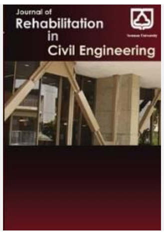

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In-Plane Shear Behaviour of Brick Masonry Wallets Strengthened with GFRP and Textile Reinforced Mortars

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ABSTRACT

This study investigates the structural behavior of unstrengthened and Textile Reinforced Mortar (TRM)-strengthened brick masonry wallets under diagonal compression through experimental testing and finite element analysis (FEA). Masonry wallets measuring 700 mm × 700 mm with a thickness of 115 mm were constructed using clay bricks and cement mortar. Five wallets were tested to failure under diagonal compression. Strengthening techniques, including fibre wrapping and TRM, were employed to enhance their performance. Unstrengthened wallets exhibited brittle failure modes, such as diagonal cracking, localized crushing, and mortar joint sliding, highlighting their vulnerability to tensile stresses. In contrast, TRM-strengthened wallets demonstrated significantly improved shear performance, enhanced ductility, distributed cracking, and increased load-carrying capacity. Failure modes for strengthened wallets included TRM debonding, textile rupture, and combined mechanisms. FEA models developed in ANSYS successfully replicated the stress distribution and failure patterns observed experimentally, with deviations of less than 8% in peak load and crack propagation—well within acceptable limits. These findings underscore the effectiveness of TRM as a retrofitting solution for improving the structural performance of brick masonry under diagonal compression.

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1. Introduction

Brick masonry has been a fundamental construction material for centuries, valued for its availability, cost-effectiveness, and structural efficiency. However, unreinforced masonry (URM) structures are inherently vulnerable to tensile stresses and external loads, particularly in seismic regions, where in-plane shear failure is a primary mode of distress. Deducting the damages and monitoring the same in the masonry is predominant in proposing retrofitting and repair technique [1]. Consequently, retrofitting and strengthening strategies have gained significant attention to enhance the structural performance and durability of masonry systems. Among various retrofitting techniques, the use of fibre-reinforced polymer (FRP) composites and textile-reinforced mortars (TRMs) has emerged as a promising approach due to their high strength-to-weight ratio, ease of application, and durability. Glass fibre-reinforced polymer (GFRP) sheets are particularly more attractive for masonry strengthening, offering excellent mechanical properties and corrosion resistance. Similarly, TRM systems, consisting of textiles embedded in a cementitious matrix, provide a sustainable and compatible alternative, offering ductility and crack distribution control. A study stated that Carbon Textile Reinforced Mortar(CTRM) enhances stiffness more effectively than Basalt Textile Reinforced Mortar(BTRM) but less effectively than CFRP. The full-strip CTRM configuration increases stiffness by 35% (from 5.40 kN/mm to 7.31 kN/mm), primarily due to the use of carbon textiles [2].

One innovative method to enhance masonry structures using steel-reinforced grout (SRG) with ultra-high tensile strength steel cords enclosed in a mortar matrix was studied [3]. Diagonal compression tests conducted on tuff masonry specimens before and after applying an inorganic matrix-grid (IMG) composite was discussed. Three different IMG system layouts were examined: single-side strengthening; single-side strengthening with steel fibre-reinforced polymer (SFRP) ties; and double-side strengthening. The tests evaluated and compared the increases in shear strength and ductility achieved with these systems to those of similar strengthening methods [4]. The study evaluated the applicability of the diagonal tensile test in assessing the cyclic response of strengthened masonry. The findings enabled the determination of the strengthening system's contribution to the load-carrying capacity of masonry elements. Additionally, the study provided insights into the evolution of damage and the mechanisms of stiffness degradation under cyclic loading [5]. A fabric-reinforced cementitious matrix (FRCM) system was evaluated as a potential alternative for externally strengthening unreinforced masonry (URM) walls. The experimental program involved testing nine clay brick walls under diagonal compression. Two different FRCM reinforcement schemes were utilized: one with a single layer of reinforcement fabric and another with four layers. An analytical model was employed to estimate the shear capacity of the strengthened URM walls, and these results were compared with the experimental data. The study also examined how design approach limitations affected the shear capacity of the strengthened walls [6]. The experimental findings demonstrated that the implemented Textile Reinforced Mortar (TRM) solutions significantly enhanced shear resistance and ductility. These improvements make TRM an effective option for seismic retrofitting and post-earthquake repairs [7]. A study presents that premature failure of the masonry wall was overcome by platering using TRM and reported that strength enhancement was upto 62% [8]. The study proposes and evaluates modified analytical models for the in-plane shear and out-of-plane bending capacities of TRM reinforced masonry elements, comparing them with existing codified procedures [9]. Presented an experimental campaign on plain and reinforced masonry wallets subjected to diagonal compression tests. The masonry panels were reinforced using two techniques: structural repointing with basalt bars inserted into the mortar bed joints, and a fiber reinforced cementitious matrix (FRCM) composite with a single-ply glass mesh applied to the sides of the specimens. The study examined the structural effects of both symmetric and asymmetric strengthening configurations [10]. Diagonal compression tests were conducted to assess the behavior of reinforced masonry, focusing on both shear strength and deformation capacity. The results confirmed that mortar coatings mixed with fibers are nearly as effective as cement mortar in terms of shear strength, while also enhancing the deformation capacity [11]. Presented a study examining the in-plane shear performance of solid clay brick masonry walls reinforced with near-surface mounted twisted steel bars [1,12] Polymer composites, specifically CFRP, were used to mitigate damage under cyclic compression. The results indicated that the failure of CFRP-strengthened masonry was primarily due to the de-bonding of the CFRP and the crushing of the material under compression [13]. The test results clearly showed that using GFRP and Ferrocement as advanced methods for repairing and strengthening bearing walls with openings is highly effective [14]. In recent years, artificial intelligence algorithms [15] were used to predict the compressive strength of the masonry block and machine learning methods [16] were deployed to calibrate the bond strength of the TRM masonry wall.

