STRENGTHENING MASONRY WALLS UNDER OUT-OF-PLANE LOADS

Rafiqul Islam Babul[1]*, Md. Amran Hossan Khan[2], Iftekher Anam[3], Abujar Gifari[4], and Mushtaq Ahmed[5]

[1] *Graduate Student, Department of Civil and Environmental Engineering, Shahjalal University of Science and Technology, Bangladesh, e-mail: rafiq31sust@gamail.com*
[2] *Graduate Student, Department of Civil Engineering, University of Asia Pacific, Bangladesh, e-mail: amran1980khan@gmail.com*
[3] *Professor, Department of Civil Engineering, University of Asia Pacific, Bangladesh, e-mail: iftekhar@uap-bd.edu*
[4] *Graduate Student, Department of Civil and Environmental Engineering, Shahjalal University of Science and Technology, Bangladesh, e-mail: abujar.gifari.cee@gmail.com*
[5] *Professor, Department of Civil and Environmental Engineering, Shahjalal University of Science and Technology, Bangladesh, e-mail: mushtaq-cee@sust.edu*

***Corresponding Author**

ABSTRACT

This study investigates the out-of-plane behavior of unreinforced masonry (URM) walls made of solid bricks and hollow concrete blocks that were retrofitted using four different strengthening techniques fiber reinforced polymer (FRP),ferrocement lamination, mild steel (MS) plate bracing, and rebar-tie reinforcement. A total of fourteen wall specimens were tested under four-point static loading to evaluate improvements in load capacity, stiffness, and ductility. The unstrengthened walls showed brittle behavior with sudden collapse but all of the strengthened specimens exhibited improved structural performance, FRP showed the highest strength and ductility increases among the retrofitting techniques; load capacity increased by up to 55% for hollow block walls and 133% for solid brick walls. While ferrocement increased stiffness but remained slightly brittle, MS plate bracing provided remarkable deformation capacity and energy absorption. Rebar ties demonstrated a balanced improvement in strength and ductility. A comparison of the types of walls showed that the solid brick walls had more stiffness and strength, while on the other hand, the hollow block walls had greater flexibility and energy dissipation. These findings demonstrate how crucial it is to carefully evaluate the type of retrofitting techniques that can be applied to significantly improve the out-of-plane stability and seismic resistance of masonry structures in developing regions.

Keywords: *Unreinforced masonry walls, Seismic performance, Out-of-plane loading, Strengthening*

1. INTRODUCTION

Masonry, one of the most commonly used ancient construction materials on the planet, has been one of the most important building elements in almost all of history, responsible for founding several ancient and historic buildings, such as the Great Wall of China, the Tower of Babylon, and the Pyramids of Egypt. These monuments not only represent the cultural traits and the legacies of their respective civilizations, but they are also a wonderful example of miracles of engineering. Due to its availability, affordability and adequate compressive strength characteristics, masonry continues to exist in low- to medium-rise structures in modern times, despite its loss of supremacy with the advent of steel and reinforced concrete in the nineteenth century (D'Altri et al., 2020; Costa et al., 2021).

Unreinforced masonry (URM) structures are brittle and have low tensile strength, which makes them especially vulnerable to lateral forces, including earthquakes and high winds (Pradhan et al., 2021). Out-of-plane failure of masonry walls is highly important among different failure modes due to the possibility of it leading to the partial or total collapse of structures during seismic events (Gattesco et al., 2023; Thomoglou et al., 2023). Consequently, comprehensive mechanics of out-of-plane behavior and the development of efficient strengthening techniques have emerged as crucial focal points for the structural research work and specifically for the seismically active and resource constrained areas.

In Bangladesh load - bearing and infill masonry walls are commonly built with solid clay bricks and hollow blocks. These walls frequently are unreinforced because of a tendency to not carefully adhere to modern seismic design guidelines. As a result, when loads are applied in lateral direction, they exhibit low ductility and low energy dissipation capability. Such walls raise major concerns for the safety of the occupants and for structural stability, due to their high susceptibility rate to strong cracking and to brittle collapse, as evidenced prior to past earthquakes (Gattesco et al., 2023). Therefore, practicable, cost-effective retrofitting techniques, that can substantially enhance the seismic resistance of existing masonry structures, are urgently needed.

There is a wide range of strengthening techniques that have been proposed and implemented in the last years. Conventional approaches include addition of steel or reinforced concrete frames; however, these often increase overall mass and occupy a valuable space (Kadam et al., 2015). Contemporary innovations have been focused on externally bonded or surface-applied materials such as Fiber Reinforced Polymer (FRP), ferrocement or steel meshes. Numerous studies have shown the use of FRP sheets or strips on the masonry surfaces to increase the flexural capacity, reduce the crack propagation, and increase ductility (Bui & Limam, 2014; Dizhur et al., 2014). Research have also found that the out-of-plane strength and ductility of existing masonry walls can be significantly enhanced using Composite-Reinforced Mortar (CRM) coatings reinforced with glass fibre mesh (Gattesco et al., 2023). A comprehensive review of modern out-of-plane strengthening methods, namely FRP, textile Reinforced Mortar (TRM) and Course Reinforced Mortar (CRM) has highlighted their structural effectiveness and ease of application (Zoppo et al., 2022; Thomoglou et al., 2023).

