Investigation of in-plane seismic retrofit of unreinforced masonry walls by means of vertical steel ties

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HIGHLIGHTS

- Experimental study of seismic retrofit of URM walls using vertical steel ties.
- The URM walls consist of solid clay bricks with low shear strength mortar.
- The technique shows significant improvement of walls hysteresis behavior in terms of strength.
- The proposed technique enhance URM walls ductility.

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ABSTRACT

In this paper, a technique for seismic retrofit of unreinforced masonry walls is studied which comprises addition of two vertical steel ties on both edges of the walls. In total, four specimens have been tested under cyclic lateral load in combination with vertical constant load: two specimens with ties and two without ties. The tests show that vertical ties cause significant increase in seismic capacity in terms of both strength and ductility not only at yield but also at maximum. The ties also cause the failure modes to transform from either shear slip or diagonal tension into a combination of diagonal tension and toe-crushing.

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1. Introduction

Unreinforced masonry (URM) buildings are common in many countries. The existing URM structures are usually susceptible to earthquake and retrofitting of such buildings is an important concern worldwide. For example, based on the Ref. [1,2] this group of structures sustained heavy damages in the latest major earthquakes of Mangil (1990) and Bam (2003).

During the last decade, many researchers have investigated seismic retrofit of unreinforced masonry walls. Various techniques have been investigated such as adding fiber reinforced polymer (FRP) and reinforced concrete (RC) layers, grout and epoxy injection, post-tensioning, and external reinforcement [3–11]. Among different techniques, it has been established that retrofitting of the walls with horizontal and vertical ties constitutes an effective way for seismic retrofit. Most of the available studies deal with reinforced concrete ties [12–18]. The confinements usually include reinforced concrete tie-columns and edge-beams. This technique usually causes significant improvement in strength and ductility of URM walls and show satisfactory performance against earthquakes.

Despite of little research, the retrofitting with steel ties has widely been used to improve seismic performance of URM walls in different countries [19–23]. This method consists of adding diagonal or/and vertical steel strips on either one side or both sides of URM walls. The ties comprise steel strips which are anchored to the walls using steel bolts, and the ties are either fixed or not fixed to the foundation.

The present study proposes a technique for seismic retrofitting of URM walls which comprises steel strips as vertical ties on both edges of a wall. This technique has advantages such as simplicity to apply, relatively low costs, little deal of preparation work, relatively fast construction, and less disruption of service functions during repair. The experimental program includes cyclic in-plane lateral load in combination with constant gravity load of retrofitted and URM walls. The specimens are fabricated with solid clay bricks (105 × 49 × 31 mm), cement mortar joints, and the retrofitted
includes vertical steel strips \((30 \times 3 \text{ mm})\) on both edges of the wall. The aspect ratio of the specimens is either 0.5 or 0.7 to represent different failure modes.

2. Experimental program

Experimental research was performed in the structure laboratory of the University of Tehran to investigate the effectiveness and performance of using vertical steel strips to improve seismic behavior of URM walls.

2.1. Test specimens

In total, four specimens were built, two of them unreinforced masonry walls as reference specimens with nominal dimensions of \(1900 \times 1400 \times 110 \text{ mm}\) \((\text{length} \times \text{height} \times \text{thickness})\) and \(2700 \times 1400 \times 160 \text{ mm}\) \((\text{length} \times \text{height} \times \text{thickness})\). They were built with characteristics similar to existing URM buildings in Iran. Two other specimens were built identically to the reference ones, but retrofitted with vertical straps (Fig. 1 and Table 1). The four specimens were half scale with aspect ratios of 0.5 and 0.7 (height to length) and were tested under simultaneous combination of cyclic in-plane lateral load and constant gravity. The specimens were fabricated with solid clay bricks \((105 \times 49 \times 31 \text{ mm})\) and cement mortar joints. The thickness of joint was approximately 6 mm.

2.2. Materials

2.2.1. Brick, mortar, and masonry prism

The solid clay bricks were half scale with nominal dimensions of \(105 \times 49 \times 31 \text{ mm}\) \((\text{length} \times \text{width} \times \text{height})\). The compressive strength of the clay bricks, tested on nine specimens according to ASTM C67-02C [24], was 8.7 MPa with a standard deviation of 1.9 MPa.

The cement mortar used for the masonry walls had a mixed composition of 1:6 (cement: sand, by volume) ratio with an approximate thickness of 6 mm. The water content was adjusted to achieve a workable mortar. The compressive strength of the cement mortars, tested on eight specimens according to ASTM C109/109M-99 [25], was 8.4 MPa with a standard deviation of 0.6 MPa.