1.1. Novelty and reaserch Gap

The notable research gap in the area of masonry reinforcement is the lack of standardized design guidelines for confined masonry structures. The variability in materials, detailing, and construction practices across different regions makes it challenging to develop universally applicable guidelines. Additionally, there is a need for more experimental studies on the performance of confined masonry structures under earthquake loads and the use of new materials and construction techniques. Thus, this study focused on the experimental and numerical comparison of the masonry wallet confined with GFRP and TRM plastering as full or strip wrapping subjected to diagonal compression. By examining the effectiveness of these materials in enhancing shear capacity, failure modes, and crack distribution, the research seeks to provide insights into the comparative performance of these techniques and their suitability for retrofitting masonry structures.

2. Materials and methods

2.1. Material properties

The material used for the preparation of masonry wallets and their properties were discussed in this section. The traditional brick of size 230 mm x 110 mm x 75 mm was used and its compressive strength was obtained as 6 N/mm^2 as per IS 3495. The M-type cement mortar (1 : 3) was used to build the masonry unit and plastering of thickness 5 mm. The 28th day compressive strength of the 50 mm cube mortar was 21 Mpa and it was confirmed as per IS 2250. The commercially available glass fibre of woven roving type was utilized to strengthen the masonry wallet along with the cement mortar matrix of 1 : 3. The properties of the glass fiber are listed in Table 1 as provided by the supplier.

Table 1. Properties of Glass Fiber.

Properties	Values
Density	2550 kg/m^3
Elastic Modulus	30,000 N/mm^2
Tensile strength	≥ 550 N/mm^2
Yield strength	≥ 115 N/mm^2
Elongation at rupture	2.75 %

2.2. Test specimens

The masonry wallet was made of traditional brick of size 700 x 700 x 115 mm and cement-based mortar joint of thickness 5 mm. The mix proportion of 1:3 cement mortar was used for bonding the bricks and plastering the wallets. Fig. 1 shows the flow chart, which explains the process involved in the current study. The schematic diagrams and different strengthening techniques used in the study are shown in Fig. 2. Diagonal compression tests were carried out on five brick masonry wallets with one unstrengthen and four strengthened wallets (1) Brick Masonry wallet without plastering; (2) Brick Masonry wallet with plastering; (3) Brick Masonry wallet with GFRP strip wrapping; (4) Brick Masonry wallet with TRM full plastering; and (5) Brick Masonry wallet with TRM strip plastering. GFRP full and strip wrapping was done on the wallets using TRM techniques. Strengthening of the wallets involves the following process, first masonry wallets were pre – wetting; the first coating of 2.5 mm of cement mortar matrix; hand pressing of GFRP grid into the wet matrix and apply the second coating of 2.5 mm thick cement mortar matrix. All the five brick masonry wallets before and after strengthening are shown in Fig.3. Table 2 illustrates the specimen identification and its description with their dimensions.

