Performances of Un-Reinforced Masonry Walls Retrofitted with Ferrocement Belts

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Abstract

A large inventory of Un-Reinforced Masonry (URM) buildings which are most vulnerable to earthquakes, exists in Sri Lanka. Minor tremors have come off in and near Sri Lanka especially since December, 2004. An earthquake that occurred in Colombo in April 14th, 1615, has caused human death of 2000 and collapse of 200 houses. Hence it is needed to identify retrofitting techniques. Retrofitting is a new trend to strengthen the existing masonry dwellings worldwide rather than replace them with new earthquake resistant buildings. This paper discusses the behaviour of masonry walls with and without retrofitting under diagonal compression test and cyclic loading test. Ferrocement belts technique was used for the retrofitting of the masonry walls. Ferrocement strengthen wall under the diagonal shear test showed increment of load carrying capacity of 69% compared to non-retrofitted specimen. Retrofitted wall possessed a diagonal deformation of around 25 mm along the direction of loading and continued to carry load after initial failure. Non-retrofitted wall showed a sudden brittle failure with no further improvement of load carrying capacity. Under the cyclic loading, it was revealed that, ferrocement belts helped the masonry wall to increase the ultimate load by 80% compared to non-retrofitted URM wall. Non-retrofitted URM wall also showed flexural mode of failure with rocking and failure occurred between wall and foundation. The wall with ferrocement belts avoided failure through wall and foundation. Crack propagation of URM wall was limited to smaller length where crack formation of ferrocement strengthened wall was occurred in longer length along the mortar bed joint with the continuation of loading. Ferrocement belts technique delayed initiation of wall and allowed wall to regain the load that could be observed by subsequent cracks with continuation of load under both diagonal shear loading and reversed cyclic loading. Therefore, ferrocement belts method may be effective for retrofitting of URM buildings against earthquakes.

1. Introduction

The past history showed that, earthquakes have caused a high toll of human deaths and a great property loss all over the world. D’Ayala [1] has reported that the worst death toll from an earthquake, in the past century, occurred in 1976 in China, where it is estimated that 240,000 people died and most of the deaths occurred due to the collapse of brick masonry buildings. A large inventory of older brick masonry buildings which are Un-Reinforced Masonry (URM) and are accordingly most vulnerable to earthquakes, exist in Sri Lanka. Sri Lanka is located within a tectonic plate known as “Indo-Australian plate” where the intra-plate earthquakes take place. The location or magnitude of such earthquakes cannot be easily predicted. Minor tremors have come off in and near Sri Lankan region especially since December, 2004 after the Sumatra Tsunami (Mendis et al. [2]). It is believed that these tremors are due to a diffused plate boundary which is in the making at some 500 km south of the southern tip of the island (Dissanayake [3]). Sri Lanka is also located within the Indo-Australian tectonic plate where location and magnitude of an earthquake cannot be easily predicted. Also, an earthquake that occurred in Colombo in April 14th, 1615, has caused around 2000 of human deaths in and around Colombo city and it is thought that 2000 houses collapsed by this strong earthquake of maximum intensity (MM1 – Modified Mercalli Intensity) of VII (Kodipilli [4]). Hence, it is needed to exercise some caution to avoid and control the catastrophic situation which may occur in future earthquake occurrences.

In view of the continuous use of URM buildings, it is necessary to increase the seismic resistance of masonry construction by providing earthquake resistant measures. The earthquake resistant measures are intended to increase the seismic resistance in terms of strength and ductility (Agarwal and Shrikhande [5]). In this regard retrofitting of existing URM buildings may emerge as the solution which implies incorporation of earthquake resistant measures in existing URM buildings. Retrofitting or seismic strengthening is defined as upgrading the disaster resistance of an existing unsafe building, or a damaged building while repairing (Arya [6]) and the building becomes safer under future earthquakes occurrences. During disasters, retrofitting delays buildings’ collapse, so then residents can evacuate for a safer place.