Compression test was carried out on 6 masonry specimens according to ASTM C1314-02A [26], as shown in Fig. 2. The specimens have an average compressive strength of 3 MPa with a standard deviation of 0.8 MPa.

2.2.2. Steel strips

The steel strips were added as vertical ties on both sides of the URM walls. The tensile strength of the steel strips, tested on three specimens according to ASTM E8/E8M-09 [27], resulted in tensile yield and ultimate strengths of 280.3 MPa and 363.9 MPa, respectively, with standard deviations of 2.5 MPa and 8.3 MPa, respectively. The dimensions of steel strips were \(30 \times 3 \text{ mm}\)

![Fig. 1. Characteristics of vertical steel ties (Specimen RMW12TS-4).](image1)

<table>
<thead>
<tr>
<th>Retrofitted specimen</th>
<th>Reference specimen</th>
<th>Length (mm)</th>
<th>Height (mm)</th>
<th>Width (mm)</th>
<th>Height to length ratio</th>
<th>Mortar shear strength (MPa)</th>
<th>Vertical stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMW12TS-4</td>
<td>URMW-1</td>
<td>2700</td>
<td>1400</td>
<td>160</td>
<td>0.5</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>RMW22TS-5</td>
<td>URMW-2</td>
<td>1900</td>
<td>1400</td>
<td>110</td>
<td>0.7</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

![Fig. 2. Compression and shear tests on masonry specimens.](image2)
(width $\times$ thickness). The vertical and horizontal spaces between steel bolts were 200 mm and 150 mm, respectively (Fig. 1).

It should be noted that in practice, the space between the bolts and masonry is filled by either cement mortar or epoxy resin and the steel strips are protected by anti-oxide colors. Furthermore, the retrofitted wall is covered with appropriate finishing material such as cement plaster. It is evident that such measures will protect the straps against corrosion and insure durability of the technique.

2.3. Bed joint shear strength

In-situ bed joint shear strength test was carried out on two reference specimen (URMW-1 and URMW-2) according to ASTM C1531-02A [28], as is shown in Fig. 2. The average bed joint shear stress ($\tau$) was 0.2 MPa with a standard deviation of 0.03 MPa.

2.4. Test setup

The specimens are tested using a lay-out shown in Fig. 3. The specimens are constructed on a pre-cast reinforced concrete footing. Vertical loading is statically and constantly applied to the top of the specimen by a hydraulic actuator of 100 kN, and cyclic in-plane lateral load is applied by a horizontal hydraulic jack of 250 kN. Vertical Load is uniformly distributed on the top of the specimens through a rigid steel beam. The specimens are braced laterally to prevent out-of-plane movement.

2.5. Loading procedure

Constant vertical axial loads of 43.2 kN and 20.9 kN are applied, in force control mode, to specimens RMW12TS-4 and RMW22TS-5, in a row, to simulate the gravity loads that typically act on a three-story masonry building. These loads correspond to axial compressive stress of 0.1 MPa.

The cyclic in-plane lateral loads are applied, in displacement control mode, to the top of the specimens to simulate earthquake with low rate pattern loading as shown in Fig. 4. (Technical Coordinating Committee on Masonry Research [29]).

2.6. Instrumentation

Twelve linear variable displacement transducers (LVDTs) are used to monitor horizontal and vertical displacements, diagonal deformations, slip along the base, and out-of-plane deformations...
of the specimens, as shown in Fig. 5. Six strain gauges are bonded to the external surface of the steel strips to monitor the strain of the steel strips, see Fig. 5. Vertical and horizontal loads are measured using two load cells.

3. Experimental observations

This section describes the crack pattern and failure modes of the four specimens under combined lateral and gravity loads.

3.1. Specimen URMW-1

This specimen is shown in Fig. 6, which has an aspect ratio of 0.5 (height to length). Horizontal cracks appear at a drift ratio of 0.18%, at the bottom of the wall, at a distance about 300 mm above the base. At a drift ratio of 0.37%, slide mechanism, and at a drift ratio of 0.55%, brick crushing of the toe have been observed. The test finished at 1.1% drift, and the failure mode observed was shear slip [30].

3.2. Specimen URMW-2

This Specimen has an aspect ratio equal to 0.7 (height to length). At a drift ratio of 0.18%, inclined cracks in the diagonal direction extend towards the edges of the wall. By increasing displacement at a drift 0.74%, more diagonal cracks appear and crushing of the toe brickwork occur, see Fig. 7. The test finished at 1.02% drift and the observed failure mode was diagonal tension [30].

