USE OF TEXTILE-REINFORCED MORTAR JACKETS TO IMPROVE THE OUT-OF-PLANE PERFORMANCE OF MASONRY INFILL WALLS

Lampros KOUTAS¹, Dionysios BOURNAS²

ABSTRACT

This paper presents an experimental investigation on the use of textile-reinforced mortar (TRM) as externally bonded reinforcement for the out-of-plane strengthening of masonry infill walls in reinforced concrete (RC) frames. This technique comprises the use of high-strength fibers in the form of textiles combined with cement-based mortars, applied over masonry and concrete substrates. The experimental program included testing of four half-scale, single-story masonry-infilled RC frames. All specimens were subjected to out-of-plane monotonic loading with the load being distributed at four points on the infill’s body. The aim of this study was to evaluate the effectiveness of this innovative retrofitting technique in increasing the strength and deformation characteristics of the infill walls in the out-of-plane direction. For this purpose, one single-wythe wall specimen was tested without receiving any retrofitting serving as reference; whereas the rest three specimens were first retrofitted with carbon TRM jackets and then tested to failure. The key examined parameter included the anchorage of the TRM to the surrounding RC frame which depends on the boundary conditions between the infill wall and the frame. It was found that the out-of-plane strength and deformation capacity of the masonry infill walls was significantly increased in all cases, whereas the boundary conditions had a strong influence on the effectiveness of the technique. Overall, the risk of collapse of the walls was drastically eliminated, thus enhancing the resilience of masonry-infilled RC buildings.

Keywords: Infill walls; Reinforced Concrete; Textile Reinforced Mortar; Strengthening; Resilience

1. INTRODUCTION

The issue of upgrading unreinforced masonry (URM) walls serving as infills in existing reinforced concrete (RC) buildings is of great importance due to: (a) their vulnerability to man-made hazards such as acts of terrorism; (b) their poor performance under extreme natural events, such as strong earthquakes or even tornados. Acts of terrorism usually involve blasts next to buildings, imposing extreme loads to the buildings facades which typically comprise URM infill walls, and which are extremely vulnerable to such a type of loading. Earthquakes can frequently result in out-of-plane collapse of masonry infills, possibly triggering the progressive collapse of the building.

Particularly in the case of moderate or severe seismic actions, although the presence of masonry infills can be beneficial for the overall performance of a building, they tend to crack early and detach from the surrounding RC frame members either due to in-plane or out-of-plane action (or a combination of the two). Collapse of the damaged infill wall can then be triggered by forces acting in the out-of-plane direction of the wall. The impact of such behaviour of masonry infill walls is socio-economical, as it results in huge economic losses and casualties. Thus, an effective strengthening solution of masonry infilled RC frames can improve the resilience of such structures. Conventional techniques include RC jacketing (i.e. Pinto et al. 2002), whereas more modern studies include the application of thin layers of lightweight epoxy-based composite materials, such as fibre-reinforced polymers (FRP) (e.g. Ozden et al. 2011).

¹Elected Assistant Professor, Dept. of Civil Engrg., Univ. of Thessaly, Volos GR-38221, Greece. Formerly: Post-Doctoral Research Associate, Dept. of Civil and Structural Engrg. Univ. of Sheffield, UK. Email: koutasciv@gmail.com
²Scientific Officer, European Commission, Joint Research Centre, Directorate for Space, Security and Migration, Safety and Security of Buildings Unit, via E. Fermi 2749, I-21027 Ispra, Italy. Email: dionysios.bournas@ec.europa.eu
Recently, Koutas et al. (2014) proposed the use of textile-reinforced mortar (TRM) jackets for the in-plane strengthening of masonry-infilled RC frames, with successful results. TRM comprises open-mesh high strength textiles combined with inorganic mortars (lime or cement based) resulting in composite materials with many advantages over FRP systems [i.e. resistance to high temperature (Tetta and Bournas 2016, Raoof and Bournas 2017a, b), compatibility to masonry or concrete substrates, applicability at low temperatures or on wet surfaces, lower cost]. Based on the current state-of-the-art studies, TRM has been proved effective for strengthening both concrete and masonry structures (i.e. Triantafillou and Papanicolaou 2006, Bournas et al. 2007, Papanicolaou et al. 2008, D’ Ambris and Focacci 2011, De Felice et al. 2014, Loreto et al. 2015, Tetta et al. 2016, Koutas and Bournas 2017, Raoof et al. 2017).

