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Review of current application schemes in reinforcing masonry walls with modern materials

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Abstract. Masonry, one of the oldest construction materials, has a historical significance in building structures. However, unreinforced masonry (URM) structures frequently exhibit poor performance in the face of seismic events, strong winds, shocks and impacts, often failing in a brittle manner. The primary objective of reinforcing URM structures is to enhance their resilience against lateral loads and tension forces. Recent decades have witnessed a concentrated effort on seismic retrofitting and strengthening methods, employing composite and mesh-type materials. This comprehensive review focusses on the practical applications of various reinforcement types for masonry walls, emphasizing three commonly used systems: external surface reinforcement, near surface reinforcement and internal surface reinforcement. The main goal is to evaluate the effectiveness of these techniques, providing a thorough overview of their advantages and limitations. Additionally, an in-depth exploration of the literature examines how different reinforcement systems impact the mechanical properties of distinct categories of masonry walls, including clay brick, concrete blocks, and autoclaved concrete blocks (AAC) blocks. This systematic review not only provides valuable insights for researchers and engineers but also highlights current research trends and suggests potential avenues for future exploration.

Keywords: external surface; internal surface; masonry; near surface; retrofitting; review; strengthening

1. Introduction

The utilization of masonry as a construction material dates back to ancient times and has since been widely adopted in India and across the globe. Its popularity can be attributed to its durability, versatility, and cost-effectiveness (Babatunde 2017, Zhuge 2010). Masonry is an assembly or a connection of units and mortar (Oyguc and Oyguc 2017). Masonry units can be stone, adobe, clay bricks, concrete blocks, flyash bricks and AAC blocks. Masonry mortar can be lime mortar, mud mortar and cement mortar. Majority of masonry units used for construction in India are of clay bricks. However, AAC blocks (a green material) have recently emerged as a potential replacement for clay bricks (Badonbok Lyngkhoi *et al.* 2023a, Thakur and Kumar 2021, Zade *et al.* 2023).

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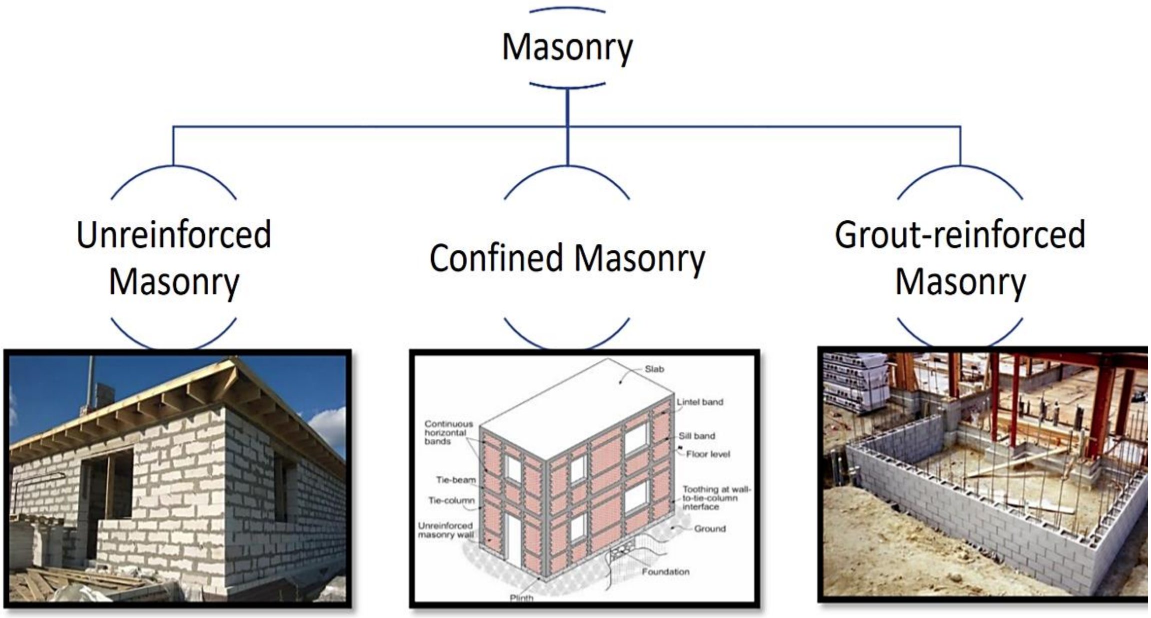


Fig. 1 Categories of masonry walls (Source: Lyngkhoi *et al.* 2023b, Syiemiong and Marthong 2021a)

Cement sand mortar is the most commonly used masonry mortar in India with ratio ranging from 1:4 - 1:6 (Raj *et al.* 2020)**.** Masonry is further classified as unreinforced masonry (URM), confined masonry (CM) and reinforced masonry (RM), as shown in Fig. 1 (Lyngkhoi *et al.* 2023b, Syiemiong and Marthong 2021a).

CM is a type of construction in which walls are built first with toothing to connect to the column. RM has reinforcement in the grout. CM and RM buildings have been found to perform well under earthquake when built in accordance with seismic codes. URM generally has no reinforcement (Oyguc and Oyguc 2017). URM can either be a structural member such as load-bearing URM walls mostly found in old constructions in rural areas and a non-structural member such as non-load-bearing URM walls (also referred to as infill walls) mostly found in new constructions in urban areas. Old constructions are of important infrastructure and government activities and monumental masonry buildings such as churches, mosques, temples, castles, etc., as well as ordinary masonry buildings (Syiemiong and Marthong 2021a). These constructions are in need of preserving as a part of the architectural and cultural heritage (Karantoni and Fardis 1992)**.** URM are generally strong in compression forces or vertical loading but weak in tension forces or lateral loads induced by earthquakes (Yavartanoo and Kang 2022)**.** Both load-bearing and non-load-bearing URM walls have been found to be vulnerable to earthquake events. In the event of an earthquake, URM walls are subjected to either in-plane or out-of-plane failure which further leads to in-plane cracking and out-of-plane collapse (Thomoglou *et al*. 2023)**.** Past earthquakes demonstrated that majority of unreinforced masonry (URM) structures are subjected to cracking and collapse. This poses not only safety risks to the building occupants but also poses a threat to the other neighbouring buildings and their occupants. The collapse of buildings leads not only to human loss but also to economic loss. So, to address this problem, researchers have tried

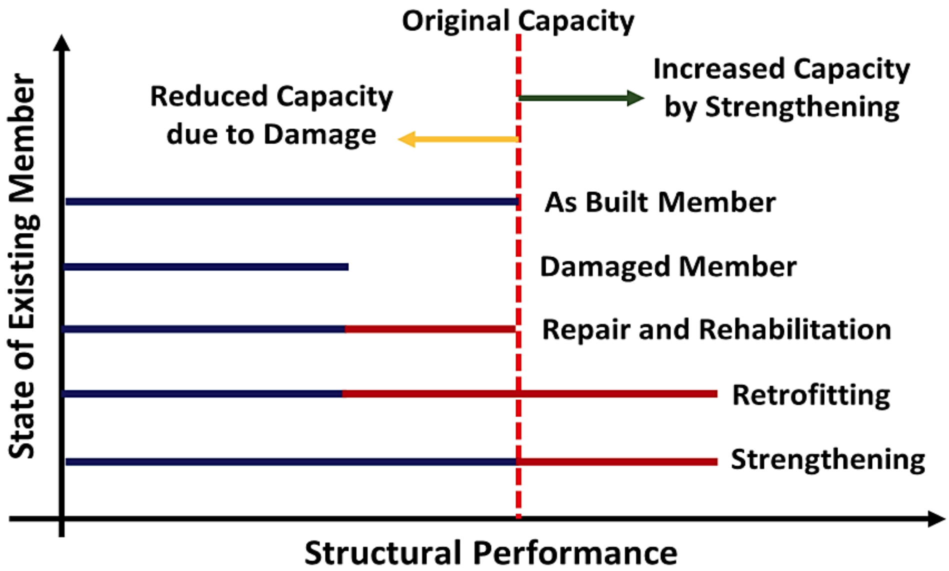


Fig. 2 Improved performance resulting from the implementation of strengthening, retrofitting and rehabilitation (Source: Maheswaran *et al.* (2022))

retrofitting or strengthening as a solution to extend the collapse time of URM buildings under seismic events and thus reduce the loss of life and economy resulting from the sudden collapse of a building while also helping preserve historical buildings and important structures (Heydariha *et al.* 2019, Oyguc and Oyguc 2017). Numerous reinforcing approaches have been established and utilized to enhance insufficiencies linked to insufficient structural functioning of URM structures under seismic actions. The key goal of reinforcing techniques is to improve lower masonry parameters like tensile and shear strength. As discussed earlier, URM buildings are highly vulnerable to seismic damage. For this reason, this deficiency is to be overcome by retrofitting or strengthening techniques. Fig. 2 presents a schematic representation of members that have sustained damage, illustrating the impact of applied reinforcing methods versus the absence of such methods.