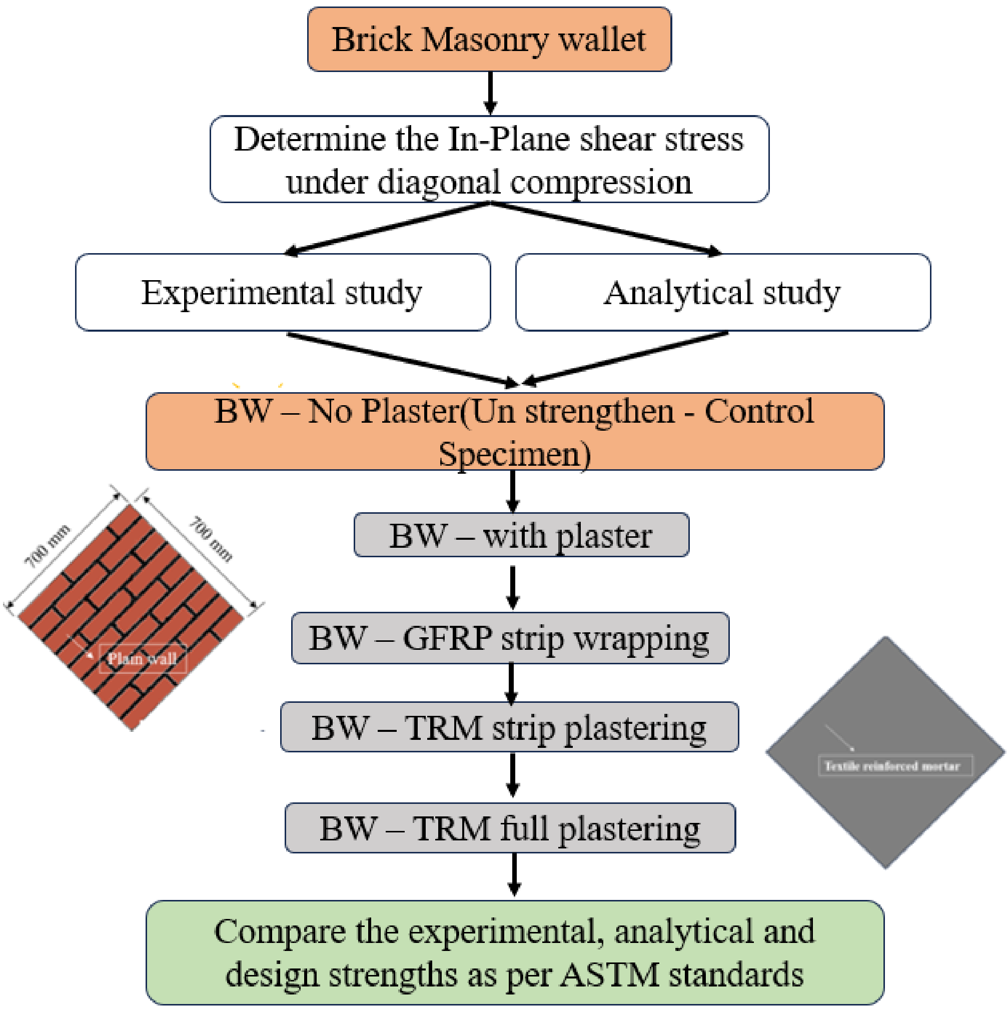


Fig. 1. Process flow chart of the current study.

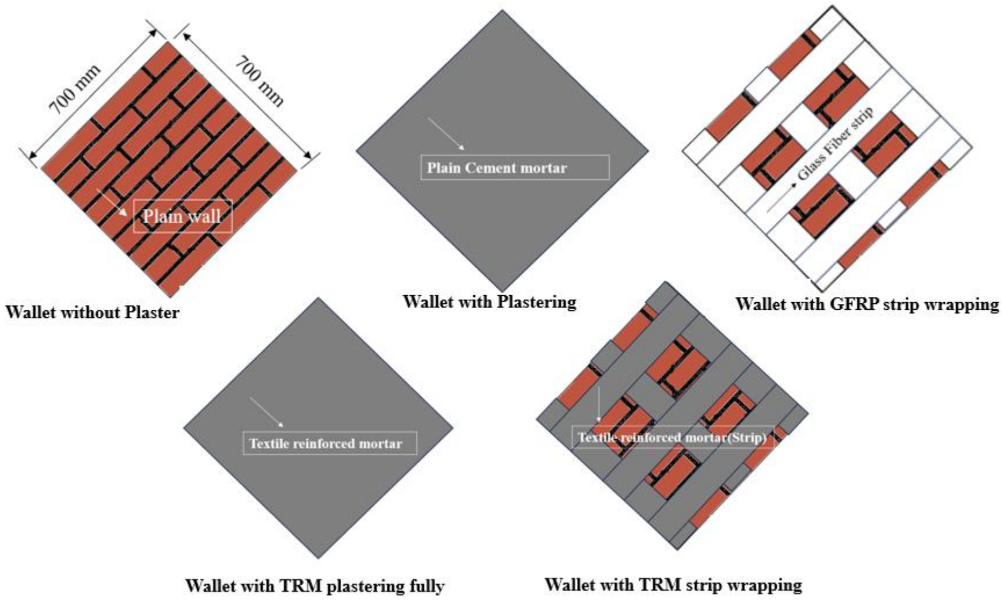


Fig. 2. Schematic diagrams and different strengthening techniques of the Brick Masonry wallets.

(a) Brick Masonry wallets before strengthening.

(b) Brick Masonry wallets after strengthened.

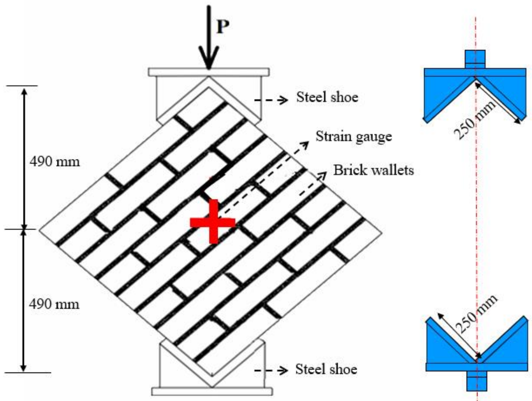
Fig. 3. Specimens before and after strengthening.

Table 2. Specimen identification and dimensions of the brick wallets.

Specimen Identification	Description of Specimen	L	H	t
			[mm]	
BW – No Plaster	Brick Masonry wallet without plastering	700	700	115
BW – With Plaster	Brick Masonry wallet with plastering	702	701	115
BW – GFRP strip wrapping	Brick Masonry wallet with GFRP strip wrapping	701	702	117
BW – TRM full plastering	Brick Masonry wallet with TRM full plastering	700	704	114
BW – TRM strip plastering	Brick Masonry wallet with TRM strip plastering	699	700	115