Although several studies exist in the literature investigating the out-of-plane performance of simply-supported unreinforced masonry walls (URM) strengthened with TRM layers (Papanicolaou et al. 2008, Harajli et al. 2010, Babaeidarabad et al. 2014, Valluzzi et al. 2014, Martins et al. 2015, Triantafillou et al. 2017), there is still no research on the out-of-plane strengthening of masonry-infilled RC frames with TRM. As also highlighted by Lunn and Rizkalla (2011), which investigated the out-of-plane strengthening of masonry infill walls with FRP, the simply supported boundary conditions may be appropriate for certain cases of masonry walls types but they do not simulate the boundary conditions of masonry infill walls in RC frames. The interface between the wall and the RC frame members, as well as the restrain provided by the RC frame cannot be taken into account in simply supported masonry elements. Hence, significant sources of over strength (such as the arching action), are ignored.

This paper aims at investigating the out-of-plane strengthening of masonry infill walls in RC frames with TRM to improve the resistance and resilience of such structures in catastrophic events, by simulating for the first time as realistic as possible the boundary conditions between the infill walls and the surrounding RC frame members. The effectiveness of the novel strengthening technique is assessed in terms of out-of-plane strength, stiffness and deformability enhancement, energy dissipation capacity and residual strength. More details are given in the following sections. The complete study on the out-of-plane strengthening of masonry infills with TRM jacketing including more parameters (i.e. double walls) and an extensive discussion are given by Koutas and Bournas (2018).

2. EXPERIMENTAL PROGRAMME

2.1 Test Specimens and Parameters

Four RC frames with identical geometry were constructed and infilled with single-wythe masonry walls. One was tested without strengthening and therefore served as reference specimens. The rest three frames were first retrofitted with carbon-fibre TRM jackets and then tested to failure. The geometry of the tested frames is shown in Fig. 1a. The length and height of the infill wall panels was 1.70 m and 1.25 m, respectively, which yields a length-to-height aspect ratio of 1.36. The sections of the columns and the T-beam are shown in Fig. 1b and Fig. 1c, respectively. It is noted that the longitudinal reinforcement of all members was continuous with no lap-splices. The concrete base of the RC frame, which was used to fix the frame to the strong floor of the lab, was heavily reinforced to avoid the development of cracks during testing.

![Figure 1](image-url)
The masonry infill walls were constructed using 215x102.5x65 mm solid (fired clay) bricks, which were laid with the small side (65 mm) and were bonded to the bed mortar joints, resulting in a thickness of 65 mm (half of the columns width). The bed and head mortar joints of the walls in all cases had a thickness of approximately 10 mm.

The role of a key parameter on the effectiveness of TRM strengthening technique was investigated, namely the connection configuration between the wall and the surrounding RC frame members, which depend on the boundary conditions. A description of the specimens follows, supported by Fig. 2:

- **S_CON**: Control specimen with unretrofitted single-wythe infill wall.
- **S_NOC**: Double-sided TRM-strengthened single-wythe wall specimen, no connection (NOC) between the wall and the RC frame members is applied.
- **S_BCK**: Double-sided TRM-strengthened single-wythe wall specimen, with back side (BCK) connection of the wall to the RC frame members.
- **S_FRN**: Double-sided TRM-strengthened single-wythe wall specimen, with front side (FRN, side of loading) connection of the wall to the RC frame members.

Note that in all strengthened specimens, two layers of carbon-fibre TRM were applied (for details of the strengthening material see Section 2.2.2).

![Figure 2. Section view of the tested specimens to illustrate the various strengthening configurations](image)

**2.2 Materials**

**2.2.1 RC Frame and Masonry Infill Walls**

Casting of the RC frames was made in three groups on different dates by the same mix design targeting to a concrete compressive strength of 20 MPa. The average compressive strength on the day of testing the infilled frames, measured on 150x150 mm cubes (average values from three specimens), is given for each specimen in Table 1. The 6 mm-diameter smooth longitudinal bars had a yield stress of 470 MPa, a tensile strength of 508 MPa and an ultimate strain of 7.2%. The respective values for the 10 mm-diameter deformed bars were 545 MPa, 637 MPa and 11.2% (average values from three specimens).

The compressive strength of the non-engineered bricks used in this study to build the masonry infill walls, was equal to 21.2 MPa. This value was obtained as the average from three compressive tests on bricks capped with rapid hardening mortar and loaded perpendicular to their length with a bearing area of 215x65 mm.