As shown in Fig. 2, it is evident that masonry walls can experience a significant reduction in their original capacity due to various factors such as earthquakes, strong winds, moisture absorption, etc. To address this issue and restore the original capacity of masonry, various strategies such as repair, rehabilitation, retrofitting and strengthening are employed. The term "repair" in this context refers to tasks aimed at achieving the original shape similar to the as-built member. However, it's noted that the repair process alone cannot fully restore the original capacity and necessitates rehabilitation. Rehabilitation involves tasks like replacing damaged reinforcement with new materials and grouting with high-strength cementitious substances. Additionally, retrofitting or strengthening becomes crucial for enhancing the strength of the member beyond its original capacity (Maheswaran *et al*. 2022). Retrofitting is the technique employed when a member undergoes a reduction in its original capacity, and its application extends beyond the restoration of the original capacity; rather, it aims to enhance the robustness and durability of the member beyond its initial limits. This process is predominantly utilized for old and existing structures, where reinforcing becomes imperative to ensure resilience and performance under diverse and challenging conditions. On the other hand, strengthening is a method employed when the member still maintains its original capacity, and this technique focuses on enhancing the strength beyond its initial limits. Typically applied to new or freshly constructed structures, strengthening ensures that the member is equipped to withstand varying loads and conditions while maintaining its overall structural integrity.

Depending upon the method and materials used, these techniques are categorized as traditional and modern techniques. Traditional techniques include: i) grouting to fill cracks and voids; ii) stitching large cracks and weak areas with metallic or brick elements; iii) external or internal post-tensioning with steel ties; iv) shotcrete jacketing; and v) confining with RC tie columns (Kalali and Kabir 2012, Triantafillou 1998). Traditional strengthening techniques are a good way to enhance the structural behavior of Un-reinforced masonry buildings, but they have some drawbacks, such as the time it takes to apply them, the amount of space they take up, how they affect the aesthetics of the building, and so on. Furthermore, the added weight of the reinforcing techniques may improve the earthquake-induced inertial forces, possibly requiring foundation strengthening. Development of new materials and techniques came as a necessity to overcome the limitations of traditional strengthening techniques (Mustafaraj 2017). Modern techniques and innovative materials have been proposed and allowed in current practice for strengthening or retrofitting ordinary masonry structures, even for restoration historical structures where there the preservation criteria is of the utmost importance (Valluzzi *et al*. 2014). The major difference between modern and traditional techniques is in the materials used (Hafner *et al.* 2023). Modern methods are based on the use of composite materials such as Fiber-reinforced polymer (FRP), Engineered cementitious composites (ECC), Textile reinforced mortar (TRM) and mesh-type materials including steel wire mesh, PP-band mesh, and industrial geogrid mesh. A detailed review of these composite and mesh-type reinforcing materials, including their material properties, cost, advantages and disadvantages has been presented in previous studies (Furtado *et al*. 2020, Sathiparan 2015). This review paper, however, focuses more on the current practices and application schemes relating to the use of these modern reinforcing materials to masonry walls. Most common applications of these reinforcing materials can be broadly classified as: 1) External surface reinforcement, 2) Near surface reinforcement, 3) Internal surface reinforcement.

2. External surface reinforcement

2.1 Introduction

External surface (ES) or externally bonded (EB) system is probably the most common and oldest form of application scheme for retrofitting or strengthening both old and new construction. This strengthening application is highly valued especially in developing countries like India, since this method is simple and can be performed by any unskilled labour. The general idea of this method is to add some sort of external reinforcement to either one or both sides of the walls to increase the flexural and shear strength as well as ductility of unreinforced masonry walls. Commonly used reinforcing materials for this method includes composite materials (FRP, ECC, TRM) and mesh-type materials (SWM, PP-band, Geogrid). These materials may be applied to the entire surface of a wall, referred to as full wrapping, or as discrete strips oriented in horizontal, vertical, diagonal, and grid patterns, referred to as strip wrapping (Fig. 3).

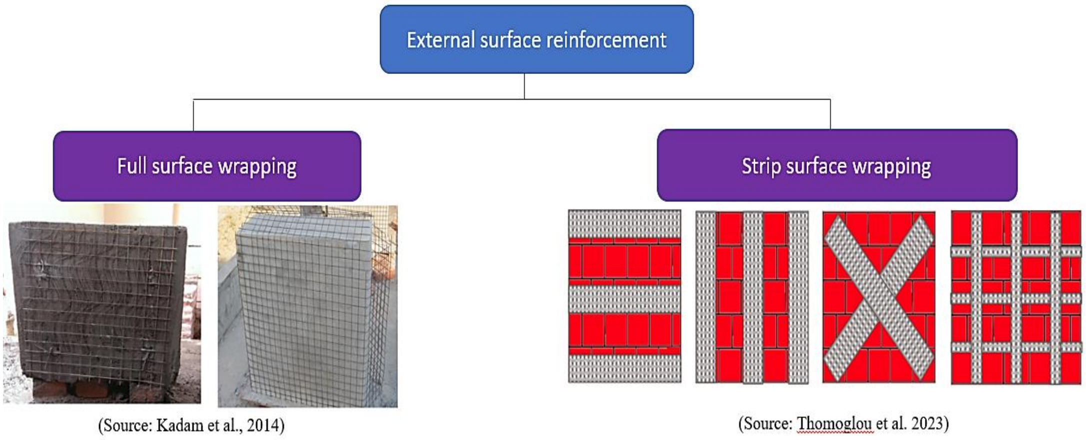
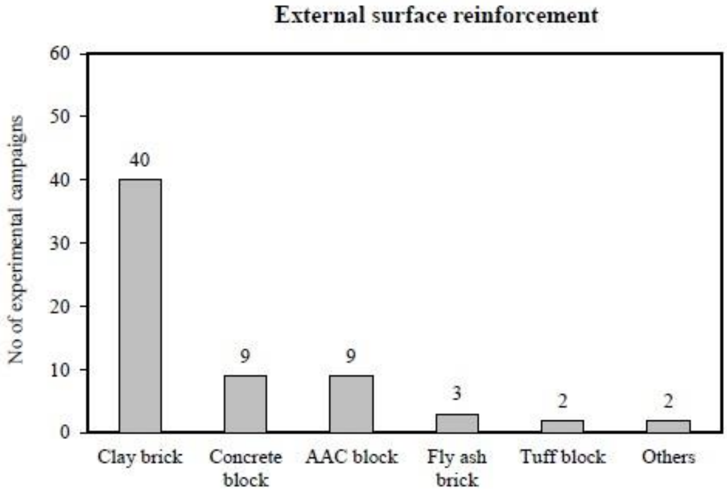


Fig. 3 Various applications of external surface reinforcement

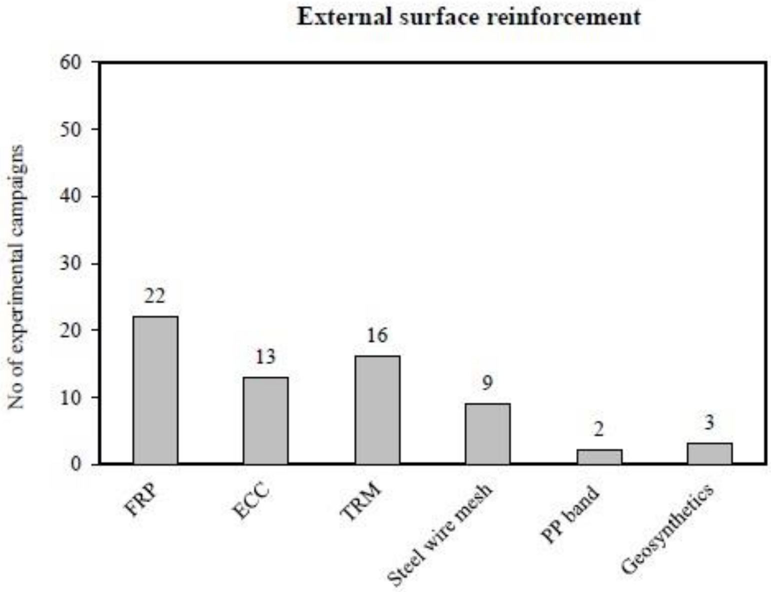
2.2 Full surface and strip surface wrapping

