

Article

Shear Strengthening of Stone Masonry Walls Using Textile-Reinforced Sarooj Mortar

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Abstract: Most historical buildings and structures in Oman were built using unreinforced stone masonry. These structures have deteriorated due to the aging of materials, environmental degradation, and lack of maintenance. This research investigates the physical, chemical, and mechanical properties of the local building materials. It also presents the findings of an experimental study on the in-plane shear effectiveness of a modern strengthening technique applied to existing stone masonry walls. The technique consists of the application of a textile-reinforced mortar (TRM) on one or two faces of the walls. Shear loading tests of full-scale masonry samples (1000 mm width, 1000 mm height, and 350 mm depth) were carried out on one unreinforced specimen and six different cases of reinforced specimens. The performances of the unreinforced and reinforced specimens were analyzed and compared. We found that strengthened specimens can resist in-plane shear stresses 1.5–2.1 times greater than those of the unreinforced specimen; moreover, they demonstrate ductility rather than sudden failure, due to the presence of fiberglass and basalt meshes, which restrict the opening of cracks.

Keywords: strengthening; historical; stone masonry wall; textile-reinforced mortar; rehabilitation



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1. Introduction

Masonry structures have been constructed since the earliest days of civilization [1]. Unreinforced masonry wall (URM) construction is widely used around the world but is not suitable for withstanding in-plane loading, and brittle failure may occur. Retrofitting masonry walls with materials such as externally bonded fiber-reinforced polymers (FRPs) effectively enhances their shear capacity [2]. This technique may be applied in Oman, which has more standing historic buildings per square kilometer than most Arab countries. In addition, there are over 500 forts, castles, and towers in the country [3]. Old Omanis utilized local materials in the construction process of historical buildings in Oman. Since it is a large country with varied geography, geology, and topography, an extensive range of local resources were applied, which were available for use at relatively lower costs than imported construction materials. Otherwise, the selection of building materials was based on the intended use of the structure.

Many traditional buildings possess greater character and are more charming than their counterparts, having been constructed by skilled artisans using high-quality natural materials [2,4]. However, today, one of the main causes of damage to historical buildings is climate and environmental change (e.g., rainfall, flooding, storms, wind, temperature, and humidity). Natural disasters, such as earthquakes, volcanic eruptions, hurricanes, floods, and landslides, also have a significant effect on buildings' lifespans [3].

Masonry structures differ in the properties of their load-bearing members and construction methods. A structure may have remarkable strength against vertical compressive stresses [5,6], but conversely, its shear and tensile strengths may not be sufficient to withstand seismic and in-plane loading. Accordingly, strengthening masonry structures is

important to ensure their safety and extend their service life. Generally, two strengthening techniques can be implemented: conventional and non-conventional. Conventional methods include enhancing the seismic resistance of existing structures by reducing the adverse effects related to design or construction by introducing bracings and shear walls. Retrofitting and jacketing/confinement are the most popular non-conventional strengthening methods [4].

As many URM brick or stone wall structures are standing today, the reconstruction of their partial or whole structures to conserve them is not feasible. Instead, we may study their performance under seismic effects and investigate appropriate strengthening methods. The most popular treatment for URM is a surface treatment, but this can be performed with multiple techniques, such as epoxy and grout injection, external reinforcement, confining, ferrocement, and fiber-reinforced polymers' (FRPs') application [7,8].

The use of FRPs has grown rapidly in civil engineering applications because of their properties such as corrosion resistance, ease and speed of application, minimal change in the geometry of the strengthened structure, and high strength-to-weight ratio. Nonetheless, despite their advantages, there are still many negatives due to the organic resins used to bind or saturate the fibers. Their key drawbacks can be summarized as follows: (i) the relatively high cost of epoxy resins; (ii) dampness incompatibility, where it is impossible to apply epoxies to humid surfaces as freezing problems may arise due to isolated water; (iii) a lack of vapor permeability; (iv) the incompatibility of epoxies, resins, and substrate materials; and (v) irreversibility, since once epoxies are applied, they cannot be detached from structures [9]. The solution to overcome the drawbacks of epoxy organic resins is to replace them with inorganic binders, such as cement-based mortars. For better adhesion between inorganic materials and fibers with masonry structures, grid textiles are preferable to fiber sheets. This replacement of epoxy resins with textiles embedded in mortars is known as textile-reinforced mortar (TRM) [10].

TRM, also known as FRCM (fabric-reinforced cementitious matrix) or TRC (textile-reinforced concrete), is a composite material consisting of fiber rovings embedded in an inorganic matrix. It can be used either in the construction of new structures or in the strengthening or rehabilitating of existing structures. Particularly for masonry structures, the application of TRM provides strengthening against in-plane shear, out-of-plane flexure, or axial loads. TRM can be applied as a substitute for FRPs to overcome their drawbacks. It is easy and safe to apply, withstands low and high temperatures, has chemical and mechanical compatibility with various substrates of masonry structures, and has a high strength-to-weight ratio. Textile fibers can be made of carbon, basalt, glass, aramid, poly-paraphenylene benzodioxol (PBO), polypropylene (PP), or steel. The most commonly used matrix is cement-based, where textiles are embedded. However, hydraulic lime mortars can also be used [9,10]. This article presents the results of our experiments on strengthening stone masonry walls using textiles bonded with sarooj mortar, which is a locally fabricated pozzolanic mortar.

Over the last few decades, a limited number of research studies have been conducted on strengthening masonry structures [11–17], including different masonry structures such as historical building bricks, sand lime bricks, rubble stone walls, and ordinary concrete blocks. These studies have explored the strengthening cover, types of textiles, and number of layers covering one or both sides of the structure, as well as investigated both static and dynamic reactions. Almost all studies have found that using TRM in the strengthening scheme improves the in-plane shear capacity compared to normal unreinforced walls. Nonetheless, despite this initial research, Oman has over 500 historical structures, mainly castles and forts consisting of unreinforced masonry, so further research is required, particularly on ancient structures.

When preserving Oman's historical structures, local materials should be used as much as possible. Hago and Al-Rawas reported in their study [18] that clay mineral components such as alumina and silica underpin the applicability of sarooj, where silica and alumina react with water and lime to provide their binding properties. Nonetheless, physical

properties, the burning temperature, and the chemical composition influence the reactivity of sarooj [19]. A cement/sarooj ratio of 0.6 and a sand/sarooj ratio of 0.3 were recommended in a previous study to achieve the highest compressive strength of the mixture [20].

This article presents our experimental work performed to evaluate the use of TRM in strengthening masonry walls against in-plane shear stress. Our research work involved construction, strengthening, and testing the wall specimens. We started by conducting a physical analysis of textiles and sarooj to determine their properties. Then, rock masonry walls were constructed using available local materials. Strengthening systems were applied to the wall specimens using basalt fiber and fiberglass textiles bonded with sarooj mortar. Through testing, we found that the innovative strengthening technique used in this study has the potential to contribute significantly to preserving the inventory of historical structures, with minimum change to the aesthetics and geometry of such structures compared to the conventional and traditional strengthening techniques.