Experimental studies confirm that the URM walls can be strengthened by using expanded steel plates combined with shotcrete to substantially improve the lateral strength and deformation capacity (Yaman et al., 2025). Introducing rebar ties across masonry panels enhances the flexural ductility and delays the initiation of cracks under cyclic loading (Yazdi et al., 2023). Retrofitting of stone masonry walls using FRP and carbon fiber mesh (CFM) composites helps in improving the shear strength and stiffness (Celik, 2025). A cost-effective spray-on polyurethane coating provides a light weight and easily applicable alternative for increasing the ductility of walls (Chen et al., 2023). Collectively these studies show that both traditional and composite based retrofitting materials can be effectively used to upgrade the seismic performance of masonry structures.

In spite of this development, there have been few studies that compared different strengthening methods expressly in the context of local materials available, such as solid clay bricks and hollow concrete blocks. Hollow blocks with their light weight and environmental friendliness have other issues like complex stress distributions and susceptibility to localized cracking due to voids (Zhou et al., 2017). Studies have shown that, even though hollow block masonry can achieve good strength, its out-of-plane response and failure characteristics are quite different from those of solid brick walls (Bui & Limam, 2014; Domenico et al., 2021). Therefore, the choice of suitable strengthening strategies for each type of wall is still a practical and technical challenge. Furthermore, most of the existing solutions are costly or technically challenging to be adopted widely in the developing countries.

The objective of this study is to compare and experimentally evaluate the out-of-plane structural performance of unreinforced masonry (URM) walls made from hollow concrete blocks and solid clay bricks both in their unstrengthened state and under various strengthening techniques. The effectiveness of the included retrofitting is assessed based on of load bearing capability, failure modes, stiffness, ductility and energy absorption. The results will help in identifying strengthening methods that can be used locally and at a reasonable cost to improve the seismic capability of masonry walls in developing nations.

2. METHODOLOGY

This study experimentally investigates the out-of-plane behaviour of solid and hollow masonry walls under static loading conditions. The primary objective is to assess the improvement in strength, stiffness, and ductility achieved through four retrofitting methods Fiber Reinforced Polymer (FRP), Ferrocement Lamination, Mild Steel (MS) Plate Bracing, and Rebar-Tie Reinforcement in comparison to unstrengthen control specimens. The test program was designed to ensure a consistent comparison between wall types and strengthening methods.

2.1 Specimen Preparation

2.1.1 Selection of Geometric Sizes of Masonry Wall

Two groups of wall specimens were constructed: Group 1 (using solid bricks) and Group 2 (using hollow blocks). All walls were built to a height of 2 ft and a length of 4 ft 2 in, suitable for testing in a hydraulic loading frame have shown in figure 1.

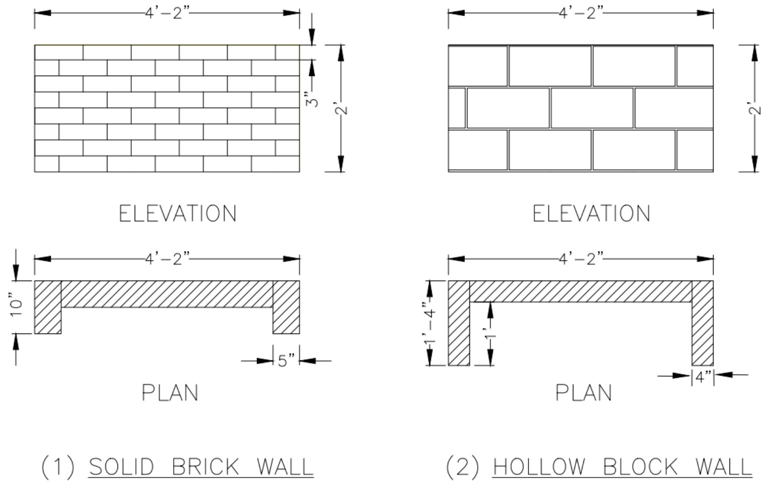


Figure 1: Geometric dimension of masonry wall.

2.1.2 Material Properties

2.1.2.1 Cement

The experimental work of this research was conducted using CEM – I.

2.1.2.2 Fine aggregate

Fine local sand (FM < 2) was used for mortar preparation for the purpose of brick or block laying. Coarse Sylhet sand (FM > 2.5) has been used for Ferrocement lamination mixing with local sand.

2.1.2.3 Steel reinforcement

The reinforcing bar has a 10 mm diameter, 13% elongation, and a cross-sectional area of 78.5 mm². It exhibits a yield strength of 555 MPa and an ultimate strength of 665 MPa.