FRP, the initial and widely used system for masonry reinforcement, offers ease of application, lightweight design, durability, corrosion resistance, and high tensile strength in various forms like carbon (CFRP), glass (GFRP), basalt (BFRP) and aramid (AFRP). Commonly, CFRP sheets, GFRP sheets and meshes are used with epoxy resins and mortar coating for full wall reinforcement. Less common are AFRP (Zamani-Ahari and Yamaguchi 2022) and BFRP (Padalu *et al*. 2019) sheets for full wall strengthening. Researchers like Chagas and Moita 2015, Elgawady *et al*. 2007 and Padalu *et al*. 2019 confirm the effectiveness of EB_FRP composites in enhancing URM walls' in-plane, out-of-plane, and compression capacity. However, FRP retrofitting may lead to failure modes like masonry crushing, FRP rupture, and debonding due to use of epoxy resin. Disadvantages of epoxy adhesive, including high cost and poor adhesion to rough and humid surfaces, limit FRP use in rural areas of developing countries. ECC strengthening methods include overall layer, single-side, and both-side options, offering advantages like bonding without agents, distinguishing it from FRP. Unlike systems with mesh reinforcement, ECC eliminates the need for anchors, reducing formwork (Lin *et al*. 2014). Proposed for masonry retrofitting, ECC faces economic challenges due to high fiber costs, leading scholars to suggest alternatives like single-side and strips strengthening (Che *et al.* 2023). Highly ductile concrete (HDC), a representative of ECC, designed using micromechanics and fracture mechanics, has been improved to create ultra-high ductile concrete (UDHC) with a 12% tensile strain capacity. Proven useful for construction and retrofitting without steel reinforcement, UDHC highlights ECC's potential (Dong *et al.* 2022). Externally bonded FRP laminates face limitations due to the use of organic binders. A novel alternative, fabric-reinforced cementitious matrix (FRCM), has emerged, replacing organic binders with a cementitious matrix. FRCM, known as mineral-based composites (MBC), cementitious matrix grid or fabric (CMG or CMF), textile reinforced mortar or concrete (TRM or TRC), and inorganic matrix grid (IMG), outperforms organic binder-based FRP systems in fire resistance, durability, and bonding with masonry. FRCM-strengthened masonry surpasses FRP-strengthened counterparts in strength and ductility, dissipating more energy due to effective fabric debonding control from superior cementitious matrix bonding (Sagar *et al.* 2017). TRM, comprising textiles in an inorganic matrix (glass, carbon, basalt, aramid, polypropylene (PP) polyparaphenyle benzobisoxazole (PBO), or steel), often cement-based, has been studied for parameters like layering, one-sided versus two-sided strengthening, anchors, and fabric orientation (Kouris and Triantafillou 2018, Sagar *et al.* 2017). Despite its advantages, TRM has limitations, including lower mechanical properties of inorganic mortars compared to epoxy resins, potentially impacting force transfer to the masonry substrate (Tripathy *et al.* 2020). Reinforcing unreinforced masonry (URM) walls with externally bonded or near-surface embedded steel strips, bars, wires, or welded wire mesh (WWM) offers an economical retrofitting method. This approach, more cost-effective than FRP and ECC systems, enhances masonry strength (Kadam *et al.* 2014). Steel wire mesh, including chicken wire mesh (CWM), expanded mesh (EWM), and WWM, is affixed to the masonry surface using bolts, screws, or rods and covered with plaster (Shermi and Dubey 2018). WWM, recommended by IS 13935:2009, is commonly used for URM reinforcement. Researchers like Kadam *et al*. (2014, 2015) and Shermi and Dubey (2017, 2018) employed WWM with various specifications for strengthening. Sandoval *et al*. (2021) explored different transverse connector layouts for WWM, enhancing shear and flexural strength. Strengthening masonry walls with WWM proves efficient for low-cost buildings, offering a cost-effective and robust method requiring a cost-effective and robust method requiring minimal skilled labor. Experimental studies by Syiemiong and Marthong (2021b) on low-strength hollow concrete block masonry walls and Warlarpih and Marthong (2023) on AAC block walls demonstrate improved flexural strength, ductility, and shear capacity with WWM reinforcement. Polypropylene (PP) bands are increasingly used for cost-effective strengthening of masonry walls, significantly improving flexural, shear strength, and ductility by uniformly distributing stress. Despite the absence of PP bands in mesh form in the market, they can be prepared using joint clips or welding. Banerjee *et al*. (2019, 2020b) studied their effectiveness in enhancing the in-plane and out-of-plane strength and ductility of masonry walls with clay and fly ash bricks. Comparing PP bands and steel wire mesh, both materials effectively increased load-carrying capacity, shear strength, flexural strength, and deformation ability. Steel wire mesh exhibited superior strength and flexural capacity, while PP bands contributed more to deflection and energy ductility. This research underscores the efficacy of PP bands and steel wire mesh in reinforcing masonry structures, offering insights into their respective strengths and contributions to structural performance.

Researchers, including Al-Salloum *et al.* (2007), Albert *et al*. (2001), Kuzik *et al*. (2003) and others have used externally bonded FRP strips to significantly enhance the in-plane shear and out-of-plane flexural resistance of unreinforced masonry walls. Luccioni and Rougier (2011) studied clay masonry panels reinforced with CFRP laminates, finding that total reinforcement increased stiffness and strength, while diagonal strips doubled the ultimate load. CFRP strips parallel to mortar joints showed no improvement. Marcari *et al.* (2007) favored the diagonal configuration for its applicability without evacuating buildings during application. Capozucca (2011) strengthened walls with vertically, horizontally, and diagonally applied CFRP strips, noting that diagonal reinforcement notably increased resistance without delamination issues. Kalali and Kabir (2012) reported the efficiency of diagonal GFRP configuration compared to grid configuration. Rahman and Ueda (2016) found that diagonal bracing with PET-FRP sheet was optimal, enhancing capacity and ductility while avoiding catastrophic failure. The authors stressed that fully covering walls with FRPs is not a viable option for external strengthening. Deng and Yang (2018) explored ECC configurations, including strips and coatings, for in-plane cyclic behavior, proving effective for unreinforced masonry (URM) walls. In a related study, Deng *et al*. (2020) assessed HDC strips with built-in steel bars and single-sided HDC layer in enhancing in-plane seismic resistance of



(a) Masonry unit types



(b) Reinforcing material types

Fig. 4 Experimental campaigns on external surface reinforcement involving (a) Masonry unit types and (b) Reinforcing material types

unreinforced AAC block masonry walls, showing significant improvements. Che *et al*. (2023) investigated ECC splint strengthening in brick masonry walls, favoring frame strip strengthening as a more economical and cost-effective option over overall layer strengthening. Bui *et al.* (2015) focused on the quasi-static in-plane response of hollow concrete block masonry walls, emphasizing the advantages of vertical TRC sheets in enhancing structural integrity and ductility. Ismail, El-Maaddawy, and Khattak (2018) conducted cyclic in-plane testing of reinforced concrete frames, highlighting the effectiveness of basalt-FRCM in increasing strength and the efficacy of diagonal bands with specific width configurations. Reboul *et al*. (2018) explored the use of vertical composite sheets for masonry reinforcement, demonstrating improved lateral load capacity and ductility with selective placement of composite materials. Wang *et al*. (2018) investigated the impact of reinforcement configurations, revealing that a grid of symmetrical and directional strips enhances shear behavior, while Garcia-Ramonda *et al*. (2020) focused on diagonal compression tests with different TRM systems, showing improvements in strength, particularly in full and grid systems. In recent times, cost-effective materials like polypropylene (PP) band and welded wire mesh have gained popularity for strengthening walls, offering notable improvements in strength and ductility. Banerjee *et al.* (2020a) explored various orientations of steel wire mesh (horizontal, diagonal, grid, partially and fully covered) for in-plane and out-of-plane behavior of wallets, revealing its effectiveness in significantly enhancing shear and flexural strength. Full coverage was identified as the most effective strengthening system, but substantial improvement was also achieved when reinforcing along the bed-joint, offering a cost-efficient alternative when budget constraints exist. Geosynthetics, though uncommon in structural works, play a crucial role in repairing and strengthening heritage and reinforced concrete structures (Maras and Kose 2021, Sreekeshava *et al.* 2021). Khan *et al.* (2017) investigated the in-plane strength of solid clay brick masonry panels using different strengthening patterns (parallel, diagonal, cross) with non-woven geotextile under diagonal compression tests. The study revealed that geosynthetic reinforcement significantly increased load-carrying capacity, shear strength, in-plane strength, and stiffness, with the cross pattern exhibiting the most favorable performance. Building on this, Khan and Nanda (2020) explored the out-of-plane flexural strength of masonry wallettes in four-point bending tests. Consistent with the earlier study, the research affirmed that geosynthetic strengthening led to remarkable improvements in load-carrying capacity, displacement, stiffness, ductility, flexural strength, and energy dissipation, with the cross pattern demonstrating the most pronounced effects.

A summary of experimental studies employing external surface reinforcement is presented in Table 1, and Fig. 4 complements this overview by illustrating the experimental campaigns, categorizing them into a) different masonry unit types and b) various reinforcing material types.

2.3 Concluding remark

The emergence of innovative materials and the evolution of advanced techniques in recent years have introduced novel approaches to reinforce masonry walls. One such method involves the application of composite and mesh-type materials through the externally bonded (EB) technique. In general, the utilization of external surface reinforcement system proves advantageous in enhancing the ultimate load-carrying capacity, lateral resistance, energy absorption, and ductility of retrofitted walls. This retrofitting approach not only mitigates sudden failure patterns in URM walls but also introduces a more gradual failure pattern. Nevertheless, it is essential to acknowledge the limitations, as composite materials have demonstrated suboptimal performance in high-temperature environments when directly applied to the faces of structural members using the EB technique (Yavartanoo and Kang 2022).