2.3. Test setup

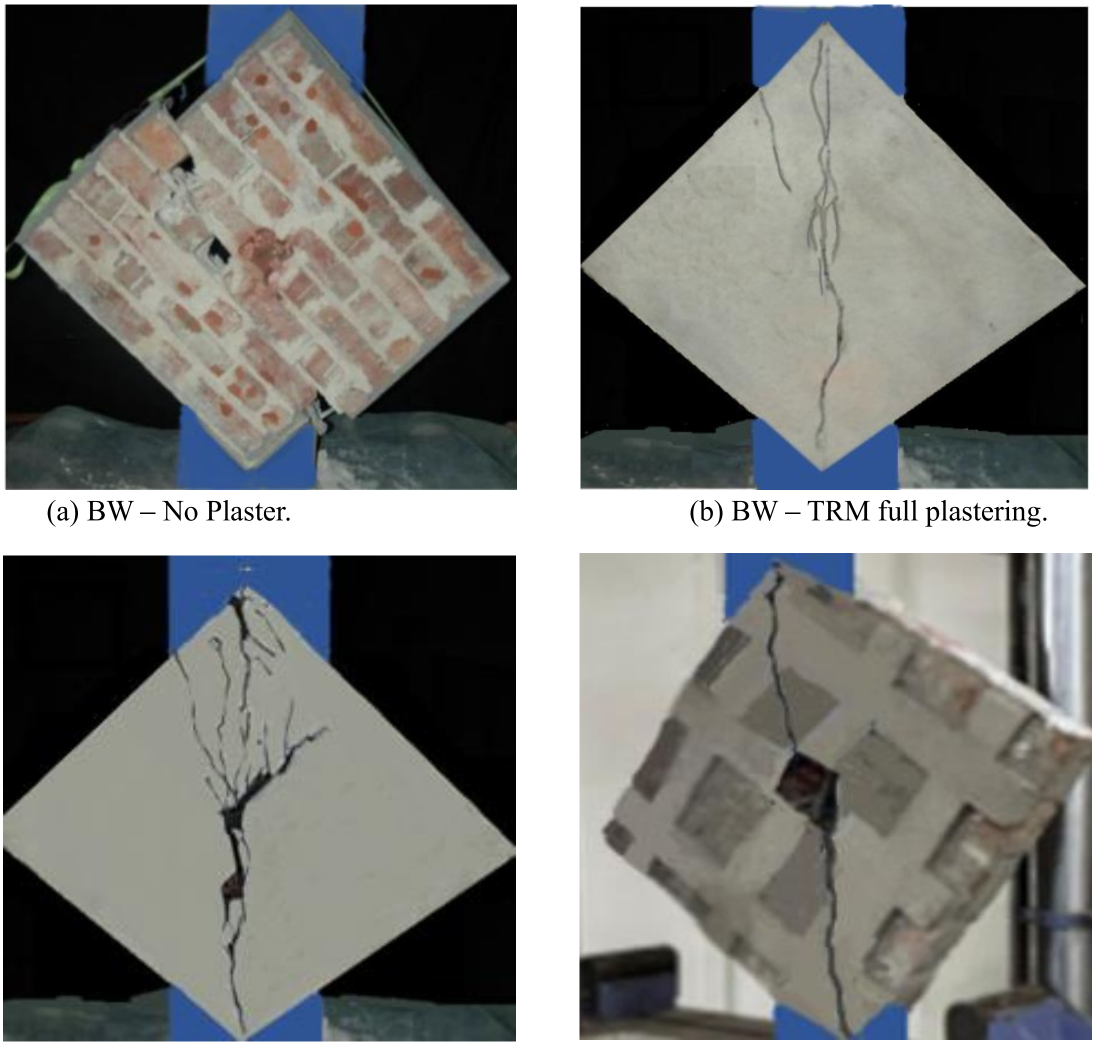
All five-masonry brick wallet strengthened with GFRP and TRM were tested to failure under diagonal compression using Universal Testing Machine (UTM) of capacity 600 kN. The static load was applied at a rate of 0.5 mm/min using hydraulic stroke control. Loading was done on the UTM for diagonal compression with the help of loading shoe of size 250 mm long and 152 mm width which was fabricated as per ASTM E-519-2 [17] . The two 20 mm strain gauge was deployed along the center which is at 490 mm from the corner of the diagonal to measure the transverse and longitudinal strain and it was recorded using five channel strain indicator. The strain gauge was pasted along parallel and perpendicular to the direction of loading. The position of the strain gauges and details of the steel loading shoe was shown in Figure 4(a). Figure 4(b) shows the brick wallet under diagonal compression in UTM.



(a). Test Set-up with shoe details and positioning of strain gauge in brick wallet.

(b) Brick wallet under axial loading in UTM0.
Fig. 4. Test set-up.

The wallet after testing was shown in Fig. 5. From the failure, it was noted that shear failure was occurred as sliding along mortar joints, causing brick separation, because of low strength and inadequate mortar bonding for unstrengthen specimen(Fig.5(a)). Mulpile cracks of average width of 20 mm cracks were seen on the surfaces of mortar in the specimen BW-With plaster(Fig. 5(c)) . Whereas in TRM strengthened wallet, instead of a single dominant crack, multiple fine cracks(Fig. 5(b)) were formed which distribute stresses across the masonry surface of the brick masonry wallet.Fig. 5 (d) shows the spalling of concrete from the strip along the diagonal of TMR – strip plastered specimen.



(a) BW – No Plaster. (b) BW – TRM full plastering.

(c) BW – with plastering. (d) BW – TRM strip plastering.