Fig. 6. Damage and crack pattern of Specimen URMW-1.

Fig. 7. Damage and crack pattern of Specimen URMW-2.
3.3. Specimen RMW12TS-4

The first noticeable damage in this specimen is a horizontal crack at a distance of one-fourths of the wall height from the bottom at the southern side. The crack extends through mortar joints and appears at a drift ratio of 0.29%. By increasing displacement, more diagonal, horizontal and vertical cracks appear. At a lateral drift of 0.58%, the first diagonal crack formed at the eastern bottom corner. Sliding mode also occurred at 0.73% drift at the tenth bed joint above the base. At a lateral drift of 1.89%, brick crushing of the toe, local buckling of steel strips and vertical cracks at the border between steel strips and masonry panel also happen, see Fig. 8. The test finished at 2.19% drift and the observed damages indicate a combination of diagonal tension and toe-crushing mode of failure.

3.4. Specimen RMW22TS-5

The first diagonal and horizontal cracks appear in the middle of the specimen at 0.29% drift. Sliding mode also formed at 0.44% drift at the fifteenth, twenty-first and twenty-third bed joints above the base. By increasing displacement, at a drift of 2.19%, brick crushing of the toe, local buckling of the bottom and upper steel strips, and vertical cracks at the border between steel strips and masonry panel appear, see Fig. 9. Failure of the specimen is controlled by a combination of diagonal tension and toe-crushing mode as the test finished at 2.92% drift.
4. Cyclic behavior of the specimens

Hysteresis curves of the URM walls (reference walls URMW-1 and URMW-2) and the retrofitted walls (RMW12TS-4 and RMW22TS-5) are discussed in this section.

4.1. Specimen URMW-1

Fig. 10 shows in-plane hysteresis behavior of lateral load-lateral displacement of Specimen URMW-1. The maximum lateral strength is recorded as 40.5 kN in pull and 35 kN in push, at lateral drifts of 0.74% and 0.56%, respectively. The hysteresis curve shows a relatively high energy dissipation capacity and a uniform shape in both pull and push directions. The initial stiffness is measured as 37 kN/mm in pull and 25.6 kN/mm in push which deteriorates to 0.48 kN/mm and 0.8 kN/mm at ultimate load in pull and push, respectively. Displacement ductility (ratio of displacement at maximum to displacement at yield) of this specimen is an average value of 7.7, see Section 5.

4.2. Specimen URMW-2

As is illustrated in Fig. 10, the specimen has initial stiffnesses of 27.1 kN/mm and 17.4 kN/mm in pull and push side, respectively. The maximum lateral strength of Specimen URMW-2 is recorded as 21.2 kN in pull and 15.4 kN in push, at lateral drifts of 0.22% and 0.31%, respectively. The hysteresis curve shows relatively good energy dissipation capacity and a uniform response in both pull and push directions. Displacement ductility of this specimen shows an average value of 3.1, see Section 5.

4.3. Specimen RMW12TS-4

This specimen is identical to the reference Specimen URMW-1, but with vertical steel strips on both sides. Fig. 10 shows in-plane hysteresis behavior of lateral load-lateral displacement of Specimen RMW12TS-4. The maximum lateral strength is recorded as 56.8 kN in pull and 67.7 kN in push which deteriorates to 1.2 kN/mm and 1.8 kN/mm at ultimate load in pull and push, respectively. Displacement ductility factor of this specimen is calculated as an average value of 17.8, see Section 5.

4.4. Specimen RMW22TS-5

This is identical to the reference Specimen URMW-2, but, with vertical steel strips on both sides. Fig. 10 shows in-plane hysteresis behavior of lateral load-lateral displacement of Specimen RMW22TS-5. The maximum lateral strength is recorded as 53.7 kN in pull and 49.8 kN in push at a lateral drift of 2.92%. The shape of hysteresis loops exhibits pinching effect. This pinching may be attributed to closing and opening of cracks, local buckling of vertical steel strips, and crushing of the toe brickwork. The initial stiffness is calculated as 25.5 kN/mm in pull and 9 kN/mm in push which deteriorates to 0.82 kN/mm and 1.52 kN/mm at ultimate load in pull and push, respectively. Displacement ductility of this specimen shows an average value of 9, see Section 5.