However, the use of composite materials for strengthening has inherent limitations, with the most significant challenge lying in the premature debonding of these materials associated with the EB method. This issue becomes even more critical in masonry structures due to the intrinsic

Table 1 Summary of experimental studies external surface reinforcement

Sl. no	References	Masonry unit	Masonry unit strength (MPa)	Mortar compressive strength (MPa)	Specimen size mm (l×h×t)	Reinforcing material	Orientation/ Pattern	One side/both sides	Type of Test/ Loading	Increase in strength with respect to URM	Common Failure Mode
1	Stratford *et al.* (2004)	Clay bricks, Concrete bricks	62, 36	5.5-11	1200×1200	GFRP sheets	Full	One side	In-plane	38-65%	Debonding of GFRP
2	Mosallam (2007)	Clay bricks	25	21.37	2640×2640×101.6	CFRP sheet/laminate	Full	One side	Out-of-plane	9.22 - 12 times	Combination of compression failure of red bricks followed by a cohesive failure
3	Ozsayin *et al.* (2011)	Hollow clay bricks	4-13.9	6.36-15.34	500×500×70 350×350×70	CFRP sheets	Full	Both sides	In-plane, compression	94 - 159%, 14-83%	Diagonal crack
4	Kałuza (2017)	AAC block	4.65	12.4	900×800×240	GFRP mesh	Full	Both sides	In-plane	71%	Detachment of mesh, Ductile failure
5	Thamboo *et al.* (2021)	Solid clay bricks	4.05-17.3	6.6	410×590×200, 430×550×210	CFRP sheets	Full	Both sides	Compression	10-20%	Crushing failure of masonry
6	Prakash and Alagusundaramoorthy (2008)	Clay brick	9.6	7.1	396×406×129	GFRP sheet	Full	One side	Compression	5-20%	Compression failure of masonry
7	Zamani-Ahari and Yamaguchi (2022)	Fired clay brick	9	10	1090×1060×110	AFRP sheet	Full	Both sides	In-plane	75.4%	Toe crushing of masonry
8	Padalu *et al.* (2019)	Solid clay bricks	26.16	14.75	1190×482×230, 1210×505×226	BFRP sheet	Full	One side	Out-of-plane	2.93-6.40 times	Debonding of BFRP
9	Gattesco and Boem (2015)	Solid clay bricks	44	4.09	1160×1160×250	GFRP mesh	Full	Both sides	In-plane	70-90%	Gradual failure of the mesh wire
10	Li *et al.* (2021)	Clay bricks	29.1	3.93	740×1900×240	HDC	Full	One side, Both sides	Compression	1.37-2.29	Debonding of outer HDC layer, HDC layer buckling
11	Niasar *et al.* (2020)	Clay brick	20	9.6	2000×1400×110	ECC	Full	One side	In-plane	175-330%	Rocking (flexural behaviour) failure
12	Deng *et al.* (2023)	Fired solid clay bricks	13.38	2.31	870×120×240	ECC, TRM, CFRP	Full	One side	Out-of-plane	2210%	Flexural failure
13	Qiu *et al.* (2023)	AAC block	3.49	5.08	2240×180×400	HDC	Full	Both sides	Out-of-plane	6.07-30.45 times	High ductility flexural failure
14	Lyu *et al.* (2022)	AAC block	5.52	3.20	3900×2500×200	HDC	Full	Both sides	In-plane	8.85 times	Corner crushing, sliding shear
15	Dong *et al.* (2022)	Solid clay brick	31.92	1.11	710×710×230	UHDC	Full	One side, Both sides	In-plane	1.8-2.4 times, 4.2-5.7 times	Ductile failure
16	Ahmadi and Nateghi-Alahi (2022)	Solid clay brick	31.7	4.9	450×450×105	ECC	Full	Both sides	In-plane	209%	Multiple crack
17	Kazem Sharbatdar and Tajari (2021)	Hollow clay brick	8.64-13.75	5.1	1300×900×150	ECC	Full	One side, Both sides	In-plane	89%, 215%	Shear failure
18	Deng *et al.* (2020)	AAC blocks	3.5	3.1	2400×1400×190	HDC	Full	One side	In-plane	17-31%	Sliding failure
19	Deng *et al.* (2019)	Solid clay bricks	8.87	18.11-27.62	1500×1800×240	ECC	Full	One side, Both sides	Out-of-plane	9%, 18%	Flexural dominant failure
20	Ismail *et al.* (2018)	Hollow concrete units	20.1	16.9	1045×1070×150	FRCM (Basalt,glass,carbon)	Full	Both sides	In-plane	104-258%	Diagonal cracking and/or toe crushing
21	Koutas and Bournas (2019)	Solid fired clay bricks	21.2	11.5-12.9	1700×1250×65	TRM (carbon)	Full	Both sides	Out-of-plane	3.79-5.45	Debonding
22	Gkournelos *et al.* (2020)	Clay brick	25.8	7.2	1700×1250×65	TRM (glass)	Full	Both sides	In-plane, out-of-plane	25%	Debonding
23	Babaeidarabad *et al.* (2014)	Concrete blocks	19.5	22	1220×1220×92	FRCM (Carbon)	Full	Both sides	In-plane	1.95-2.36 times	Toe crushing
24	Cevallos *et al.* (2015)	Solid clay bricks	41.77	18.49	510×660×250	FRCM (Flax, polyparaphenylene benzobisoxazole)	Full	One side	Compression	56%,28%	Composite debonding of PBO-FRCM
25	Marcari *et al.* (2017)	Tuff blocks	8	6.60	1000×1000×250	TRM (Basalt)	Full	One side, Both sides	In-plane	40%, 60%	Diagonal cracking
26	Castori *et al.* (2021)	Solid clay bricks	38.75	2.69	1200×1200×240	FRCM (AR-glass)	Full	One side. Both sides	In-plane	2-3 times	Shear failure
27	Gupta *et al.* (2023)	AAC blocks	3.71	10.8	387×387×130 777×410×130	FRCM (AR-glass)	Full	One side	In-plane, Out-of-plane	1.7-1.8 times, 4.7-6.9 times	Diagonal shear failure, Rupture of fabric
28	Qiu *et al.* (2023)	AAC blocks	3.49	5.08	2240×400×180	TRM (carbon)	Full	Both sides	Out-of-plane	19-31 times	Flexural failure
29	Papanicolaou *et al.* (2007)	Fired clay brick	3.7-8.9	3.91	1300×800×85	TRM (carbon)	Full	Both sides	In-plane	65-70%	Toe crushing
30	Kadam *et al.* (2014)	Clay brick	21.07	2.45	700×700×110	Welded wire mesh	Full	Both sides	In-plane	7 times	Diagonal cracks
31	Kadam *et al.* (2015)	Clay brick	21.07	2.45	930×400×110	Welded wire mesh	Full	Both sides	Out-of-plane	10 times	Flexural crack
32	Shermi and Dubey (2017)	Clay brick	10	2.5	1000×500×230	Welded wire mesh	Full	Both sides	Out-of-plane	20 times	Flexural crack