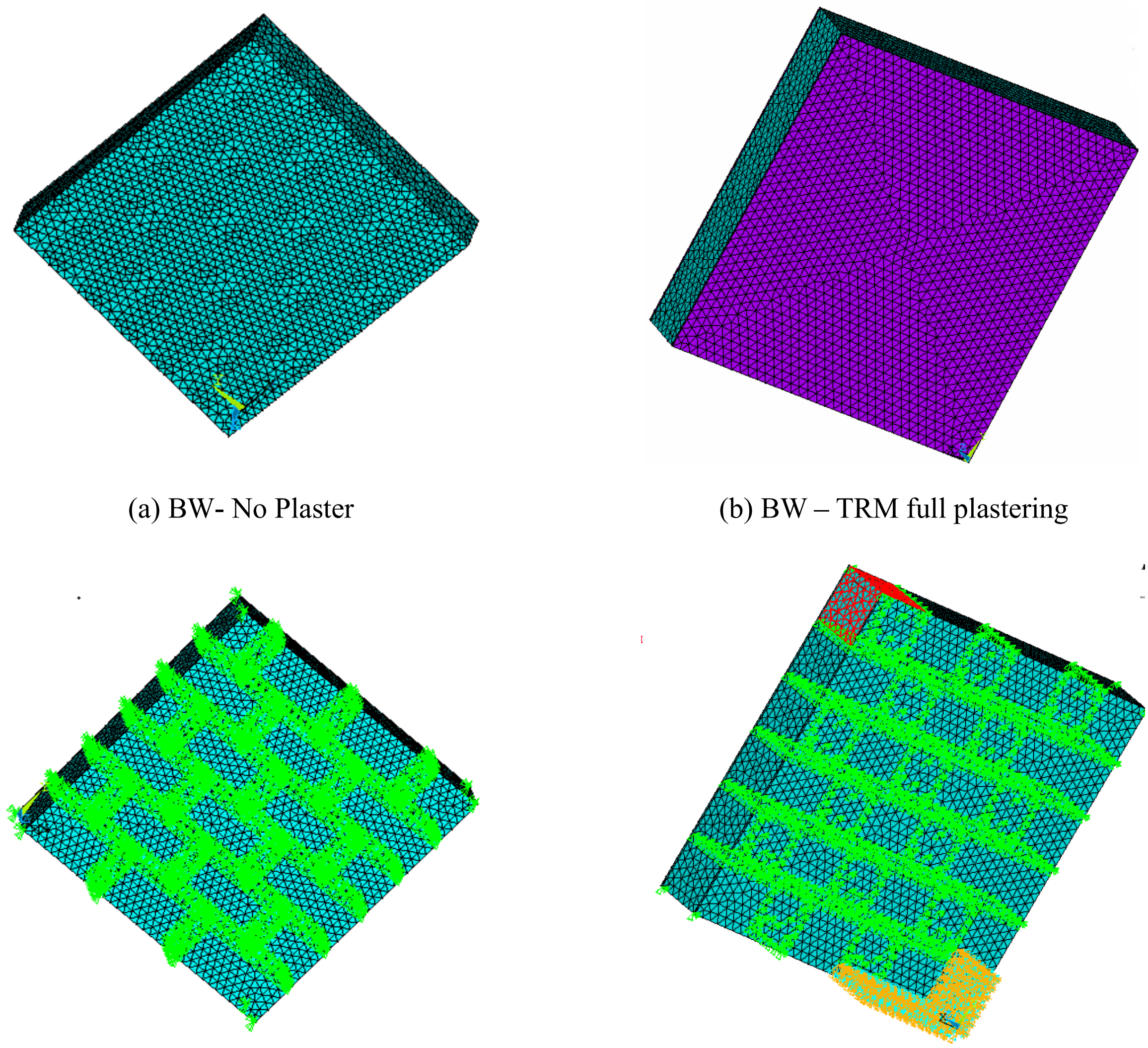
Fig. 5. Failure mode of the test specimen.

3. Finite element modeling

Finite Element Analysis (FEA) using ANSYS version 2024 offers a robust framework for evaluating the structural performance of masonry wallets strengthened with Glass Fiber Reinforced Polymers (GFRP) and Textile Reinforced Mortars (TRMs) under diagonal compression. The detailed geometric model, including the masonry wallet, mortar joints, and retrofitting layers like GFRP and TRM are made. The elements from the ANSYS library SOLID 185 and SHELL 181 were used to mesh the brick and cement mortar plaster respectively. Material properties [18], derived from experimental tests, including an elastic modulus of 3000 N/mm^2, Poisson's ratio of 0.2 and compressive strength of 6 N/mm^2 for bricks, similarly 2500 N/mm^2 and 21 N/mm^2 for mortar with the Poisson's ratio of 0.15 was given as input for FEA model. The properties of GFRP including 30,000 N/mm^2 elastic modulus, 600 N/mm^2 tensile strength and 0.3 Poisson's ratio were used for analysis.

The mesh model of the unstrengthened and strengthened brick masonry wallet was done considering the aspect ratio of 1, with both coarser mesh (brick) and finer mesh(mortar and fibre). The contact between the brick and mortar was achieved by partial coupling allowing translation along x, y and z directions. The bottom portion of the diagonal-placed wallet was fixed in all directions based on the dimensions of the shoe provided in the experimental study. The load is applied as incremental at the top surface considering the shoe dimensions of the specimen. The mesh model, loading and boundary conditions of specimens are shown in Fig.6.

Nonlinear analysis was performed to capture material and geometric nonlinearity, employing the Drucker-Prager criterion for bricks and mortar to simulate a failure, and bilinear stress-strain behavior for the GFRP strip layer and TRM platering layers. The Newton-Raphson iterative technique was utilised to solve the nonlinear equations, ensuring convergence for load increments despite complex deformation patterns. The non-linear analysis was also performed to determine the shear capacity, deformed shapes and failure mode of wallets under diagonal compression.



(a) BW- No Plaster (b) BW – TRM full plastering

(c) Bonding between cement matrix and brick (d) Diagonal compression loading and boundary condition

Fig. 6. Mesh mode, loading and boundary condition of Brick Masonry wallets.

