

Out-of-Plane Strengthening of Unreinforced Masonry Walls with Openings

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Abstract: Collapse of unreinforced masonry (URM) walls is the cause of many casualties during extreme loading events. The objective of this current research was to investigate effective and practical approaches for strengthening URM block walls with openings to resist extreme out-of-plane loads. Five full-scale masonry block walls were constructed. The walls had different opening configurations such as a single center window, one window off center, two windows, a wide window and a door. The walls were tested when subjected to uniformly distributed lateral load up to failure. The walls were then strengthened using carbon fiber-reinforced polymer laminate strips and then retested. The walls were set up in a vertical test frame and were subjected to cyclic out-of-plane distributed pressure using an airbag. Failure of the unstrengthened URM block wall was along the mortar joints. In the strengthened walls, failure occurred in the mortar joints as well as in concrete blocks near the carbon strips. The lateral load carrying capacity of the strengthened walls was found to be significantly higher than that of the unstrengthened walls and had much more ductile performance.

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Introduction

Unreinforced masonry (URM) block walls are utilized in buildings as wall bearing structural elements or nonstructural infill. Masonry walls are relied upon to resist high out-of-plane force. In case of moment resisting frames, URM infill provides additional in-plane stiffness. Although some building codes discourage the use of unreinforced masonry walls in zones of high seismicity, many URM buildings exist and they are still being built in many parts of the world.

A serious life-safety hazard for URM construction during extreme loading events such as earthquakes, strong winds, or blast loads is potential out-of-plane failure. Out-of-plane failure of a bearing wall will cause the loss of both the lateral load and vertical load carrying capacities of the wall. The type of failure of infill walls is significant because it influences the mode and sequence of failure of the reinforced concrete moment resisting frame.

In lightly reinforced and unreinforced masonry walls, such as concrete masonry units and brick, fiber-reinforced polymer (FRP) material systems have demonstrated several benefits by adding shear and flexural resistance to the in-plane and out-of-plane strength and by improving the ductility of the walls. Experimental research has been conducted on the out-of-plane performance of masonry walls and panels. However, the testing is often limited to

scaled models and small panels. A limited number of tests have been carried out on large-scale walls.

Ehsani et al. (1997) investigated the in-plane shear behavior of unreinforced masonry walls strengthened with fiber-reinforced polymer overlays to exterior surfaces. The specimens were tested under static load. They found that both the strength and ductility of tested specimens were significantly enhanced with this strengthening technique. They also concluded that the orientation of the angle of fibers with respect to the plane of loading had a major effect on the stiffness of the retrofitted system but did not affect the ultimate strength significantly.

Triantafillou (1998) presented a numerical analysis procedure for the short-term strength of masonry walls strengthened with externally bonded FRP laminates under monotonic out-of-plane bending, in-plane bending, and in-plane shear. An experimental program on 12 small wall specimens was performed to validate the analysis and it showed that strengthening of masonry walls with externally bonded FRP laminates appears to be effective. It was noted that, when out-of-plane bending response is dominant, the increase in bending capacity due to strengthening is substantial.

Hamoush et al. (2001) investigated the effectiveness of using fiber-reinforced composite overlays to strengthen existing unreinforced masonry walls to resist out-of-plane static loads. Fifteen small wall panels 1.2 m × 1.8 m × 0.2 m were tested. Two configurations of external reinforcement were evaluated. The first reinforcement configuration consisted of two layers of fiber-reinforced plastic webbing and the second consisted of vertical and horizontal bands of unidirectional fiber composites. It was concluded that, in general, the flexural strength of masonry walls could be increased if shear failure at the support is controlled.

Recently, Brown and Maji (2002) conducted an experimental program that demonstrated a significant increase in load carrying capacity of URM walls retrofitted with various combinations of glass fiber-reinforced polymer (GFRP) and GFRP/shotcrete. A 3.6-m high room was constructed of hollow concrete masonry units. The dimensions of the room were 3.4 m × 5.5 m. The walls

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Table 1. Description of Walls Tested

Wall	Opening	Size (m)	Location	Number and location of CFRP strips	
				Vertical	Horizontal
1	Small window	1.2×1.2	Center	4 ^a	2 ^b
2	Small window	1.2×1.2	Off center	4	2 ^b
3	Small windows	Two 1.2×1.2	Symmetric	4 ^a	2 ^b
4	Wide window	3.6×1.2	Center	2 ^a	2 ^{c,d}
5	Door	1.2×2.0	Center	4 ^a	1 ^e

Note: CFRP=carbon fiber-reinforced polymer.

^aAnchored CFRP vertical strips (at the top and the bottom).