Table 1 Continued-

33	Shermi and Dubey (2018)	Clay brick	10	2.5	500×500×230	Welded wire mesh	Full	Both sides	In-plane	4 times	Diagonal cracks
34	Sandoval *et al.* (2021)	Hollow clay brick	2.28	27	850×900×220 850×860×220	Welded wire mesh	Full	Both sides	Axial compression, Diagonal compression	2.3 – 2.6 times	Compression crushing, Diagonal crack
35	Tripathy and Singhal (2021)	Clay brick	13.5	4.7-11.7	630×400×124 770×400×125 400×400×125	Welded wire mesh	Full	Both sides	Diagonal compression, Four-point bending	1.4-3.3 times 1.6-11.3 times	Shear failure or debonding failure of wire mesh
36	Syiemiong and Marthong (2021b)	Hollow concrete block	2.47-3.15	7.32-26.96	1141×468×135	Welded wire mesh	Full	Both sides	Four-point bending	2.02 times	Flexural failure
37	Warlarpih and Marthong (2023)	AAC block	3	23.28	812×836×120	Welded wire mesh	Full	Both sides	Diagonal compression	1.6-2.38 times	Diagonal cracks
38	Banerjee *et al.* (2019)	Clay brick Flyash brick	7.9 8.2	5	500×500×120 250×250×60	PP band	Full	Both sides	Four-point bending	1.7 times	Flexural/shear failure
39	Banerjee *et al.* (2020b)	Clay brick Flyash brick	7 7.8	5	500×500×120 250×250×60	PP band	Full	Both sides	Diagonal compression	1.3-2 times	Flexural/shear failure
40	Alcaino and Santa-Maria (2008)	Hollow clay bricks	11.3	23.4	1975 × 2400 × 140	CFRP strip	Horizontal, diagonal	Both sides	Cyclic in-plane shear tests	13-84%	Progressive delamination of CFRP reinforcement
41	Ghobarah and El Mandooh Galal (2004)	Concrete blocks	27.9	12.1	6000 × 2800 × 190	CFRP strip	Horizontal, vertical	One side	Out-of-plane pressure	5 times	Debonding of CFRP strip
42	Rahman and Ueda (2016)	Clay brick	30	22	1270 × 1020 × 120	polyethylene terephthalate-FRP (PET-FRP) sheets	Crossdiagonal, Grid, Full	One side	In-plane static shear test	83.33-250 %	Diagonal cracking
43	Silva *et al.* (2008)	Concrete blocks, clay bricks	16.8, 13.2	14.7	1626 × 1626 × 152 1219 × 1219 × 92	GFRP grids	Horizontal, vertical	One side, Both sides	Closed-loop diagonal compression load	42.5-120.2%, 63.7-99.38%	Shear sliding failure
44	Valluzzi *et al.* (2002)	Clay brick	8.83	6.03	515 × 510 × 120	CFRP, GFRP, polyvinyl-alcohol (PVAFRP)	Grid, diagonal	One side, both side	Diagonal compression tests	0.3-74%	Splitting failure, rupture of the FRP strips
45	Marcari *et al.* (2007)	Tuff units	2.1	2	1570 × 1480 × 530	CFRP, GFRP	Grid, cross	Both sides	In-plane shear-compression tests	18.03-66.96	Shear/flexural failure
46	Zamani-Ahari and Yamaguchi (2022)	Clay bricks	9	10	1090 × 1060 × 110	AFRP sheet	Full, diagonal	Both sides	Cyclic in-plane shear tests	75-81%	Toe crushing,
47	Padalu *et al.* (2019)	Clay bricks	26.16	14.75	1187 × 479 × 229	BFRP strips	Vertical, diagonal, grid, full	One side	Out-of-plane	2.9-6.4 times	Debonding failure
48	Kubica and Galman (2017)	AAC blocks	4.65	12.4	900 × 805 × 240	CFRP strip	Vertical	Both sides	Diagonal compression tests	75-90%	Progressive failure
49	Deng and Yang (2018)	Clay bricks	13	3.18	2300 × 1250 × 240	ECC	One horizontal strip and two vertical strips	Both sides	In-plane static cyclic lateral loading	36-45%	Rocking
50	Deng *et al.* (2020)	AAC blocks	3.5	3.1	2400 × 1400 × 190	HDC	One horizontal strip and two vertical strips	Both sides	In-plane reversed cyclic loading	17-28%	Sliding failure
51	Che *et al.* (2023)	Common fired bricks	6.31	1.84	1780 × 1780 × 240	ECC	Frame strip	One side	Quasi-static loading	14.61%	Diagonal shear failure
52	Ismail *et al.* (2018)	Concrete blocks	12	4.53	2270 × 1670 × 150	FRCM (Carbon, Basalt, AR Glass)	Diagonal	One side	Quasi-static cyclic in-plane loading	22.6-99.4%	Diagonal crack, infill-frame interface separation
53	Bui *et al.* (2015)	Concrete blocks	6.5	48	1030 × 1260 × 75	TRC (Glass)	Vertical	Both sides	In-plane combined shear–compression	9.33-140%	Shear–flexure failure
54	Reboul *et al.* (2018)	Concrete blocks	6.5	48	1030 × 1260 × 75	TRC (Carbon, Glass)	Vertical	Both sides	In-plane combined shear–compression	87-262%	Shear failure
55	Wang *et al.* (2018)	Grey clay bricks	10.3	31.8	910 × 900 × 110	SRG/TRM (Steel)	Horizontal, vertical, grid, full	Both sides	Diagonal compression test	30-121%	Toe failure, TRM (or SRG) failure
56	Garcia-Ramonda *et al.* (2020)	Clay brick	17.99	2.51	1270 × 1270 × 310	TRM (Basalt, steel)	Grid, Full	Both sides	Diagonal compression tests	59-94%	Textile-to-mortar interface failure
57	Banerjee *et al.* (2020a)	Clay and fly ash bricks	7-7.8	5	500 × 500 × 120	Steel wire mesh	Horizontal, diagonal, grid, partially and fully covered	One side, both sides	Diagonal compression tests, four-point bending	148.28-436.36 % 107.24-276.56%	Diagonal crack
58	Khan *et al.* (2017)	Clay brick	9.43	4.46	600 × 600 × 125	Geotextile	Horizontal, diagonal, grid	One side	Diagonal compression tests	52-72%	Shear and sliding failure
59	Khan and Nanda (2020)	Clay brick	9.43	4.46	600 × 600 × 125	Geotextile	Horizontal, diagonal, grid	Both sides	Four-point bending	73.73-128.28%	Geotextile strip debonding
60	Maras and Kose (2021)	Stone	12.52	2	340 × 340 × 180	Geogrid	Vertical, diagonal, grid, full	Both sides	Vertical and diagonal compression	21.31-104.64% 3.75-251.25%	Vertical and diagonal crack

weaknesses of these materials and additional factors such as irregular surfaces resulting from mortar joints. Indeed, the most prevalent cause contributing to the deterioration or failure of masonry structures strengthened with composite materials via the EB method is the debonding failure as emphasized by Shahzamani and Eftekhar (2023).

The application of reinforcement technology, such as externally wrapped FRP/FRCM, encounters limitations when employed in historical buildings. This is primarily attributed to its impact on the structural aesthetics, challenging the inherent visual characteristics of the building (Jing *et al*. 2023a, Zhang *et al.* 2023). While retrofitting walls with external overlays like reinforced concrete, cementitious materials, or FRP sheets proves efficient in significantly enhancing both axial, in-plane, and out-of-plane behaviors, it remains unsuitable for historical monuments (Soleymani *et al.* 2023).

The predominant method for strengthening often involves reinforcing the wall surfaces, necessitating meticulous surface preparation to ensure optimal bonding, as irregularities may lead to inferior adhesion and delamination. Additionally, this approach faces challenges, including susceptibility to environmental factors such as fire, moisture, and others, as identified by (Behera and Nanda 2022). Encasing the complete wall surface with reinforcing materials stands out as the widely embraced method. Nevertheless, in extensive construction projects, this approach proves economically impractical, as highlighted by Badonbok Lyngkhoi *et al*. (2023b).

3. Near surface reinforcement

3.1 Introduction

The near surface reinforcement technique is a widely employed method for retrofitting structures, serving as an alternative to the use of external bonded (EB) sheets or strips. Its success in enhancing the flexural capacity of reinforced concrete (RC) members has led to its expanded application for strengthening and retrofitting unreinforced masonry (URM) walls. One notable advantage is that the near surface reinforcement method doesn't require extensive surface preparation, except for cutting slots, and has a minimal installation time. This technique has garnered considerable attention as a viable and economical alternative to externally bonded reinforcement methods in structural engineering. In comparison to the EB technique, the near-surface approach has been found to result in a significantly higher axial strain at debonding and a reduced construction time, as reported by Türkmen *et al.* (2020). The near surface strengthening technique consists of two variants :1. Structural repointing (SR) and 2. Near surface mounted (NSM).

The structural repointing (SR) technique is a method involving the insertion of a reinforcing bar or a thin pultruded strip into a groove cut on the surface of mortar joints in masonry structures. Typically, these reinforcements are positioned horizontally within mortar bed joints, but they can also be placed vertically in the mortar head joints, particularly in the context of stack-bonded masonry. Fig. 5 illustrates a typical cross-section of masonry, showcasing a structurally repointed reinforcing bar. The reinforcing material is commonly embedded into the mortar joint space using epoxy, although alternative adhesives, such as latex-modified cement paste (Turco *et al*. 2006) and cement sand mortar (Jafari *et al*. 2018) have been employed. Grooves in the mortar joint are typically created using a circular saw equipped with a brick cutting blade. Notably, the process of

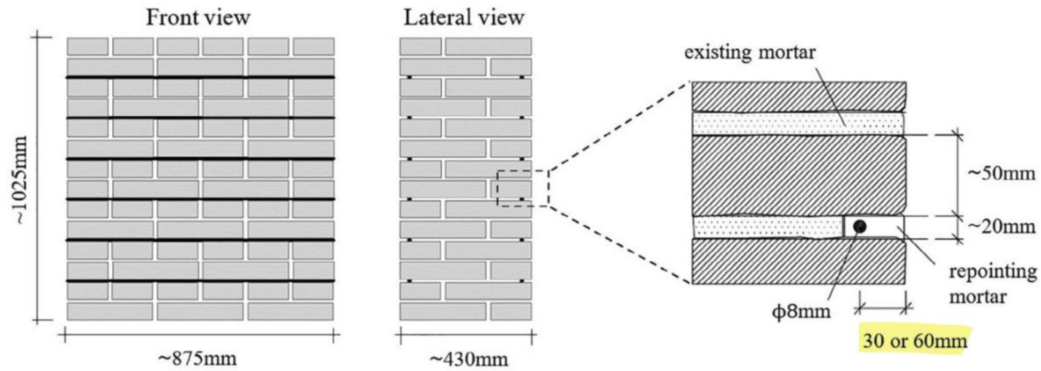


Fig. 5 Detailed cross-section of structural repointing (source: Sandoval *et al*. (2021))

cutting a groove into the wall is comparatively simpler than the surface treatment required for externally bonded reinforcement. An additional advantage of structural repointing lies in the concealed nature of the strengthening intervention once it is installed. While structurally repointed FRP reinforcement proves effective in restraining diagonal cracking failure modes, its efficacy is limited in addressing sliding or in-plane flexural cracking. To mitigate the risk of failure along unstrengthened bed joints, it is generally advisable to apply structural repointing to all mortar bed joints.

