UNREINFORCED MASONRY WALLS STRENGTHENED WITH ORTHOGONAL NEAR-SURFACE MOUNTED CFRP SUBJECTED TO OUT-OF-PLANE LOADING

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1 INTRODUCTION

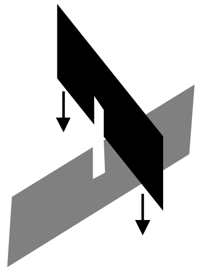
Unreinforced masonry (URM) structures comprise a considerable proportion of the building stock worldwide. However, these structures generally do not behave well under extreme wind or earthquake loading. As part of on-going research, methods of repairing or strengthening URM walls subject to out-of-plane loading using fiber-reinforced polymers (FRP) are being investigated. For several reasons, one method showing particular promise is the use of near-surface mounted (NSM) Carbon FRP strips. Research to-date has made significant progress in quantifying the fundamental behavior of the bonded FRP-to-masonry interface and the behavior of URM walls repaired with vertical FRP strips subject to out-of-plane loading. This paper presents the experimental results of five large-scale clay-brick masonry walls strengthened using NSM CFRP strips and loaded out-of-plane statically to failure using an airbag system. Vertical and Horizontal NSM configurations were tested separately as well as orthogonal grid configurations constructed using two different techniques. The experimentally observed failure mechanisms are described in detail for each wall.

2 EXPERIMENTAL STUDY

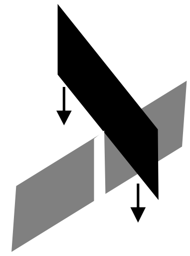
2.1 Experimental test set-up

Five single-wythe 2.13 m square URM walls with approximately 590 mm long return walls were constructed using three-core clay-brick units with nominal dimensions of 190.5 x 57.2 x 85.7 mm. Type-S mortar was used to construct the walls in a mix ratio of 1:1:6 (cement:lime:sand) by volume. The running bond method with a mortar joint thickness of approximately 10 mm was used. The walls were constructed and stored outdoors and exposed to the elements before being moved into the laboratory for testing. The FRP system was also installed while the walls were outdoors. During this time the walls were exposed to hot summer temperatures and heavy rainfall events. Despite being constructed by professional brick layers, the condition of the mortar was very poor and in the worst areas it could be scratched off by finger.

One wall, WC, was tested as a control with no strengthening. The remaining four walls were strengthened on the tension face using the NSM technique with 25.4 mm wide by 1.90 mm thick CFRP strips having a tensile modulus of 139000 MPa. Grooves were cut with a circular saw to a width of approximately 5.7 mm and a depth of 25.4 mm. Note that at this depth the groove passed through the cores, which made it difficult to ensure that the groove was completely filled with adhesive. The CFRP was adhesively bonded into the grooves according to the manufacturer's recommendations. Four NSM strips were used in both the horizontal and vertical orientations spaced at approximately 457 mm from the edges of the wall and 406 mm between adjacent strips. The grooves were located such that they would not coincide with mortar joints in the longitudinal direction. Note that the use of a circular saw did not allow the grooves to be cut all the way to the left, right, and bottom edges of the wall. One of the strengthened walls only had horizontal NSM CFRP strips, WH, and one wall had only vertical NSM CFRP strips, WV. The other two walls, WOn and WOc, were strengthened with an orthogonal grid of NSM CFRP strips. Due to the narrow thickness of the single-wythe wall both vertical and horizontal NSM strips were located at the tension face, hence, two construction techniques were considered at the intersection points of the grid. The first approach cut notches in the FRP where the horizontal and vertical strips intersect, as illustrated in Figure 1a. This approach was used in wall WOn. The second approach involved cutting through the horizontal FRP strips after they were installed to allow the vertical strips to pass across them, as illustrated in Figure 1b. The horizontal strips were cut as they were expected to contribute less to the out-of-plane bending resistance of the strengthened walls. This approach was used in wall WOc.



(a) Notch (Wall WOn)



(b) Cut (Wall WOc)

Fig. 1 Construction techniques for orthogonal NSM grid.

Figure 2 gives an overall view of the experimental test set-up. Steel angles were used at the top and bottom edges of the wall to restrain the wall from out-of-plane displacement. The angles also served to anchor the vertical FRP strips by preventing them from displacing out-of-plane relative to the wall. No form of FRP anchorage was provided near the ends of the horizontal FRP strips. The return walls were also prevented from displacing or pivoting about their base by tying them to an external reaction frame. The supports on all four edges were designed to allow two-way bending to develop. It is also expected that some degree of rotational restraint would be provided along all four edges. An airbag was used to apply the out-of-plane loading, and no precompression was applied to the wall. Instrumentation included string potentiometers to measure out-of-plane displacement, and electrical resistance strain gauges that were attached to the FRP where cracks in the masonry were expected to occur. The out-of-plane displacement field was also measured using an optical sensing technique, but the data has not been processed at the time of writing this paper.