^bOne CFRP horizontal strip at the top and one at the bottom of the opening.

^cOne CFRP horizontal strip at the top and one at the bottom of the opening extending along the whole width of the wall.

^dHorizontal strips extend along the whole width of the wall.

^eOne CFRP horizontal strip at the top of the opening.

were reinforced with E-glass fabric on the exterior and in two cases reinforced with 50 mm of 27.6 MPa shotcrete on the interior. The room was subject to an internal blast from a 9 N TNT equivalent charge that generates pressure as high as 496 MPa of 0.08 s duration. The GFRP fabric performed effectively in mitigating the hazards of a blast. The walls tested had no openings.

The tests of URM walls described were conducted on small-scale models or solid walls. Most walls, however, have either window or door openings which are expected to influence the load carrying capacity and mode of failure of the wall. The objective of the experimental research described was to investigate the out-of-plane performance enhancement of URM walls with

openings using CFRP laminate strips. The study of full-scale walls with openings is a practical representation of most existing URM construction.

Test Program

The current study was part of a research program at McMaster University to investigate the out-of-plane behavior of full-scale masonry walls. In a previous research program, eight URM walls were constructed and tested under out-of-plane pressure using an airbag (Chen 2002). One of the walls was solid, while the other seven had openings of different size and different locations. In addition, tests were conducted on small-scale auxiliary specimens, including masonry assemblages, concrete blocks and mortar, in order to determine material characteristics and specimen properties. Details of the behavior of the eight URM walls was discussed by Chen (2002). In this study, the effect of strengthening five of the eight URM tested walls with openings using CFRP laminate strips is presented.

The walls' outer dimensions are 6 m×2.8 m×0.19 m. Masonry blocks with dimensions 390 mm×190 mm×190 mm of running bond were used for construction of the walls. The walls were placed in the test frame with hinged boundary conditions along the four edges of the wall. Table 1 contains a summary of the walls tested and a description of the openings. The unstrengthened walls were subjected to increasing uniformly distributed lateral pressure up to failure. Cracks initiated along the mortar joints and then propagated until a failure mechanism was formed. The failure load was identified as the maximum lateral capacity of the wall after which the load starts to drop.

The five walls tested in the current program were not repaired before strengthening using CFRP laminate strips. Fig. 1 shows a

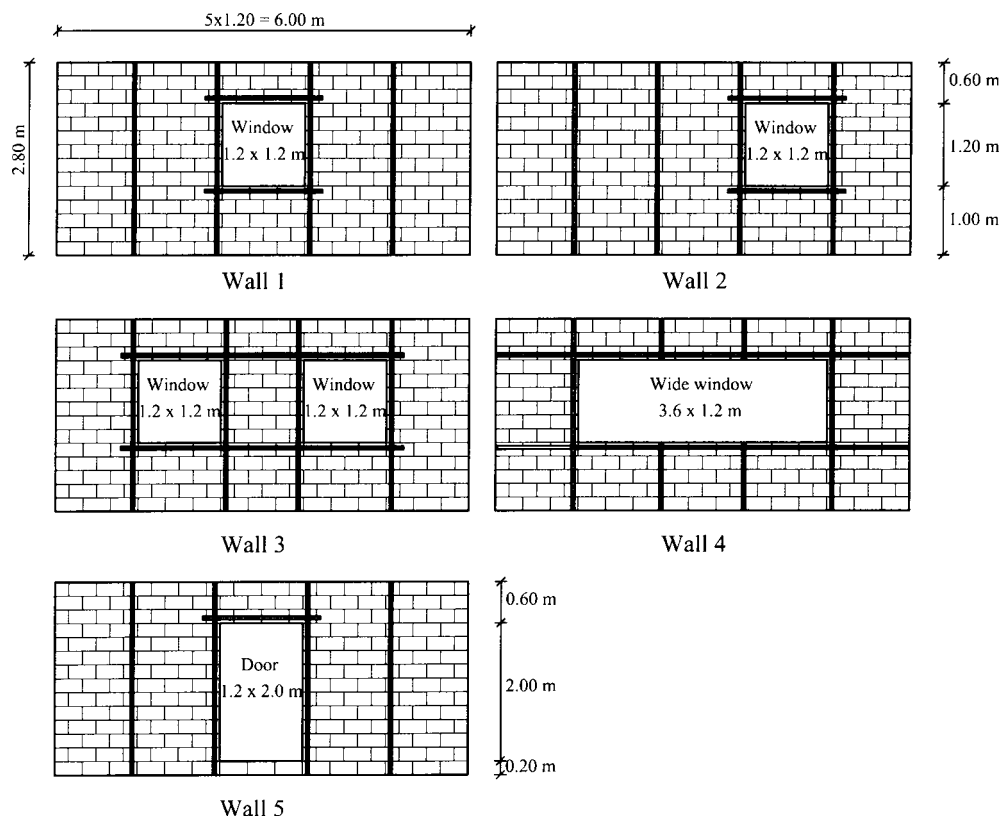
**Fig. 1.** Elevation of strengthened walls

Table 2. Properties of TufLam-CS Carbon Fiber Strips Provided by Supplier (Tested at McMaster Univ.)