2. Material Properties

2.1. Limestone

Historical buildings in Oman are widely constructed of limestone, as it provides good humidity and heat insulation, it is aesthetically pleasing, it is widely available in all regions of the country, and it can be cut easily. For this research, limestone was obtained from Wadi Al-Khoud, Oman, in random crushed sizes, as shown in Figure 1. ASTM standard C51-18 [21] defines limestone as an initially sedimentary rock consisting mainly of calcium carbonate or the carbonates of calcium and magnesium. Limestone may be high in calcium and magnesium or dolomite. Al-Saidy et al. [22] tested limestone for mechanical properties such as compressive strength and water absorption. Compressive strength was measured according to ASTM D7012, 2004 [23]. It was found at an average of 57.8 MPa based on several 70 mm × 70 mm × 70 mm cubes, and water absorption was determined according to ASTM D6473, 2010 [24] and averaged at 2.20%.



Figure 1. Limestone.

2.2. Sarooj

Artificial pozzolana (sarooj) has been used in Oman in various engineering structures for hundreds of years. Previous research [20,25] has indicated that the reactivity of sarooj is affected by several elements, involving its chemical, mechanical, physical, and geotechnical properties. The sarooj utilized in this study was provided by the Ministry of Heritage and Culture (MHC) [26]. The maintenance department of the MHC uses sarooj significantly in the repair work of historical buildings such as forts. Al-Saidy et al. [22] conducted a chemical analysis of sarooj where they applied standard procedures to define its chemical composition. They found that SiO_2 , Al_2O_3 , and Fe_2O_3 are the three main chemical

components, amounting to approximately 52% of the contents, which led sarooj to be defined as a pozzolanic material. However, ASTM standard C618 [27] specifies that, for natural pozzolanic materials, the total of these three elements should exceed 70%; hence, sarooj provided by the MHC cannot be identified as a natural pozzolana. These chemical composition results are highly affected by the clay used in the calcination process and its source, and they indicate that sarooj may require cement addition [20].

2.3. Bed Jointing Mortar

The cementing materials used in the matrix were sarooj (passed through a 2.36 mm sieve), ordinary Portland cement (OPC), white cement, and lime. Cement was included to improve the binding properties of the mortar, as advised by Hago et al. [20]. White and gray cements were used in the jointing mortar; however, just white cement was utilized in the plaster mortar to maintain the genuine color of sarooj. Fine sand (passed through a 2.36 mm sieve) was utilized to avoid shrinkage and micro-cracking in all mixtures. The matrix of the bed jointing mortar consisted of sarooj, sand, ordinary Portland cement, white cement, lime, and water with a ratio by weight of 1:0.5:0.24:0.24:0:0.5, respectively (see Figure 2a). This mixture was chosen from various mixtures based on its mechanical properties and workability. Each mixture was cast into steel molds, creating three identical cubes with dimensions of $70 \times 70 \times 70$ mm and prisms with dimensions of $100 \times 100 \times 500$ mm. All mixtures were cured at a lab temperature of 22 ± 2 °C and a relative humidity of 20–30%. The workability was determined using a flow table test and measured to be 81% (Figure 2b). Sarooj absorbs more water in comparison with sand and this results in low slump. The compressive strength of the cubes was determined using a uniaxial compressive test according to ASTM 349 [28] (Figure 2c). The average result for the 28-day compressive strength was recorded as 13.84 MPa.

2.4. Plaster Mortar

Hago et al.'s [20] recommendations were embraced in selecting the ideal design mixture ratio of sarooj, sand, and cement to give the maximum strength. The plaster mortar mixture comprised sarooj (passed through a 0.6 mm sieve), sand, white cement, lime, and water with a ratio by weight of 1:0.5:0.5:0.375:0.85, respectively. The workability of the plaster mortar was determined using a flow table test and measured to be 80%. This mixture was chosen from several based on its mechanical properties and workability. The same process was followed as used in the jointing mortar for casting and curing the specimens. The average 28-day compressive strength and tensile strength were measured to be 14.30 MPa and 3.1 MPa, respectively, using a uniaxial test of the cubes. Note that a flexural test was performed for plaster mortar only.

2.5. Basalt Textile

Basalt textile was utilized in the reinforcement systems of the wall specimens. The textile comprised a bidirectional grid with cross-sectional dimensions of 0.5 mm thick by 1.6 mm wide in the longitudinal direction and 0.5 mm thick by 0.6 mm wide in the transverse direction, with an average spacing of 10 mm in both directions (see Figure 3). Al-Saidy et al. [22] investigated the tensile resistance of basalt mesh and composite samples of mortar with basalt fiber mesh through a uniaxial tensile test according to ASTM D5034-09 (2013) [29]. Here, three specimens were cut to 100 mm wide and 500 mm long, as can be seen in Figure 3. Moreover, three composite samples of sarooj mortar with 1-ply embedded textile samples were cast to determine the uniaxial tensile strength, as illustrated in Figure 4. A flat wooden mold of 100 mm wide, 500 mm long, and 22 mm thick was used to cast the composite panel. The first layer was cast and smoothed. Subsequently, a ply of fiber mesh was applied, and finally, the second layer of mortar was cast and smoothed, as can be seen in Figure 4. Steel plates of nearly 2.5 mm thickness were fixed to the edges of the test samples using grout to prevent stress concentration under the machine grip. A load was monotonically applied at a rate of 1 mm/min in a displacement-controlled routine.

Figure 5 illustrates the results of the tensile test of the textile and the composite samples, with the maximum tensile load recorded for basalt fiber mesh at 1.7 kN. Comparatively, composite specimens reached a maximum load averaging 3.0 kN.



Figure 2. Jointing mortar (a) materials used; (b) flow table test; (c) compression test; (d) flexural test for plaster mortar.

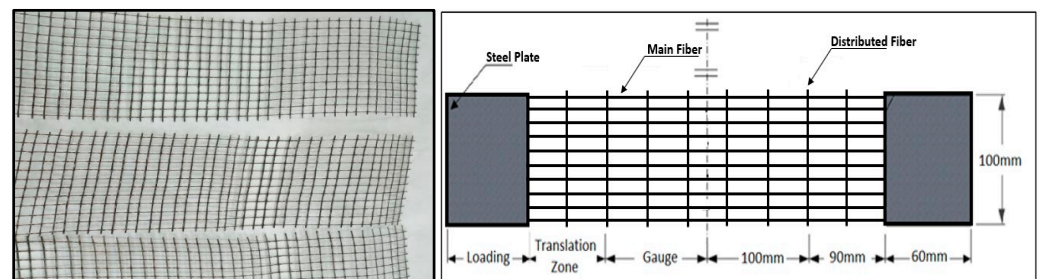


Figure 3. Basalt textile grid testing sample.