Near surface mounting (NSM) technique is a modern approach to retrofitting, offering an alternative to externally bonded (EB) sheets or strips. This method entails the adhesion of slender reinforcing strips or bars into grooves carved into the surface of a masonry wall. The grooves are created using a circular saw equipped with a brick cutting blade, and the reinforcement is securely bonded into these grooves using a two-part epoxy or cement sand mortar. It's important to note that the SR technique, previously discussed, is a specific case of NSM where the reinforcement is inserted into grooves along mortar bed joints rather than within the block themselves. Often referred to as near-surface mounted, structural repointing involves inserting reinforcing material into 10-20 mm deep grooves carved into mortar bed joints. These grooves can be oriented in any direction, and potential applications are illustrated in Fig. 6, showcasing configurations that can effectively restrain diagonal cracking and sliding failure mechanisms. For instance, vertical FRP strips may be inserted into grooves exclusively cut into brick units for higher FRP-to-masonry bond strength but increased visual impact. Conversely, they could be placed into alternating brick units and mortar head joints for reduced visual impact but with a compromise on bond strength. Similar considerations apply to horizontal strips, which can be bonded into grooves cut into brick units or mortar bed joints (referred to as structurally repointed reinforcement). Strategies to minimize the aesthetic impact include bonding the FRP into mortar joints or choosing an epoxy color closely matching the brick. Additionally, burying NSM reinforcement slightly below the wall surface and applying a filler material with a color matching to that of the brick can further address aesthetic concerns.

3.2 Structural repointing (SR) and near surface mounted (NSM)

Numerous researchers have employed the structural repointing (SR) technique on the

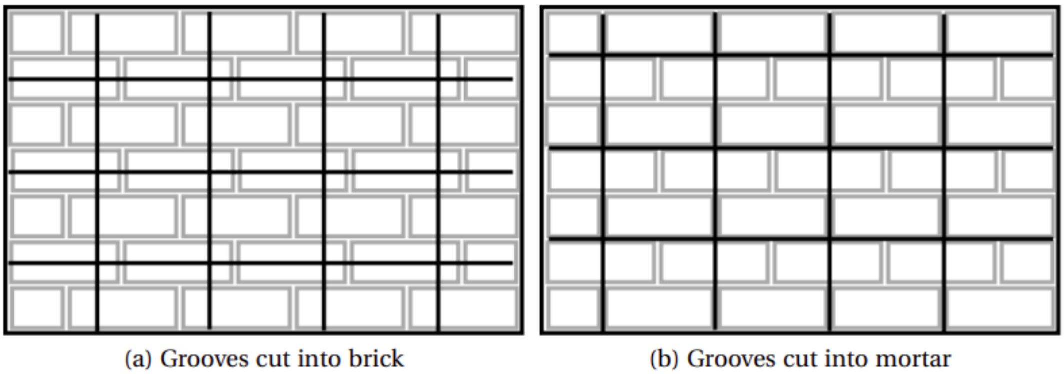


Fig. 6 Possible NSM reinforcement schemes (source: Petersen (2009))

horizontal mortar joints, using a variety of materials like FRP (bars, plates, strips wires, etc), steel (bars, plates, strips wires, etc) and ECC. This application aims to mitigate diagonal cracking in masonry walls. The reinforcements were introduced into every bed joint or every second bed joint on one or both sides of the wall. Turco *et al*. (2006) expanded FRP bar applications from concrete to unreinforced masonry (URM) walls for near-surface mounting (NSM) and structural repointing (SR). Glass and carbon FRP bars were embedded in grooves using latex-modified cementitious paste or epoxy. Different horizontal configurations were tested on one or both sides of the wall. Despite glass FRP's lower elastic modulus, it effectively strengthened masonry, often outperforming carbon FRP. Comparable results were seen with epoxy or cementitious paste. For flexural strengthening with cementitious paste, increasing groove size was advised. Due to cost-effectiveness and preserving the original appearance, cementitious paste holds promise for retrofitting existing masonry structures. In a study by Yu *et al*. (2017), NSM GFRP bars effectively enhanced shear capacity in URM walls. Reinforcing one side, especially when only the exterior is accessible, proved viable. However, caution is warranted as horizontal NSM GFRP bars may not efficiently prevent horizontal cracks along the bed joints, indicating shear sliding surpassing shear friction capacity. Li *et al.* (2005) found NSM GFRP or steel bars effective for enhancing shear capacity in URM walls, emphasizing symmetric distribution for stability and high pseudo-ductility. Reinforcing every other joint was deemed inefficient due to unfavorable failure modes. Using steel rebars offers a cost-effective and easily installable solution compared to materials like GFRP bars or twisted stainless steel bars. In a study by Sandoval *et al*. (2021), reinforcing steel bars proved effective for bed-joint repointing in masonry panels under diagonal compression. They enhance deformation capacity and structural integrity in unreinforced masonry (URM) elements facing shear loads, such as seismic events. The use of organic epoxy resin as a bonding material in reinforcement systems may pose challenges, such as compatibility issues with the masonry matrix, lack of reversibility, and performance degradation in high-temperature and humid environments. Fiber-reinforced cementitious matrix (FRCM) and engineered cementitious composite (ECC) systems with inorganic matrices are superior alternatives for reinforcing historic masonry buildings, offering better compatibility and reversibility. While steel bars face corrosion susceptibility and diameter constraints in thin mortar joints, embedding ECC in horizontal mortar joints, as suggested by Jing, Zhou and Lin (2023), emerges as a promising solution, ensuring aesthetic preservation and competitive strength for cultural heritage buildings. This method provides an advanced solution for retrofitting unreinforced masonry (URM) buildings compared to organic adhesive-based FRP reinforcement systems. In a study by Jing, Zhang and Lin (2023), the out-of-plane strengthening of masonry structures using ECC in horizontal mortar joints demonstrated significant improvements in flexural performance, indicating its effectiveness in enhancing the out-of-plane behavior of URM walls.

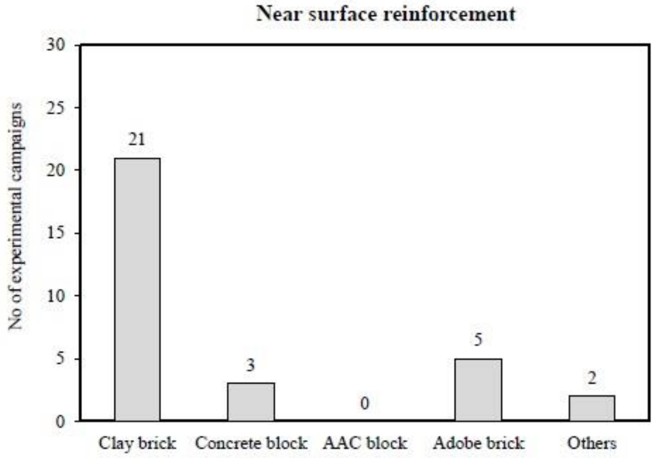
Unlike the structural repointing technique, which targets only the horizontal mortar joints, the near-surface mounted technique, however, focuses on different orientations such as horizontal, vertical, a combination of both vertical and horizontal (Grid), and diagonal orientations on one side or both sides of the wall. Petersen *et al.* (2010) conducted experiments on the in-plane shear behavior of masonry panels strengthened with NSM CFRP strips, exploring different orientations such as vertical, horizontal, and a combination of both. The goal was to reinforce against common unreinforced masonry failure modes, particularly bed joint sliding and diagonal cracking. Horizontal reinforcement aimed to curb diagonal cracking but lacked effectiveness in preventing sliding unless applied in every bed joint. To address this, vertical reinforcement was introduced, proving more efficient. Contrary to concerns about the efficacy of vertical FRP, especially thin strips, the tests demonstrated its effectiveness in restraining both sliding and diagonal cracking, preventing unreinforced masonry failure. Mahmood and Ingham (2011) found horizontal FRP on walls with weak mortar ineffective for mitigating sliding deformation in unreinforced masonry. Vertical or diagonal FRP retrofit, with or without horizontal FRP, effectively prevents sliding in wallettes, and vertical FRP significantly enhances shear strength. Studies by Dizhur *et al.* (2013; 2014), Griffith *et al*. (2013) and Hernoune *et al.* (2020) also support the superiority of vertical NSM FRP reinforcement in shear, flexural strength, and ductility capacity over horizontal reinforcement. Contrary to some findings, studies by Konthesingha *et al.* (2013, 2015), Jafari *et al.* (2018), Eslami *et al.* (2021), and Soleymani *et al.* (2023) indicated that retrofitting schemes combining horizontal and vertical reinforcement outperforms those using only one orientation. The superior performance is evident in terms of ultimate load capacity, displacement capacity, and energy dissipation. Incorporating both horizontal and vertical NSM strips proves effective, with horizontal strips preventing diagonal crack openings and vertical strips mitigating sliding failures. In comparison to competing materials, steel offers advantages like compact dimensions, buckling resistance, cost-effectiveness, and easy installation (Shahzamani and Eftekhar 2023). Ismail *et al*. (2011) found that vertical and grid pattern reinforcement in URM wallettes outperformed horizontal reinforcement, showing increased strength and displacement capacity. Soti and Barbosa (2019) observed less brittle behavior in masonry wallettes retrofitted with both horizontal and vertical NSM reinforcing bars. Demaj *et al.* (2022) highlighted the limited efficiency of single-direction reinforcement and emphasized the superior energy dissipation in solutions with horizontal and vertical (grid) reinforcement. Mirabi Banadaki *et al*. (2019) and Eslami *et al.* (2021) also favored grid patterns. Shahzamani and Eftekhar (2023) reported a remarkable 16-fold increase in load-bearing capacity and a 45-fold increase in energy dissipation with diagonal steel wire arrangement, proving its superiority over other layouts. Raji *et al.* (2022) innovatively explored the grooving method using TRM to enhance the ultimate load-carrying capacity of masonry walls subjected to out-of-plane loading. This approach, distinct for its textile rupture failure mode, significantly increased the lateral load-bearing performance. Overall, the grooving method demonstrated an outstanding 87% increase in the out-of-plane bearing capacity of the masonry wall compared to the same reinforced wall without grooving, opening new possibilities for lateral load performance improvement. Most NSM reinforcement methods focus on solid clay bricks, but