Fig. 2 Overall view of experimental test set-up.

2.2 Test Results

Figure 3 shows the classical two-way bending crack pattern (highlighted by black lines) developed in the control wall WC prior to collapse due to the large out-of-plane displacement. The maximum pressure applied to the wall was 2.93 kPa, and the maximum out-of-plane displacement measured near the mid-point of the wall was 85 mm.

Figure 4 shows the crack patterns observed for the four FRP strengthened walls prior to failure. Failure of the walls was by partial collapse due to large out-of-plane displacements, generally in the order of the thickness of the bricks. The cracks are again identified by solid black lines, and for reference, the location of the NSM CFRP strips are identified by dashed lines.

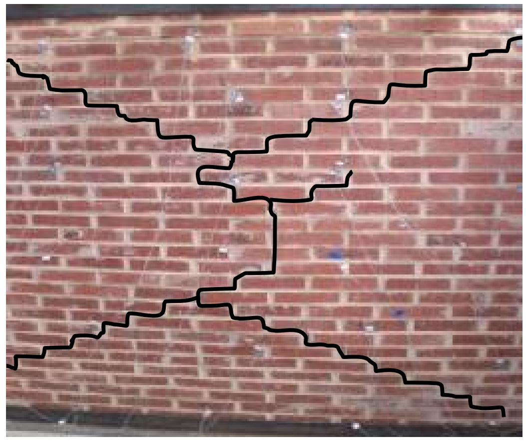


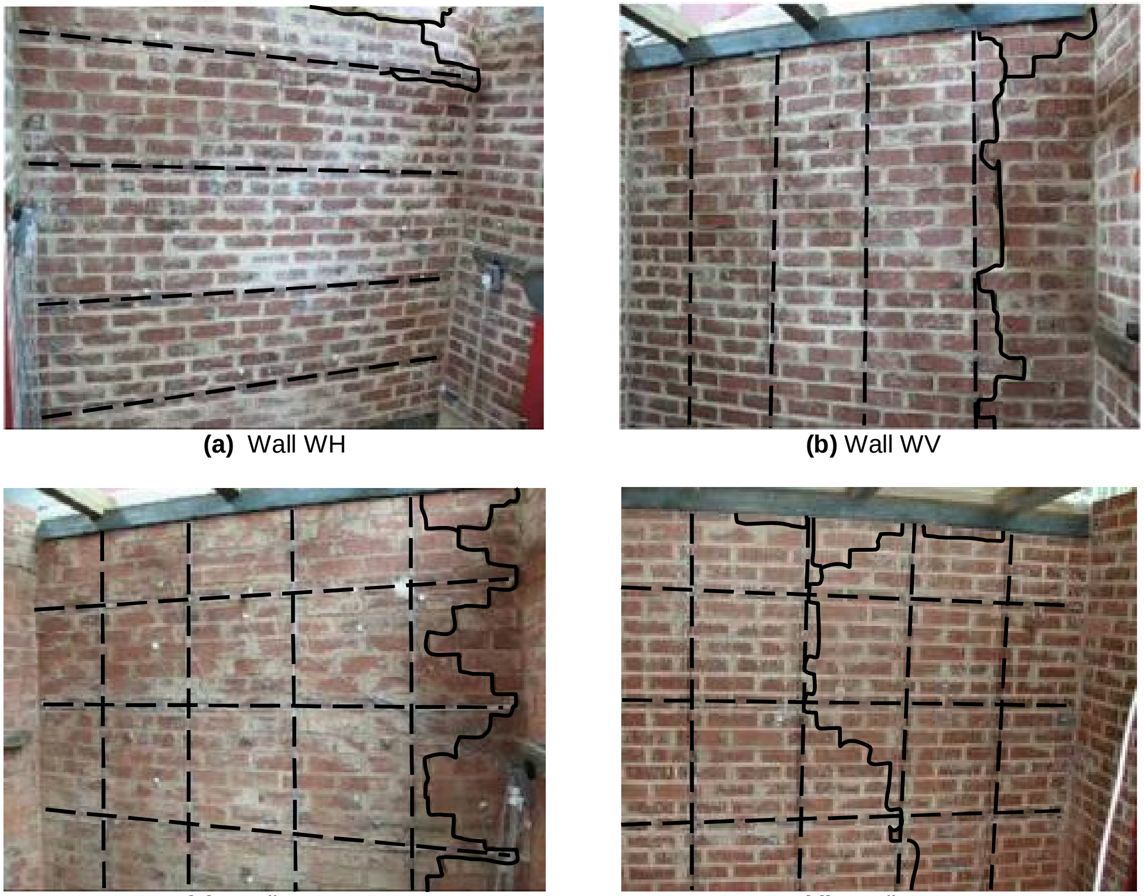
Fig. 3 Crack pattern of wall WC.

