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EXPERIMENTAL INVESTIGATION OF SHEAR STRENGTH OF SOLID BRICK URM WALLS RETROFITTED WITH TRM JACKET

Athanasia K. Thomoglou[1], **Athanasios K. Karabinis**[2]

[1] Civil Engineering Department, Democritus University of Thrace (DUTh),

Kimmeria, 67100 Xanthi, Greece
e-mail: athomogl@civil.duth.gr

[2] Civil Engineering Department, Democritus University of Thrace (DUTh),

Kimmeria, 67100 Xanthi, Greece
e-mail: karabin@civil.duth.gr

Abstract

This study is part of an experimental program on full-scale strengthened Un-Reinforced Masonry (URM) walls with Textile reinforced mortars (TRM). Four solid brick walls (one control and three strengthened specimens with central opening), were tested under the diagonal tension (shear) test method in order to investigate the effectiveness of the strengthening system on the in-plane behavior of the walls. All the URM panels consist of solid bricks and a high strength binder mortar. Both of them have increased mechanical properties leading to improved shear behavior of the masonry walls. Several parameters pertaining to the in-plane shear behavior of the retrofitted panels were investigated, including shear capacity, failure modes, the number of layers of the external TRM jacket and the existence of the central opening of the wall. The experimental work allowed an evaluation of the shear behavior in the case of the bidirectional textile (TRM) system applied on URM walls. The experimental results of URM and retrofitted walls with different layers are compared with each other. The purpose is to investigate in depth and to draw conclusions about the in-plane shear behavior.

Keywords: TRM, solid brick URM, in-plane performance, seismic strengthening, diagonal compression test, wall's opening.

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1 INTRODUCTION

The existence of the doors and/or windows openings of the Unreinforced masonry (URM) walls significantly affects the shear behavior of the structure. Hence, there is an urgent need to investigate the influence of the retrofitting technique on URM walls with openings. In the field of rehabilitation and strengthening of the existing masonry buildings, Textile Reinforced Mortar (TRM) has attracted considerable research interest as an alternative to the traditional strengthening methods due to its better compatibility with the URM substrate, fire resistance, excellent mechanical strength and stiffness in the direction of the fibers, while it improves the seismic capacity of URM walls (Thomoglou et al 2020). Nevertheless, there is limited experimental research on full-scale walls.

The existence of openings in masonry walls is often responsible for in-plane collapse mechanism creation, leading to the entire building collapse (Chalioris et al. 2013, Chalioris et al. 2015). Considering this critical parameter, there is a limited experimental study on retrofitting masonry walls with openings. Several works on infill masonry walls with openings were carried out by Kakaletsis and Karayannis (2008), Kakaletsis and Karayannis (2009), Decanini et al. (2014), Mansouri et al. (2014), Sigmund and Penava (2014), Tasnimi and Mohebkhah (2011), or without openings by Lee et al. (2010), Rousakis (2017) and Rousakis (2020). From the abovementioned research, it is concluded that openings have a significant effect on the characteristics of masonry infill walls, such as failure mode and lateral strength, and ductility reducing shear strength, stiffness, and energy dissipation capacity.

The work concerns diagonal compression tests on solid brick URM and retrofitted walls with TRM jacket on both sides of the walls. The TRM reinforcement system comprises one, two, or three plies of glass fiber mesh in a cement mortar matrix. This strengthening method has an advantage over other traditional solutions in easy application, excellent adhesion of the mortar to the brick substrate, high tensile strength, and low elasticity increasing compatibility with masonry. The purpose is to investigate and to draw conclusions about the shear behavior of strengthened full-scale brick URM walls with a central opening.

2 EXPERIMENTAL PROGRAMM

This experimental study deals with full-scale URM walls comprising solid bricks and a high strength binder mortar (Durostick D-31). The TRM strengthening system consist of one, two or three layers of glass mesh in a cementitious matrix applied to both of the specimen with central opening. The strengthening concept is based on the observation that the strengthening mortar matrix plays a key role to the contribution of the total shear capacity (Thomoglou et al. 2020). All the experiments were conducted at the Laboratory of Reinforced Concrete and Seismic Design of Structures of the Department of Civil Engineering of the Democritus University of Thrace.

