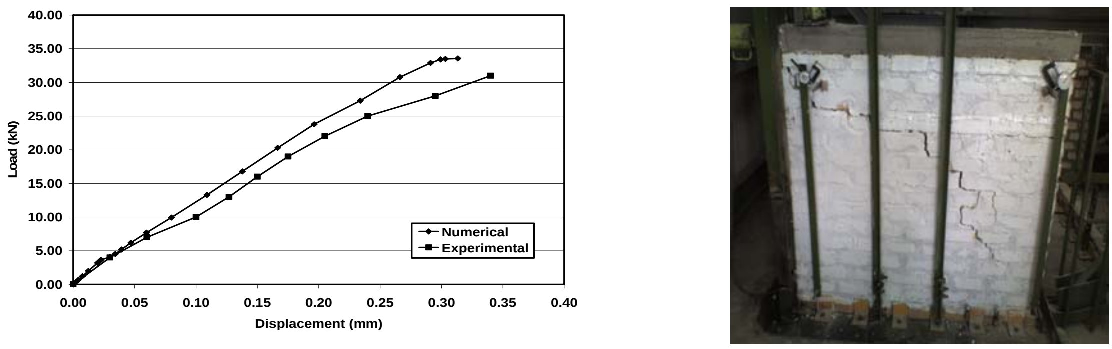
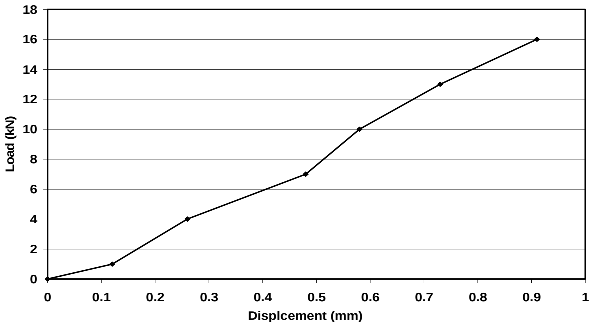


Figure 4. (a) Experimental and numerical pushover curves for wall NWFS and (b) mode of failure of the wall

2.5. Test of Non-standard Wall without Head Joints (NWES)

The pushover force-displacement curve deduced from the test of this wall is shown in Fig. 5.a. Similar to the wall NWFS, the first visible crack developed horizontally, one brick layer below the concrete beam, indicating some form of slippage between the loading beam and the wall. The load corresponding to this local failure was measured as 13 kN. The main crack in the form of a classic and clean stepwise bond failure on the compression diagonal appeared at the load of 17 kN (Fig. 5.b). With application of further loads, a somewhat ductile failure continued with widening of the stepwise crack. The shear stiffness of this wall is calculated as 17.8 kN/mm. This is many folds less than the stiffness of the wall NWFS indicating a drastic reduction in the stiffness of the wall due to the lack of head joints. By comparing the ultimate shear capacity of this wall with wall NWFS, the shear strength contribution of the head joints for these non-standard wall panels is measured as 48%, which is appreciably more than that for the standard walls.

(a)



(b)

Figure 5. (a) Experimental pushover curve for wall NWES and (b) mode of failure of the wall

3. OUT-OF-PLANE FLEXURAL INVESTIGATIONS

3.1. Test Specimens and Setups

Similar to the in-plane shear investigations, four, single-layer brick wall panels were constructed for the out-of-plane bending experiments. The wall panels for these tests were 120cm square. Of the four panels, two were made with standard materials and workmanship and two panels were constructed using non-standard materials and workmanship. Also, in each pair of the standard and non-standard panels, one panel was constructed with mortar head joints and another without the mortar head joints. The test set-up for the out-of-plane testing of the wall panels is shown in Fig. 6. It consists of a loading frame, against which a horizontally placed hydraulic jack exerts the out-of-plane point load on the specimens. The value of the applied load is determined through a ring load cell. Five mechanical dial gauges were used to record the deflections of each specimen. The locations of these gauges are shown in Fig. 6.b.

(a)

(b)

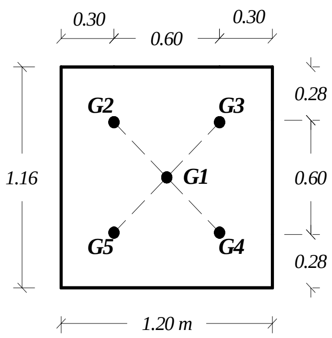
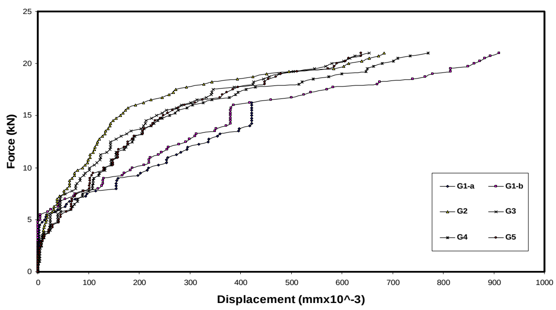


Figure 6. (a) Test setup and (b) position of mechanical gauges for the out-of-plane bending tests

3.2. Standard Walls

The out-of-plane incremental loading of the standard wall panels with head joints (SWFB) and without head joints (SWEB) was carried our in 0.25 kN steps and in each step, the corresponding displacements were recorded. The pushover curves thus obtained for the test panel SWFB are plotted in Fig. 7.a. This figure indicates that the response of the panel with the head joints is linear throughout the panel up to the load of 14 kN.; the linear stiffness being about 25.5 kN/mm using the displacements for the centre of the panel, increasing to between 50 kN/mm to 75 kN/mm using the deflections at the locations 2 to 5 on the panel (Fig. 7.a).