2.1.2.4 Mortar

Two different types of mortar were utilized: one for bricklaying in masonry walls, and another for Ferrocement lamination to encase wire mesh. The water-to-cement (W/C) ratio was 0.5, with the mixing ratios provided: for brickworks: cement: sand = 1:4 (volume basis) & for ferrocement: cement: sand = 1:2 (volume basis).

2.1.2.5 Solid bricks

The size of block was 240mm x 110mm x 70mm. The crushing strength of solid bricks was found 12.95 MPa.

2.1.2.6 Hollow blocks

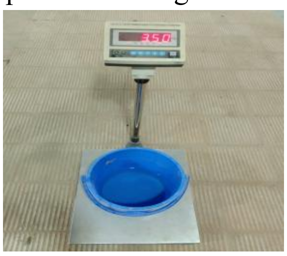
The size of hollow block was 390mm x 100mm x 190mm. The crushing strength of hollow blocks was found 14.7 MPa.

2.2 Specimen Preparation

All masonry wall specimens were built in two phases. First, solid brick and hollow block walls were constructed using standard mortar and curing practices. In the second phase, selected walls were retrofitted using four strengthening methods: FRP wrapping, Ferrocement lamination, MS plate bracing with nut–bolt connections, and Rebar-tie reinforcement.

2.2.1 Masonry Wall Preparation

The process of preparing the masonry wall was carried out in a sequence of methodical and planned steps that ensured uniformity and structural integrity in the construction, which are displayed on Figure 2. Initially, the requisite materials- cement, sand and water- were measured quantitatively and homogenized well to prepare mortar of the right consistency. After this, the solid bricks and hollow blocks were placed up and laid with the prepared mortar as a bonding medium. Each one of the strata was carefully aligned and levelled to maintain the planned wall dimensions and stability. The procedure continued in succession till the wall reached its full height vertically. Ultimately, the finished wall was covered by Hessian cloth to allow it to cure properly ensuring sufficient strength development and long-term durability of the masonry.

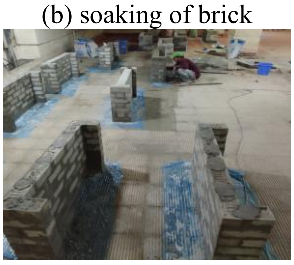


(a) measurement of water

(b) soaking of brick

(c) mixing of mortar

(d) making of brickwall



(e) arrangement of brickwall

(f) curing of brickwall

Figure 2: Preparation of masonry wall.

2.2.2 Strengthening of Masonry Wall

The four strengthening techniques were used to enhance the performance of both solid brick and hollow block masonry walls. Fiber- reinforced polymer (FRP) strips of width 20 mm and thickness 1.4 mm were bonded diagonally in an X shape on both faces of the wall using high-strength epoxy adhesive to provide high tensile resistance to the wall faces and prevent crack propagation. Ferrocement lamination consisted of the addition of a layer of mortar of thickness 16 mm, which had a fine wire mesh of 8.5 * 8.5 mm openings on every face incorporated to form a composite layer to increase surface stiffness and to reduce cracking. Mild Steel (MS) plate bracing consisted of 40 mm wide and 3 mm thick steel plates on diagonal, with the nuts and bolts to keep them together - offering external confinement and greater resistance to out of plane bending. Finally, Rebar-tie reinforcement consisted of 10 mm-diameter rebars threaded at both ends and anchored through the wall using washers and nuts, providing internal confinement, improving ductility, and preventing wall separation under load.

(a) Strengthening by Fiber Reinforced Polymer

(b) Strengthening by Ferrocement lamination

(c) Strengthening by Mild Steel Plate

(d) Strengthening by Reinforcement

Figure 3: Strengthening method of masonry walls.

2.3 Test Setup and Procedure

All Out-of-plane loading was applied to all wall specimens in a four-point bending arrangement as illustrated in Figure 4. The test system modeled the flexural response of masonry walls when lateral forces like wind or earthquake forces are present. Each specimen was placed in a rigid steel loading frame vertically. The wall was supported at the bottom and top to give simply supported boundary conditions, and to avoid horizontal movement. The load was monotonically applied using a hydraulic jack at the top of the specimen. A steel loading beam was used to transfer the applied force to the wall and in such a way that would produce a uniform distribution of the load. Gradual increment of the load was carried out up to failure.

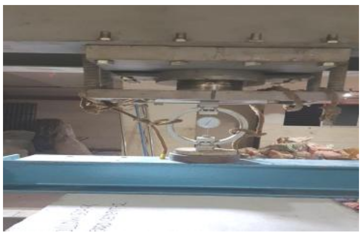


Figure 4: Experimental setup for out-of-plane four-point bending test of masonry wall specimens using a hydraulic loading frame.

To constantly measure the load, a load cell was placed in series with the hydraulic jack. Linear variable differential transformers (LVDTs) were used to measure the vertical deflections at the mid-span of the wall. Extra dial gauges were placed around the areas of support to check any local deformations and check displacement measurements. All of these data were measured continuously by digital data acquisition system. Crack initiation, crack development, and failure modes were also observed visually during the test and were recorded on high-resolution photographs. Failure was determined as the stage where there was a great decrease in the load carrying capacity or when it was so excessively cracked and deformed that it was unstable.