4. Result and discussion

4.1. Shear stress of brick masonry wallet

All the five unstrengthen and strengthened wallet were subjected to diagonal compression and load carrying capacity was noted upon failure. Using the measured load, the shear stress of the brick masonry wallet is found by testing the specimen under diagonal compression. The following formula was used to calculate the shear stress as per ASTM E-519-2 [18]

$$\tau = \frac{0.707P}{A_n} \tag{1}$$

Where τ = shear stress on net area (N/mm^2)

P = Applied load at failure(N)

A_n = net area of the specimen, calculated as follows:

$$A_n = \left(\frac{w+h}{2}\right) t\, n \tag{2}$$

w= width of specimen (mm)

h = height of specimen(mm)

t = total thickness of the specimen (mm)

n = per cent of the gross area of the unit that is solid expressed as a decimal

The shear strain is computed as shown in Eq. (3)

$$\gamma = \left(\frac{u_v + u_h}{g}\right) \tag{3}$$

where γ is the shearing strain, u_v is the vertical shortening, u_h is the horizontal elongation and g is the vertical gauge length.

Finally, the modulus of stiffness in shear is calculated as shown in Eq. (4)

$$G = \frac{\tau}{\gamma} \tag{4}$$

The stress-strain graph presented in Fig. 7 illustrates the behavior of all tested wallets. The shear stress was calculated using Eqs. (1) and (2), while the shear strain was recorded through a strain indicator connected to strain gauges positioned along the diagonal of the wallets. The results indicate that the shear strength of the TRM fully plastered strengthened specimens was approximately twice that of the control specimens (BW-No plaster). When analyzing the shear strain values, it was observed that the control specimens exhibited greater scatter in results, primarily due to the absence of a strengthening system to stabilize the fracture process. Conversely, the strengthened specimens also showed significant scatter in ultimate shear strain values, likely due to brittle failure modes such as the formation of typical diagonal tensile cracks and the detachment of the TRM layers.

The unstrengthened wallets exhibited brittle behavior with low shear capacity, failing through mechanisms such as diagonal cracking, mortar sliding, or localized crushing. In contrast, TRM-strengthened wallets demonstrated significantly improved shear strength and ductility, as reflected in gradual stress-strain curves that indicated enhanced energy absorption capacity and delayed failure. Full TRM plastering performed better than strip application due to its uniform confinement effect. While GFRP strengthening (if tested) offers higher initial stiffness, TRM stands out for its superior ductility and crack-control capabilities.

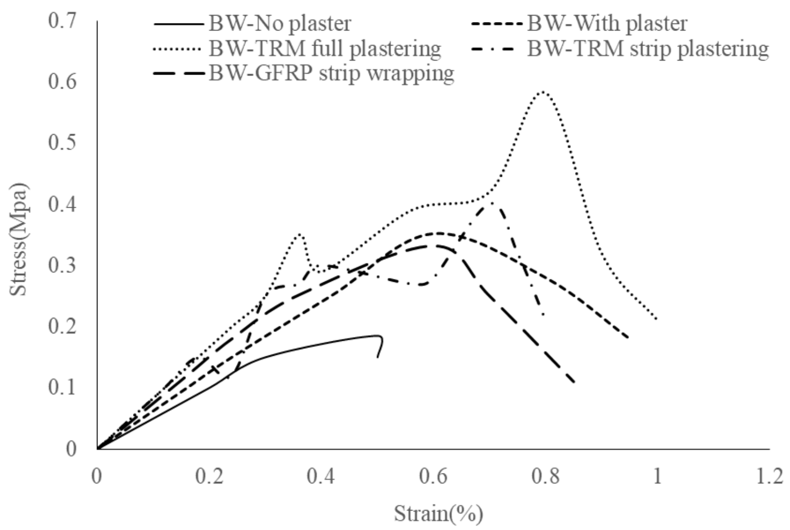


Fig. 7. Shear stress Vs Shear strain responses of all specimens.

Fig. 8 gives the comparison between the shear stress obtained from test specimen and FEA model. The bar chart shows that wallet strengthen with textile reinforced mortar (TRM) were able to resist more shear load than the GFRP strip wrapping and unstrengthen wallet.