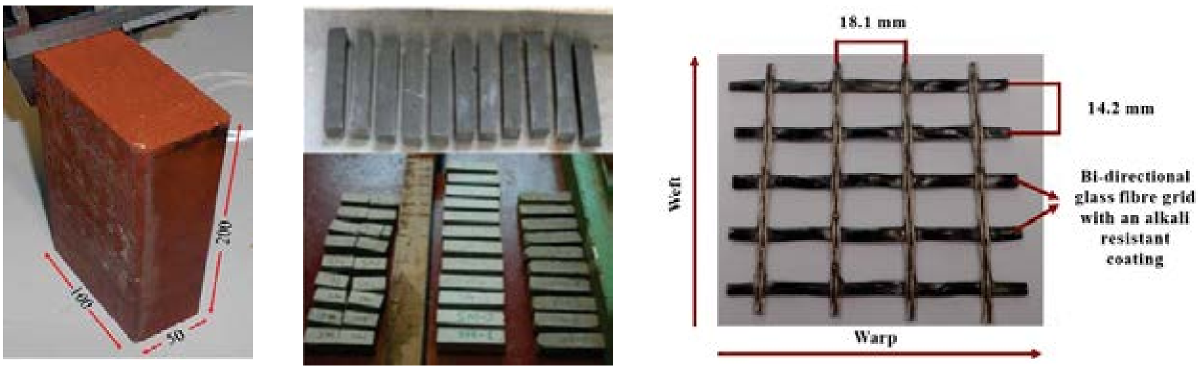
3 MECHANICAL PROPERTIES OF MATERIALS

3.1 Mechanical properties of bricks and mortar and exterior strengthening

The nominal dimensions of the solid bricks were 200 mm (Length) x 100 mm (Width) x 50 mm (Height) (Figure 1a). The compressive behavior of brick units is determined in two load directions: perpendicular and parallel to the bed joints. Six units were tested in total under an axial load after grinding of their loading surfaces according to procedures established in the European standard EN 772-1 (2000). Two displacement transducers (LVDTs) and a laser meter were used to measure the vertical and horizontal deformations, Δv and Δh (Thomoglou et al. 2018). The compressive strength of the bricks equals to 116.17 MPa. A render mortar of

20M class was used to construct all the walls, with a nominal mortar thickness of about 10 mm. The 28-day compressive strength of the Durostick D-31 mortar obtained by testing 40 mm × 40 mm × 160 mm mortar prisms according to EN 1015-11 (1993) with an average value of 38.15 MPa, while the tensile strength is 15.76 MPa (Figure 1b).

Prior to the application of the TRM jacket, the masonry specimen was coated with light-heavy, reinforced cementitious mortar (SikaRep®-200 Multi) in order to smooth the protrusions and to get a flat layer on the external surface. The exterior strengthening system consisted of 1, 2 or 3 plies of glass grid embedded into a cementitious matrix. The glass fibers were arranged along two rectangular directions with axial spacing of 18.1 mm in the longitudinal and 14.2 mm in the lateral direction, respectively, as shown in Figure 1c, while its mass was 360 g/m^2 per unit area. The modulus of elasticity in the longitudinal direction was 80 GPa. Fiber reinforced cementitious mortar with pozzolanic admixtures had a 28-day compressive and flexural strength of 28.85 MPa (based on EN 1015-11) and 6.78MPa, respectively, while the Modulus of elasticity was 8.03 GPa (according to the manufacturer) (Thomoglou et al. 2019b).



a) b) c)

Figure 1 a) Dimensions of solid brick, b) Maturing mortar prisms and test pieces after a three-point bending test, c) Dimensions of fiberglass grid SikaWrap®-350GGrid.

