Experimental study on the out-of-plane strengthening of unreinforced masonry walls using cement-based fiber composites

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Abstract. This paper presents results from an ongoing research that is intended to study the behavior of URM walls for out-of-plane action. The effect of fiber reinforced shotcrete (FRS) as a strengthening method for the URM walls is examined. Eight URM walls were built inside a precast reinforced concrete boundary frame and strengthened with cement-based shotcrete mixes reinforced with different types of fibers. The masonry wall is 1.2x 1.2 m, and the masonry units were hollow concrete blocks (10 x 20 x 40 cm). Conventional fiber reinforced concrete (FRC) and engineered cementitious composite (ECC) were used as the strengthening layers sprayed on the surface of masonry walls. Control walls with plain shotcrete and conventional plastering mortar were also examined. Synthetic macro-fibers at dosage rate of 6 kg/m³ in FRC mix and Polyethylene micro-fibers at a dosage rate of 16 kg/m³ in ECC mix were considered in this study. The walls were placed in a carefully designed set up and tested under static central load using a hydraulic actuator with a capacity of 500 kN. The parameters recorded during testing were the applied load and out-of-plane displacement of the walls. Cracking pattern and failure modes were also monitored. The reported test results demonstrate that FRC and ECC mixes can significantly increase the out of plane strength and ductility of the URM walls.

1. Introduction

Unreinforced masonry (URM) walls are most vulnerable to damage in the event of an earthquake, wind load, or blast pressure. When a building with URM walls is subjected to lateral forces, the URM walls might experience in-plane/out-of-plane failure modes or a combination of both [1]. Basically the URM walls are designed to resist in-plane compression loads without considering the lateral forces and it not considered as part of building seismic load path [2]. Noting that out-of-plane failure can trigger partial or full collapse of the wall which may endanger integrity of the building [3].

Many existing URM structures are not up to the standards of today’s code requirements and are categorized as earthquake-prone buildings or maybe structurally deficient for current use. Studies have reported that the out-of-plane collapse was noted during earthquake in the buildings where the walls were not designed for lateral loads [4]. Therefore, to enhance their out-of-plane capacity, ductility, energy absorption, and to upgrade their safety requirement, it is necessary to strengthen these structures [5]. Otherwise, even local failure of these masonry elements can trigger partial or full collapse of a structure or pose significant hazard to the occupants and pedestrians [2] [6].
Numerous researches have been conducted in recent years to develop effective methods for retrofitting the URM walls against lateral loads and improve their out-of-plane behavior [1], [6–9]. Those researches have resulted in developing and proposing a number of methods to enhance the out-of-plane response of URM walls. The methods proposed and used for retrofitting the URM walls subjected to lateral forces are: bonding the fiber reinforced polymer (FRP) sheets to the surface of the walls, applying textile reinforced mortar (TRM) on the surface of the walls, installation of unbonded post-tensioning, fiber reinforced cementitious composites with and without additional steel reinforcement, etc. [6] [10].

The proposed methods provide some enhancement to the strengthened structure, however, there are some drawbacks associated with some of those proposed methods. For example, strengthening using FRP sheets is a very simple application and when applied significantly increase the out-of-plane response of URM walls, but due to its high rigidity it eventually fails abruptly and occurs without much warning. It is also reported in the literature that the walls retrofitted with externally bonded FRP system fails prematurely by shear at the end connections of the wall and FRP system [5]. Similarly the application of some other of those strengthening system inherit disadvantages like time-consuming applications [1].

The objective of this research study is to develop a rapid method of strengthening URM walls using FRC & ECC, and to study the out of plane behavior of the strengthened walls. The paper presents and discusses results obtained from static testing of walls strengthened with different cement-based composites. To this end, an experimental program was carried out to test eight URM wall panels strengthened with FRS mixes. The results are used to assess the performance of each wall and compare with that of the control wall.