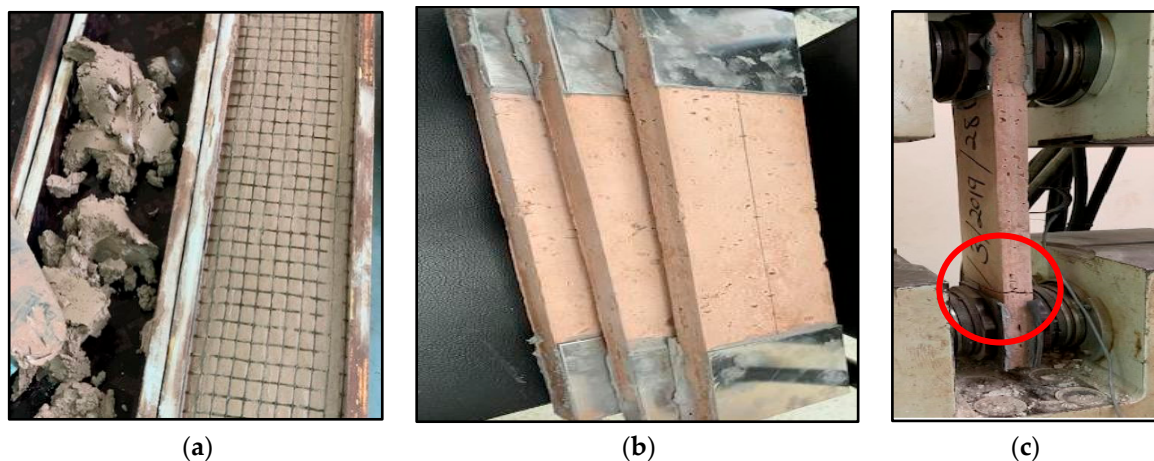


Figure 4. (a) Composite specimens' (basalt mesh + mortar) tensile test setup; (b) preparing the sample with steel plate ends; (c) failure mode.

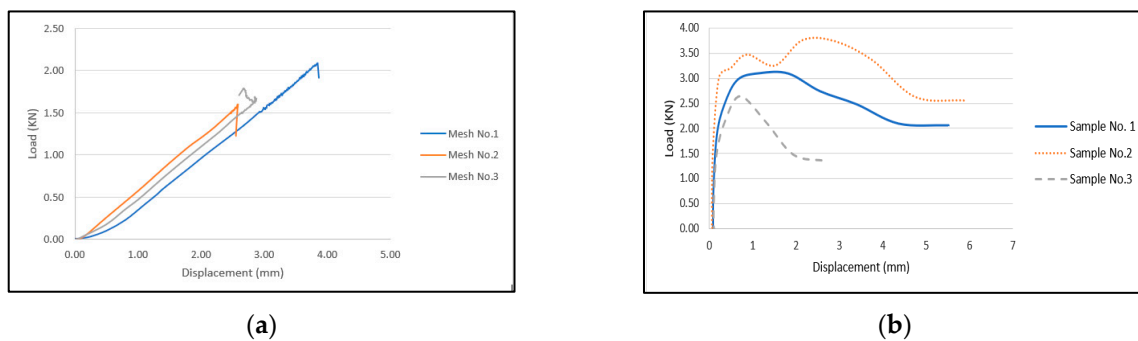


Figure 5. Load vs. elongation: (a) basalt grid results; (b) composite sample results.

2.6. Fiberglass

Similar to basalt mesh, fiberglass mesh was used to strengthen the masonry walls, and the same tests and preparations as for basalt were applied according to ASTM standard D5034-09 [29]. The textile had cross-sectional dimensions of 0.5 mm thick by 2 mm wide in the longitudinal direction and 0.5 mm thick by 1.1 mm wide in the transverse direction (Figure 6). TRM specimens were prepared and tested. For the fiberglass mesh with mortar, the same approach as that for basalt was adopted, where specimens measuring 500 mm in length, 100 mm in width, and 22 mm in thickness were cast in two layers on a wooden mold. The mold was removed after 24 h of casting and cured in a standard curing room (20 °C, 95% humidity) for 28 days. The process is demonstrated in Figure 7. At both ends of the specimens, stiff channel plates were bonded with an epoxy to avoid stress concentration under the testing machine's grip. A linear variable differential transducer (LVDT) was attached to one side of the specimens. A uniaxial load was applied at a rate of 1 mm/min until failure. Figure 8 illustrates the results of the tensile test for both the fiberglass textile and the composite specimens. The load against the displacement of the fiberglass mesh displays a linear curvature until failure, whereas the curvature for the composite specimens shows two characteristic stages that can be identified in a stress–strain diagram: (a) early steep curvature denoting the non-cracked segment stage, and (b) a decreased-slope curvature corresponding to the cracked segment stage. The failure of textiles was considered by monitoring the successive tear of weft fibers, where the rupture occurred randomly. The composite samples' failure occurred due to the complete rupture of the specimens. Regarding the cracking behavior, all the cracks were initiated and then propagated within the unbonded region of the tested specimens, with no indication of separation or slippage within the epoxy-joined clamping areas. As can be seen in Figure 8a, the maximum tensile load recorded for fiber mesh was an average of 6.6 kN. Comparatively,

composite specimens reached a maximum load averaging 3.1 kN, as shown in Figure 8b. For the composite samples, the mortar helped spread the load between the textile fibers, leading to a greater load-resisting capacity.

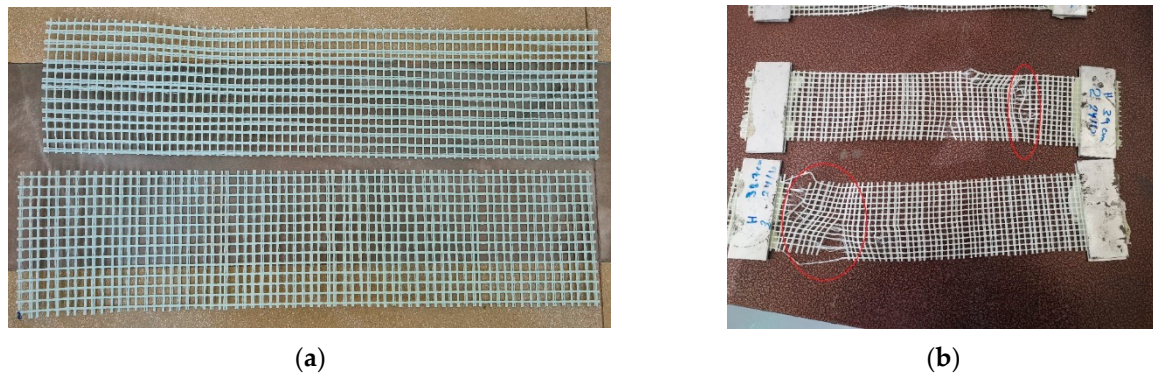


Figure 6. Tensile test setup: (a) fiberglass grid testing samples; (b) failure mode.

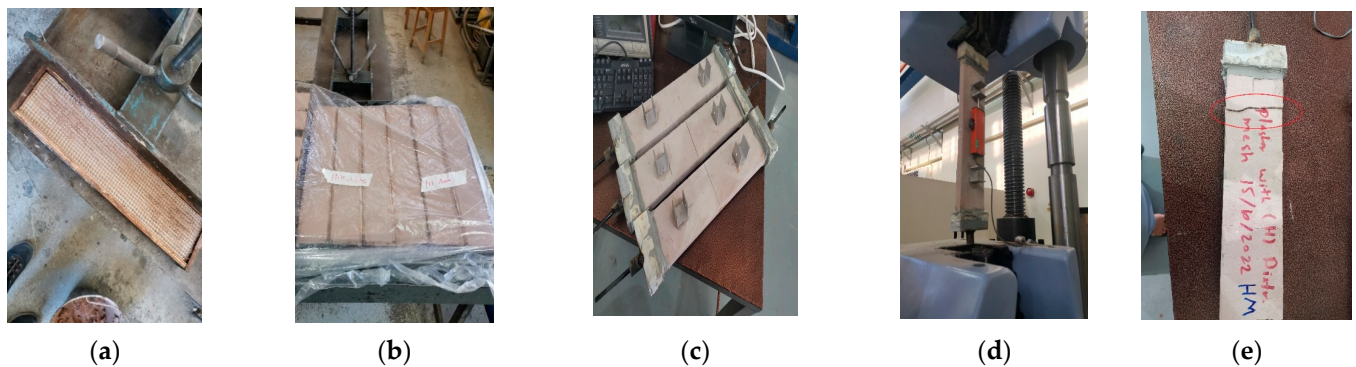


Figure 7. (a,b) Composite samples' (fiberglass + mortar) tensile test setup; (c,d) preparing the sample with steel plate ends; (e) failure.