Property	Supplier information and (tests)
Tensile strength (MPa)	2,896 (2,850)
Tensile modulus (GPa)	151.7 (168.0)
Ultimate strain	1.8% (1.7%)

view of the elevation of the five strengthened walls. The CFRP strips were applied to the tension side only. The strengthening scheme was kept consistent for the five walls. The CFRP strips were applied in the vertical (perpendicular to bed joints) and the horizontal (parallel to bed joints) directions of the wall. Two vertical CFRP strips were applied at each side of the openings and vertical strips were installed 1.2 m (three blocks) apart. The CFRP strips were located 50 mm from the edge of a block (or opening) in order to support the block at its web not the flanges of the face shell. Horizontal strips framed the top and bottom of the opening with an anchorage distance of 150 mm. The vertical strips were applied on top of the horizontal strips. The horizontal strips in walls 3 and 4 were continuous between the windows and reached the outer edge for the wide window case (wall 4). Anchors were used at the ends of the vertical CFRP strips in four of the tested walls, whereas wall 2 had unanchored strips.

The design criteria for the strengthening scheme were to change the load distribution and the overall behavior of the URM wall from one way in the vertical direction spanning 2.8 m to one way in the horizontal direction spanning 1.2 m between the vertical CFRP strips. This arrangement will allow the formation of new vertical cracks at the joints and lead to higher load carrying capacity.

The walls were subjected to cyclic out-of-plane pressure using an airbag from the back side of the wall. The cycles included loading and unloading of the lateral pressure. The increase in air pressure was in increments of 1 kPa. After each increment, the load was kept constant to check for new cracks, signs of delamination between the CFRP strips and the blocks, or block failure. After the cyclic lateral pressure reached 10 kPa, monotonic pressure was applied on the wall until failure. Cyclic loading from zero to the maximum was applied in the tests rather than reverse loading due to equipment limitations. However, for the case of carbon strips applied to both sides of the wall, cyclic loading may provide a conservative estimate of one-half the symmetric reverse loading response cycle.

Materials

Mortar

During the construction process, double-sized batches of mortar were frequently mixed to meet standard test requirements (Chen 2002). In order to ensure consistency of the mortar, the batch not used by the mason within 30 min of mixing was discarded. The

Table 3. Properties of Bonder Gel Adhesive Provided by Supplier

Property	Strength (MPa)
Bond strength per ASTM C-882-99 (1999)	17.9
Tensile strength per ASTM D638-02 (2002)	41.4
Compressive yield per ASTM D695-02a (2002)	75.8

**Fig. 2.** Carbon fiber-reinforced polymer strips before removing the duct tape

mortar used throughout the test program was classified as type S mortar in accordance with ASTM Standard C270-96a (1997).

The average initial flow recorded for the mortar was 123.3% with a coefficient of variation of 2%. The mean compressive strength of the mortar cubes was 12.1 MPa with a coefficient of variation of 17.1%. The mean air content of the mortar was found to be 7.2% with a coefficient of variation of 8.9% according to ASTM Standard C91-96 (1997).

Blocks

Four series of auxiliary specimens were tested to determine strength, Poisson ratio, and elastic modulus of the masonry assemblages. The compressive prism strength, Poisson ratio, and elastic modulus in the vertical direction were determined, according to method B in ASTM Standard C447-92b (1997), to be 27.9 MPa, 0.213, and 25,888 MPa with coefficients of variation of 2.5, 1.5, and 1.5%, respectively. Also, the mean flexural tensile strengths normal and parallel to the bed joints were determined to be 0.315 and 0.988 MPa, respectively.