(a)



(b)

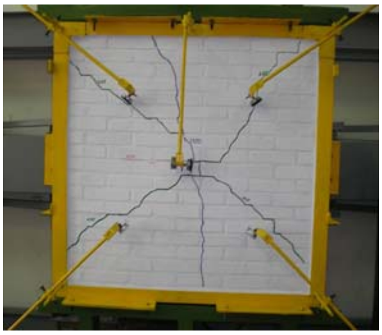
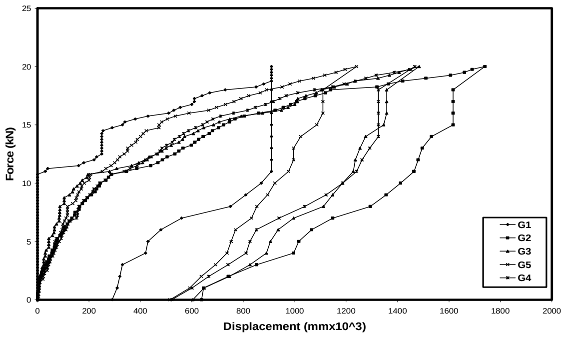


Figure 7. Results of out-of-plane bending test of panel SWFB (a) pushover curves and (b) modes of failure

Fig. 7.a, also indicates that the first crack occurred at the same load of 14 kN. The crack, however, did not become visible until the load reached the value of 17 kN. Contrary to the yield line theory prediction for isotropic materials, the first crack occurred almost vertically at the centre of the panel (see Fig. 7.b). The formation of this crack reinforced the notion that the masonry wall is stiffness orthotropic. Following the reduction in the stiffness of the panel in horizontal direction and the redistribution of stresses, the panel started to behave increasingly isotropic. This point is evident in the pushover curves of Fig. 7.a, wherein, after the appearance of the vertical crack, all gauges show similar reduced stiffness of about 9 kN/mm throughout the panel. The change from the orthotropic behaviour to isotropic performance was noted when at the ultimate load of 21 kN, simultaneous, diagonal cracking, pertinent to an isotropic behaviour occurred (Fig. 7.b).

The pushover curves obtained for the SWFB panel are plotted in Fig. 8.a. The data for all five locations show that the first major change of slope occurred at 9.5 kN. The crack itself became visual at the load 10.7 kN in the form of a vertical crack running along the centre of the panel (Fig. 8.b). This crack was similar in position and orientation to the first crack that occurred in sample SWFB. It, however, occurred at a load, 32% less than the corresponding load in sample SWFB. This indicates a considerable decrease in the out-of-plane capacity of the panel due to the omission of the head joints.

(a)



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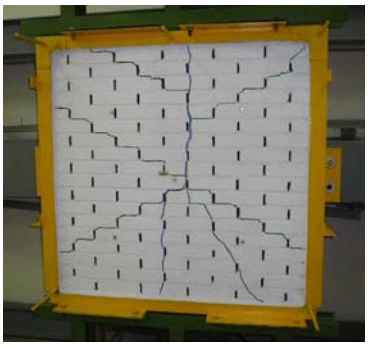


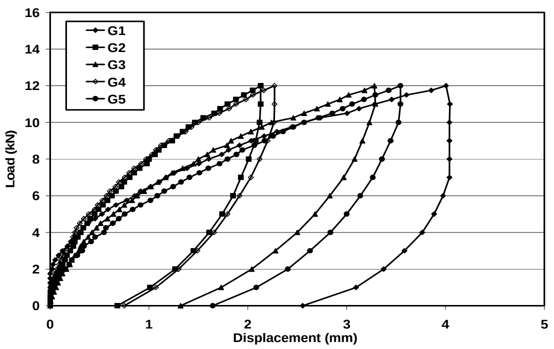
Figure 8. Results of out-of-plane bending test of panel SWEB (a) pushover curves and (b) modes of failure

The occurrence of the vertical crack indicates that this panel also behaved initially orthotropic. Following the first crack and due to the redistribution of the stresses caused by this crack, some transfer of load in the vertical direction can be noted as the central gauge starts to record some deflections at that location and the slope of force-deflection curves for all locations become comparable. This indicates a more uniform distribution of the load or a more isotropic behaviour. The force-deflection curves indicate a further softening of the panel at 15.5 kN. This softening became visible during the test at the load of 15.75 kN by the formation of a cross-diagonal crack (Fig. 8.b) similar to that which occurred in the panel SWFB at the higher load of 21 kN. Contrary to the behaviour of panel SWFB, which could not sustain further load beyond that point, the panel SWEB continued to carry further loads at higher deflections, indicating a substantial ductile performance. The load was increased to 20 kN at which load due to excess opening of the cracks, it was decided to discontinue loading up and to unload to obtain a complete half cycle (Fig. 8.a).