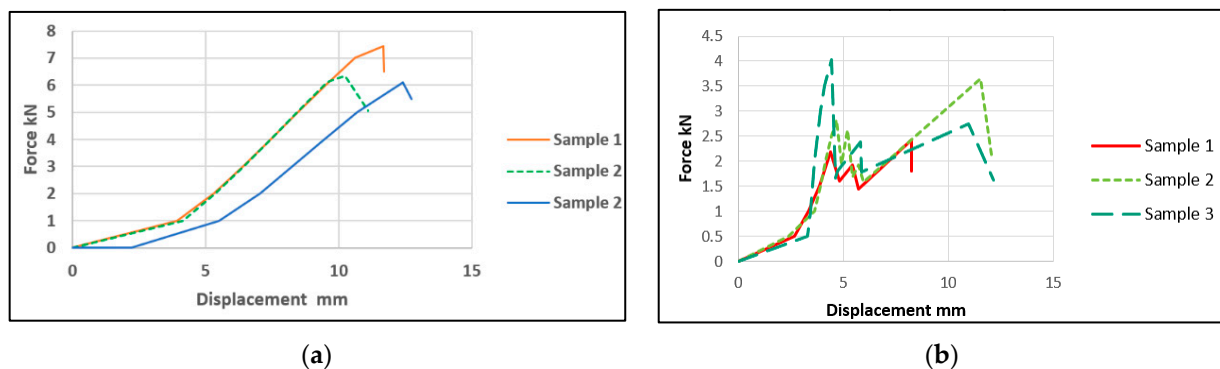


Figure 8. Load vs. elongation: (a) fiberglass grid results; (b) composite samples' results.

3. Stone Masonry Wall Construction and Test Setup

3.1. Wall Specimens

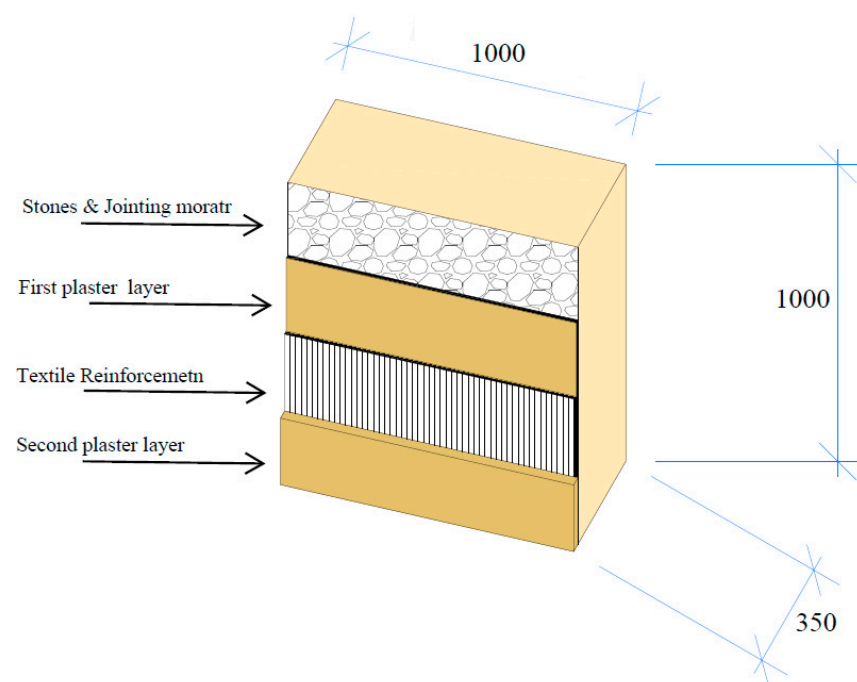
The wall specimens used in this research were 1000 mm wide, 1000 mm high, and 350 mm thick, made of stone masonry and strengthened with TRM composite materials. Six walls were constructed for shear testing: one control unreinforced wall, four reinforced with basalt textile mesh, and one reinforced with fiberglass mesh. The details of the wall specimens are represented in Tables 1 and 2 and Figure 9.

Table 1. Wall abbreviations.

Wall Abbreviation	Wall Description
UC	Unreinforced control wall
TR-1SB	Textile-reinforced one-sided basalt mesh
TR-2SB	Textile-reinforced two-sided basalt mesh
TR-2SB-2L	Textile-reinforced two-sided basalt mesh with two layers
TR-2SB-S	Textile-reinforced two-sided basalt with screws
TR-2SG	Textile-reinforced two-sided fiberglass

Table 2. Walls identification.

Specimen No.	1	2	3	4	5	6	7
Abbreviation	UC	TR-1SB	TR-2SB	TR-2SB-2L	TR-2SB-S	TR-2SG	Dummy
Textile	-	Basalt	Basalt	Basalt	Basalt	Fiberglass	-
Anchorage	-	-	-	-	Brass screws + washers	-	-

**Figure 9.** Geometry of walls.

3.1.1. CASE I: Unreinforced Control Wall (UC)

The unreinforced wall (UC) was the control specimen. It consisted of stones and jointing mortar only, with no strengthening. The method followed in the construction of the UC and all other walls involved laying mortar and stones alternatively. Stones were soaked in water before use to reduce water absorption from the mortar. Each wall took approximately two days to complete. Each day, approximately half of its height was completed. All walls were left to cure for 60 days. The construction pictures can be seen below in Figure 10.