3. RESULTS AND DISCUSSION

This section presents the experimental results of out-of-plane loading tests, which were carried out on solid-brick and hollow-block masonry walls, both in their unreinforced condition, and after retrofitting using fiber-reinforced polymer (FRP), ferrocement, MS plate bracing, and rebar ties. The load-deformation behaviour, ultimate load-bearing capacity, ductility, and failure modes are analysed in order to assess the effectiveness of each strengthening technique. Comparative performance of the solid and hollow masonry walls is addressed to find the most efficient and practical strengthening method.

3.1 Test Results of Unstrengthened (Control) Walls

Figure 5 indicates that between the solid and the hollow block unreinforced masonry walls are separated in their load and deflection performance as well as their stiffness and deformation. Both types of the wall behaved almost elastically up to the state of failure, which confirmed the brittle behavior of the unreinforced masonry under out-of-plane loading. The solid brick wall took 5.4 kN of load at a deflection of 0.305 mm while the hollow block wall took 9 kN at 0.55 mm, which indicates the lighter hollow block system can take slightly higher loads and deflection because of its geometry and lower self-weight. Accordingly, two types of walls exhibited poor ductility and energy consumption, which reveals the need for strengthening measures to improve seismic performance.

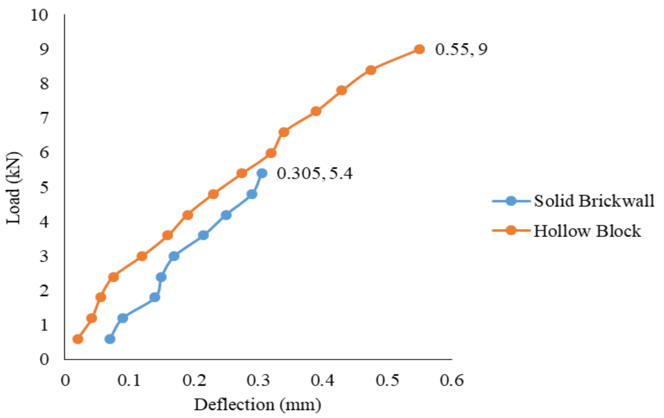
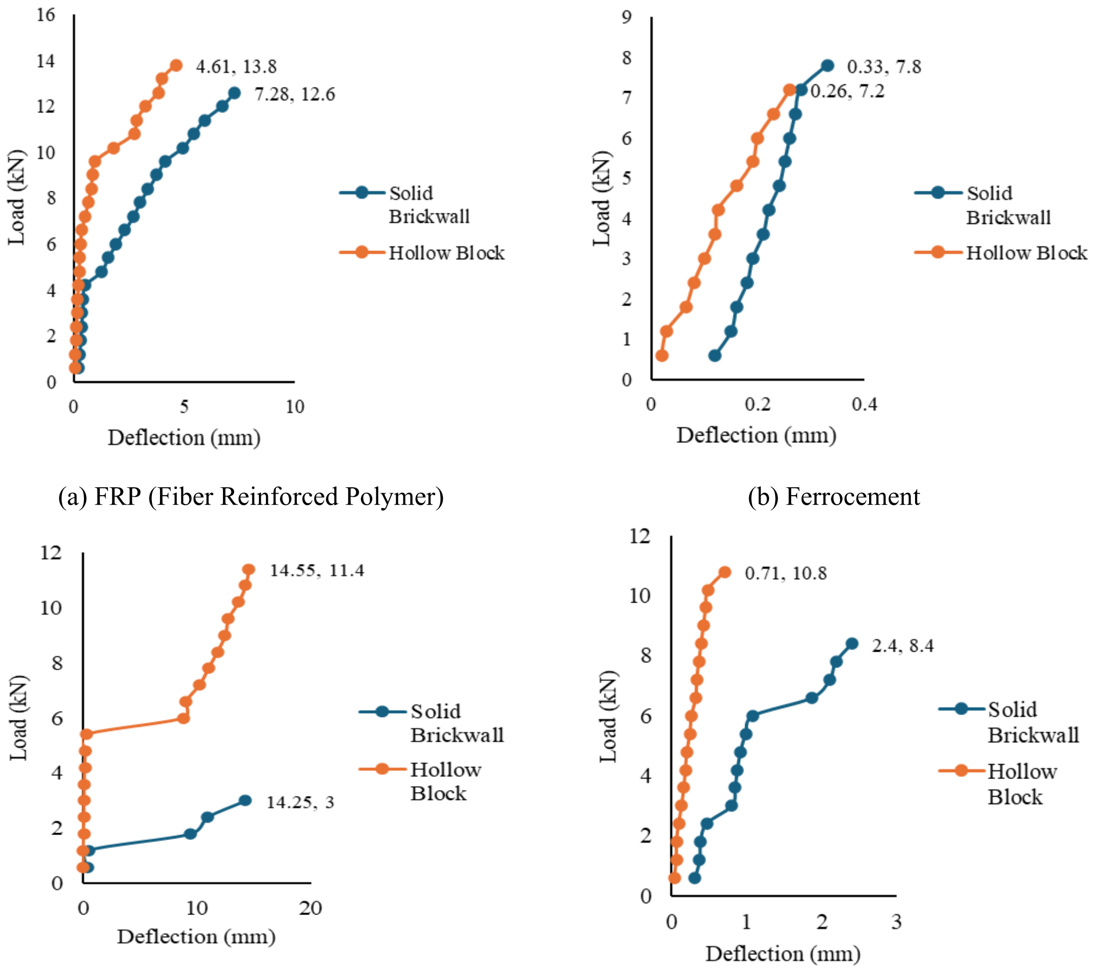


