INNOVATIVE INTEGRATED SEISMIC AND ENERGY RETROFITTING SYSTEM FOR MASONRY WALLS USING TEXTILE REINFORCED MORTARS COMBINED WITH THERMAL INSULATION

Kyriakos KARLOS\textsuperscript{1}, Thanasis TRIANTAFILLOU\textsuperscript{2}

ABSTRACT

The application of a new system is proposed and investigated, which combines textile reinforced mortars (TRM) and thermal insulation as a means of combined seismic and energy retrofitting of masonry walls. Medium scale tests were carried out on masonry walls subjected to out-of-plane and in-plane cyclic loading. Several parameters were investigated, including the use of fire-resistant versus polymer-based insulating material, one-sided versus two-sided insulation and/or TRM jacketing, placement of the TRM outside the insulation or in a sandwich form (over and under the insulation) and the displacement amplitude of the loading cycles. From the results obtained in this study the authors believe that TRM jacketing may be combined effectively with thermal insulation, which can be fire-resistant too.

Keywords: Fire resistance; Masonry; Seismic retrofitting; Textile reinforced mortar; Thermal insulation

1. INTRODUCTION

Masonry walls are prone to failure during high or moderate intensity earthquakes or high wind pressure, hence they represent a significant hazard to life safety. Yet, structural decay due to ageing or cumulative seismic-induced damage poses a direct threat to the preservation and safeguarding of masonry structures that comprise an important part of many countries’ cultural heritage. Hence, there is an urgent need for upgrading existing masonry structures, both in seismic areas, where structures designed according to old seismic codes have to meet upgraded performance levels demanded by current seismic design standards, and in non-seismic areas, e.g. due to change of usage and/or the introduction of more stringent design requirements.

Numerous techniques have been developed aiming at increasing the strength and/or deformation capacity of masonry walls, including the use of metallic or polymer-based grid reinforced surface coatings, shotcrete overlays, internal or external prestressing with steel ties, externally bonded or near-surface mounted fiber reinforced polymers (FRP) and textile reinforced mortar (TRM) jacketing. TRM-based solutions for masonry structures are becoming increasingly promising, as they combine the favorable properties offered by FRP systems (e.g. high strength and stiffness to weight ratio, high deformation capacity, corrosion resistance, ease and speed of application and minimal change in the geometry) while addressing most of the problems associated with the use of organic resins, namely: poor behavior at elevated temperatures, incompatibility with substrates, combustibility, high costs of epoxies, lack of breathability, potential hazards for the workers, difficulty to conduct post-earthquake assessment behind FRP jackets, reversibility requirements etc.

The TRM system, also known as TRC (textile reinforced concrete) or FRCM (fabric reinforced cementitious matrix), comprises an open weaved fabric made of long woven, knitted or even unwoven fiber rovings (e.g. glass, basalt, carbon, steel) in at least two (typically orthogonal) directions, and an inorganic mortar matrix (Triantafillou et al. 2006). The density, that is the quantity of the spacing of

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rovings in each direction can be controlled independently, thus affecting the mechanical characteristics of the open weaved fabric and the degree of penetration of the mortar matrix through the woven mesh. TRM systems in combination with masonry were used by Faella et al. (2004) and Prota et al. (2006) as a means of increasing the strength of tuff masonry wallets tested in diagonal compression, by Kreviakas (2005) and Nurchi and Valdes (2005) in the form of confining jackets for small scale rectangular column-type masonry specimens tested in uniaxial compression, and by Papanicolaou et al. (2007, 2008) as a means of seismic retrofitting of unreinforced masonry walls subjected to in-plane or out-of-plane loading. Additional studies focused on bond testing and behavior (D’Ambrisi et al. 2013, De Felice et al. 2014, Alecci et al. 2016, Askouni and Papanicolaou 2016), in-plane loading of walls (Parisi et al. 2011), out-of-plane loading of walls (Harajli et al. 2010, Babaeidarabad et al. 2014), strengthening of arches (Garmendia et al. 2011), and seismic retrofitting of infill masonry walls (Koutas et al. 2015a,b).