A typical mix design was used for the mortar to bind the bricks, with 1:4 cement-to-sand proportions. To obtain its compressive and flexural strength, three mortar prism samples (dimensions of 40x40x160 mm)
were taken during the construction of the infill wall of each test specimen. Compressive and three-point bending tests were conducted according to the EN 1015-11 (CEN 1999a), on the day of the large-scale testing; the results are summarised in Table 1 (average values from three specimens).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Concrete strength (MPa)</th>
<th>Mortar for joints</th>
<th>Strengthening mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Compressive (MPa)</td>
<td>Flexural (MPa)</td>
</tr>
<tr>
<td>S_CON</td>
<td>22.1</td>
<td>11.5</td>
<td>3.1</td>
</tr>
<tr>
<td>S_NOC</td>
<td>23.4</td>
<td>11.8</td>
<td>2.8</td>
</tr>
<tr>
<td>S_BCK</td>
<td>23.4</td>
<td>12.9</td>
<td>2.9</td>
</tr>
<tr>
<td>S_FRN</td>
<td>22.1</td>
<td>12.3</td>
<td>2.6</td>
</tr>
</tbody>
</table>

2.2.2 Strengthening Material

A carbon-fibre textile was used as reinforcement of the TRM composite material, which was externally applied in layers to retrofit the masonry infill walls. The textile used (Fig. 3a), had a weight of 348 g/m² with uncoated carbon fibre rovings in two orthogonal directions and a 50-50% distribution of fibres in each direction. The nominal thickness of the textile in each direction was 0.095 mm (based on the smeared distribution of fibers). According to the manufacturer datasheets, the tensile strength and the modulus of elasticity of the carbon fibers were 3800 MPa and 225 GPa, respectively.

The mortar used as matrix of the TRM composite and as binding material between the textile and the substrates (masonry or concrete), was a polymer-modified cement based mortar with an 8:1 cement to polymers ratio by weight. The water to cementitious material ratio by weight was equal to 0.23, resulting in plastic consistency and good workability. Table 1 includes the strength properties of the mortar (average values of 3 specimens) obtained experimentally on the day of testing using prisms of 40x40x160 mm dimensions, according to the EN 1015-11 (CEN 1999a).

To obtain the mechanical properties of the composite material, tensile tests on TRM coupons were conducted. Three dumbbell specimens (Fig. 3b) were fabricated, comprising one layer of carbon-fibre textile (same as the textile used for strengthening) embedded in the middle of a 10 mm-thick layer of mortar (same as the mortar used for strengthening). According to the results, the mean tensile strength was 1382 MPa (calculated on the basis of the textile-fibres cross-sectional area), the mean ultimate strain was 0.79% (calculated as the average strain over a gauge length of 200 mm), and the modulus of elasticity was 163.3 GPa (calculated as the secant modulus of elasticity of the post-cracking response, which reflects the activation of the textile-fibres in tension). Figure 3c shows the stress-strain curves obtained from the coupon tests.
2.2.3 Strengthening Procedure

The strengthening procedure was a typical wet lay-up application including the following steps:
(a) Removal of a thin layer of concrete and formation of a grid of grooves (2 mm deep) at the surface of the columns and the beams to receive strengthening; (b) Rounding of the column corners with a radius of 15 mm, to avoid stress concentration of the TRM jackets; (c) Dampening of both concrete and masonry surfaces to receive strengthening (Fig. 3a); (d) Application of a first mortar layer with a thickness of 3-4 mm using a smooth metal trowel (Fig. 3b); (e) Application of the first textile layer into the mortar by hand pressure (Fig. 3c); (f) Application of a mortar layer to cover completely the textile layer previously applied; and (g) Application of the second TRM layer by repeating steps (c)-(e) while previous layer was still in fresh state.

Figure 4. Pictures during strengthening application procedure: (a) dampening of surfaces to receive the TRM jacket; (b) application of 1st layer of mortar; and (c) textile application on the wall’s face

Each specimen was strengthened on both sides, but the strengthening configuration on each side was depending on the boundary conditions between the wall and the adjoining RC frame members (see Fig. 2). In specific, when there was no step between the wall and the frame members, the TRM jacket was extended to the faces of all the frame members and to sides of the columns. In contrast, when there was a step, the TRM jacket was applied only on the face of the wall.

2.3 Test Set-up and Procedure

All specimens were subjected to monotonic out-of-plane loading and tested to failure. Figure 7 illustrates the test-up implemented for the tests. The specimens were fixed to the lab’s strong floor via prestressing 12 steel rods passing through the RC base (Fig. 5a). The load was applied by a 500 kN-capacity servo-hydraulic actuator, which was mounted on a stiff steel reaction frame. A system of steel beams was used to spread the load into four points as shown in Fig. 7a; allowing to achieve more uniform load distribution. The four load-application areas were centrally located at horizontal and vertical distances equal to 1/3 of the clear length and height of the infill walls, respectively. To avoid concentration of high local stresses in these areas, square rubber pads (150x150x40 mm) were placed in-between the wall and the spreading beams. For convenience, the face of the specimen that was in contact with the loading configuration is hereafter mentioned as “front face”, while the other is called “back face”.