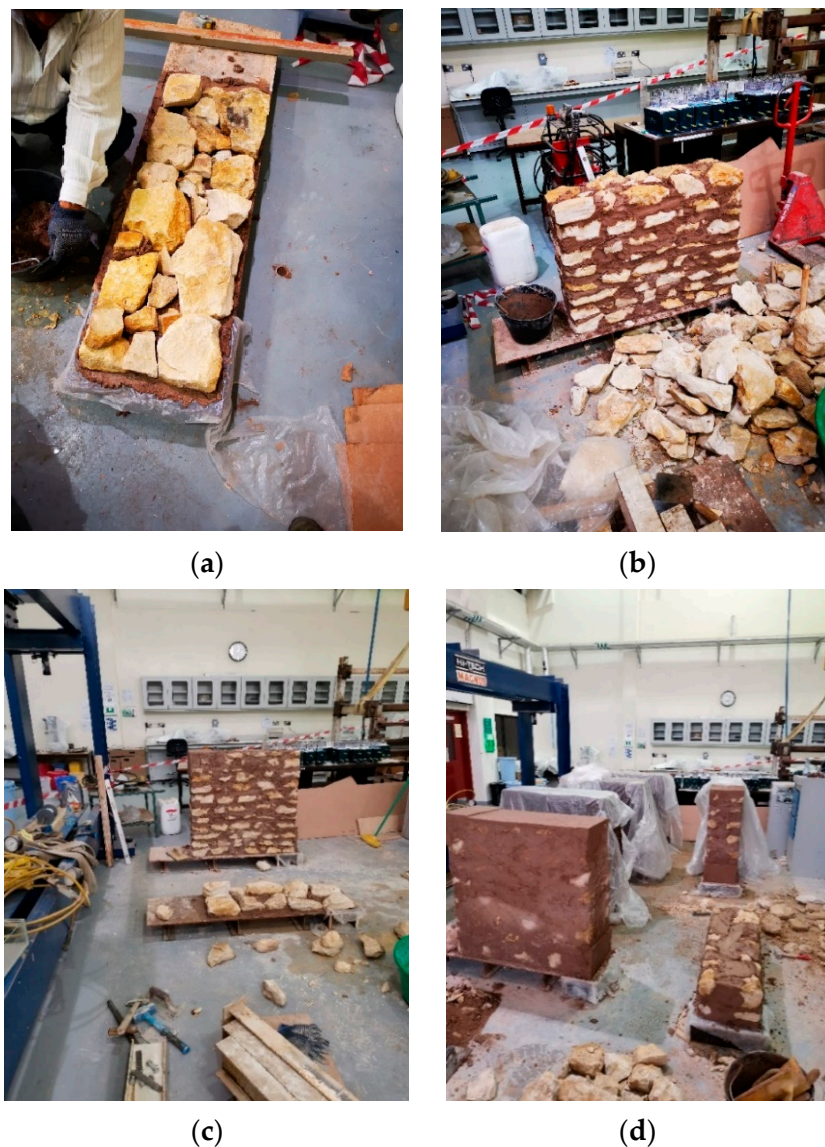


Figure 10. Construction of unreinforced masonry walls: (a) starting construction of the first wall; (b) halfway through the wall construction; (c) completion of first wall; (d) completion of most of the unreinforced wall samples.

3.1.2. CASE II: Textile-Reinforced One-Sided Basalt Mesh (TR-1SB)

After construction and curing using hessian cloth for all walls, the specimens were plastered and strengthened. For the second wall, plastering was carried out on one side in two layers along with basalt mesh. An initial layer of plaster mortar between 2 and 3 cm thick was applied, depending on the irregular shape of the stones. After placing the basalt mesh, another plaster layer 0.5 cm thick was applied and left to cure for 60 days. The procedures can be seen in Figure 11 below.

3.1.3. CASE III: Textile-Reinforced Two-Sided Basalt Mesh (TR-2SB)

Similar to the second wall, the same methods were used on the third wall. In addition, both sides of this wall were strengthened with plaster and basalt mesh and then left to cure for 60 days. Construction pictures can be seen in Figure 12.



(a)



(b)

Figure 11. Construction of one-sided basalt mesh reinforcement: (a) applying basalt mesh to the wall; (b) applying the covering layer of plaster.



(a)



(b)

Figure 12. Construction of a two-sided reinforced wall with basalt mesh: (a) applying basalt mesh on both sides; (b) applying the covering layer of plaster on both sides.

3.1.4. CASE IV: Textile-Reinforced Two-Sided Basalt Mesh with Two Layers (TR-2SB-2L)

The same method was used again, with the addition of a second layer of basalt mesh. The initial layer of plaster was 2–3 cm thick. Subsequently, the first basalt mesh was applied and adhered to the wall, after which a cover layer 0.5 cm thick was applied. Finally, the second layer of basalt mesh was placed and covered with a plaster mortar 0.5 cm thick, which was left to cure for 60 days. The construction pictures are illustrated below in Figure 13.

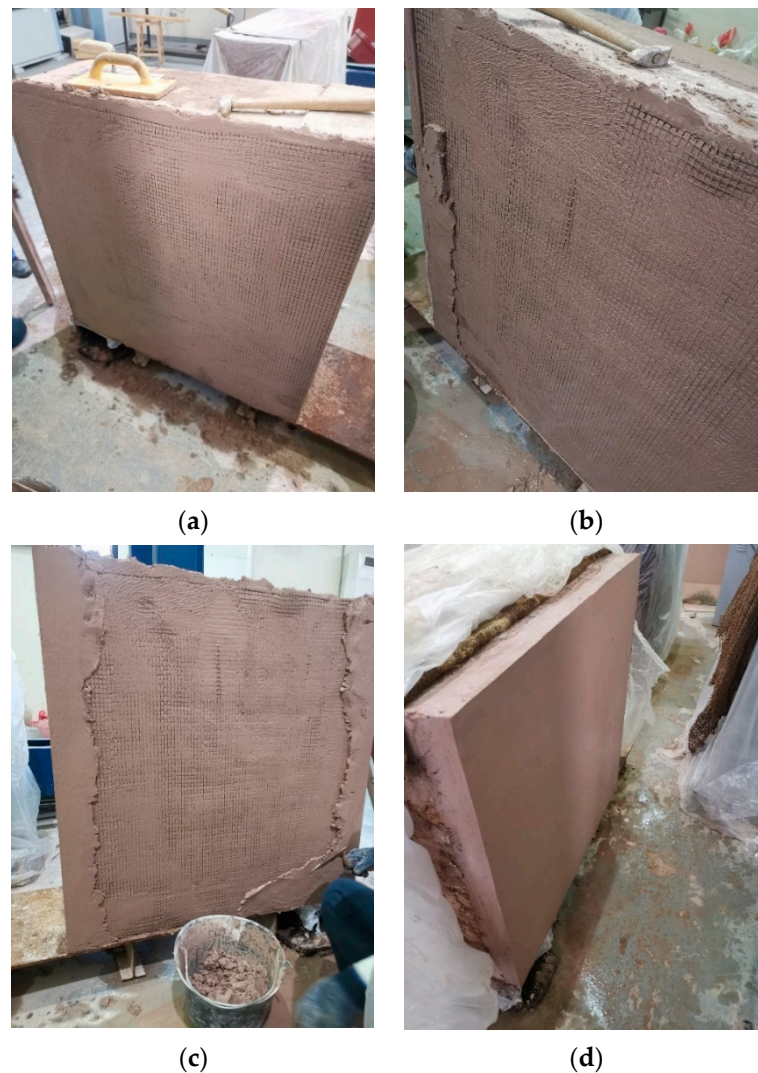


Figure 13. Construction of a two-sided reinforced wall with two layers of basalt mesh: (a) applying first ply of basalt mesh; (b) applying second ply of basalt mesh after first plaster cover; (c) applying second plaster cover; (d) completion of strengthening process.

3.1.5. CASE V: Textile-Reinforced Two-Sided Basalt with Screws (TR-2SB-S)

The fifth wall was constructed similarly to all others from stones and jointing mortar in the first phase and cured for 60 days. Subsequently, before plastering the wall, holes for screws were drilled into the wall, spaced at 20 cm center-to-center in both directions, as presented in Figure 14f. Plastic plugs with brass screws were inserted into the drilled holes. The first layer of plaster with a thickness of 2–3 cm was applied to obtain a uniform surface to apply the basalt mesh. Once the mesh was applied, the screws were removed and reinserted with stainless steel washers to firmly connect the basalt mesh to the wall. Finally, the last layer of plaster was applied with a thickness of 0.5 cm and left to cure for 60 days. Construction pictures are presented in Figure 14.