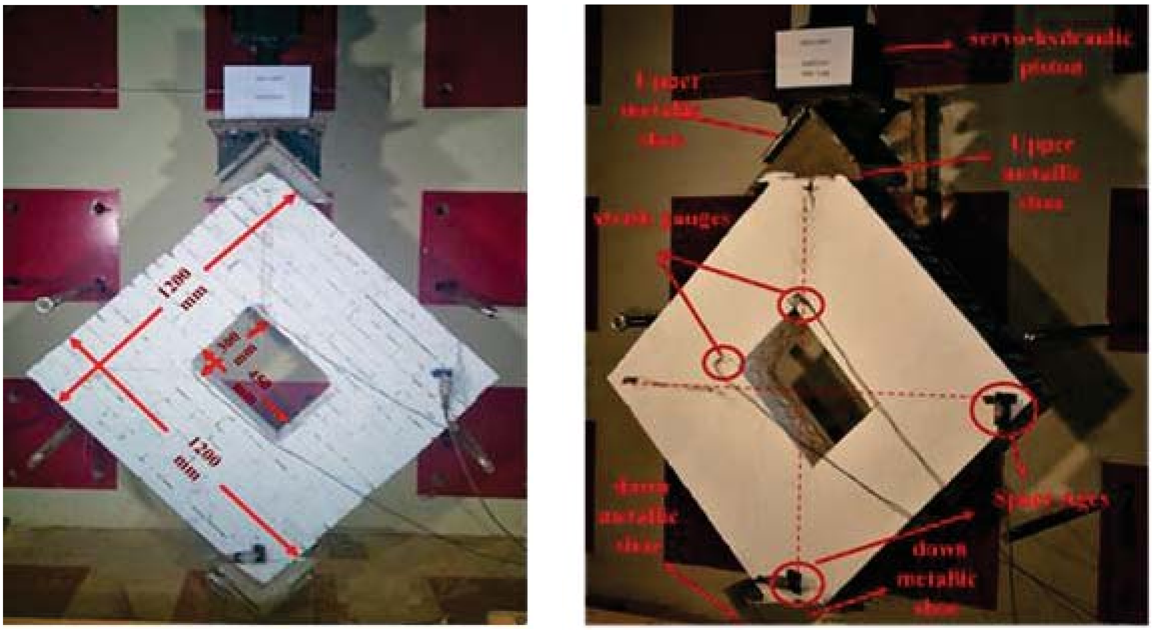
4 TEST SET-UP AND LOADING

4.1 Main headings

In order to investigate the shear behavior of the strengthened walls under lateral loading, the diagonal compression test, was standardized by ASTM E 519-07 (ASTM 2010) to determine the shear capacity of 1200 mm x 1200 mm masonry panels. The specimens were loaded in compression along one diagonal to cause tension failure, with the specimens splitting apart parallel to the direction of loading. For this study, four specimens were constructed in full scale and the thickness for all panels was 210 mm. All specimens were with central opening (one control and three strengthened walls with 1-ply, 2-ply or, 3-ply glass TRM, respectively). The dimensions of the opening are 450 mm (length) and 300 mm (height) (see Figure 2a). The layers of the glass TRM were applied over each side of the panel.

The in-plane test setup comprises of two steel loading shoes, according to ASTM E519, placed diagonally opposite to the corners of the specimen, while they attached the upper shoe to the MTS servo-hydraulic piston (Figure 2b). Diagonal compression was applied via a 450 kN MTS servo-hydraulic piston. High-performance shrinkage compensated a cementitious, free-flowing mortar SikaGrout-312 HP which was used to fill the two shoes (capping), maturing for at least 24 hours.

The compressive load applied uniaxially and monotonically to the failure point at a rate of 0.01 mm/s. The diagonal compression test was widely used to broaden the knowledge on masonry subjected to in-plane behavior. Although diagonal compression does not reproduce a field condition behavior of the masonry field, however, it is more conservative because of the limited value of the vertical load and is standardized according to ASTM 2010, (Thomoglou et al. 2019a).



a) b)

Figure 2 a) Experimental set up of solid brick URM wall with central opening, b) Arrangement of measuring instruments on the URM wall.

5 RESULTS-DISCUSSION

5.1 Displacement Force Diagram

The mechanical parameters of the tested specimens are presented in Table 1. The results of the experimental tests on the maximum applied load, the ultimate shear stress, the ultimate displacement, the ultimate shear strain, and the failure mode for each specimen are presented in columns (2)-(6) of Table 1, respectively. The production of the reinforcement is defined as the ratio between the maximum load applied to each strengthened panel to the unreinforced control wall. It can be observed that there is an increase in shear capacity and therefore an improvement in the production of external strengthening amounting to 339%, 470%, and 701% for 1, 2, and 3-ply TRM jacket, respectively, compared to the value of 61.49 kN of the control wall. Besides, the displacement of the retrofitted specimen shows 2.31, 2.71 and 3.04 times the value of 4.19 mm of the control one, for 1, 2, and 3-ply TRM jacket, respectively.

The results from those masonry specimens with a central opening retrofitted with 1 to 3-ply TRM jacket are summarized in the response curves of Figure 3 and compared with each other. In the load-displacement diagram, the strengthened masonry specimen with central opening and 3-ply of fiberglass mesh (SS-O-UMG3), presenting more plastic behavior and showing the best shear response from all the strengthened walls. An important observation is that as the shear capacity so the ultimate displacement of retrofitted masonry walls increases proportionally to the amount of TRM for 1 and 3 plies.