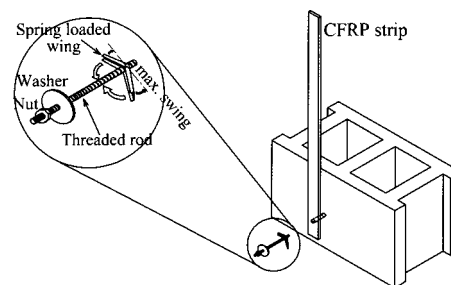
**Fig. 3.** Anchoring of carbon fiber-reinforced polymer (CFRP) strips to face shell of block



Fig. 4. Carbon strip anchored at bottom of wall

Carbon Fiber-Reinforced Polymer Laminate Strips and Bonding Adhesive

Fifty-mm wide CFRP laminate strips (TufLam-CS) were used to strengthen the walls. The nominal thickness of a strip is 1.2 mm and the nominal fiber volume fraction is 60%. The CFRP strips were tested according to ASTM D3039-00 (2000) procedures. Table 2 shows the properties of the carbon laminates as provided by the supplier and as tested at McMaster University. The properties of Bonder Gel adhesive used to bond the strips to the block surface as provided by supplier are summarized in Table 3.

Strengthening Procedure

A three-step procedure was followed when installing CFRP strips on the walls tested.

Surface Preparation

The blocks were marked where the CFRP strips were to be placed. Whenever the marked location of a strip crosses a bed or



Fig. 5. Typical wall instrumentation

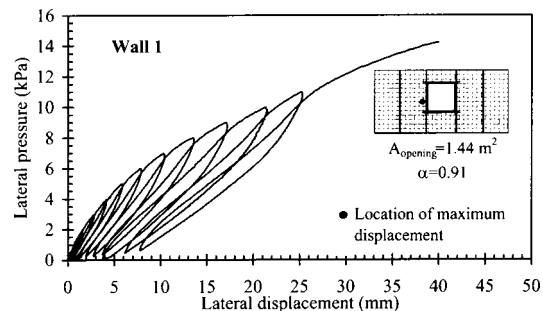


Fig. 6. Lateral pressure-displacement relationship for wall 1

head joint, the joint groove is filled with Bonder Gel until it is aligned with the block surface. After hardening, the filled grooves are ground with sand paper, flush with the block surface. Duct tape was applied along the outer sides of CFRP strip locations on the masonry. Duct tape pieces were removed at zones where strips intersected. The CFRP strip location is cleaned using a wire brush. For the CFRP strips, the face in contact with the masonry wall is thoroughly cleaned using cleaning solvent (alcohol), while the outer face was covered with a 50-mm wide duct tape.

Carbon Fiber-Reinforced Polymer Strip Application

The two parts of the Bonder Gel are mixed together. About a 2-mm layer of adhesive is applied to both the CFRP strip contact surface and the CFRP location on the blocks between the two installed duct tapes. The excess bonding gel is squeezed out by applying pressure using a wide steel roller. The excess bonding gel runs off and onto the duct tape. The purpose of the duct tape is to retain clean masonry and strip surfaces.

Finishing

Two to three hours after completing application of the CFRP strips, the side duct tape is removed with excess gel. After 1 day, the duct tape on the surface of the CFRP strips can be removed. This will leave the strengthened wall with an aesthetically good looking clean surface. Fig. 2 shows the carbon strips at the point at which they intersect before removing all the duct tape from the side of the strip.

In the case of anchored vertical strips, a 12-mm diam hole is drilled and a 6-mm threaded toggle bolt with spring loaded wings is used to clamp the CFRP strip to the outer face shell of the blocks at the top and bottom edges of the strip. The anchor hole is filled with bonding gel before tightening the bolt. A schematic of

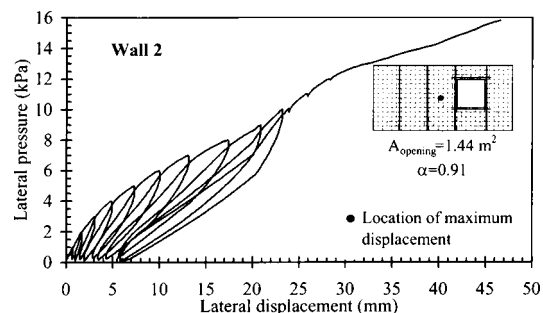


Fig. 7. Lateral pressure-displacement relationship for wall 2

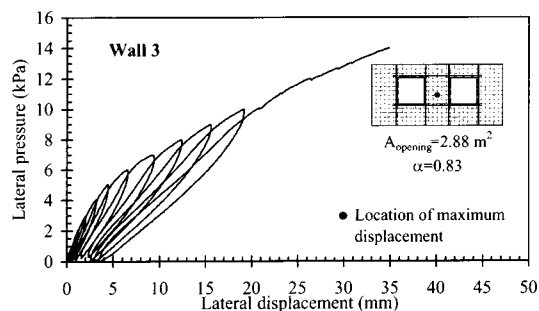


Fig. 8. Lateral pressure-displacement relationship for wall 3

the anchoring system is shown in Fig. 3. Fig. 4 shows a typical anchor installed at the bottom end of the CFRP strip.