3.1.6. CASE VI: Textile-Reinforced Two-Sided Fiberglass (TR-2SG)

The last reinforced wall was constructed similarly to all the others from stones and jointing mortar in the first phase and cured for 60 days. The first layer of plaster, which was 2–3 cm thick, was applied. Then, after placing a layer of fiberglass mesh, another 0.5 cm thick plaster layer was applied and left to cure for 60 days. The procedures are presented in Figure 15 below.

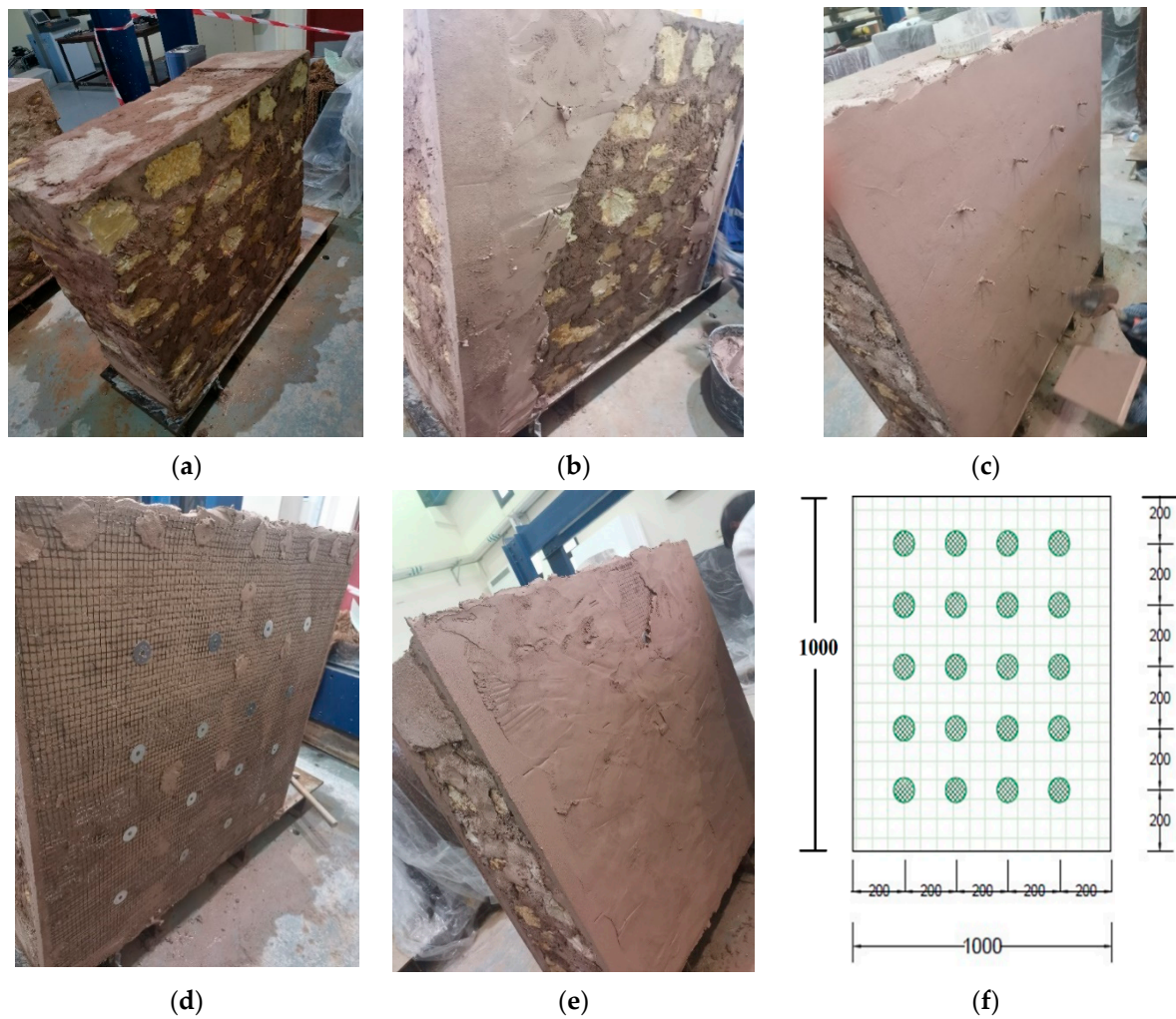


Figure 14. Construction of two-sided screw-reinforced wall with basalt mesh: (a) drilling holes into the wall; (b) applying first layer of plaster; (c) completion of first plaster layer; (d) applying mesh and fastening with screws; (e) applying the covering layer of plaster; (f) sketch of the screws' arrangement.

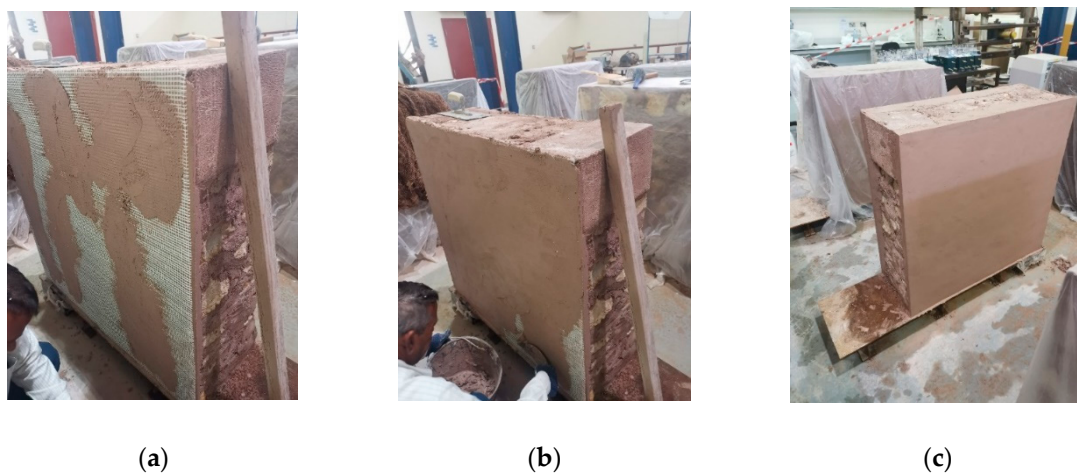


Figure 15. Construction of two-sided reinforced wall with fiberglass mesh: (a) applying fiberglass mesh; (b) applying covering layer of plaster; (c) completion of wall construction.

4. Test Setup

The wall specimens were tested under compression (monotonic load) at a 45-degree angle using a 4000 kN Universal Testing Machine. The load was applied at the rate of 0.3 kN/s, and the loading and displacement were controlled by the attached computer. The load was measured using the machine load cell. Displacements were measured using an LVDT attached to the machine loading head and two LVDTs directly attached to the walls. The test setup is illustrated in Figure 16, and the wall arrangement with LVDTs is illustrated in Figure 17.



Figure 16. Photograph of Universal Testing Machine: (1) moving crosshead; (2) top actuator loading; (3) load support column; and (4) bottom loading plate.