Various conventional and non-conventional retrofitting techniques are available worldwide such as Fiber Reinforced Polymer (FRP) sheets, ferrocement overlay, shotcrete, bamboo-band, Poly-Propylene band, center core technique, post-tensioning, stitching of wall corners, confinement with Reinforced Concrete (RC) or steel elements, grout injection and old tire strips.

High mass of URM structures is one of the most important problems that must be considered. In accordance to this view point, retrofitting methods with low additional mass are preferable. The method chosen

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2.1.2 Strengthening Procedure
The masonry wall was wrapped with two numbers of 1650 mm long and 150 mm high meshes (Figure 2(a)) and each end of mesh was connected with binding wires as shown in Figure 2(a).

Figure 2: Installation of ferrocement on masonry wall;
(a) Wrapping the wall with steel wire meshes,
(b) Partially retrofitted wall (with ferrocement casing) at test setup

Further, the meshes were connected to wall using bolts (Figure 2(a)). Then the areas only covered by both meshes were plastered with a cement rich mortar of which cement: sand ratio is equal to 1:3 (Figure 2(b)). The sand used in mortar was sieved by using 3 mm riddle.

2.1.3 Test Setup
The test setup was arranged as stipulated in ASTM E-519-02 standard guidelines. Figure 3 shows the schematic diagram of experimental set up used in the laboratory to determine the shear failure of non-retrofitted URM and retrofitted URM walls as well as to evaluate the effectiveness of proposed retrofitting method of ferrocement belts against in-plane static loads.

Figure 3: Schematic diagram of the test setup for diagonal shear loading

Two steel angle plates were used to fix the specimens to the loading frame. A 5 mm thick plaster of paris layer was applied on both steel plates where this layer is essential to carry out a better load transformation from actuator to the test wall. One of steel angle plates was fitted to hydraulic actuator and other steel angle plate was placed on a support below the actuator as shown in Figure 3. Then, specimen was carefully installed into loading frame and the specimen was checked for vertical alignment using plumb bob.

2.2 Lateral Reversed Cyclic In-Plane Load Test
After developing ferrocement belts retrofitting through static tests, next step is to carry out dynamic loading test. Accordingly, in-plane shear behavior of ferrocement strengthened wall was tested against lateral reversed cyclic loading. Non-retrofitted URM wall was also tested as control specimen.

2.2.1 Test Walls
Figure 4 shows the dimensions of the wall panel which were selected considering aspect ratio (height/width) of 1:2. Therefore the test specimens were cast as double wythe with the size of 720 x 600 x 225 mm (Figure 4).

Figure 4: Wall geometry and brick bond pattern for lateral reversed cyclic load test

Two wall panels: one for URM wall and one for retrofitting, with the size of 600 x 720 x 225 mm and 10 mm thick, 1:6 cement sand mortar joints, were cast and allowed for 28 days of curing. Afterwards, retrofitting of walls was completed.

2.2.2 Top Beam and Bottom Foundation Beam
The test specimens were supported by top beam and bottom pre-cast foundation beam. The main objective of using top beam was to provide a constant vertical load during the experimental loading period. Dead load and imposed load which is arrives from roof and other elements above the wall were represented by the top beam. The size of the top concrete beam was depended on the required constant load to be acted on the wall and the constant load was based on the dead and imposed load acted on load bearing masonry walls. Therefore size of the top beam was selected as 65 x 600 x 225 mm.

Objectives of providing bottom beam were to provide strong foundation for the wall and restrain the wall and avoid slipping of wall at the wall bottom. The bottom beam also helps to tie down the wall to testing frame. Size of the bottom beam or foundation was determined based on the load from wall panel and the top beam. Hence, the size of bottom beam was selected as 100 x 750 x 375 mm. Dimensions of the bottom beam were much greater than those of the test wall panel. This additional spacing were used to clamp the wall and top beam to the foundation. In addition, top beam, wall and
should also be affordable and feasible depending on several factors like the seismicity of the area, existing or expected damage to the building and required level of application of technology, simplicity, availability of material and costs of materials and labour. It seems that ferrocement method is simple, cost effective, and adding limited mass to the existing structure. Ferrocement is a content of steel wire mesh that is completely penetrated with a mortar which is rich in cement. The mortar is a mixture of sand, water and cement where sand particle size is not bigger than about 5 mm. The wire mesh is very thin and the wires are closely spaced. Several layers of meshes can also be used. There are various types of meshes used for ferrocement construction such as chicken mesh, welded mesh, woven mesh and expanded mesh.