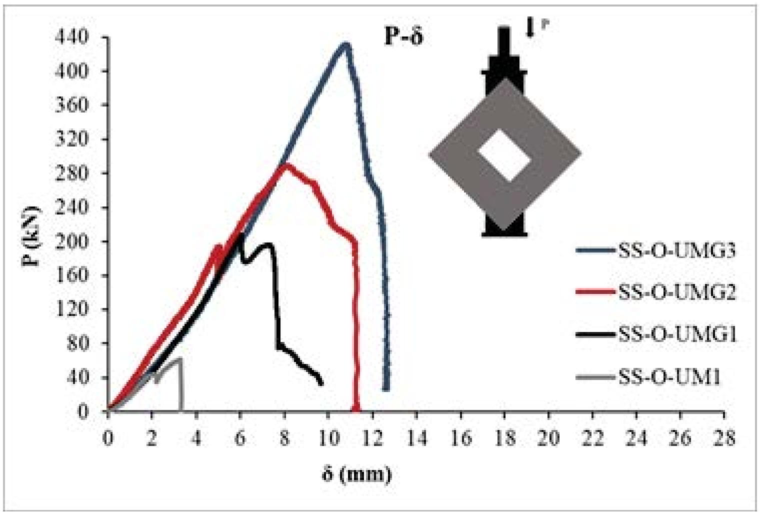


Figure 3 Experimental set up of solid brick URM wall with central opening.

Specimen Codes (1)	Plies of TRM textiles (2)	Maximum applied failure load P_u (kN) (3)	Ultimate Shear stress τ_u (Mpa) (4)	Displacement δ_u (mm) (5)	Ultimate Shear strain γ_u (mm/mm) (6)	Failure Mode (7)
SS-O-UM1	Control	61.49	0.17	4.19	0.0028	SF
SS-O-UMG1	1 ply	208.19	0.59	9.67	0.0051	TRM failure-DT
SS-O-UMG2	2 plies	289.23	0.82	11.35	0.0068	TRM failure-DT
SS-O-UMG3	3 plies	431.20	1.22	12.72	0.0091	TRM failure-DT

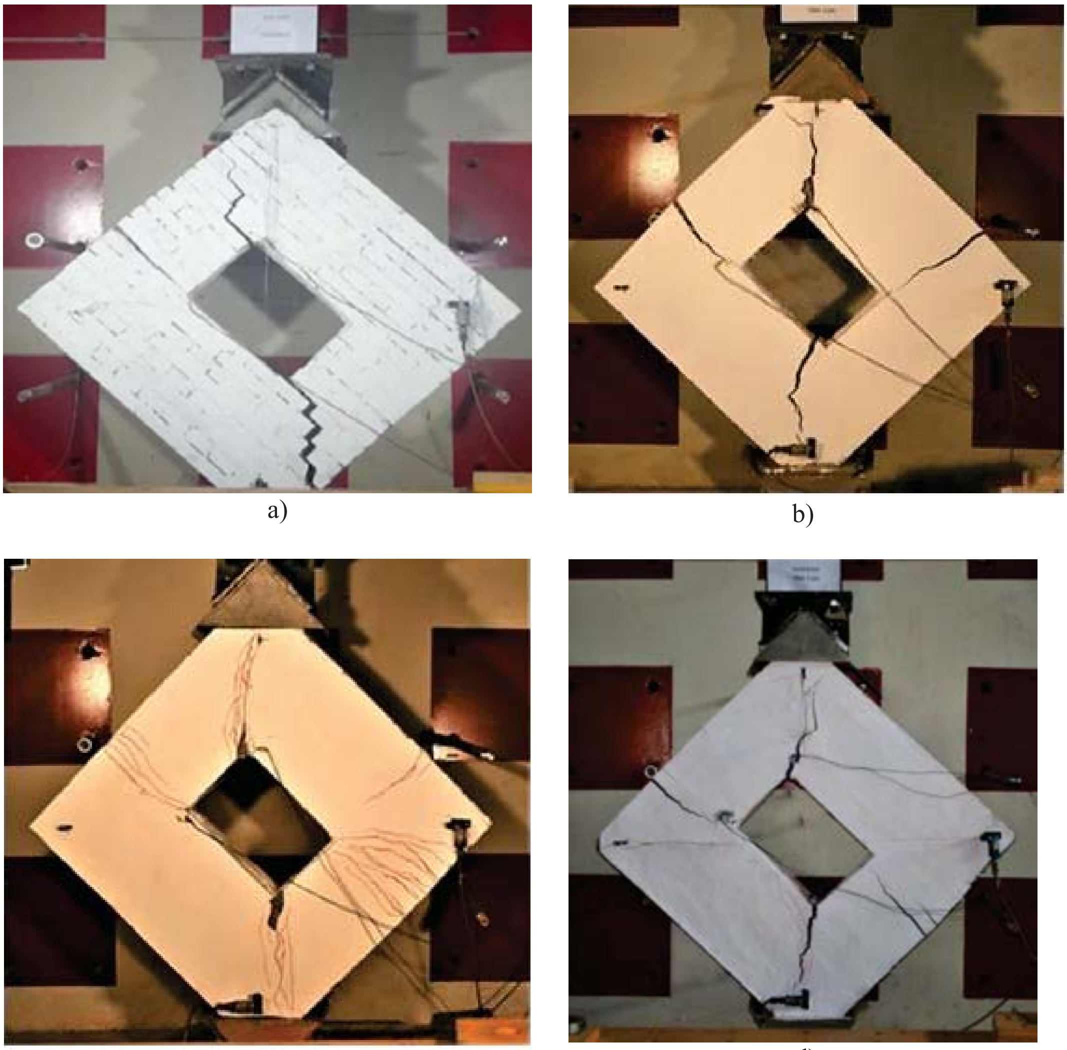
DT: Diagonal Tension, SF: Shear Friction