In addition to seismic retrofitting, given the high energy consumption associated to old buildings and their significant environmental impact, there is a strong need for effective solutions for the building envelope energy retrofitting. Towards this goal, a wide range of solutions has been proposed, with external and internal insulations becoming increasingly popular, due to high energy savings, the quick and easy application and the low cost (e.g. Bomberg et al. 1997, Anastaselos et al. 2009). Various types of thermal insulation boards are currently used in external and internal insulation, mostly made by expanded polystyrene (sintered or extruded), expanded polyurethane and mineral wool. The finishing typically involves continuous and applied during placing mineral or polymeric renders and coatings (e.g. Huang et al. 2013, Kolaitis et al. 2013), although some discontinuous tile finishing (applied on site instead of the render) has recently been proposed too (e.g. Jelle 2011). Textile reinforced mortar (TRM) jacketing has minimal, if any, thermal insulation capacity, while external or internal insulation has no load bearing capacity. In this study we propose the combination of the two systems into a single unit, which provides both seismic and energy retrofitting. In this new system, illustrated in Figure 1, the TRM is combined with the insulating material as a single unit, which may be either in the form of a prefabricated board or constructed in situ. Depending on the aesthetics and the constructability requirements, the system may be placed either on both sides of existing masonry walls or on one side. The TRM may be placed outside the insulating material, or inside, that is between the insulation and the masonry wall. All the above is investigated experimentally in the present study for the case of masonry walls subjected to in-plane or out-of-plane cyclic loading. More details for the case of out-of-plane and in-plane loading are given by Triantafillou et al. (2017a) and Triantafillou et al. (2017b), respectively.

![Figure 1. Schematic view of proposed structural and energy retrofitting system on one side of the masonry wall.](image-url)
2. EXPERIMENTAL PROGRAM

2.1 In-plane Loading

The investigation was carried out on three series of medium-scale, single-wythe, fired clay brick wallets comprising running bond courses: (a) Series A ("shear walls") specimens measured 1300 mm in height and 1000 mm in width (Figure 2a); (b) Series B ("beam-columns") specimens measured 1300 mm in height and 400 mm in width (Figure 2b); and Series C ("beams") measured 400 mm in height and 1300 mm in width (Figure 2c).

All specimens were subjected to cyclic in-plane loading, such that the plane of failure would form parallel to the bed joints for series A and B and perpendicular to the bed joints for Series C. The specimens were insulated using expanded polystyrene with a density equal to 29 kg/m³ and a thermal conductivity coefficient equal to $\lambda_p = 0.029$ W/mK.

All specimens were constructed in the laboratory by an experienced mason using ridge-faced, 6-hole, horizontally perforated clay bricks (185x85x60 mm), supplied by a local manufacturer, and a general-purpose masonry cement mortar. The first row of bricks was laid on a 10 mm thick horizontal layer of mortar and all joints (bed and head) were approximately 10 mm thick.

The mean compressive strength of the masonry units in the directions parallel and perpendicular to the perforations was measured equal to 18.1 MPa and 4.4 MPa, respectively; the flexural and compressive strength of the mortar strength was measured equal to 2.3 MPa and 9.2 MPa, for flexure and compression, respectively; and the mean compressive strength of the walls in directions parallel and perpendicular to the bed joints was measured equal to 11 MPa and 3.71 MPa, respectively.

Whereas all specimens received the same amount of structural retrofitting (two layers of bidirectional textile with total weight 560 g/m²) and the same amount of insulation (total thickness of insulation plates 40 mm), the investigation considered the following key parameters: one-sided versus two-sided insulation and TRM jacketing; placement of the TRM jackets outside the insulation or between the insulation and the masonry.