Instrumentation and Data Acquisition

Each wall tested was instrumented with up to 16 linear variable differential transformers (LVDTs) to measure out-of-plane deflection, and by 13 10-mm strain gauges on the CFRP strips to measure strain. Deflections were measured at the CFRP strip location, between strips, and at the top and bottom of the wall opening. CFRP strains were measured at three locations along the strip length in order to provide a strain distribution profile. The airbag pressure was measured using two pressure gauge transducers, one at the air inlet and the other at the outlet. Data were recorded every 5 s using a computer controlled data acquisition system. Fig. 5 shows typical instrumentation of the wall. The walls were tested 2 weeks after application of the CFRP strips.

Test Results

Results of wall tests are discussed in terms of out-of-plane load deflection response, energy dissipation capacity, secant stiffness, displacement and fiber strain distribution profiles, and failure patterns.

Load-Deflection Response

Figs. 6–10 show the variation in out-of-plane displacement with the cyclic lateral pressure relationship for the five strengthened walls. The maximum displacement response of the wall plotted in Figs. 6–10 is located at the position indicated by a closed circle on the wall shown in each inset. During the unloading cycle, the walls unload with reduced stiffness, resulting in permanent plastic

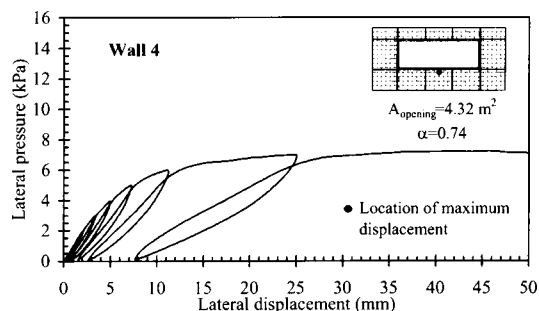


Fig. 9. Lateral pressure-displacement relationship for wall 4

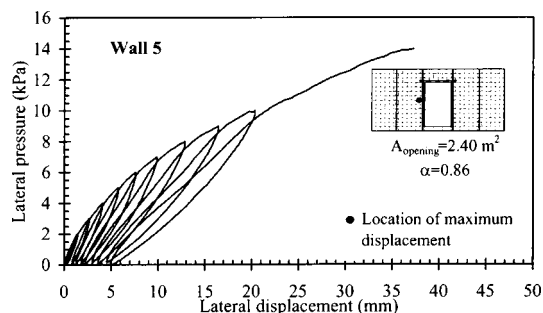


Fig. 10. Lateral pressure-displacement relationship for wall 5

deformation at the end of the cycle in the range of 20–30% of the maximum displacement reached. Upon reloading, the walls attained 95% of their previously attained load at the same level of displacement. After that, the displacement increased with an increase in load. This type of response of strengthened walls produced significant energy dissipation compared to the nonductile behavior of URM.

In comparing Figs. 6 and 7, it can be seen that changing the location of a center opening more to the edge of the wall with eccentricity of 20% of the wall width causes a small change in wall displacement ductility and load capacity. The measured increases in the maximum load and displacement capacity of wall 2 in comparison to wall 1 were 11 and 17.5%, respectively.

Fig. 11 shows a comparison between the variation of lateral pressure with the displacement envelope for the strengthened and unstrengthened walls. It should be noted that the strengthened walls possess high ductility and high load carrying capacity compared to the unstrengthened walls. The lateral load capacity of the strengthened walls increased up to fivefold, while the lateral displacement capacity increased up to 10 times that of the unstrengthened URM walls. The maximum lateral deformation of the walls ranged from 1.25 to 1.8% of the wall height, and the total lateral force capacity of the wall reached seven times its weight. The lowest lateral load capacity of the strengthened walls was that of wall 4. This particular wall had the largest window opening with an area of solid wall to total wall area ratio of $\alpha = 0.74$. The ratio α is a measure of the size of the opening relative to the total area of the wall.