Table 1: Experimental results.

5.2 URM Failure Modes

The typical crack patterns of the four masonry walls after shear failure are illustrated in Figure 4. The control wall with central opening showed a brittle failure caused by the loss of the bond between the mortar and the bricks, as well as a diagonal tensile stress with a simultaneous fracture of the mortar and bricks, which caused a stair-step cracking and shear friction (Thomoglou et al. 2019a). Hence, the failure mode of the control wall with central opening (SS-O-UM1) is a shear friction. The failure mode of the strengthened wall with 1-ply (SS-O-

UMG1) is diagonal tension, which appears with a thorough crack along the entire length of the diagonal parallel to the direction of the load and across the width of the panel. The evolution of the diagonal crack started from the point where the maximum concentrated tensile stresses appear. This point is the two opposite corners of the hole in the vertical direction, while at the two opposite corners of the other direction maximum compressive stresses develop. Also, two cracks are developed from the external side of the panel and end at the two opposite corners of the opening, which are located almost perpendicular to the load direction (Figure 4a)-b).



a) b) c) d)

Figure 4 Failure mode of a) control brick URM wall (SS-O-UM1), b), c), d) strengthened wall with 1-ply (SS-O-UMG1), 2-ply (SS-O-UMG2) and 3-ply (SS-O-UMG3) glass textile, respectively.

The failure mode of the retrofitted solid brick URM (SS-O-UMG3) with 3 plies of glass textile and a central opening is similar to the specimens with 1 and 2 plies of TRM jacket (see Table 1 and Figure 4 b)-d)). Nevertheless, a wider vertical crack is observed and parts of the strengthening mortar of the TRM jacket are effectively detached. The glass textile failure is observed here as well as in the case with 1 and 2 plies (SS-O-UMG2, SS-O-UMG3), respectively (Figure 4b)-d)). Finally, the effectiveness of this significant strengthening technical is highlighted, if we include the fact of preventing the final collapse of the masonry, which is very important for the safety of human and material resources.

6 AKNOWLEGMENTS

We acknowledge KEVE. SA for the supply of Orthoblock K300 bricks and building masonry specimens, as well as Sika Hellas SA for providing all masonry strengthened materials and for our excellent cooperation.

7 CONCLUSIONS

A full-scale experimental investigation was aimed to assess the effectiveness of the TRM external jacket in order to improve the in-plane behavior of the four solid brick specimens with a central opening. The masonry panels were retrofitted using three different configurations (with 1, 2, 3 plies of a both-sided TRM application) and were tested under monotonic diagonal tension (shear) test. From the aforementioned results, the following concluding observations arise:

- The TRM jacket has improved the shear capacity and deformation capacity, which caused the failure of the strengthened walls in a more plastic way.
- There is an increase in shear capacity and therefore an improvement in the production of external strengthening amounting to 339%, 470%, and 701% for 1, 2, and 3-ply TRM jacket, respectively, compared to the value of 61.49 kN of the control wall.
- The displacement of the retrofitted specimens shows 2.31, 2.71 and 3.04 times for 1, 2, and 3-ply TRM jacket, respectively, compared to the value of 4.19 mm of the control wall.
- The best shear behavior was demonstrated by the masonry specimen with 3-ply of TRM and a central opening of solid bricks compared to all masonry walls.
- The failure mode of the control wall with central opening is shear friction, while the strengthened masonry specimens exhibited TRM failure and diagonal tension.
- The tests results demonstrated that the glass TRM jacket plays an important role in retaining and protecting the solid brick masonry wall. The strengthening system prevents the abrupt reduction of the resistance and significantly reduces the brittle behavior, avoiding an explosive collapse.

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