Table 2 Summary of experimental studies employing near surface reinforcement

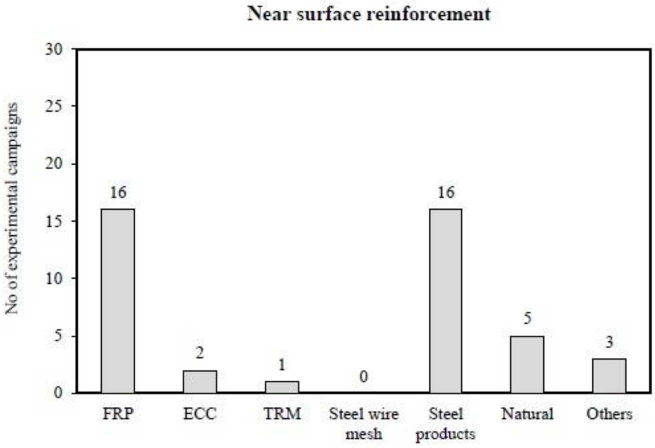
Sl. no	References	Masonry unit	Masonry unit strength (MPa)	Mortar compressive strength (MPa)	Specimen size mm (l×h×t)	Reinforcing material	Orientation/ Pattern	One side/Both side	Grooves Dimensions mm (width×depth)	Groove filling method	Type of Test/ Loading	Increase in strength with respect to URM	Observed Failure Mode
1	Ghorbani *et al.* (2013)	Concrete blocks	7.2	8.3	1200 × 1200 × 200	Corrosion resistant aluminum strips	Horizontal	One side	10 × 15	Cement mortar	In-plane cyclic load	18-40%	Diagonal crack
2	Jing *et al.* (2023)	Solid clay bricks	10.9	2.56	2250 ×1500 × 240	CFRP plates	Horizontal	One side	10 × 60	Epoxy	Combined axial and cyclic in-plane shear loading	3.74-10.16%	Ductile flexural failure
3	Jing *et al.* (2023)	Solid clay bricks	10.9	6.34	1130 ×240 × 240	ECC	Horizontal	One side	12 × 60	ECC	Four-point loading	28-139%	Flexural failure
4	Jing *et al.* (2023)	Solid clay bricks	10.9	2.93	365 ×750 × 240	CFRP plates, ECC	Horizontal	Both sides	60	Epoxy, ECC	Axial concentric compressive loading	19.02-86.31%	Debonding failure
5	Jasieńko *et al.* (2023)	Solid clay brick	62.4	2.4	380 ×510 × 380	Stainless steel cords and PBO fibres	Horizontal	Both sides	10×15 10×25 10×30	Cement mortar, Lime mortar	Static axial compression	8-67%	Vertical cracking
6	Casacci *et al.* (2019)	Fired-clay brick	14.3	5.8	520 ×530 × 100	Basalt bar (BFRP)	Horizontal	One side, Both sides	10×20	Structural mortar	Diagonal compression	8-44%	Sliding along the interface between bricks and mortar
7	Witzany *et al.* (2016)	Brick	10	1.5	1350 ×1330 × 285	CFRP strips	Horizontal	One side	15×50	Polymer cement mortar	Uniform concentric compression	22-55%	Tensile crack
8	Singh *et al.* (2018)	Clay bricks	8.76	22.15	780 ×480 × 230	CFRP bars	Horizontal	One side	-	Epoxy	Three-point bending	6-9 times	Masonry crushing
9	Yao *et al.* (2021)	Clay bricks	31.35	2.38	1600 ×910 × 210	Steel strip	Horizontal	Both sides	15 40	Polymer mortar	In-plane cyclic loading	6-25%	Bed joint sliding shear failure
10	Galati *et al.* (2006)	Clay bricks Concrete blocks	19.43 11.4	7.6	1220 × 610 × 95 1220 × 610 × 143	GFRP & CFRP bars	Vertical	Both sides	3 × 17 14.3 × 14.3 21.4 × 21.4 9.5 × 9.5	Epoxy (or) cementitious paste	Four point bending	2-14 times	Debonding
11	Ismail *et al.* (2011)	Solid clay bricks	39.4	1.4	1200 ×1200 × 110 1200 ×1200 × 220	Twisted steel bars	Vertical, horizontal and combination of both	One side, both sides	10 × 30 14 × 30	Thixotropic injectable grout	Diagonal compression	114-189%	Diagonal cracking, Bed-joint sliding
12	Ismail and Ingham (2012)	Vintage clay bricks	8.8,18.8	3.3	1200 ×3325 × 155 1200 ×2640 × 240	Twisted steel bars	Vertical	One side	10 × 30 14 × 30	Thixotropic injectable grout	Cyclic out-of-plane loading	143-434%	Horizontal cracking
13	Griffith *et al.* (2013)	Clay bricks	-	-	1070 ×2312 × 110	CFRP strips	Vertical	One side, both sides	3.6 × 10, 4.2 × 10	Epoxy	Three-point bending, Four-point bending	20 times	IC debonding
14	Shahzamani and Eftekhar (2023)	Perforated clay bricks	8.83	5.40	920 ×920 × 100	Steel wires	Horizontal, Vertical, Grid, Diagonal	Both sides	8 × 10	Epoxy	Diagonal compression	21 times	Slippage of mortar joints, Diagonal cracks
15	Zhang *et al.* (2023)	Adobe brick	5.53	6	1900 ×1200 × 200	Reinforced mortar strip, bamboo plywood and wood	Vertical, horizontal, Diagonal	Both sides	100 × 30 100 × 36	Non-shrink special mortar	Quasi-static test	4-122%	Diagonal cracking, rocking and sliding
16	Mirabi Banadaki *et al.* (2019)	Adobe brick	4.43	3.31	1020 ×800 × 200	Steel rebars	Combination of both horizontal and vertical	Both sides	24×24 24×30	Cementitious grout and mortar	In-plane cyclic loading	20-181%	Diagonal cracking, Toe crushing
17	Eslami *et al.* (2021)	Adobe brick	4.43	3.31	1020 ×900 × 200	Steel bar, GFRP bar, Sand-coated reed	Combination of both horizontal and vertical	Both sides	24×24 24×30	Cementitious grout	In-plane lateral loading	33-88%	Rocking/ Toe crushing, sliding
18	Jafari *et al.* (2018)	Bricks	17.9	3.7	1020 ×900 × 200	Steel bar, GFRP bar,	Combination of both horizontal and vertical	One side	15×15	Cement- sand mortar	Diagonal compression	297%	Diagonal and sliding
19	Misnon *et al.* (2020)	Solid clay brick	27.98	2.92	1200 ×1200 × 235	Steel wire rope	Vertical, Combination of both horizontal and vertical	One side, Both sides	15	Epoxy, Cement-based grout	Diagonal compression	261%	Diagonal cracking
20	Soleymani *et al.* (2023)	Solid clay brick	11.07	1.11, 3.02, 5.20	910 ×700 × 200	GFRP bar	Combination of both horizontal and vertical	One side, Both sides	12×15	Epoxy and Latex Modified Cementitious Paste	Diagonal shear test	1.63 times	Debonding
21	Meybodian *et al.* (2020)	Adobe bricks	4.43	1.14, 3.31,5.78	1000 ×900 × 200	Reeds, palm	Diagonal	Both sides	25×30	Gypsum clay mortar	In-plane cyclic loading	19-50%	Diagonal cracking, rocking and toe crushing
22	Demaj *et al.* (2022)	Solid clay bricks	25.3	13.8	760 ×760 × 250 860 ×860 × 250	Stainless steel bars, Ribbed steel bars	Vertical, horizontal and combination of both, diagonal	One side, Both sides	25×25 40×40	Premixed mortar	Axial compression, Diagonal compression	4.7-96.1%	Vertical cracking, Diagonal cracking
23	Hernoune *et al.* (2020)	Perforated clay bricks	14.5	3.6,7.2	400 ×400 × 105	CFRP strips	Vertical, horizontal and combination of both,	One side, Both sides	-	Epoxy	Combined shear-compression loading	123-196%	Diagonal cracking, sliding shear failure
24	Hracˇov *et al.* (2016)	Adobe bricks, Clay bricks	5.10, 7.50	3.16	1050 ×1367 × 240	Steel wire ropes	Diagonal	Both sides	-	Adobe mortar	In-plane cyclic loading	-11%	Diagonal shear crack
25	Kanani *et al.* (2023)	Brick	3.7	18	1200 ×1200 × 200	Non prestressed and prestressed GFRP bars	Vertical	Both sides	10×10	Adhesive	In-plane cyclic loading	38% & 58%	Diagonal shear crack, sliding shear failure
26	Soti and Barbosa (2019)	Clay bricks	49	9.65	1320 ×1320 × 193 2438 ×1829 × 193	Steel bars	Horizontal and combination of both horizontal and vertical	One side, Both sides	-	Epoxy	Diagonal compression, In-plane cyclic loading	-	Shear and sliding failure
27	Türkmen *et al.* (2020)	Clay bricks	31.7	10.6	700 ×700 × 95	CFRP strips	Vertical	One side	10×65	Epoxy	Diagonal compression	8%	shear friction
28	Raji *et al.* (2022)	Solid clay brick	-	-	1400 ×440 × 100	Glass textile	Vertical	One side	10×10	-	Four-point loading	87%	Textile rupture