Fig. 12 shows the ratio of the lateral load carrying capacity of the strengthened to the unstrengthened wall with center openings plotted against the solid wall area ratio. The circles represent the test data. A second-order polynomial best fit is plotted in the same graph. The equation of the curve is

$$L = -60.4\alpha^2 + 108.8\alpha - 45.0 \quad (1)$$

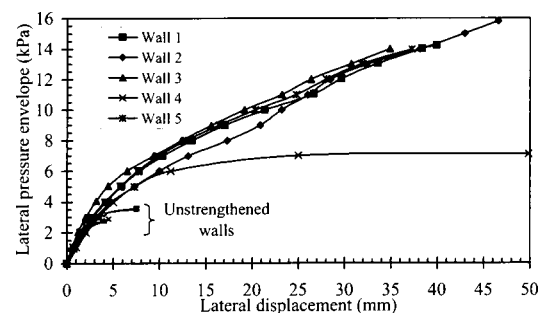


Fig. 11. Comparison of lateral pressure-displacement relationships of the five walls

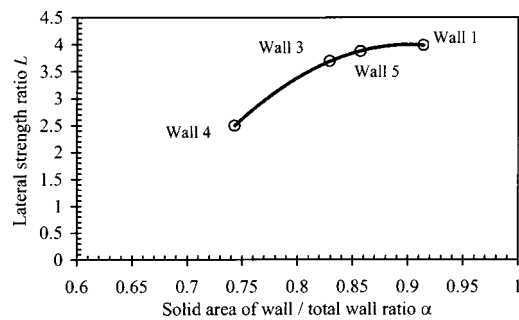


Fig. 12. Effect of center opening size on increase of lateral load carrying capacity due to wall strengthening using carbon strips

with coefficient of determination $R^2=0.99$, where L represents the ratio of lateral load carrying capacity of the strengthened/unstrengthened wall with a center opening and α represents the ratio of the solid area to the total area of the wall.

Fig. 12 indicates that increasing the area of the opening, which corresponds to decreasing the solid wall area ratio, decreases the enhancement in wall lateral load carrying capacity due to strengthening. The formula in Eq. (1) is applicable to α ratios between 0.74 and 0.91, which is the range verified by the current tests. The relationship derived is based on a limited number of wall tests. When more tests results are available, Eq. (1) can be refined.

Energy Dissipation Capacity

The cumulative energy dissipation of the five strengthened walls at different levels lateral pressure is shown in Fig. 13. In comparing the energy dissipation capacity of walls 1 and 2, it can be concluded that shifting the center opening of a strengthened wall towards the wall edge increases its energy dissipation capacity by approximately 22%. From the behavior of the other four walls with center openings, as expected it is observed that increasing the wall opening area decreases their energy dissipating capability. A wall with a wide window opening with ratio of solid area to total area of 0.74 has 20% less energy dissipation capacity compared to a wall with a small window opening with ratio of solid area to total area $\alpha=0.91$.

Wall Stiffness

Variation of the secant stiffness of the five strengthened walls with the lateral pressure is plotted in Fig. 14. Fig. 14 shows that increasing the lateral pressure decreases the secant stiffness of the strengthened walls. The final secant stiffness at failure of the five

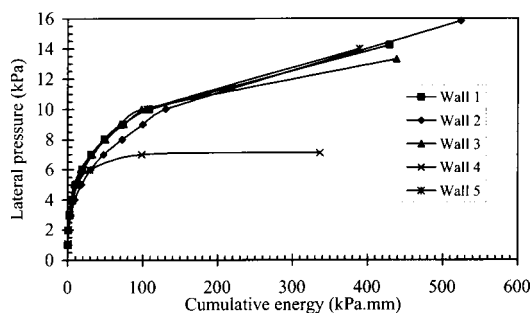


Fig. 13. Cumulative dissipation of energy

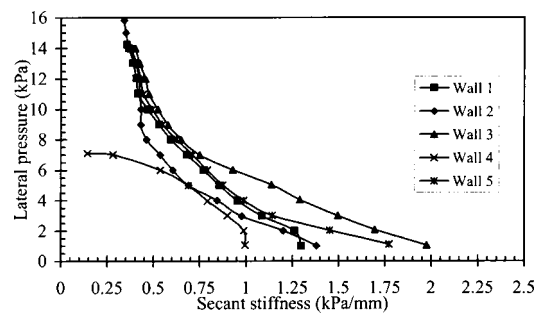


Fig. 14. Variation of wall secant stiffness with lateral pressure

strengthened walls is approximately equal. This can be attributed to the fact that, near failure, the overall wall stiffness is mostly that contributed by the strengthening system's stiffness.

Wall Displacement and Fiber Strain Distribution

The displacement distribution along the height and the strain distribution along the CFRP strips at different load levels are shown in Figs. 15–19. From Figs. 15–19 it can be concluded that the displacement tends to increase at the center of the wall near the sides of the opening. The displacement decreases towards the outer edges where the wall is simply supported. In general the strain recorded in the CFRP strips was low. However, near failure maximum fiber strain of 0.0063 mm/mm was recorded. Although the strain was generally low, the CFRP strips prevented the broken blocks from collapsing and scattering. Anchored CFRP strips showed better performance compared to unanchored ones. The high stiffness of the CFRP strips kept the out-of-plane deformation of the wall reasonably small, with minimum negative impact on the stability of the wall.