Figure 5: Load vs deflection curve of unstrengthen solid brick wall and hollow block wall.

3.2 Test Results of Strengthened Walls

Figure 6 shows that the retrofitted solid brick and hollow block walls show significant improvement in terms of strength and deformation behaviour as compared to unreinforced specimens, each technique shows different characteristics.

FRP Retrofitting resulted in the highest strength and ductility as the solid wall and the hollow block yield 12.6kN and 13.8kN, where the deflection is given by 7.28mm and 4.61mm, respectively. Both showed linear elastic behaviour followed by controlled cracking - however the solid wall displayed greater ductile behaviour compared to the hollow wall that showed greater stiffness with a sharper drop after peak. Ferrocement increased stiffness and strength and had poor ductility; the solid wall was 7.8kN and the hollow wall was 7.2kN, with deflection of less than 0.33 mm. The mesh-seqementum mortar delay cracking effectively but it suddenly failed after debonding. MS plate bracing had high ductile and energy absorbing functions and low strength enhancement: solid wall can bear 3 kN at 14.25 mm deflection, hollow block at 11.4 kN at 14.55 mm. Gradual load deflection behavior reflected stable deformation and good deformation tolerance. Rebar tied walls provided good balanced improvement in strength and ductility; the solid wall reached 8.4 kN at 2.4 mm deflection and the hollow block reached 10.8 kN at 0.71 mm. Rebar ties give good integrity and crack controls; delayed failure time and good load transfers.



(a) FRP (Fiber Reinforced Polymer)

(b) Ferrocement

(c) Mild Steel plate

(d) Rebar

Figure 6: Load vs deflection curve of four strengthened methods for solid brickwall and hollow block wall.

3.3 Comparative Performance Analysis

Table 1 explains more clearly the effect of various retrofitting techniques on both solid-brick and hollow-block masonry walls. Among all the methods, the strengthening effect of FRP has the best balance, the ultimate load of solid brick and hollow block walls increases by 133 percent and 53 percent, respectively, while at the same time greatly improving the ductility of the structure due to the tensile strength and effective bonding of the fiber. MS plate bracing, with less degree of strength enhancement but the most ductility enhancement (4572 and 2545 per cent for solid and hollow walls, respectively), proved with the biggest potential of energy dissipation under seismic loads. Ferrocement lamination had a moderate effect on the strength of solid brick walls and poor strength of hollow blocks, indicating bond restrictions between the mortar layer and block substrate. Rebar-tie retrofitting was found to have a balanced performance that imparted moderate increases in both the strength and the deformation capacity-therefore, it should be viewed as a feasible low cost strengthening alternative. Overall FRP was found to be the most effective approach for strength dominant retrofitting while MS plate bracing was the best approach for ductility and flexibility, showing the need to consider the method selection depending upon the desired structural performance and economic viability.

Table 1: Comparative Strength and Ductility Performance of Retrofitted Masonry Walls.

Wall Type	Strengthening Methods	Ultimate Load (kN)	Deflection at Failure (mm)	Strength Gain (%)	Ductility Gain (%)
Solid Brick	Control	5.4	0.305		
	FRP	12.6	7.28	133	2287
	Ferrocement	7.8	0.33	44	8
	MS Plate	3	14.25	-44	4572
	Rebar	8.4	2.4	56	687
Hollow Block	Control	9	0.55		
	FRP	13.8	4.61	53	738
	Ferrocement	7.2	0.26	-20	-53
	MS Plate	11.4	14.55	27	2545
	Rebar	10.8	0.71	20	29

3.4 Failure Modes and Crack Patterns

Figure 7 shows the pattern of the crack structure of the unstrengthen masonry wall showing the brittle failure under out of plane loading. In the solid brick wall (a), a significant diagonal crack developed through the mid span, which would indicate a flexural failure due to poor tensile resistance of the masonry. The hollow- block-wall (b) developed smaller but distributed cracks near the centre indicating good stress redistribution and similar behaviour of collapse. Both specimens showed negligible post - peak deformation, proving that the unstrengthen masonry is brittle and non - ductile and strengthening is necessary to improve the out of - plane performance.

(a) Solid brick wall (b) Hollow brick wall

Figure 7: Crack pattern of unstrengthen masonry wall.