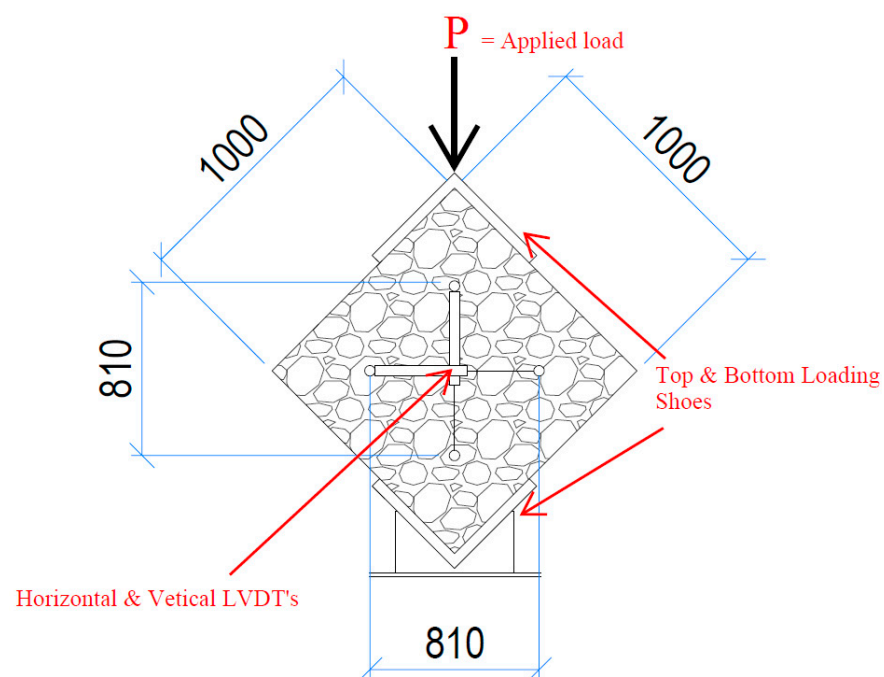


Figure 17. Walls positioning and LVDTs.

5. Test Results of the Stone Masonry Walls

In accordance with ASTM E519/E519M-10 [30], Equation (1) was used to compute the shear stress values, where τ represents the shear stress, P represents the applied load, and A_n represents the net area of the cross-section of the masonry wall. Equation (2) was used to determine the value of A_n , where L and H are the length and height of the wall specimens, and t and n represent the thickness of the specimen and the percentage of the gross area of the unit, respectively. Moreover, n was considered to be 1 since solid stones were used. Equation (3) was then used to calculate the shear strain values. In Equation (3), γ represents shear strain, ΔV and ΔH are, respectively, the shortening alongside the direction parallel to the load and the extension along the perpendicular direction, and g is the gauge length of the LVDTs (810 mm).

$$\tau = \frac{0.707 P}{A_n} \quad (1)$$

$$A_n = \left(\frac{H + L}{2} \right) tn \quad (2)$$

$$\gamma = \frac{\Delta V + \Delta H}{g} \quad (3)$$

For the unreinforced control wall (UC), the shear stress–strain behavior in the initial stage was linear, with no cracks observed. Cracks started when the load had almost reached a maximum of 360 kN; then, a sudden failure occurred (Figure 18a), and cracks developed in the wall. The cracks occurred in a diagonal pattern across the mortar–masonry interface. No separation was observed between the plaster mortar and the masonry.

The wall strengthened on one side with basalt mesh (TR-1SB) showed linear behavior in the initial stage. With the force increasing, cracks started from the unreinforced side at the mortar–masonry interface (since it was the weaker side) and propagated to the reinforced side (see Figure 18b). Once a maximum force of 317 kN was reached, which was lower than for the UC specimen, the stress started decreasing gradually, showing some elongation in the textile mesh, until the basalt mesh ruptured. Note that the unreinforced side was not plastered, which marked a difference compared to the control wall (UC), which was plastered on both sides; this may have contributed to the higher capacity of the UC wall.

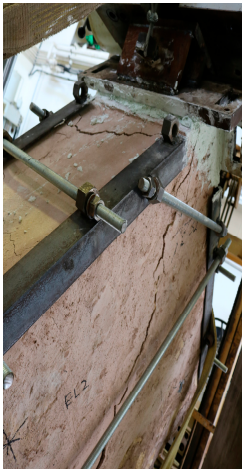
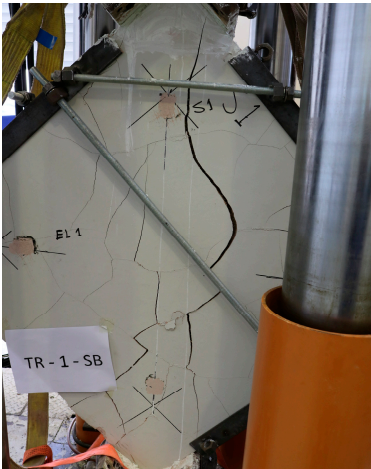
The second strengthened wall with basalt mesh on both sides (TR-2SB) demonstrated similar behavior. Cracks started at a load level of 655 kN. The stress then started decreasing gradually, providing some elongation before complete failure (Figure 18c). Compared to the UC specimen, this wall provided almost double the capacity, at approximately 1.82 times that of the control specimen.

The wall specimen strengthened with double layers of basalt on both sides (TR-2SB-2L) illustrated the same initial behavior. Cracks started at a load level of 528 kN (Figure 18d). Stress then started decreasing gradually to a certain point, after which elongation reached approximately 5 mm before complete failure. Both layers of the textile ruptured. This wall had a capacity of 1.47 times higher than that of the UC specimen. The main advantage of doubling the layers of reinforcement provided is increasing the ductility rather than the capacity, which still results in improved strength.

The wall strengthened from both sides with basalt and screws for anchorage (TR-2SB-S) exhibited similar initial behavior. Once the load reached a maximum of 542 kN, the stress decreased gradually to a certain point, providing some elongation before complete failure (Figure 18e). Compared to the UC specimen, this wall provided almost 1.5 times the capacity of the control specimen. Two modes of failure were observed in this wall. It cracked a diagonal pattern across the mortar masonry interface, and toe crushing also occurred when the stress at a corner equaled the masonry compressive strength [31]. We surmise that drilling holes for screws in the stones may have effectively reduced the wall's compressive strength.



(a)

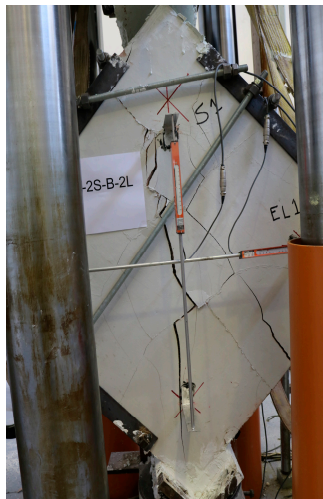


(b)



(c)

Figure 18. Cont.



(d)



(e)



(f)

Figure 18. Failure modes and crack patterns. (a) Failure mode of UC wall; (b) Failure mode of TR-1SB wall; (c) Failure mode of TR-2SB wall; (d) Failure mode of TR-2SB-2L wall; (e) Failure mode of TR-2SB-S wall; (f) Failure mode of TR-2SG wall.

The last reinforced wall was strengthened using fiberglass mesh from both sides (TR-2SG), and in the initial stage, we noted linear behavior with no cracks observed. However, when the load had almost reached a maximum of 774 kN, the stress started decreasing gradually to a certain point, followed by a sudden failure (Figure 18f). This wall

had 2.15 times the capacity of the UC wall, and compared to the basalt-reinforced walls, this wall had lower ductility but a higher load capacity. Visibly, no rupture in the fiber was observed.