Effect of ferrocement has been evaluated by Shah [7] by conducting an experiment under axial compression using twenty one masonry columns of 221 mm x 221 mm x 784 mm and they were tested. In the study, it was revealed that, encasement of unreinforced masonry brick columns by ferrocement cover which of 6.125 mm thick and 1.2 cement sand mortar with water cement ratio of 0.5 and mesh pitch of 12.25 mm, increased ultimate failure load by 121% or 1.33 times larger than that of non-retrofitted masonry wall. Also, test results have showed that, failure of columns initiate only after failure of the casing. Ferrocement can also be used to repair columns, which have been loaded close to failure. The method discussed in Shah [7] can be applied in masonry walls as columns and walls are nearly similar in behaviour theoretically and practically.

Shahzaada et al. [8] carried out axial compression on twenty brick masonry walls having size of 20 x 16 x 9 inch (i.e., 508 mm x 406.4 mm x 228.6 mm). Authors found that retrofitting method of ferrocement overlay (i.e., with 12.5 mm pitched steel wire mesh and 5 mm thick 1:2 cement-sand mortar overlay) improved the overall strength of unreinforced brick masonry walls by 48% and also their ductility. Further, the technique avoids the brittle failure of masonry walls.

A type of in-plane cyclic loading test of increasing intensities with constant vertical loading has been carried out by Ashraf et al. [9] on URM walls (i.e., with size of 3087 mm x 3262 mm x 225 mm) before and after retrofitting by ferrocement overlay. As authors have stated, lateral in-plane strength and lateral stiffness of the URM wall could be increased by 110% and 68%, respectively after retrofitting the wall by ferrocement overlay. The ferrocement overlay has consisted of 12.5 mm mesh pitched steel welded wire mesh (i.e. 1.0 mm diameter wires) and 19 mm thick 1:3 cement-sand mortar layer.

Objective of this study is to introduce seismic belts or ferrocement belts as a retrofitting technique for strengthening of existing URM dwellings in Sri Lanka and to evaluate proposed retrofitting techniques for strengthening of existing masonry dwellings against earthquakes.

Out-of-plane and in-plane failures are two possible failure mechanisms in individual load bearing brick masonry walls and in-plane failure is a fundamental failure mode for URM. A retrofitting technique should also be tested for both static and dynamic loadings.

Accordingly, this paper discusses test results based on diagonal shear test with static loading and lateral reversed cyclic in-plane loading test.

2. Methodology

Experimental study was conducted as two separate tests: diagonal compression or shear test and reversed cyclic lateral in-plane load test. Two masonry walls were used for each test: one specimen for control (or non-retrofitted URM wall) and the other for retrofitting with ferrocement technique to evaluate the beneficial effects of ferrocement belts technique against earthquakes. Burned solid clay brick (i.e., size of a brick: 215 x 100 x 60 mm) were used to build the test walls to simulate practical situation. Full scale models were used in these experiments, because a full scale model test makes possible to obtain data similar to real structure. A square-welded mesh type was used in ferrocement technique discussed in this test programme. The mesh was also plain waved and electro galvanized steel wire mesh with mesh pitch of 2.03 mm and diameter of 0.5 mm.

2.1 Diagonal Compression Test

Diagonal compression test was carried out on masonry walls retrofitted and without retrofitting to evaluate the beneficial effect of proposed retrofitting technique of ferrocement belts reinforcement.