As shown in Fig. 5b, the horizontal out-of-plane displacement of the two RC frame's beam-columns joints was restrained by adding two stiff steel beams on the back face of the specimens, which were mounted on an external stiff steel reaction frame. The contact area between the steel beams and the beam-column joints was equal to 160x160 mm. Recorded measurements included load and displacement values from the actuator, and out-of-plane displacement values from nine potentiometers attached on the back face of the specimen. In specific, four potentiometers were fixed on the perimeter of the infill to measure the relative out-of-plane movement of the wall with respect to the frame, whereas five potentiometers were mounted on an external reference system to monitor the absolute out-of-plane displacements of the the masonry wall in both bending directions.

The testing procedure included application of the load monotonically at a constant displacement rate of 1 mm/min. A data acquisition system was employed to monitor and record synchronised data from all sensors at a sampling rate of 4 Hz. The termination point of the tests was decided individually for each specimen, taking into consideration risks from possible wall’s collapse.
Figure 5. Test setup: (a) picture of loading configuration (front face); and (b) out-of-plane supports in the opposite direction of loading (back face)

3. TEST RESULTS

Table 2 summarises the test results in terms of peak load, displacement at maximum load, strengthening effectiveness, initial stiffness and energy absorption. The strengthening effectiveness is defined as the ratio of the maximum load attained by a retrofitted specimen to the capacity of the corresponding control specimen. The initial stiffness values have been calculated as the secant stiffness of the load versus displacement curves (Fig. 6) from 0 to 40% of the peak load. Finally, the energy absorption values represent the area under the load versus displacement curves from 0 to 57 mm, which is the minimum, among all specimens, ultimate displacement value recorded. The out-of-plane behaviour of the specimens is described below, grouped based on the thickness of the infill wall. It is noted that the out-of-plane displacement used to describe the behaviour of all specimens is the displacement measured by the potentiometer positioned at the centre of the back face of the wall.

Table 2. Summary of test results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Peak load, $P_{\text{max}}$ (kN)</th>
<th>Central displacement at $P_{\text{max}}$, mm</th>
<th>Strengthening effectiveness factor, $P_{\text{str}}/P_{\text{con}}$</th>
<th>Initial stiffness* (kN/mm)</th>
<th>Energy absorption** (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_CON</td>
<td>29</td>
<td>22.5</td>
<td>-</td>
<td>7.4</td>
<td>1.53</td>
</tr>
<tr>
<td>S_NOC</td>
<td>110</td>
<td>28.4</td>
<td>3.79</td>
<td>13.1 (77%)</td>
<td>3.89 (154%)</td>
</tr>
<tr>
<td>S_BCK</td>
<td>118</td>
<td>31.1</td>
<td>4.07</td>
<td>19.5 (164%)</td>
<td>5.03 (229%)</td>
</tr>
<tr>
<td>S_FRN</td>
<td>158</td>
<td>19.8</td>
<td>5.45</td>
<td>20.1 (172%)</td>
<td>5.52 (261%)</td>
</tr>
</tbody>
</table>

* Secant stiffness of the load versus central displacement curve, from 0 to 40% of the peak load. The values in the brackets represent the percentage increase with respect to the corresponding control specimen

** Cumulative energy absorption at a central out-of-plane displacement of 57 mm. The values in the brackets represent the percentage increase with respect to the corresponding control specimen

The reference frame (S_CON) attained a maximum load of 29 kN at a corresponding out-of-plane displacement at the centre of the wall equal to 22.5 mm, whereas its initial stiffness was equal to 7.4 kN/mm. The first cracks appeared at a load level of 10 kN, at a bed joint in the central region of the wall’s back face. As the load was increasing, the cracks on the back face were propagating towards the four corners, following mainly the mortar joints, whereas on the front face (loading side) the wall was separated from the RC frame on the perimeter. With the main mechanism of carrying forces being the arching action, the max load of 29 kN was reached and remained almost constant until the arching action started degrading at a displacement of approximately 30 mm (Fig. 6). With increasing out-of-plane displacements, the load dropped gradually until the test was terminated. The cumulative energy absorption at 57 mm displacement was 1.53 kJ. Fig. 7a shows specimen S_CON after the termination of the test.
The specimen without connection between the strengthened wall and the RC frame (S_NOC), reached a peak load of 110 kN, at a displacement of 28.4 mm. The initial stiffness of S_NOC specimen was equal to 13.1 kN/mm. The first cracks in the TRM jacket appeared at a load of 50 kN on the back face of the wall (at a displacement of 4 mm), whereas at 60 kN the infill panel was detached from the middle region of the top beam and experienced shear sliding (visible in Fig. 7b, after the test completion). With the wall being supported practically only at the three sides of the frame (the two columns and the base), the load continued to increase. Full detachment of the wall from the beam and columns led to sudden load drop. Relatively low residual strength was provided by the wall, which was moving as a solid panel after failure occurred. The cumulative energy absorption at 57 mm displacement was equal to 3.89 kJ.