Figure 8 shows the crack pattern of masonry walls reinforced with FRP, which shows a definite improvement in out of plane performance. In the solid-brick wall (a), the diagonal cracks formed however remained fine and well-distributed, meaning that the FRP strips were able to effectively restrain the crack growth and postpone the failure. The hollow - block wall (b) showed narrower cracks oriented in the direction of the FRP as proof of efficient bonding and stress transfer between FRP and the masonry surface. Overall, FRP retrofitting improved crack controlling, strength and ductility through a change in crack failure mode from brittle to more ductile and controlled.

(a) Solid brick wall (b) Hollow brick wall

Figure 8: Crack pattern of masonry wall strengthening by FRP.

Figure 9 shows that the ferrocement-strengthened masonry walls exhibited better strength and crack control but a relatively brittle failure mode. In the solid-brick wall (a) diagonal cracking occurred through the mortar joint indicating flexural failure, controlled by the tensile capacity of the wire mesh and mortar. The hollow aggregate wall (b) showed similar cracking with partial debonding of the ferrocement layer which indicated weaker adhesion at the interface. While ferrocement was an effective method to delay cracking and improve the initial stiffness, failure was sudden once the delamination started. Overall, the ferrocement layer was beneficial in terms of enhanced load capacity and stiffness, but it provided little ductility enhancement under out-of-plane loading.

(a) Solid brick wall (b) Hollow brick wall

Figure 9: Crack pattern of masonry wall strengthening by Ferrocement

The deformation capacity of MS-plate-strengthened walls has shown in figure 10. For solid brick wall, there were diagonal cracks observed near the plate anchors, which indicated progressive stiffness loss by local yielding. The hollow block wall had uniformly distributed cracks, indicating good transfer of effective stress through the steel bracing.

(a) Solid brick wall (b) Hollow brick wall

Figure 10: Crack pattern of masonry wall strengthening by MS plate

Rebar-tie strengthened walls are shown in figure 11 and have improved integrity and relatively stable failure pattern. In the solid brick wall, diagonal and stepped cracks formed but were contained by the rebar ties, preventing separation. The hollow - block wall developed the process of controlled mid-span cracking without sudden collapse due to the restraining action of the ties. Overall, the rebar - tie system provides an improved crack control, strength and ductility resulting in a gradual and stable failure under load.

(a) Solid brick wall (b) Hollow brick wall

Figure 11: Crack pattern of masonry wall strengthening by Rebar

3.5 Comparative Behaviour of Solid and Hollow Masonry Walls

Figure 12 shows the load deflection curves of the solid brick masonry walls for various strengthening schemes. The control wall failed at 5.4 kN, with a slight amount of deformation which would be indicative of brittle failure. FRP strengthening had the best load capacity (12.6 kN) and ductility (7.28 mm) indicating excellent stiffness and energy dissipations. Ferrocement gave moderate improvement in strength (7.8 kN) but very little ductility. The MS plate braced wall exhibited large deflections (14.25 mm) under low loads, which signifies flexibility and not stiffness. Rebar-tied walls were balanced in terms of both strength (8.4 kN) and deformation (2.4 mm) showing the performance of the wall remained stable even after cracking. Overall, FRP provided the best reinforcement in terms of combining high strength and ductile failure behaviour.behaviour.