2. Experimental program

2.1 Test specimens
A total of Eight URM walls were built and tested in this research study. The walls were constructed using masonry infill units inside a precast reinforced concrete boundary frame. Figure 1 shows the dimensions and the reinforcement details of the walls and the boundary frame. The URM walls are built of ordinary hollow concrete blocks acquired locally and have a dimensions of 10 x 20 x 40 cm. The masonry units (hollow blocks) were made of plain concrete that had a compressive strength of 7.5 MPa. The overall dimension of the walls is 1.5x1.55 m including both the boundary frame and the masonry units. The net dimensions of URM walls without the boundary frame is 1.2 x 1.2 m with a thickness of 0.1 m.

2.2 Strengthening materials and test setup
Three different types of concrete mixes were sprayed to the surface of the wall using shotcrete technology. First mix was a plain concrete mix (OPC), second mix was Fiber Reinforced Concrete (FRC), and the third mix was Engineerid Cementitious Composite (ECC). The mix proportions of these concrete mixes are presented in Table 1. Each mix was used to strengthen a pair of duplicate URM
walls. A total of six walls were sprayed using shotcrete technology with concrete layers from both sides with an average thickness of 45mm on each side as shown in Figure 2. In addition, two URM walls were plastered using normal cement mortar with a thickness of 15mm on each side, to present the traditional practice of building walls and assess the effectiveness of proposed strengthening method.

**Table 1.** Mix details of the concrete mixes used for strengthening the walls.

| Mix Proportions          | OPC  | FRC  | ECC  |
|--------------------------|------|------|------|
| Type I Cement (kg)       | 420  | 420  | 1449 |
| Silica Fume (kg)         | 25   | 25   | 145  |
| Aggregates 0-5 mm (kg)   | 1480 | 1480 | 0    |
| Dune Sand (kg)           | 345  | 345  | 0    |
| Water (L)                | 190  | 190  | 478  |
| Superplasticizer (L)     | 6    | 12.6 | 11.5 |
| Macro-Fibers (kg)        | 0    | 6    | 0    |
| Micro-Fibers (kg)        | 0    | 0    | 16   |

In the fiber reinforced concrete mix, synthetic macro-fibers (Strux™ 90/40) were incorporated to the mix with a dosage of 6 kg/m³. In the ECC mix a polyethylene micro-fibers commercially called (Spectra™ 900) was used with a dosage rate of 16 kg/m³. Properties of both the fibers are presented in Table 2. In the FRC and OPC mixes, the water to cement ratio (w/c) was 0.45 and type I Portland cement with a percentage of silica fume was used. The ECC mix had w/c ratio of 0.3 and it is a mixture of cementitious material, water, and fibers only. Adding fibers in the concrete mix reduce the workability of concrete. Therefore, to improve the workability without compromising the compressive strength, a locally available superplasticiser called ADVA Flow 480 was added to the concrete mixes. Table 3 shows the 28-day average compressive strength of the mixes measured according to ASTM C39 and flexural strength measured according to ASTM C78.

**Table 2.** Materials properties of nonmetallic fibers used in the shotcrete mixes.

| Type          | Length (mm) | Diameter (mm) | Modulus of Elasticity (GPa) | Tensile Strength (MPa) |
|---------------|-------------|---------------|-----------------------------|------------------------|
| Strux™ 90/40  | 40          | 1.4 x 0.105 (rec) | 9.5                         | 620                    |
| Spectra™ 900  | 12          | 0.039         | 66                          | 2610                   |

**Table 3.** Average compressive strength and flexural strength of the mixes

| Mixes  | Avg Compressive Strength (MPa) | Avg Flexural Strength (MPa) |
|--------|--------------------------------|-----------------------------|
|        | One day | Seven days | 28 days | 28 days |
| OPC    | 46      | 60         | 68      | 4.7     |
| FRC    | 31      | 46         | 60      | 5.6     |
| ECC    | 38      | 45         | 53      | 4.6     |