One specimen of each series was used as control, without TRM or insulation (Figure 3a). Each series included four different designs: (i) specimen i1M1i retrofitted on both sides with TRM containing one layer of textile and 20 mm thick insulation plates applied externally on both sides (Figure 3b); (ii) specimen i1Mi1 retrofitted on both sides with TRM containing one layer of textile and 20 mm thick insulation plates applied on both sides between the TRM and the masonry (Figure 3c); (iii) specimen M2ii retrofitted on one side with TRM containing two layers of textile and two 20 mm thick insulation plates applied on the outside (on the same face with the TRM) (Figure 3d); and (iv) specimens Mii2 retrofitted on one side with TRM containing two layers of textile and two 20 cm thick insulation plates applied between the TRM and the masonry (Figure 3e).

A total of 15 tests were performed (three series with five specimens in each series). The notation of specimens comprises a series of numbers and letters. The letter “A”, “B” or “C” at the beginning of the specimens’ notation denotes Series A, B or C respectively; the numbers (1 or 2) indicate the number of layers in the textile; “i” stands for a 20 mm thick insulation plate and “M” stands for
Moreover, the sequence of numbers and letters represents the sequence of the different materials in each specimen. For instance, A_1iMi1 = Series A, one-layered TRM – insulation – masonry – insulation – one-layered TRM, C_M2ii = Series C, masonry – two-layered TRM – two layers of insulation etc.

Figure 3. Specimens for in-plane loading: (a) Control; (b)-(e) retrofitted.

2.2 Out-of-plane Loading

A total number of 17 wall specimens were constructed using ridge-faced, 6-hole, horizontally perforated clay bricks, supplied by a local manufacturer, and a general-purpose masonry cement mortar. One specimen was used as control (M), without TRM or insulation (Figure 4a). Series D included six different designs: (i) specimens 2M2 and 2M2s retrofitted on both sides with TRM containing two layers of textile and no insulation (Figure 4b); (ii) specimens 2Mi2 and 2Mi2s retrofitted on both sides with TRM containing two layers of textile and one layer of insulating material on both sides, between the TRM and the masonry (Figure 4c); (iii) specimens 1i1Mi1 and 1i1Mi1s retrofitted on both sides with TRM containing one layer of textile, one layer of insulating material and a second TRM jacket with one layer of textile, such that the TRM forms the faces of a sandwich system with the insulation as the core material (Figure 4d); (iv) specimens 2ii2M and 2ii2Ms retrofitted on one side with a sandwich system comprising TRM faces with two layers of textile and a core with two layers of insulation material (Figure 4e); (v) specimens 2iMi2 and 2iMi2s with two layers of insulation material on one side and TRM jackets with two layers of textile on the outside (Figure 4f); and (vi) specimen 2iMi2_na as in (ii) above (Figure 4c), but with retrofitting materials “non-anchored” (hence the letters “na” at the end of the specimens’ notation), i.e. not extending all the way to the end of the walls, so that they were not clamped between the end supports and the masonry. All specimens in Series A, except the ones in design (vi), that is the one with “non-anchored” retrofitting, were tested in pairs, corresponding to two different displacement amplitudes (1 mm and 2 mm) of the loading cycles.

Series F included five different designs, subjected to fire testing prior to mechanical testing: (i) one specimen (F_2iMi2) retrofitted on both sides with TRM containing two layers of textile and one layer of fire-resistant insulating material on both sides, between the TRM and the masonry (Figure 4g); (ii) one specimen (F_2i2M2i) retrofitted on both sides with TRM containing two layers of textile and one layer of fire-resistant insulating material on both sides, outside the TRM (Figure 4h); (iii) one specimen (F_i2iMi2i) retrofitted on both sides with two layers of fire resistant insulating material and TRM containing two layers of textile between the two insulating layers (Figure 4i); (iv) one specimen (F_2Mi2) with one layer of fire-resistant insulating material on one side (interior) and TRM jackets with two layers of textile on the outside (Figure 4j); and (v) one specimen (F_2Mi2_th) retrofitted on both sides with TRM containing two layers of textile and one thicker layer (hence the letters “th” at the end of the specimens’ notation) of fire-resistant insulating material on one side (interior) (Figure 4k).