Failure Patterns

Failure of the unstrengthened URM wall was along the mortar joints. Fig. 20 shows the failure patterns of the five strengthened walls. Prior to failure, some cracks in the masonry bricks along the sides of the CFRP strips were observed. These cracks propagate and widen with the increase in lateral pressure. For the five strengthened walls, failure occurred in the mortar joints as well as in the concrete blocks near the carbon strips.

Different types of failure mechanisms for strengthened walls are shown in Fig. 21. In general, failure of the strengthened walls was due to a combination of these mechanisms. Fig. 21(a) shows cracking of the masonry blocks around the CFRP strips that in-

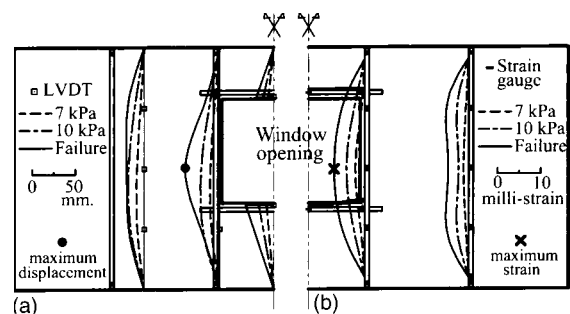
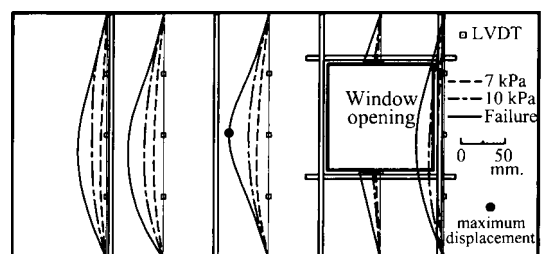
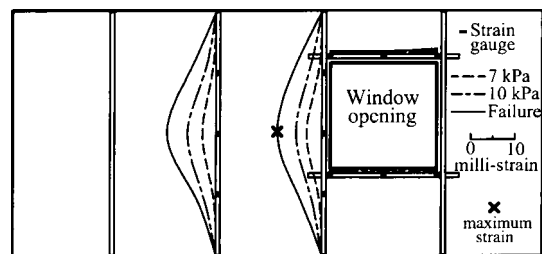


Fig. 15. Distribution of (a) displacement along height (left side) and (b) strain along carbon fiber-reinforced polymer strips (right side) for wall 1



(a)



(b)

Fig. 16. Distribution of (a) displacement along height for wall 2 and (b) strain along carbon fiber-reinforced polymer strips for wall 2

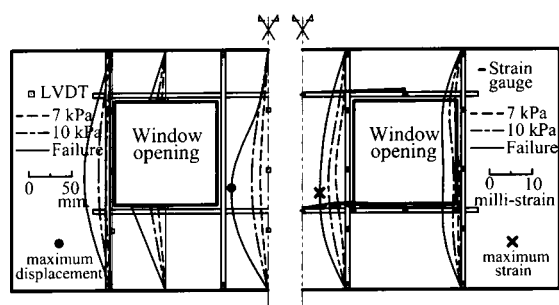


Fig. 17. Distribution of (a) displacement along height (left side) and (b) strain along carbon fiber-reinforced polymer strips (right side) for wall 3

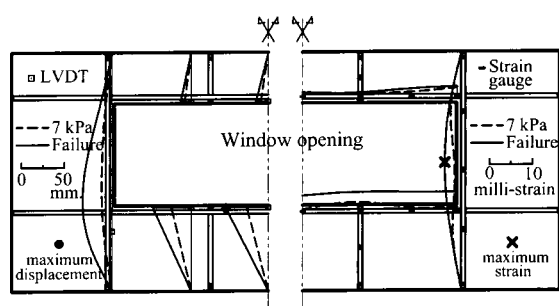
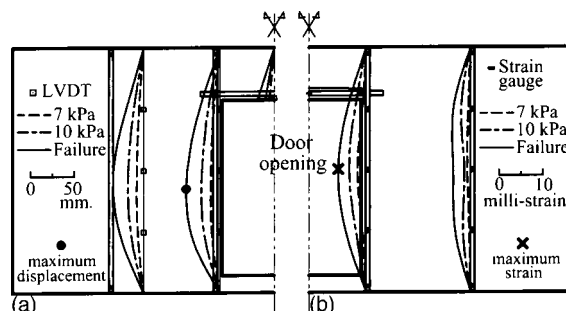