5. Comparison of retrofitted specimens with reference specimens

As has already been mentioned, two reference specimens are unretrofitted, and two others have the same characteristics as the reference ones, with the exception of being retrofitted by vertical steel strips on both sides. In this section, the retrofitted specimens are compared with the reference ones. The envelope of the hysteresis curves are idealized according to FEMA356 and ASCE41 [31,32], see Fig. 11. Based on the equivalent bilinear curve, different hysteresis characteristics such as yield and maximum strength and displacement, displacement ductility, and effective stiffness of all specimens are calculated.

The initial stiffness, \( K_e \), is defined as the slope of the experimental envelope curve at the origin. The effective stiffness, \( K_e \), and displacement ductility, \( \mu \), are defined as:

\[
K_e = \frac{V_y}{\delta_y}
\]

\[
\mu = \frac{\delta_{m}}{\delta_y}
\]
where $V_y$, $\delta_y$ and $\delta_m$ are yield strength, yield displacement, and displacement at maximum, respectively.

5.1. Comparison of URMW-1 with RMW12TS-4

These specimens have identical nominal dimensions of $2700 \times 1400 \times 160$ mm (length × height × thickness). The envelope curves of two specimens are plotted in Fig. 12 and their hysteretic characteristics are also presented in Table 2. Fig. 12 and Table 2 show that adding vertical ties cause: (a) a decrease of both initial stiffness by 65% and effective stiffness by 49%, (b) a decrease of strength by 76% but an increase of drift by 33% at yield, (c) relatively significant increase of strength (65%) and relatively high increase of drift (more than three folds) at maximum strength, (d) relatively large improvement of ductility (ratio of displacement at maximum to displacement at yield) as much as more than two folds, (e) an increase of energy dissipation capacity (up to maximum strength) by 30%. In total, an addition of vertical ties to long specimen causes significant increase of seismic capacity over large deformation phase while little change of pre-yield characteristics.

5.2. Comparison of URMW-2 with RMW22TS-5

These specimens have identical nominal dimensions of $1900 \times 1400 \times 110$ mm (length × height × thickness). The envelope curves of two specimens are plotted in Fig. 12 and their hysteretic characteristics are also presented in Table 2. Fig. 12 and Table 2 show that adding vertical ties cause: (a) a decrease of both initial stiffness by 77% and effective stiffness by 54%, (b) an increase of strength (more than two folds) and relatively large variation (more than three folds) in drift at yield, (c) relatively significant increase of strength (2.8 times) and relatively high increase of drift (more than ten folds) at maximum strength, (d) relatively large improvement of ductility (ratio of displacement at maximum to displacement at yield) as much as more than two folds, (e) an increase of energy dissipation capacity (up to maximum strength) by 37 times. In total, an addition of vertical ties to medium specimen causes significant increase of seismic capacity over large deformation phase.

If medium specimen ($H/L=0.7$) is compared with long specimen ($H/L=0.5$), this technique is more effective for medium
specimen than for long specimen. That is, improvement of maximum strength and ductility are much higher for medium specimen relative to long specimen. This may indicate that vertical ties are more effective for controlling mechanism of diagonal tension than mechanism of horizontal sliding. Despite being more effective for medium specimen, the technique has improved both specimens in almost all hysteresis characteristics in a significant value, and the ties show an important role in enhancement of seismic behavior of both specimens.

6. Summary and conclusions

This paper studies a technique to retrofit URM walls against earthquake. The technique comprises addition of two vertical steel ties on both edges of the wall. In total, four specimens have been tested: two of them with steel strips on both vertical edges and two of them without strips. The specimens undergo cyclic lateral load in combination with vertical constant load. For the tested specimens, it has been observed that an addition of vertical steel strips to URM walls,

- decreases yield strength by 70% but increases maximum strength by 160%, for specimen with aspect ratio of 0.7,
- increases both yield and maximum strengths by 210% and 280%, respectively, for specimen with aspect ratio of 0.7,
- increases drift ratio at yield by 30% and at maximum by 50%, respectively,
- reduces both initial and effective stiffnesses by 70% and 50%, respectively,
- increases ductility (displacement at maximum to displacement at yield) by values between 140 to 400 percent with an average value of 270%,
- transforms failure mode from shear slip (URMW-1) and diagonal tension (URMW-2) into a combination of diagonal tension and toe-crushing for both specimens,
- causes formation of thinner and more disperse cracks relative to unreinforced walls.

As a general conclusion, the study shows that addition of vertical steel strips to both edges of URM walls enhances seismic capacity of the specimens significantly, and the technique has advantages such as simplicity to apply and relatively low costs. It should be noted that because of the limited number of tests, and limited reports available in the literature, more tests may be needed to generalize the above conclusions.

References