The walls are named with specific labels showing the type of shotcrete mix used for strengthening as reported in Table 4. For example, RF stands for the reference wall (wall with plastering mortar), PLS stands for the walls strengthened with plain shotcrete (OPC), FRS stands for fiber reinforced shotcrete, and ECCS which stands for engineered cementitious composites shotcrete, specify the walls sprayed with a pure cement-based mix reinforced with polyethylene micro-fibers.
Table 4. Strengthening Matrix.

| Labels | Strengthening Mixes | Qty | Wall Dimensions | Shotcrete or Mortar Plaster Thickness (mm) | Total Thickness (mm) |
|--------|---------------------|-----|-----------------|------------------------------------------|---------------------|
| RF     | Reference           | 2   | 1200 (mm)       | 100 (mm)                                 | 15 (mortar plaster) | 130 |
| PLS    | Control             | 2   | 1200 (mm)       | 100 (mm)                                 | 45                  | 190 |
| FRS    | FRC (6 kg/m³)       | 2   | 1200 (mm)       | 100 (mm)                                 | 45                  | 190 |
| ECCS   | ECC (16 kg/m³)      | 2   | 1200 (mm)       | 100 (mm)                                 | 45                  | 190 |

Figure 2. Photos of the walls before and after shotcrete application.

A test set up was designed to test the walls for out-of-plane action as shown in Figure 3. The load was applied at the center point of the walls in a displacement control mode with the rate of 0.01 mm/s. The applied load and wall deflection at different locations were measured. The load was measured using the load cell attached to the actuator head and the displacement was recorded using LVDTs deployed at different locations on the walls. Cracking patterns and failure modes were also monitored and documented.

Figure 3. Test setup with a wall during testing.

3. Experimental results

3.1. Load-deflection relationship

Figure 4 shows the load-deflection diagram of all the tested walls plotted together for ease in comparing the behavior of the walls. Each curve in Figure 4 presents the average test results obtained from testing two duplicate walls. However, and since the compressive strength of the FRS mix and ECCS mix was lower than the PLS mix, a direct comparison of the results will not reveal the real effect of macro-fibers and micro-fibers in enhancing the out-of-plane behavior. Therefore, the results of the FRS and ECCS walls were normalized using the ratio of the square root of their compressive strength relative to the plain concrete and then plotted in Figure 4.

It can be revealed from Figure 4 that the reference walls (RF) showed a linear behavior until the occurrence of the first crack at a load level equal to 20 kN and turns into a nonlinear behavior until it reached a failure load of around 45 kN and a central deflection of almost 25mm at peak load. Thereafter,
the load carrying capacity drops and associated with punching failure at a load level of around 40 kN followed by a sudden drop in load deflection diagram. The load deflection curve in Figure 4 correspondent to the plain shotcrete wall (PLS), shows that the wall is behaving linearly until the load level of around 40 kN. With further increase in the applied load, the wall started exhibiting nonlinear behavior until the appearance of the first crack at load level around 70 kN after which it drops slightly. After the first drop, the wall started again resisting the applied load and eventually failed at load level around 130 kN with the central deflection of 30 mm at peak load. The loading was continued a bit more after failure until the wall resistance was degraded noticeably & dropped from peak to 100 kN, then the test was stopped.

Figure 4 also shows the load-deflection diagram of the walls sprayed with fiber reinforced shotcrete and it can be inferred from the figure that the FRS wall was behaving linearly until the onset of the first crack at a load level around 80 kN. After which a slight drop was noticed in the load resisting curve. However, after the first drop, the wall started resisting the applied load again and kept increasing. The FRS wall started failing at a peak load of 150 kN and central deflection of almost 30 mm. Similar to the PLS walls, the loading was stopped for the FRS walls after the applied load dropped to around 100 kN. The load-deflection relationship for the ECCS walls plotted in Figure 4 shows that the load was constantly increasing without any significant drop even though the ECCS wall exhibited multiple distributed crack at different load levels. It can be noticed that the ECCS walls were continuously resisting the applied load until it reached its maximum capacity at a load level of around 170 kN with the corresponding central deflection of around 30 mm. Thereafter the load resistance trend started to degrade until it dropped gradually from peak load to a load level equal to 140 kN and then the test was stopped manually.