The notation of specimens in Series D comprises a series of numbers and letters. The numbers (1 or 2) indicate the number of layers in the textile, “i” stands for insulation and “M” stands for masonry.
Moreover, the sequence of numbers and letters represents the sequence of the different materials in each specimen. For instance, 2M2 = two-layered TRM – masonry – two-layered TRM, 2iMi2 = two-layered TRM – insulation – masonry – insulation – two-layered TRM, 2iiM2 = two-layered TRM – two layers of insulation – masonry – two-layered TRM etc. The symbol “s” at the end of the specimens’ notation denotes “small” displacement amplitude (1 mm). The notation of specimens in Series F follows the same logic; the letter “F” at the beginning denotes “fire”, as all specimens in this series were tested in fire prior to cyclic loading. The control specimen is denoted as M (masonry only).

![Diagram of specimens](image)

Figure 4. Specimens for out-of-plane loading: (a) Control; (b)-(f) Series A; and (g)-(k) Series B.

![Diagram of specimens](image)

Figure 5. Series D and F specimens.

### 2.3 Construction Technique

All textile layers were applied “as usual”, that is each specimen was first ground at points where mortar was protruding from the brickwork face and brushed clean, then dust and any loose particles were removed with high air and water pressure and, finally, a standard wet lay-up procedure was followed to bond the textile on the walls, covering the entire surface. The procedure involved the application of mortar on the dampened wall surface and the subsequent bonding of the textile by hand and roller pressure. The mortar was also applied in between layers of the textile, on top of the last textile layer, in between the masonry and the insulating material, in between layers of the insulating material and in between the insulating material and the textile. Hence, the mortar served as the matrix of the TRM as well as the binding agent of the insulating material.

Application of the mortar was made in approximately 2 mm thick layers with a smooth metal trowel. The textile was pressed slightly into the mortar, which protruded through all the perforations between fiber rovings. Of crucial importance in this method was the application of each mortar layer while the
previous one was still in a fresh state. Curing of the mortar was achieved in room conditions. Typical photographs of the application method of textiles and insulating materials on wall specimens are shown in Figure 6.

![Figure 6](image)

Figure 6. Application of the textile reinforcement and the insulation material: (a) Application of mortar on masonry wall; (b) application of textile; (c) impregnation of textile with mortar; (d) application of insulation material; (e) application of mortar on top of insulation material; (f) typical cross section of masonry wall.

### 2.4 Materials Testing

All specimens were strengthened with a commercial alkali resistant glass fiber bi-directional ($0^\circ/90^\circ$) grid. The areal weight, without the alkali resistant SBR coating, was 280 g/m$^2$, with 145 g/m$^2$ in the longitudinal (warp) direction and 135 g/m$^2$ in the transverse (weft) direction. The overall weight, including the coating, was 360 g/m$^2$. The nominal thickness for each direction was 0.052 mm and 0.056 mm for warp and weft, respectively. The characteristic strength for both directions (when the nominal thickness is used) was 1460 MPa for warp and 1360 MPa for weft, respectively. The elastic modulus of glass fibers was 74 GPa.

![Figure 7](image)

Figure 7. (a) Photograph of bi-directional textile used in this study; (b) geometry of TRM coupons tested in tension (dimensions in mm).