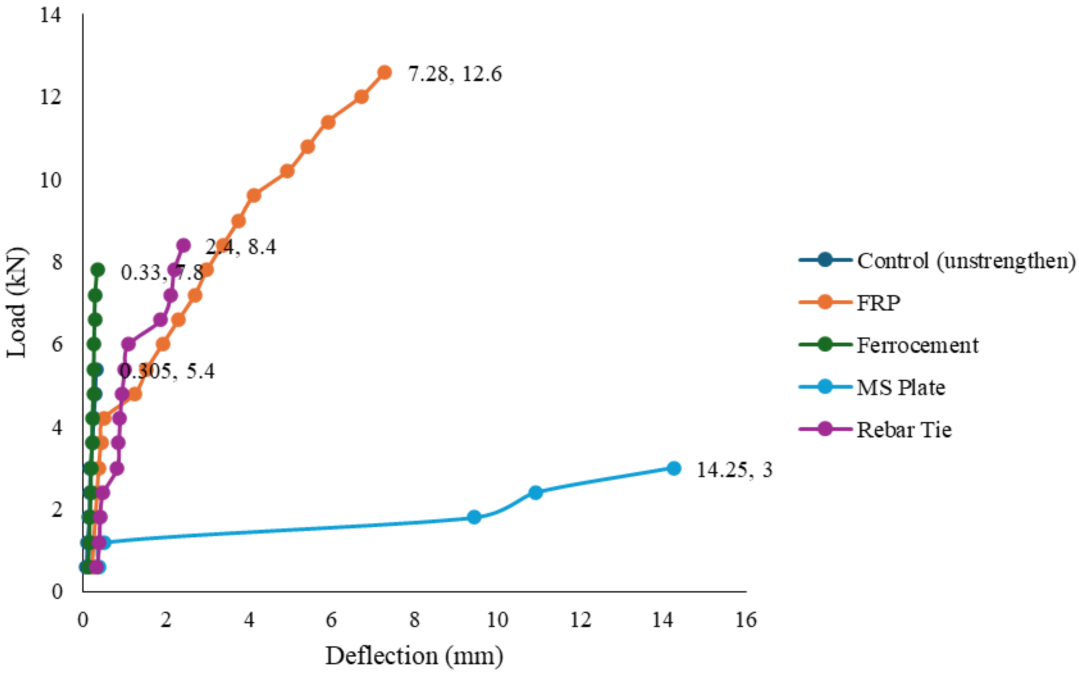


Figure 12: Load vs deflection curves for solid brick masonry walls.

The load-deformation curves for hollow block walls strengthened in various ways are illustrated in Figure 13. The control wall, with the low deflection (0.55 mm) failed at 9 kN exhibiting brittle failure like unreinforced masonry. The FRP strengthened wall got the largest strength (13.8 kN) and ductility (4.61 mm) among all, indicating the efficient remedial stress redistribution and crack resistance for FRP strengthened walls. Ferrocement increased the strength to 7.2 kN but the deformation was still small (0.26 mm) resulting in the behavior being presumably dominated by stiffness. The value of MS plate braced wall was 11.4 KN with very high deflection (14.55mm) which indicates its outstanding flexibility but mate stiffness. Rebar tied walls showed balanced strength (10.8 kN) and moderate ductility (0.71 mm) that confirm the better confinement and energy absorption of this wall compared to the control wall. Overall, FRP offered the best strength enhancement while MS plate offered the best deformation capacity.

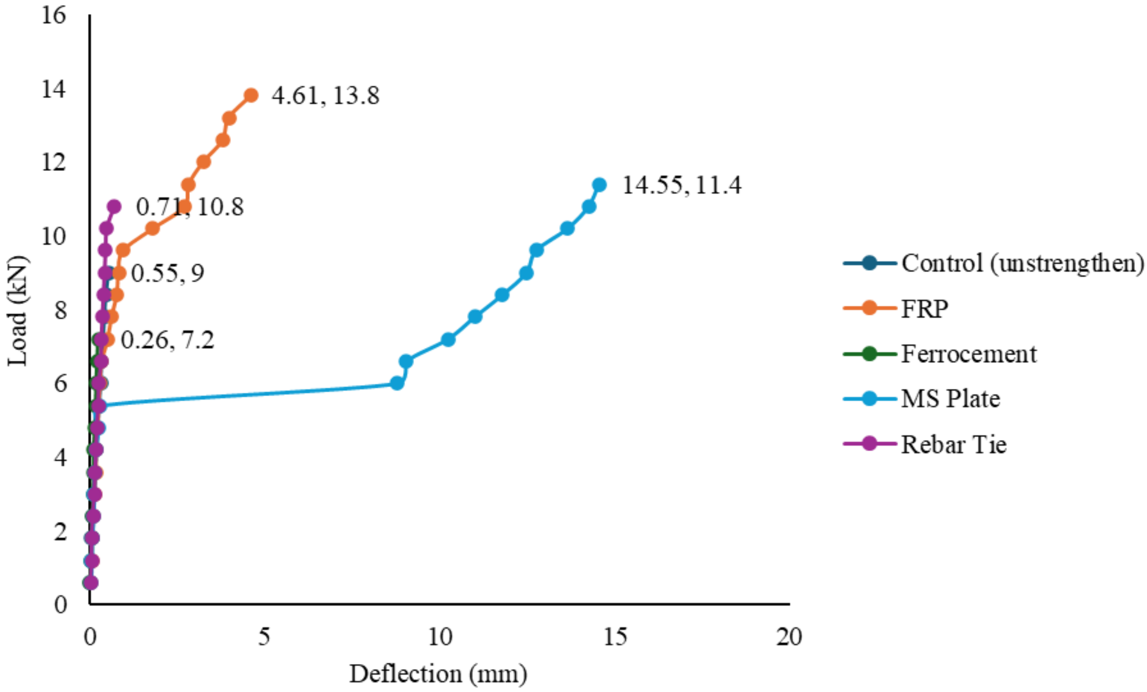


Figure13: Load vs deflection curves for hollow block masonry walls

4. CONCLUSIONS

This experimental study evaluated the out of plane performance of solid brick and hollow block masonry walls strengthened by different retrofitting ways. The results showed that all strengthening systems improved the wall performance when compared to unreinforced control systems to a greater or lesser extent. FRP retrofitting was found to be the most effective, resulting in the greatest increase of load-carrying capacity and ductility as a result of the high tensile strength and crack bridging behaviour. MS Plate bracing provided the highest ductility and energy dissipation capabilities which suited them for flexible/seismic applications Rebar-tie reinforcement provided a balance strength and ductility improvement, and Ferrocement lamination improved the stiffness and was relatively brittle due to interface debonding. A comparison of masonry types indicated that solid brick walls showed high stiffness, as they had lower deflections under similar load conditions, while hollow block walls showed high ultimate strength due to their enhanced ductility and energy absorption capacity. Overall, the results prove that through proper retrofitting, the seismic resilience and safety of unreinforced masonry structures can be significantly increased.