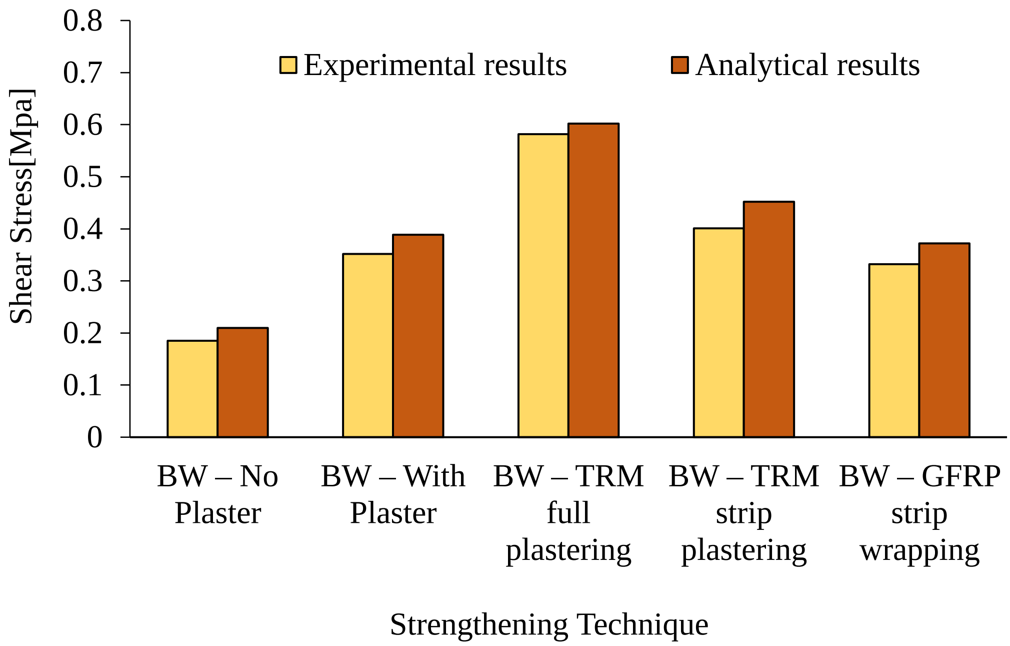


Fig. 8. Comparison between experimental and analytical shear stress of the masonry wallet.

4.2. Comparison between experimental, analytical and design ultimate load

The test specimens, experimental ultimate load-carrying capacity and shear stress under diagonal compression are shown in columns 2 and 3 of Table 3, respectively. The ultimate load listed in column 2 shows that BW – with plaster was 40.17 kN, while the ultimate load registered for BW – TRM strip plastering was 45.39 kN, which was about 1.5 times higher. The BW – TRM full plastering wall experienced the ultimate load of 67.56 kN which was about 1.7 times more than that of the BW with normal plastering. Similarly, a comparison can be made between BW – No plaster and BW – GFRP strip wrapping; the percentage increase in the ultimate load is 44 %. The analytical shear stress presented in column 3 of Table 3 shows that the average percentage difference between the experimental and analytical is less than 8 %. Thus, a good correlation between the experimental and FEA models was obtained, however, the analytical result is higher than the experimental because of the assumptions and boundary conditions made in the FEA models. The strength enhancement is the ratio between the ultimate load-carrying capacity of the TRM plaster wall to that of the control one. It was observed that strengthening shows the enhancement of 1.13 and 1.68 for walls with TRM strip and TRM full plastering respectively.

The ASTM design loads calculated for all the brick wall specimens and their ratio with experimental are presented in columns 5 and 7 respectively. The ratio between the experimental and design loads is higher for all the strengthened specimens particularly the noticeable value of 2.95 for the TRM full plastering specimen, which shows that design provisions are conservative.

Table 3. Comparison between the experimental, analytical and design shear stress.

Specimen	$P_{u, Exp}$	τ_{Exp}	τ_{FEA}	τ_{Des}	τ_{Exp} / τ_{FEA}	τ_{Exp} / τ_{Des}
	kN	N/mm^2				
BW – No Plaster	21.06	0.185	0.21	0.197	0.88	0.94
BW – With Plaster	40.17	0.352	0.389	0.197	0.90	1.79
BW – TRM full plastering	67.56	0.582	0.602	0.197	0.97	2.95
BW – TRM strip plastering	45.39	0.401	0.452	0.197	0.89	2.04
BW – GFRP strip wrapping	37.77	0.332	0.372	0.197	0.89	1.69

4.3. Failure mode of unstrengthen and TRM strengthen Brick Masonry wallet

Fig 9 shows the failure of unstrengthen brick masonry wallets. From the Fig. 9 it was observed that unstrengthen brick masonry wallets typically fail under diagonal compression because they lack the capacity to withstand tensile stresses effectively. Diagonal cracking is the most frequent failure mode, characterized by the formation of a single prominent crack along the diagonal, leading to a brittle response with limited stress redistribution. In some instances, localized crushing failure have occurred at the corners under compressive forces, may be due to weak or degraded mortar joints. Shear failure was also observed as sliding along mortar joints, causing brick separation, because of low strength and inadequate mortar bonding.

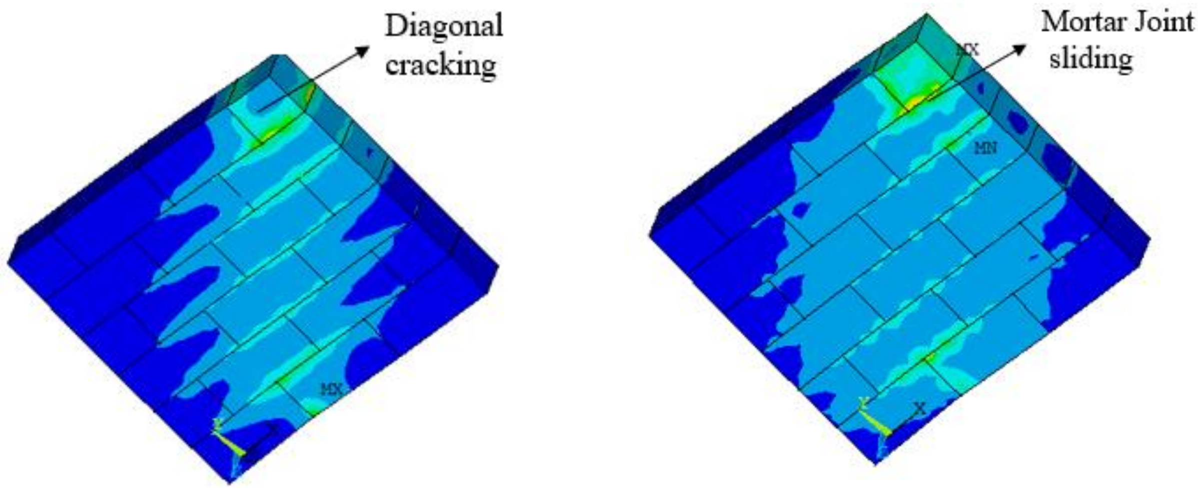


Fig. 9. Failure of unstrengthen Brick Masonry Wallet.