For the matrix of the TRM a commercial inorganic dry binder was used, consisting of cement and polymers at a ratio of approximately 15:1, by weight. The binder to water ratio was 4:1 by weight, resulting in plastic consistency and good workability with a retention period of approximately half an hour in ambient temperature ($20^\circ$C). The binder’s flexural and compressive strengths were measured equal to 4.5 MPa and 12 MPa, respectively, on the day of the strengthening execution. The tensile properties of TRM were obtained by testing two pairs of specimens (one pair with a single layer of textile and a second one with two layers) with the geometry shown in Figure 7b. The average
values of properties from two tests on TRM coupons with one layer of textile were as follows: maximum stress 9 MPa, ultimate strain 2.46 %. The corresponding values for TRM coupons with two layers of textile were 8.92 MPa and 2.93%. Note that stresses were calculated on the basis of the nominal thickness of TRM, taken equal to 5 mm and 8 mm for one layer and two layers of the textile, respectively.

The compression properties of the walls in directions parallel and perpendicular to the bed joints were obtained from three compression tests in each case, conducted on small wall assemblages (two bricks long by six bricks high), measuring 410x85x390 mm (length x width x height). These masonry prisms were constructed using the same bricks, mortar and bond type (that is running bond) as for the rest of the specimens used in the experimental program. Mean values for the compressive strength, the secant modulus of elasticity (between 5% and 33% of peak stress) and the ultimate strain were 11.00 MPa, 3.16 GPa and 0.43%, respectively, in the direction parallel to the bed joints. The corresponding values perpendicular to the bed joints were 3.71 MPa, 3.77 GPa and 0.22%.

2.5 Test set-up, Instrumentation and Procedure for In-plane Loading

All strengthened specimens were subjected to cyclic in-plane loading using a stiff steel frame. Series A specimens were tested as vertical cantilevers with a concentrated force at the top, at a distance of 1.18 m from the fixed base; Series B and C specimens were tested as horizontal beams in three-point bending, at a span of 1.15 m.

In addition to transverse loading, specimens in Series B and C were subjected to axial compression equal to 10% of the compressive strength. The axial load was applied using a hydraulic cylinder and a pair of threaded rods. Five external rectilinear displacement transducers were used to measure the walls’ horizontal displacements at distance of 0.15 m, 0.55 m and 1.05 m from the fixed support, as well as to monitor the probable uplift at the base, as shown in Figure 8a.

2.6 Results and Discussion for In-plane Loading

The load versus displacement hysteresis loops for specimens in Series A, B and C are given in Figures 9, 10 and 11, respectively. Typical photographs of failure mechanisms are given in Figures 12, 13 and 14. Peak load values in the push or pull directions, \( P^+_{\max} \) or \( P^-_{\max} \), displacements at failure, \( \delta^+ \) or \( \delta^- \), defined as the point of the load versus displacement envelope curve where a 20% reduction in load was noted, cumulative energy dissipation capacity and observed failure modes are given in Table 1, for all specimens. The displacements recorded in Table 1 are those at piston position for specimens of Series A (as extrapolated by the displacement profile obtained from the three horizontal displacement transducers), and at mid-span for specimens of Series B and C. In the load versus displacement plots
(hysteresis loops and envelope curves), displacement values in the push direction, that is outward movement of the piston, are taken positive.

It is concluded that all retrofitted specimens (including the ones with insulation) failed at higher loads, had higher energy dissipation capacity and showed, in general, greater higher deformation capacity than unretrofitted masonry (Table 1). The increase in strength for retrofitted specimens was approximately: 60-100% in the push direction and 75-135% in the pull direction for the Series A; 45-85% in the push direction and 15-40% in the pull direction for Series B; 100-200% in the push direction and 55-110% in the pull direction for Series C. An important – yet not surprising – conclusion is that the exact positioning of the TRM and the insulating material does not play an important role in the in-plane response of retrofitted walls, as long as proper bonding between the different layers is achieved.

Table 1. Summary of test results.