2.1.1 Test Walls

The proposed retrofitting technique aims to improve the performance of walls by increasing shear strength above their flexural strength and by increasing ductility and energy dissipation capability. Wall with aspect ratio less than 1.0 has flexural strength higher than their shear strength in shear in a non-ductile behaviour (Chuang et al., [10]). Height of specimens should also be at least 600 mm for masonry walls in lab experiments where it would be well enough for representative of a full-size masonry walls. Therefore, the minimum specimen height used in these tests was 600 mm and it was the recommended standard height. Therefore all the specimens were cast with size of 600 x 600 x 225 mm.

![Figure 1: Wall geometry and brick bond pattern for diagonal compression test](image-url)
foundation were clamped to the loading frame. Further, necessary holes were provided to facilitate steel thread bars through the foundation to tie it well to the base.

2.2.3 Strengthening Procedure

The wall was partially wrapped using two pieces of steel mesh. Each end of the meshes was connected using binding wires and nails (Figure 5(a)).

Figure 5: Ferrocement belts technique; (a) Wrapping wall using steel mesh, (b) Partially retrofitted wall and (c) Connecting the steel mesh to wall and foundation

Here, one piece of mesh was laid at 110 mm distance below the top of wall panel while other piece of mesh connected the wall and foundation as shown in Figure 5(c). Finally, only wrapped areas of wall with steel mesh, were plastered using 1:3 cement sand mortar (Figure 5(b)).

2.2.4 Test setup

Figure 6 shows the schematic diagram of experimental set up including test specimen used in the laboratory to determine the behavior of retrofitted and non-retrofitted URM walls against in-plane reversed cyclic loading.

![Diagram of test setup](image)

Figure 6: Schematic diagram of the test setup for cyclic loading

The test specimens were supported by top beam for constant vertical load and bottom concrete foundation. Ten thread bars having diameter of 12.7 mm (i.e., ‟inch”) were used to clamp the top beam, wall and foundation to the loading frame. “L” shaped steel frame was used to hold the specimen and to transfer the load from actuator to the test specimen.

2.2.5 Loading History for Reversed Cyclic Test

The load was applied as a programmed sinusoidal wave under the displacement control method using the server control hydraulic actuator. The load was also applied in three and four steps for non-retrofitted and retrofitted wall, respectively. The loading sequence is summarized in as shown in Table 1. The given amplitudes and frequencies were based on range of the actuator.

Table 1: Loading history of reversed cyclic in-plane load test

<table>
<thead>
<tr>
<th>Step of loading</th>
<th>Parameter</th>
<th>Non-retrofitted or URM or control wall</th>
<th>Ferrocement strengthened wall</th>
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<td>Amplitude</td>
<td>Frequency</td>
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3. Results and Discussion

3.1 Diagonal Compression Test

Figure 7 shows the initial crack patterns of non-retrofitted and retrofitted masonry walls.

![Figure 7: Crack formation on specimens; (a) URM or non-retrofitted wall and (b) Wall with ferrocement belts](image)

The crack formation of non retrofitted URM wall (Figure 7(a)) showed that, failure of URM walls subjected to diagonal shear loads, occurs "along the mortar joints" rather than "through bricks". This is attributed to the mortar joint weak bond strength compared to the tensile strength of the burned clay bricks.

In retrofitted walls with ferrocement belts, initial visual cracking was followed by a sharp drop (Figure 8) with remaining of 81% of its initial strength. After it, subsequent strength drop (Figure 8) was quickly regained due to both of the elastic behaviour of steel and the arrangement of mesh formation.

![Figure 8: Load vs. vertical deflection for test specimens](image)

But, after the post peak load of the wall with ferrocement belts, its residual strength was decreased (Figure 8) until it lost completely its load carrying capacity and stability.

Both URM wall and ferrocement strengthened wall showed modes of failure as shear and sliding failure as shown in Figure 9. “Diagonal shear cracking” is the common masonry failure mode under seismic loads and happens for a combination of vertical and horizontal loads where the principal tensile stresses developed in the wall due to this action, exceed the tensile strength of masonry. Later, cracks were along a bed joint causing sliding of the upper part at that location which is generally called as “shear sliding”.