The failure pattern [19]of the TRM strengthen brick masonry wallet was shown in Fig. 10. From the failure behaviour, it was noted that TRM-strengthened brick masonry wallets exhibit enhanced structural performance under diagonal compression, with failure modes differing significantly from unstrengthen masonry. Instead of a single dominant crack, multiple fine cracks distribute stresses across the masonry surface was observed which improves, ductility of the wallet. Common failure modes include debonding of the TRM layer due to inadequate adhesion, rupture of the textile reinforcement under high stress, and combined failures involving masonry cracking was also observed in the form of TRM delamination, and textile rupture. These mechanisms highlight the effectiveness of TRM in delaying failure, redistributing stresses, and increasing load-carrying capacity.

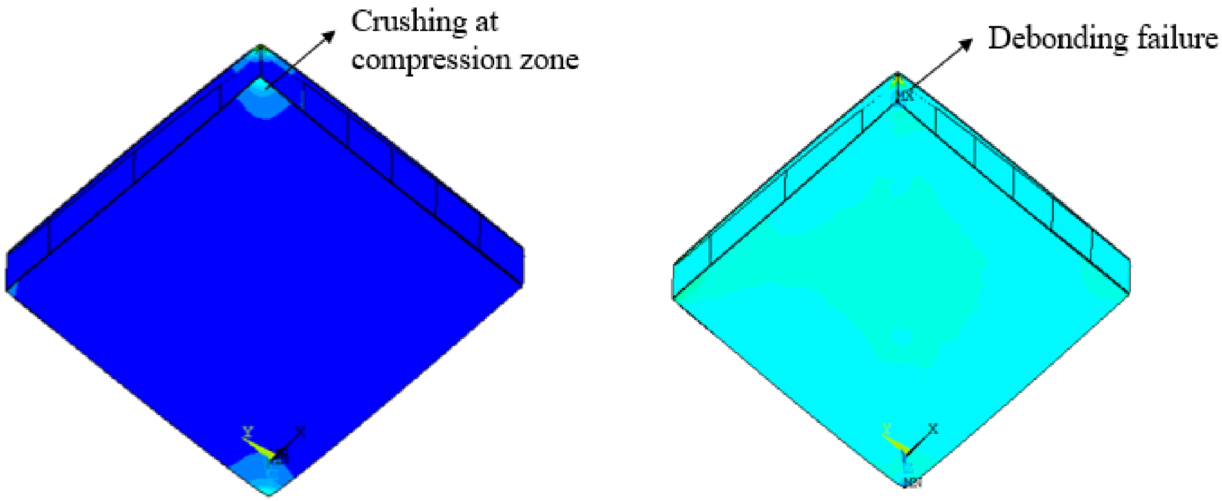


Fig. 10. Failure of TRM strengthen Brick Masonry Wallet.

Conclusion

This study highlights the structural behavior of unstrengthened and TRM-strengthened brick masonry wallets under diagonal compression, focusing on their shear performance and failure mechanisms.

- Unstrengthened masonry wallets BW-No plaster exhibited brittle failure dominated by diagonal cracking, localized crushing, or sliding along mortar joints, emphasizing their vulnerability to tensile stresses. Where as the BW-TRM full platering shows multiple fine cracks which able to resist more shear stress and delays the diagonal cracking of the wallets.
- TRM-strengthened wallets demonstrated enhanced load-carrying capacity twice than that of unstrengethen wallet with distributed cracking and TRM layer debonding as the primary failure modes.
- The ultimate load capacity of the BW-GFRP strip wrapping specimen showed a 44% increase compared to the BW-No plaster specimen, demonstrating the effectiveness of GFRP strip wrapping in enhancing load-carrying performance.
- TRM systems effectively enhance the in-plane shear strength and performance of masonry, making them a viable retrofitting solution. Strength enhancements of 1.13 and 1.68 were observed for walls with TRM strips and TRM full plastering, respectively.

- The BW – TRM full plastering wall experienced the ultimate load of 67.56 kN which was about 1.7 times more than that of the BW with normal plastering.
- FEA model slightly overestimates shear stress due to idealized material properties wan the variation is less than 8 % compared to experimental value. Thus, FEA models provide a valuable tool for understanding masonry wallet behavior, complementing experimental results.
- The ratio between the experimental and design stress calculated using ASTM E-519-2 is higher for all the strengthened specimens particularly the noticeable value of 2.95 for the TRM full plastering specimen, which shows that design provisions are conservative.
- Further integration of experimental findings with finite element analysis is recommended to refine these conclusions and develop standardized design guidelines for masonry strengthening.

In this study, the primary focus was on evaluating the structural performance of unstrengthened and TRM-strengthened brick masonry wallets under diagonal compression, with particular attention to shear strength and failure mechanisms. While the weight of the specimens is an important consideration for practical applications, especially in retrofitting, it was not included in the scope of this investigation. Future research will incorporate weight-based analysis along with structural performance to provide a more holistic evaluation of TRM systems.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution statement

Sangeetha P: Conceptualization, Methodology, Visualization, Review and supervision.

Revanth kumar G, **Sanjeev Kumar G**, **Antony Alias Abi D:** Software & Validation.

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