3.3. Non-standard Walls

The out-of-plane loading of the wall panel with head joints and without water treatment was carried out at 0.25kN loading steps and at each step the wall displacements at the five locations shown in Figure 6.b were recorded. The load-displacement pushover curves for the five positions recorded are plotted in Fig. 9.a. Observations made during the test showed that the first cracks appeared in the wall at around 2.5 kN. These cracks were diagonal, following more or less the pattern indicated by the yield line theory of isotropic materials. The cracks also appeared exclusively on the joints between the bricks and mortar. This indicates the weak bond between the two materials. The cracks at 2.5 kN can be also deduced from the pushover curves of Fig. 9.a at which load change of slope can be seen for all locations recorded. After that, a gradual decrease in the slope of the curves can be seen as the diagonal crack spread to cover the entire panel and a second set of diagonal cracks developed. Also, in line with an expected orthotropic response, a vertical line along the brick-mortar joints (Fig. 9.b) also appeared. The non-linear, somewhat ductile, response of the panel continued as the load increased to 12 kN. At this load due to widening of the cracks it was decided to unload the frame and record the response to unloading. Fig. 9.a shows that the maximum permanent displacement happened at the centre of the panel. Different stiffness and permanent displacements recorded for other four locations show local variations of stresses and strains in this non-homogenous brick panel.

(a)



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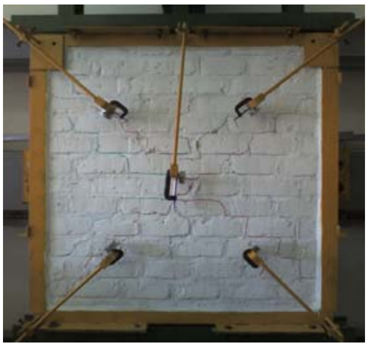

Figure 9. Results of out-of-plane bending test of panel NWFB (a) pushover curves and (b) modes of failure

The out-of-plane loading of the wall panel without head joints and without water treatment (NWEB) was carried out in a similar manner to the previous tests. Figure 10.a shows the force-displacement pushover curves for the five locations measured during the test. The loading was continued to the same level as the wall NWFB (12 kN) after which unloading was performed. The first softening of the wall appears to have occurred at the load of 1.75 kN. A second marked change of slope can be seen around 4.0 kN load after which a gradual softening of panel can be deduced from all five recording gauges. By comparing the results of walls NWFB and NWEF, a marked decrease in the over all stiffness of the wall due to the omission of head joints can be seen. Also, similar to the standard walls, lack of head joints appear to have increased the apparent ductility of the panel as the mortar bed joints become the elements dominating the response of the panel.

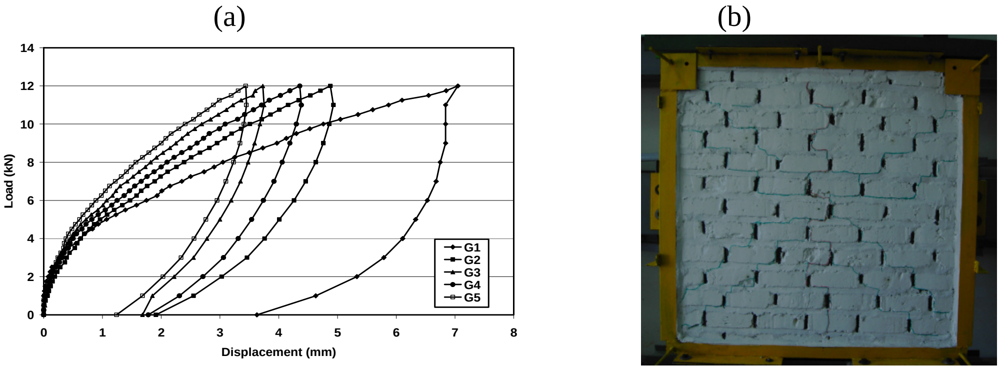

Figure 10. Results of out-of-plane bending test of panel NWEB (a) pushover curves and (b) modes of failure

4. CONCLUSIONS

The earthquake capacity of masonry walls are shown to be adversely affected by the omission of mortar head joints. Results of in-plane shear and out-of-plane flexural tests of standard and non-standard brick masonry wall panels, aimed at determining the effects of the above parameter lead us to draw the following conclusions;

1- The mortar head joints have a considerable effect on the in-plane shear capacity of brick walls. For the walls having different materials, lack of head joints resulted in reductions of 40% to 50%.

2- Omitting the head joints also substantially reduces the out-of-plane yield strength and stiffness of the wall. Post the yield point, this omission has a reduced effect on the stiffness and the ultimate strength.

3- In walls without head joints, the bed joints dominate the response of the wall to out-of-plane bending. Lack of mortar in head joints, causes a change in the performance of a wall subjected to biaxial bending from a relatively brittle response, to a largely ductile behaviour.

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