Specimen S_BCK, with the retrofitted wall being connected with the RC frame members on the back side, reached a maximum load of 118 kN at an out-of-place displacement of 31.1 mm. The initial stiffness was equal to 19.5 kN/mm. Up to a load of 70 kN there was no visible damage in the TRM jacket. As the load increased, the wall detached from the top beam’s middle region (shear sliding). Until the maximum load was reached (118 kN), the wall’s back face experienced multiple cracking, whilst extensive shear sliding occurred between the wall and the beam developed at the detached part. As a result, the TRM overlays started to gradually debond from the beam’s surface; when full debonding occurred (Fig. 7c) the load dropped to approximately 80 kN (at a displacement of 38 mm). Redistribution of stresses led in stiffness and load recovery as the wall started detaching from the two columns (shear sliding), thus activating the TRM overlays. After a load recovery of approximately 20 kN, the TRM jacket debonded from the face of the left column and the load dropped again at 80 kN (at a displacement of 55 mm). Ultimately, at very large displacements (65 mm), the TRM jacket debonded also from the face of the right column. Slippage of the textile fibres through the mortar at the side faces of the two columns resulted in gradual load drop. The cumulative energy absorption at 57 mm displacement was equal to 5.03 kJ.

Specimen S_FRN, with the strengthened wall being connected with the RC frame members on the front side, reached a maximum load of 158 kN at an out-of-place displacement of 19.8 mm. The initial stiffness of S_FRN specimen was 20.1 kN/mm. The behaviour of this specimen was smooth almost until the peak load was reached. At a load approximately equal to 70 kN, the first cracks appeared at the centre of the wall’s back face (at a displacement of 3.5 mm). As the out-of-plane displacements were increasing, multiple cracks on the wall’s back face continued to develop and propagate towards the four corners (Fig. 7d), indicating an excellent connection between the infill wall and the frame. This behaviour resulted in smooth stiffness reduction. At a load of 145 kN (at a displacement of 13 mm), damage of the wall was observed on the front face close to the loading area. The presence of the TRM jacket resulted in local activation of the textile fibres in tension, which helped to reach a peak load of 158 kN (at about 20 mm displacement). Then, local rupture of fibres led to significant load drop (to 110 kN), accompanied by stresses redistribution until a second load
drop was recorded (to 65 kN) due to fibres rupture (at a displacement of 33 mm). For larger displacements, the wall exhibited significant residual strength of approximately 80 kN, owing to the continuous stress redistribution at the perimeter of the loading area. The cumulative energy absorption at 57 mm displacement was equal to 5.52 kJ.

Figure 7. Damages of single masonry wall infilled frames: (a) S_CON; (b) S_NOC; (c) S_BCK; and (d) S_FRN

5. CONCLUSIONS

This paper presented an experimental study on the use of textile-reinforced mortar (TRM) jackets as a means of improving the out-of-plane performance of masonry infill walls in reinforced concrete (RC) frames. The effect of different connection configurations between the infill wall and the RC frame members was carefully examined in terms of ultimate load-carrying capacity, initial stiffness, energy absorption and residual strength. Overall, this study proved the effectiveness of TRM strengthening technique in improving the out-of-plane performance of masonry infill walls in RC frames, highlighting the importance of the connection configuration, which depends on the boundary conditions between the infill and the frame members.

Future research could be directed towards: examining the effect of cyclic loading on the out-of-plane response TRM-strengthened masonry infilled RC frames; investigating the combining effect of in-plane and out-of-plane actions; developing appropriate numerical models to simulate the out-of-plane behaviour of TRM-strengthened masonry infilled RC frames. Moreover TRM jacketing of masonry infilled RC frames may be combined effectively with thermal insulation materials or systems (Bournas 2018), providing promising solutions for the simultaneous seismic and energy retrofitting of the RC building envelopes.

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7. REFERENCES