<table>
<thead>
<tr>
<th>Specimen notation</th>
<th>Peak load (kN)</th>
<th>Displacement at failure (mm)</th>
<th>Cumulative dissipated energy (kNmm) at:</th>
<th>Failure modea (failure direction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A_Control</td>
<td>19.9 Push 17.3 Pull</td>
<td>&gt;12 11.9</td>
<td>94.08 471.03 Rocking, toe crushing (pull)</td>
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</tr>
<tr>
<td>A_i1M1i</td>
<td>31.5 Push 30.5 Pull</td>
<td>12.0 11.0</td>
<td>139.31 622.68 FR (pull)</td>
<td></td>
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<tr>
<td>A_i1Mi1</td>
<td>34.7 Push 40.8 Pull</td>
<td>15.5 12.4</td>
<td>129.28 545.20 FR (pull)</td>
<td></td>
</tr>
<tr>
<td>A_M2ii</td>
<td>39.3 Push 33.1 Pull</td>
<td>13.2 10.2</td>
<td>112.02 674.90 MC (pull)</td>
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</tr>
<tr>
<td>A_Mii2</td>
<td>37.5 Push 35.6 Pull</td>
<td>18.5 10.9</td>
<td>113.24 627.47 MC (pull)</td>
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</tr>
<tr>
<td>Series B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B_Control</td>
<td>20.0 Push 24.0 Pull</td>
<td>6.0 6.1</td>
<td>31.06 345.54 Flexure (push)</td>
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</tr>
<tr>
<td>B_i1M1i</td>
<td>37.1 Push 32.6 Pull</td>
<td>8.3 7.0</td>
<td>28.59 355.11 FR (pull)</td>
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<tr>
<td>B_i1Mi1</td>
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<td>10.8 10.1</td>
<td>33.21 384.07 FR (pull)</td>
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<tr>
<td>B_M2ii</td>
<td>31.4 Push 30.9 Pull</td>
<td>8.9 7.5</td>
<td>42.48 386.32 FR (pull)</td>
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</tr>
<tr>
<td>B_Mii2</td>
<td>29.2 Push 27.2 Pull</td>
<td>8.6 9.4</td>
<td>36.58 359.19 MC (push)</td>
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</tr>
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<td>Series C</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C_Control</td>
<td>12.2 Push 12.4 Pull</td>
<td>1.8 0.7</td>
<td>8.71 b Flexure (pull)</td>
<td></td>
</tr>
<tr>
<td>C_i1M1i</td>
<td>33.9 Push 18.9 Pull</td>
<td>6.2 4.8</td>
<td>5.77 267.01 FR (pull)</td>
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</tr>
<tr>
<td>C_i1Mi1</td>
<td>36.8 Push 25.8 Pull</td>
<td>6.8 5.8</td>
<td>9.43 247.63 FR (pull)</td>
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<tr>
<td>C_M2ii</td>
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<td>5.38 279.64 FR (pull)</td>
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<tr>
<td>C_Mii2</td>
<td>24.3 Push 14.6 Pull</td>
<td>8.4 10.3c</td>
<td>9.56 228.06 Combined in-plane and out-of-plane flexure (push)</td>
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</tr>
</tbody>
</table>

a FR = fiber rupture, MC = masonry crushing. b Failed in cycle 2. c Local crushing at one of the supports, hence these values should be used with caution.
Figure 9. Load versus top-displacement hysteresis loops for specimens in Series A.
Figure 10. Load versus top-displacement hysteresis loops for specimens in Series B.
Figure 11. Load versus mid-span displacement hysteresis loops for specimens in Series C.
Figure 12.  (a) Masonry toe crushing in specimen A_Control; (b) fiber rupture at the bottom part of A_i1Mi1; (c) horizontal flexural crack at the bottom part of A_i1Mi1; (d) masonry crushing at the bottom part of A_M2ii; and (e) masonry crushing at the bottom part of A_Mii2.