![Figure 9: Specimens at the failure; (a) Non-retrofitted wall and (b) Wall with ferrocement belts](image)

The observed shear slip failure mode of URM wall was highly brittle and, as soon as shear slip along a bed joint was initiated, the assemblages split into two parts and subsequently disintegrated. The shear slip occurred along the middle bed joint. No signs of cracking or distress were observed prior to failure by shear slip.

Although, the wall with ferrocement belts collapsed, it avoided scattering of bricks and mortar here and there. The wall separated into only two parts when collapse was occurred. In both separated parts of ferrocement strengthened wall, there were no significant damages (i.e., separation of bricks) in areas of the wall which were retrofitted with ferrocement belts, except cracks propagated over the ferrocement overlay. This observation clearly leads us to explore that applying ferrocement on URM wall is suitable as a retrofitting technique against static in-plane shear loads; but applying ferrocement in belt pattern is not suitable for seismic lateral loads.
URM walls shows flexural mode of failure with rocking under the in-plane seismic shear loads. Also, the failure of URM walls was first mode of failure. Further, in-plane lateral load (i.e., reversed cyclic in-plane lateral loading) causes the failure of URM walls through mortar joints between wall and the foundation. Therefore, it is urgently needed to improve the connection between wall bottom and the foundation to be resistant against earthquakes. For that purpose, ferrocement technique discussed in this paper may be effectively used where the retrofitting method allow the masonry wall to increase the load carrying capacity, dissipate the energy and distribute loads in better way and withstand the load over long period of time compared to URM wall.

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**References**


(because the wall tends to fail in area without ferrocement overlay resulted in collapse).

On the other hand, it is not worthy to say that applying of ferrocement in belt pattern instead of covering whole wall surface is not much suitable for retrofitting of masonry walls by carrying out only static diagonal in-plane shear load test, because of positioning of the test wall in diagonal direction.

3.2 Lateral Reversed Cyclic In-Plane Load Test

Both retrofitted and non-retrofitted walls showed flexural mode of failure with rocking due to lateral in-plane shear loading. Both of them were also showed first mode of failure which is one of failure modes observed in buildings subjected to earthquakes. Horizontal crack of URM wall, was occurred between wall and foundation as shown in Figure 10(a).

First crack initiated in URM wall at first step of loading. Crack propagation of URM wall was limited to a length of 200 mm (1/3 of the wall length) on both side of the wall. Afterwards, there was no further propagation of crack or development of new cracks and wall showed only the behaviour of rotation with continuation of loading. Therefore, continuation of load on the URM wall was stopped at the step 3 (where amplitude was 6 mm and Frequency 1 Hz). The peak load gained by URM wall was 5.98 kN.

![Figure 10](image)

Wall with ferrocement belts avoided failure through wall and foundation and the failure was through the mortar bed joint (i.e., near the middle height of the wall) in area between ferrocement belts or middle height of the wall. Ferrocement belts technique delayed crack initiation of wall where first crack initiation in retrofitted wall was at the third step of loading where amplitude and frequency were 4 mm and 1 Hz, respectively. Crack propagation of retrofitted wall was expanded along whole length on one side of the wall and a length of 300 mm on other side of the wall. Ferrocement belt technique allowed wall to regain of load with the continuation of load. The loading was limited for four steps of loading. But, further propagation of cracks could be observed until the end of the test. Further, ferrocement belts were help the masonry wall to increase the ultimate load (i.e., 10.74 kN) by 79.72% compared to non-retrofitted URM wall (or control wall). Therefore, ferrocement method is effective for retrofitting of URM buildings against earthquakes.

4. Conclusions

Ferrocement belts retrofitting technique can be effectively used in retrofitting existing masonry dwellings in Sri Lanka. Experimental study claimed that the ferrocement strengthened wall withstands the effect of the dynamic in-plane lateral for a longer time duration with increasing the ultimate load carrying capacity by around 80%, with compared to URM walls.