Fig. 18. Distribution of (a) displacement along height (left side) and (b) strain along carbon fiber-reinforced polymer strips (right side) for wall 4



(a)

(b)

Fig. 19. Distribution of (a) displacement along height (left side) and (b) strain along CFRP strips (right side) for wall 5

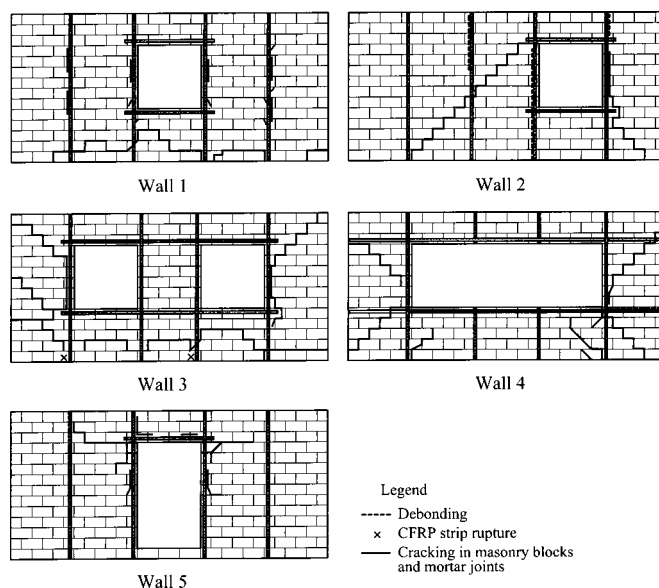


Fig. 20. Failure patterns of the five walls

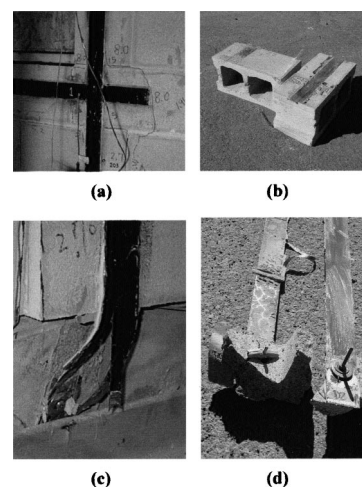


Fig. 21. Different failure mechanisms: (a) cracking of masonry blocks; (b) debonding of carbon fiber-reinforced polymer strip; (c) strip rupture at anchor; and (d) block failure at anchor

intersect at the window's bottom corners (walls 2 and 3). This crack initiated at lateral pressure of 8.0 kPa and continued to propagate and widen until the wall failed. Fig. 21(b) shows debonding between masonry blocks and CFRP strips, which led to failure of unanchored strips like that in the case of wall 2. Figs. 21(c and d) show two failure mechanisms for anchored strips, namely, CFRP strip rupture and block failure at the anchor. Although the longitudinal strain along the CFRP strip near the anchor was small, relative out-of-plane movement of the masonry blocks sheared the strip in the weak direction, which led to loss of anchorage and strip rupture as shown in Fig. 21(c) for the case of wall 3.

Conclusions

An experimental program was conducted in order to investigate performance enhancement when strengthening URM walls with openings using CFRP laminate strips. Based on the results of the experimental program, the following conclusions were reached.

1. The strengthened walls sustained lateral load of the order of five times that of the unstrengthened URM wall, behaved in a ductile manner and dissipated a significant amount of energy due to cracking along the mortar joints and movement between masonry blocks.
2. The CFRP strip strengthening system is much simpler than using steel reinforcement and can be applied to walls that have been already damaged without the need of repairing cracked mortar joints before applying CFRP.
3. Framing of openings with CFRP strips reduces the negative effects of openings on the lateral load capacity and improves the performance of the walls.
4. Proper anchoring of the ends of the CFRP laminates was found to be important in preventing debonding of the CFRP strips from the concrete blocks which is aggravated by relative shifting of the blocks following failure of the joint mortar. Moreover, anchored CFRP strips restrained the broken blocks from collapse at failure of the wall which may cause injury and hazard to life.
5. The presence of openings in walls reduces the out-of-plane load carrying capacity. A relationship between the lateral load carrying capacity and the ratio that represents the size of the opening was developed.
6. The proposed strengthening systems increased the ductility of the walls by approximately 10-fold compared to the unstrengthened walls.

The results presented and the conclusions derived are based on a limited number of large-scale wall tests. More tests can refine the results, but the qualitative conclusions remain valid.

Acknowledgments

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