From comparison of the load-deflection relationship of all the tested walls, it can be realized that the walls strengthened with ECC mix followed by the wall sprayed with FRC mix, exhibited a significant increase in the load carrying capacity and ductility of the walls relative to the control and reference walls. Strengthening the walls with ECC shotcrete increased the load resisting capacity by upto almost 4 times than the RF walls. Similarly, the walls strengthened with FRC layers resisted around 3 times higher applied load compared to the RF walls. Comparison of the load deflection of the PLS walls with that of the FRS walls indicates that the addition of macro-fibers and micro-fibers further improved the out of plane behavior of the URM walls.

![Figure 4](image)

**Figure 4.** Normalized average load deflection diagram of the tested walls.

### 3.2. Failure modes

Failure modes of the tested walls with a sketch of cracking pattern and the load levels correspond to the initiation of the cracks are shown in Figure 5. As can be seen in the photos, all of the walls exhibited multiple cracking behaviors. Figure 5a shows that the reference (RF) walls developed a vertical crack at a load level around 16 kN, followed by a horizontal crack at 20 kN. With further increase in the
applied load, some diagonal cracks were also developed along with the expansion of the previous cracks before punching at around 40 kN. It can be seen in the photo of Figure 5a that a big chunk of the wall is in the spalling position due to the punching failure.

It can be seen in Figure 5b that the PLS walls exhibited major horizontal and vertical cracks at a load level of around 70 kN, followed by some smaller diagonal cracks before failure at load level around 130 kN. Similar cracking behavior was noticed in the FRS walls but with more distributed cracks (see Figure 5c), indicating more energy absorption and improved toughness of the FRS walls relative to the PLS walls. In the FRS walls, the cracks initiated at load level around 80 kN which can also be confirmed with a slight drop in Load deflection curve shown in Figure 4. Eventually the FRS walls failed due to the propagation of multiple cracks and after reaching a peak load of 150 kN.

The ECCS walls exhibited a different cracking pattern compared to the other walls. It can be seen in Figure 5d that a highly distributed cracks are developed on the surface of ECCS walls indicating a very high energy absorption behavior. Moreover, it can be seen that in contrary to the other walls, the ECCS walls exhibited a balanced cracking behavior (two similar major diagonal cracks) indicating a highly uniform distributed load resisting behavior. The ECCS walls resisted a maximum load of 170 kN after which the resistance of the wall started declining and the diagonal cracks were widely expanded resulting in dividing the wall to almost four equal triangles. In all the walls the crack width reduced after unloading, particularly this behavior was more pronounced in the walls with FRS and ECCS mixes suggesting existance of some residual strength.

![Figure 5](image_url)

**Figure 5.** Walls after failure with the sketch of cracking pattern, a) RF, b) PLS, c) FRS, d) ECCS.

### 4. Summary and conclusions

A total of Eight URM walls were constructed and strengthened for out-of-plane action. The walls were divided into four pairs (duplicate) of which one pair has conventional plastering mortar applied to the surface. The remaining three pairs were strengthened with three different shotcrete mixes: plain concrete (OPC), fiber reinforced concrete (FRC) and engineered cementitious composites (ECC). The walls were tested under static monotonic load applied at the center of the wall. Load and displacement were measured during the test; and cracking and failure modes were monitored and reported.
The test results revealed that the out-of-plain resistance, toughness, and ductility of the walls can be significantly enhanced with application of fiber reinforced shotcrete layers. The use of ECC shotcrete layer increased the out of plane resistance of the walls by up to 4 times relative to the reference wall with conventional plaster. Similarly, the use of FRC shotcrete increase the out of plane strength by up to 3 times relative to the reference wall. In summary, the results of the load-deflection and cracking behavior demonstrated that the use of synthetic macro-fibers and polyethylene micro-fibers in the shotcrete mix can be an effective strengthening method to improve the out-of-plane response of URM walls.

5. References

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