All walls resulted in a diagonal crack pattern across the mortar–masonry interface, with no dependence observed between the plaster mortar and the masonry. Adding screws in the case of TR-2SB-S did not provide any benefits to the matrix since there was no separation. Figure 19 illustrates the shear stress vs. shear strain for all walls, and the results for all specimens are reported in Table 3 below.

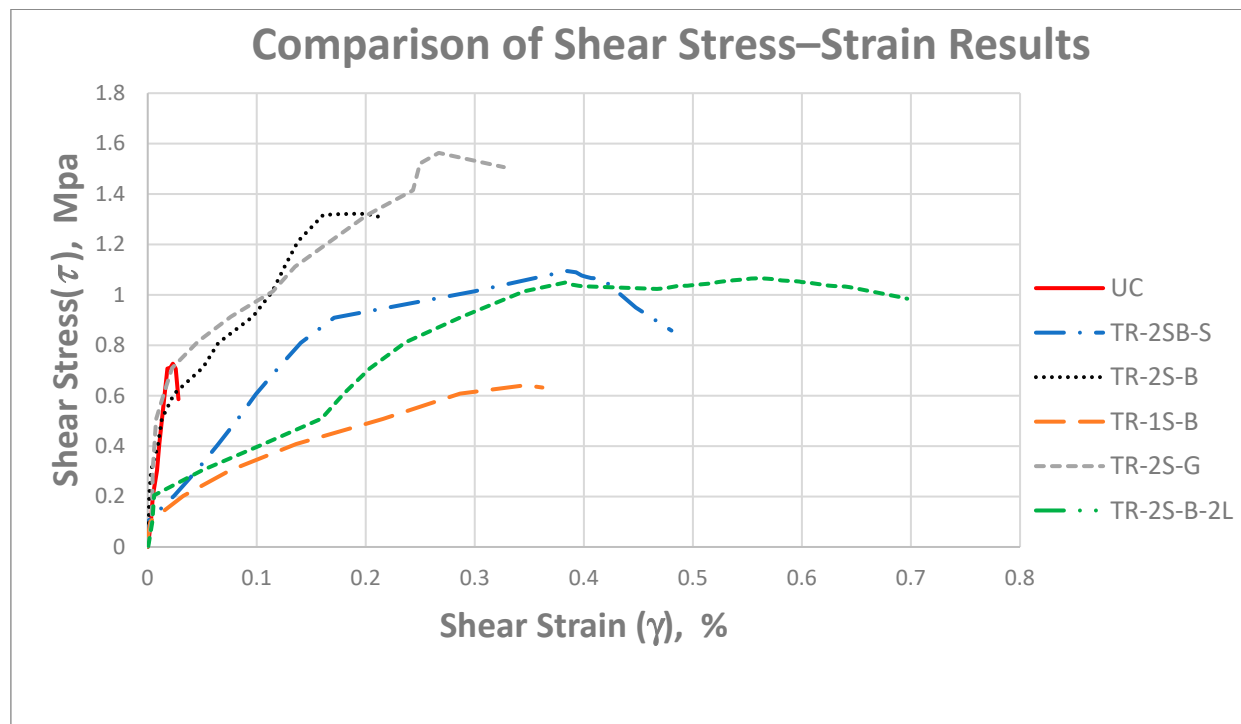


Figure 19. Comparison of shear stress–strain results for all specimens.

Table 3. Summary of the results of shear testing.

No.	Specimen	Max. Applied Load (P) kN	Shear Load 0.7 P	Stress τ Mpa	Strain γ %
1	UC	360	254	0.73	0.023
2	TR-1SB	317	224	0.64	0.345
3	TR-2SB	654	463	1.32	0.193
4	TR-2SB-2L	527	373	1.07	0.564
5	TR-2SB-S	542	383	1.09	0.384
6	TR-2SG	774	547	1.56	0.267

The stress–strain curves for the strengthened walls show that the system ensures full integration between the masonry and TRM. In the first phase, the response to force keeps increasing, resulting in greater strength values ultimately. The greatest is reached just before integrity is lost, and a decreasing second phase starts before concluding with a significant strength drop. When the second phase of the stress–strain curves of the reinforced wallets was studied, it was noted that significant strength loss occurs with the development of cracks in the plaster, which reduces the effectiveness of the bond between the wall and the TRM system. The results show that the fiberglass-strengthened wall provides the highest strength compared to all others, but it shows minimum elongation. Compared to the control specimen, it provides 2.15 times the strength. Walls reinforced with basalt

from both sides in different systems show increased strength and ductility. Compared to the control specimen, this provides better ductility and 1.47–1.82 times more strength. A wall reinforced with basalt from one side shows the worst behavior, as this modification increases ductility compared to the control specimen due to the basalt textile, but it results in lower shear strength because of the unstrengthened weak face.

6. Conclusions and Recommendations

6.1. Conclusions

This research aimed to find the optimal solution for the rehabilitation of historical structures. We explored techniques for the seismic enhancement of historical stone masonry buildings, consisting of the application of a fiberglass or basalt textile as reinforcement with a plaster mortar coating on the wall faces. Our tests focused on the effectiveness against in-plane masonry failure, with us experimentally investigating the load-carrying capacity, maximum displacement, and damage state for unreinforced and reinforced masonry walls. Shear loading tests were performed for six cases, and the failure modes of the specimens were analyzed. One test was carried out on unreinforced masonry, with the others on reinforced samples. The aims were to obtain important information on the response of reinforced masonry subject to in-plane shear loading and to gain an understanding of the actual behavior and effect of the reinforcement. Based on the experimental work presented, the following conclusions are drawn:

- Sarooj is compatible with masonry in regard to the mechanical properties analyzed (compressive strength, tensile flexural strength, etc.). Compatibility is highly important for the behavior of a strengthened wall and the performance of the strengthening solution under mechanical action.
- The unreinforced masonry specimen (UC) showed sudden brittle failure. The collapse occurred abruptly, and the crack pattern ran along the mortar joints.
- TRM strengthening improved the shear strength and stiffness of the masonry. All reinforced specimens showed relatively ductile behavior before failure compared to the unreinforced masonry wall. Fiberglass-reinforced wall specimens had the highest load capacities but the least ductility among all reinforced specimens.
- No separation or delamination was observed between the reinforcement and the masonry substrate, revealing the high bonding capacity of the materials.
- The TRM wall reinforced on only one side demonstrated the worst behavior. We noted in-plane deformation and major cracks on the plain/unplastered side before cracks occurred on the reinforced side.
- The strengthened walls showed 1.5–2.2 times higher load capacities than the unreinforced specimen, except for the one-sided reinforced wall. The wall reinforced with fiberglass (TR-2SG) had the highest shear capacity among all the walls.

Note, however, that the above conclusions are limited to the presented research and our limited number of samples, and they require further study with duplicate samples.

6.2. Recommendations

Based on these results, in order to find the optimal solution for strengthening masonry walls, we offer the following recommendations:

- For mortar, the percentage of lime in the mixture should be reduced since it dries rapidly, requiring speedy work when used.
- The water ratio in the mixture is crucial. An optimal proportion of water in the mixture can help minimize shrinkage and hair-sized cracks.
- Plaster mortar uses lime and a finer-sized sarooj. Inspired by that, scholars may further study the potential for introducing chemical admixtures such as shrinkage-reducing admixtures or set-retarding admixtures.
- Fiberglass showed a very high strength capacity, and further studies should focus on applying fiberglass in different methods to capitalize on that strength capacity.

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