DECLARATION OF USE OF AI

The authors declare that Grammarly (an AI-assisted writing tool) was used solely to improve grammar and readability of the manuscript. The tool was not used for generating scientific content, data analysis, interpretation of results, or methodological decisions. All scientific content, analysis, and conclusions are the sole responsibility of the authors.

REFERENCES

Bui, T. T., & Limam, A. (2014). Out-of-plane behaviour of hollow concrete block masonry walls unstrengthened and strengthened with CFRP composite. Composites Part B: Engineering, 67, 527–542. https://doi.org/10.1016/j.compositesb.2014.08.006

Costa, A., Di Trapani, F., et al. (2021). Experimental assessment of masonry walls strengthened with textile reinforced mortar under out-of-plane loading. Structures, 35, 2379–2392. https://doi.org/10.1016/j.istruc.2021.05.052

Celik, T. (2025). Strengthening strategies for unreinforced stone masonry walls using FRP and CFM composites. Scientific Reports, 15(1), 28167. https://doi.org/10.1038/s41598-025-13747-0

Chen, H., Liu, Y., Tian, Y., & Huang, Q. (2023). Mechanical and Deformation Performance of Masonry Walls with Low-Strength Mortar Retrofitting Using Spray-on Polyurethane Coating. Buildings, 13(10), 2470. https://doi.org/10.3390/buildings13102470

Domenico, M., De Risi, M. T., Ricci, P., Verderame, G. M., & Manfredi, G. (2021). Empirical prediction of the in-plane/out-of-plane interaction effects in clay brick unreinforced masonry infill walls. Engineering Structures, 227. https://doi.org/10.1016/j.engstruct.2020.111438

Dizhur, D., Griffith, M., & Ingham, J. (2014). Out-of-plane strengthening of unreinforced masonry walls using near surface mounted fibre reinforced polymer strips. Engineering Structures, 59, 330–343. https://doi.org/10.1016/j.engstruct.2013.10.026

D'Altri, A. M., Oliveira, D. V., & et al. (2020). Out-of-plane seismic vulnerability and retrofit of masonry walls: A review of experimental and numerical studies. Engineering Structures, 219. https://doi.org/10.1016/j.engstruct.2020.110989

Gattesco, N., Rizzi, E., Bez, A., & Dudine, A. (2023). Study on the effectiveness of a CRM system: in-plane and out-of-plane cyclic tests on masonry piers. Procedia Structural Integrity, 44, 2230–2237. https://doi.org/10.1016/j.prostr.2023.01.285

Kadam, S. B., Singh, Y., & Li, B. (2015). Out-of-plane behaviour of unreinforced masonry strengthened using ferrocement overlay. Materials and Structures/Materiaux et Constructions, 48(10), 3187–3203. https://doi.org/10.1617/s11527-014-0390-8

Pradhan, B., Zizzo, M., Sarhosis, V., & Cavaleri, L. (2021). Out-of-plane behaviour of unreinforced masonry infill walls: Review of the experimental studies and analysis of the influencing parameters. In Structures (Vol. 33, pp. 4387–4406). Elsevier Ltd. https://doi.org/10.1016/j.istruc.2021.07.038

Thomoglou, A. K., Jagadesh, P., & Voutetaki, M. E. (2023). Review of Out-of-Plane Strengthening Techniques of Unreinforced Masonry Walls. In Fibers (Vol. 11, Issue 9). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/fib11090078

Yazdi, B., Javaheri Tafti, M. R., & Mirjalili, A. (2023). Experimental study on in-plane seismic behavior of unreinforced and damaged unreinforced masonry walls retrofitted with vertical concrete ties and bed rebar with and without shotcrete. Innovative Infrastructure Solutions, 8(9), 243. https://doi.org/10.1007/s41062-023-01207-5

Yaman, Z., Cumhur, A., Ağcakoca, E., Özyurt, M. Z., Maraşlı, M., Sadid, M. S., Akrami, A., & Rasuly, A. (2025). Experimental Study and FEM Analysis on the Strengthening of Masonry Brick Walls Using Expanded Steel Plates and Shotcrete with and Without Glass Fiber Reinforcement. Buildings, 15(15). https://doi.org/10.3390/buildings15152781

Zhou, Q., Wang, F., Zhu, F., & Yang, X. (2017). Stress–strain model for hollow concrete block masonry under uniaxial compression. Materials and Structures, 50(2), 106. https://doi.org/10.1617/s11527-016-0975-5

Zoppo, M., Di Ludovico, M., Balsamo, A., & Prota, A. (2022). Fibre reinforced mortars for the out-of-plane strengthening of masonry walls. Procedia Structural Integrity, 44, 2158–2165. https://doi.org/10.1016/j.prostr.2023.01.276