Wall WH with only horizontal FRP strips is shown in Figure 4a, where it can be seen that failure was localized near the upper right corner around the uppermost FRP strip. It was observed that the course of bricks containing the FRP was so stiff flexurally that it tended to displace as a rigid body. As the pressure increased, cracks formed in the bed joints on either side of the course of bricks propagating from the end of the NSM strip. This is a result of the stiff course of brick being pulled out-of-plane from the wall as the midspan deflection increased. That is, the frictional resistance of the adjacent bed joints was not sufficient to maintain displacement compatibility with the stiffer course of bricks. This failure is related to the displacement induced (DI) debonding failure mechanism observed by Willis et al [1] and would have likely been prevented if the horizontal NSM CFRP strips were anchored through the return walls. The resistance to this failure mechanism would have been affected by the poor quality of the mortar. Further, the resistance would be enhanced if a precompression was applied to the wall, similar to that observed in the push-pull tests of Petersen et al [2]. The maximum pressure applied to wall WH was 8.51 kPa, and the maximum measured strain in the FRP was 4260 $\mu\varepsilon$. No cracks intersected the FRP, and there were no visible signs of FRP debonding.

Figure 4b shows the crack pattern at failure for wall WV with only vertical NSM CFRP strips. Because the vertical FRP strips were effectively anchored from displacing out-of-plane of the wall by the steel angles used to restrain the top and bottom edges of the wall, the premature failure mechanism observed in wall WH was prevented. Failure was localized to the rightmost panel bound by the vertical FRP strip and the return wall. A predominately vertical line crack formed parallel to the rightmost NSM CFRP strip accompanied by rotation of the right return wall. The maximum pressure applied to wall WH was 13.0 kPa, and the maximum measured strain in the FRP was 3866 $\mu\varepsilon$. Again, no visible cracks intersected the FRP, and there were no signs of FRP debonding.

Failure of wall WOn, shown in Figure 4c, is a combination of that observed in walls WH and WV. That is, failure was again restricted to the end panel bound by the vertical NSM CFRP strip and the adjacent return wall. However, rather than a vertical line crack forming as in wall WV which would have had to intersect the horizontal NSM CFRP strips, the crack followed a path of lower resistance and propagated around the ends of the horizontal NSM CFRP strips as in wall WH. The maximum measured strain was only 2582 $\mu\varepsilon$, and as a result, the notches cut out at the intersection of the vertical and horizontal strips (see Figure 1a) did not compromise the capacity of the orthogonal FRP grid. The failure pressure was increased significantly to 25.9 kPa.

In contrast, a predominately vertical crack formed in the central panel of wall WOc bound by the second and third vertical NSM CFRP strips, passing through the intersection points of the vertical and horizontal strips, as seen in Figure 4d. This is a result of the discontinuity of the horizontal NSM CFRP strips where they were cut through to allow the vertical NSM CFRP strips to pass (see Figure 1b). Interestingly, the maximum pressure applied to the wall remained high at 23.2 kPa, but the maximum measured strain in the horizontal NSM CFRP was only 65 $\mu\varepsilon$, demonstrating that the horizontal strips were not engaged.



(a) Wall WH **(b)** Wall WV

(c) Wall WOn **(d)** Wall WOc

Fig. 4 Crack pattern of strengthened walls.

3 CONCLUSIONS

While all of the strengthened walls were able to achieve a higher out-of-plane bending capacity compared to the unreinforced control wall, the axial strain developed in the NSM CFRP was relatively low. As expected, using only horizontal NSM CFRP strips resulted in the lowest increase in capacity. However, this was a result of premature failure near the ends of the FRP, which could be avoided by anchoring the NSM strips at the return walls. The anchored vertical strips performed better than the horizontal strips, and forced failure in a masonry panel bound by adjacent FRP strips, which is consistent with previous published observations. The orthogonal grids increased the capacity significantly, but raised an interesting construction issue at the intersection points of the horizontal and vertical NSM strips. It appears as though the notched technique employed in this study is satisfactory, as long as the strains developed in the FRP remain relatively low. Finally, one interesting observation that appears to contradict previous published observations is that despite the much higher pressure applied to the strengthened walls, the same crack pattern observed in the control wall did not develop in the strengthened walls.

REFERENCES

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