Figure 13.  (a) Flexural cracking and crushing near the middle section of specimen B_Control; (b) flexural cracking and fiber rupture near the middle section of B_i1Mi1, B_i1Mi1 and B_M2ii; (c) masonry crushing near the middle section of B_M2ii.
2.7 Test Set-up, Instrumentation and Procedure for Out of-plane Loading

All strengthened specimens were subjected to cyclic out-of-plane loading using a stiff steel frame. The walls were laid horizontal (with the bonded surfaces facing upwards and downwards) and were loaded in three-point bending (Figure 15) at a span of 1.30 m. Two pairs of steel hinges were placed at each support (along the specimens’ width, at top and bottom) and a third one was placed at mid-span (that is along the load application line).

All strengthened specimens were tested by applying the load in a quasi-static cyclic pattern of controlled displacements at a rate of 0.1 mm/sec. The loading sequence consisted of cycles at a series of progressively increasing displacement amplitudes in both directions (push and pull). The displacement amplitude increment was either 2 mm or 1 mm, as described above, and a single loading cycle was applied for each amplitude level.

2.8 Fire Tests Set-up, Instrumentation and Procedure

All specimens in Series F were subjected to one-sided fire testing for 90 minutes inside a 3x3x1.2 m furnace (Figure 16) according to EN 1363-1 (1999), so that the mean temperature $T$ (in °C) inside the furnace developed over time $t$ (in min) according to the following equation:

$$T = 345\log_{10}(8t + 1) + 20$$

(1)
While the mean temperature in the furnace reached 1006 °C, temperatures in the TRM on the exposed (to fire) face of each wall were measured through the use of thermocouples as follows: 870 °C in specimens F_2iMi2 and F_2Mi2, 340 °C in specimens F_i2M2i and F_i2iMi2i, and 90 °C in specimen F_2M2i_th.

Figure 16. Furnace used for fire testing of walls.

Fire resulted in full or partial damage of the TRM on the exposed face of each wall, depending on the protection provided by the insulating material. In specimens F_2iMi2 and F_2Mi2, with the insulation between the TRM and the masonry, the TRM was fully destroyed (Figure 17a). In fact specimen F_2Mi2 was so severely damaged that it fractured during handling and transport at the end of the fire test. In specimens F_i2M2i and F_i2iMi2i, with a 20 mm thick fire insulation material on top of the TRM, the insulating material developed cracks (Figure 17b) and the TRM was partially damaged. Finally, in specimen F_2M2i_th, with the 70 mm thick insulating material, damage in the TRM was minimal, if any.

2.9 Results and Discussion for Out of-plane Loading

The load versus displacement hysteresis loops for specimens in Series D and F are given in Figures 18 and 19, respectively. Typical photographs of failure mechanisms are given in Figure 20. Peak load values in the push and pull directions, $P_{\text{max}}^+$ and $P_{\text{max}}^-$, mid-span displacements at failure, $\delta_u^+$ and $\delta_u^-$, defined as the point of the load versus mid-span displacement envelope curve where either sudden load reduction was detected or a 20% reduction in load was noted in specimens with gradual post-peak load reduction, cumulative energy dissipation capacity and observed failure modes are given in Table 2, for all specimens.
Table 2. Summary of test results.

<table>
<thead>
<tr>
<th>Specimen notation</th>
<th>Peak load (kN)</th>
<th>Mid-span displacement at failure (mm)</th>
<th>Cumulative dissipated energy (kNmm) at cycle</th>
<th>Failure modeb (failure direction)</th>
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<td></td>
<td>Push</td>
<td>Pull</td>
<td>Push</td>
<td>Pull</td>
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<tr>
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<tr>
<td>M</td>
<td>3.42</td>
<td>--</td>
<td>0.72</td>
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a For specimens tested at small displacement amplitude (1 mm).

b FR = fiber rupture, D = debonding, MC = masonry cracking.

From the test results on specimens in Series D it is concluded that the proposed retrofitting system is highly effective. In terms of strength and deformation capacity of walls not subjected to fire, the combined use of TRM with insulation material is better than the use of TRM alone. TRM jacketing without insulation (specimen 2M2) increased the strength by approximately 170% \([9.28 \text{kN}-3.42 \text{kN}]/3.42 \text{kN}=1.71\), whereas this increase varied from 200% \([10.25-3.42]/3.42=1.99\) to 340% \([15.14-3.42]/3.42=3.43\) when the (double sided) textile reinforcement was combined with insulation layers, due to the increased lever arm of the tension reinforcement. The respective numbers for specimens type “s” (small displacement amplitude increment) are 135% \([8.06-3.42]/3.42=1.36\), 190% \([10.01-3.42]/3.42=1.93\) and 285% \([13.18-3.42]/3.42=2.85\]. As expected, jackets with unfavorable bond conditions (specimen 2iMi2_na) were less effective; they increased the strength by at least 200%, whereas the strength increase in specimen 2iMi2, with favorable bond conditions, was at least 235% \([11.47-3.42]/3.42=2.35\).

In terms of deformation capacity, as expressed by the mid-span displacement at failure, TRM jacketing combined with insulation was always much more effective than the TRM system alone, by up to approximately 140-145%.

The results on specimens in Series F (after fire) are summarized as follows. Specimen F_2iMi2 (Figure 19a) displayed poor behavior in the pull direction, because the TRM jacket mobilized in tension in this direction had already failed during fire testing. Failure in this direction occurred due to masonry (flexural) cracking. In the push direction failure was due to debonding at the interface between the masonry and the insulation. Specimen F_i2M2i (Figure 19b) failed due to tensile rupture of the TRM jacket both in the push and in the pull direction, following the formation of a single crack at mid-span of the wall. Partial damage of the TRM jacket on the fire-exposed face of the wall resulted in reduced capacity when this jacket was subjected to tension, that is in the pull direction. Failure in specimen F_i2iMi2i (Figure 19c) in the push direction was due to debonding at the interface between the insulating material and the masonry. In the push direction the capacity of the specimen was reduced substantially, due to damage of the TRM (subjected to tension in this direction) during fire.
testing. Finally, specimen F_2M2i_th (Figure 19d) failed due to tensile rupture of the TRM jacket at high loads both in the push and in the pull direction, following the formation of a single crack at mid-span.
Figure 18. Load versus mid-span displacement hysteresis loops for specimens in Series D.
Figure 19. Load versus mid-span displacement hysteresis loops for specimens in Series F.
Figure 20. (a) Fiber rupture at mid-span; (b) debonding at the interface between the masonry and the insulation; (c) flexural cracking through the insulating material; (d) debonding, as a result of not favorable anchorage conditions; and (e) debonding at the interface between the two insulation layers and between the masonry and the first insulation layer.

3. CONCLUSIONS

The present study presents an innovative system for both seismic and energy retrofitting of masonry walls, involving the combination of textile reinforced mortar (TRM) and thermal insulating materials. The system was tested on brick masonry wallettes subjected to in-plane and out-of-plane cyclic loading. Some of the wallettes were subjected to fire testing prior to mechanical testing, to assess the effectiveness of the new system under realistic fire conditions.

Overall, it is concluded that the new retrofitting system not only improves the thermal performance of masonry walls but also is highly effective as a means of seismic retrofitting for out-of-plane and in-plane loading, as long as proper bonding between the different layers is achieved. According to the experimental results, the exact positioning of the TRM and the insulating material does not play an important role in the in-plane response of retrofitted walls. On the other hand, in out-of-plane loading, positioning the reinforcement outside the thermal insulation improves greatly the strength and deformation capacity when compared to TRM jacketing alone.

In case of masonry walls subjected to fire prior to mechanical loading, the new system is quite effective provided that the TRM is placed under the fire-resistant insulating material. In this case, the effectiveness of the retrofitting increases with the thickness of the fire insulation.

4. ACKNOWLEDGEMENTS

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