Table 2 Continued-

29	Fam *et al.* (2016)	Concrete blocks	39.3	-	1200 ×300 × 500	Steel bars GFRP bars CFRP strips	Vertical	Both sides	32×16 16×16 6×16	Epoxy	Out-of-plane loading	-	Rupture of tension GFRP rebar Rupture of tension CFRP strip
30	Mohamed Raouf *et al.* (2023)	Clay bricks	28.39	45.4	1200 ×935 × 115	Steel bars Steel wire ropes	Horizontal Diagonal	One side	10×15	Mortar (1:2)	In-plane cyclic loading	53-103%	Diagonal shear, rupture of steel



(a) Masonry unit types



(b) Reinforcing material types

Fig. 7 Experimental campaigns on Near surface reinforcement involving (a) Masonry unit types and (b) Reinforcing material types

when reinforcing adobe, modern materials may conflict with its sustainable principles and impose high costs on communities. To address this, cost-effective seismic strengthening techniques using locally available natural materials like palm meshes, reeds, bamboo, and wood need exploration. Adobe masonry, prevalent in economically underdeveloped regions, is chosen for its low construction costs. Therefore, reinforcement material expenses should align with adobe masonry costs and local economic conditions (Meybodian *et al.* 2020, Zhang *et al.* 2023).

Table 2 offers a comprehensive overview of experimental studies employing near surface reinforcement, complemented by Fig. 7, which visually depicts the experimental campaigns on near surface reinforcement, providing insights into the various masonry unit types and reinforcing material types involved.

3.3 Concluding remark

Near surface reinforcement is an attractive method for retrofitting both old and existing structures, offering clear advantages over external bonded reinforcement (EBR) (Parvin and Shah 2016). This strengthening approach has gained attention as a practical and cost-effective alternative to external bonded reinforcement methods (Lorenzis and Teng 2007). Compared to EBR, the near surface reinforcement system provides several benefits : (1) Reduced on-site installation work, as surface preparation beyond grooving is no longer necessary; (2) Lower susceptibility to debonding from the substrate, showing better bonding advantages than EBR systems; (3) Significantly higher axial strain at debonding (4) Easier anchoring of NSM bars into adjacent members to prevent debonding failures; (5) More straightforward pre-stressing of NSM reinforcement; (6) Enhanced protection of NSM bars, as they are covered by adhesive or mortar, minimizing exposure to accidental impact, mechanical damage, fire, and vandalism; (7) Virtually unchanged aesthetic appearance of the strengthened structure, especially when NSM bars are covered by grout. This is particularly crucial in the restoration of older monuments and structures appreciated for their aesthetics.

However, a potential drawback of the NSM technique is its requirement for deep grooves, which may lead to cracking through the thickness of masonry walls, limiting its application for hollow bricks (Petersen *et al.* 2010). Overall, the application of near surface reinforcement has been shown to increase ultimate load-carrying capacity, lateral resistance, energy absorption, and ductility in retrofitted walls. This retrofitting method also transforms sudden failure patterns in URM walls into more gradual failure patterns. In the context of heritage structures with valuable features, which may be complex, preventing further deterioration post-renovation necessitates additional scientific research. Innovations in producing inorganic mortars, more durable insulating materials, and techniques like NSM with minimal disruption of appearance represent promising avenues for heritage structures (Yavartanoo and Kang 2022).

4. Internal surface reinforcement

4.1. Introduction

Internal surface reinforcement emerges as a relatively recent and robust approach to strengthen masonry structures (Xu *et al.* 2023). The utilization of internal reinforcement is a widespread practice in certain countries, involving the incorporation of reinforcement within horizontal and/or vertical bed joints. This method is predominantly employed in new constructions. During the construction process, reinforcing materials are strategically placed inside the wall, making it impractical for retrofitting purposes (Meybodian *et al.* 2020). However, for new constructions, the internal reinforcing configuration appears more logical due to its efficacy and durability. In

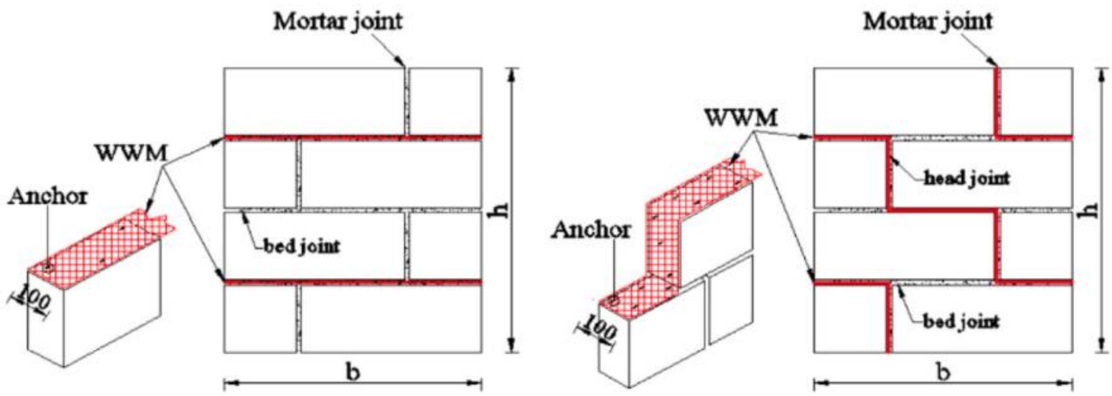


Fig. 8 Bed joint and bed head joint process (source: Badonbok Lyngkhoi *et al*. (2023c))

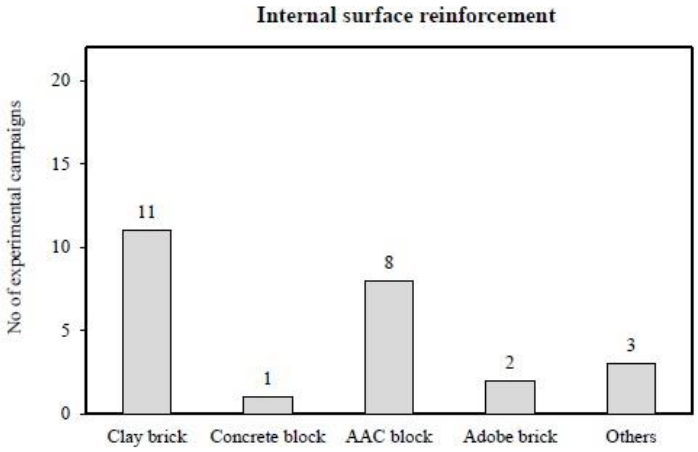
contrast, externally bonded reinforcements often entail extensive drilling and surface preparation (Eslami *et al*. 2022). Many wall-surface strengthening technique require meticulous surface preparation to avoid poor bonding and delamination caused by irregularities. Moreover, this method is susceptible to environmental impacts such as fire, moisture, and frost. Internal surface strengthening provides an effective solution to overcome these challenges (Behera and Nanda 2022). Embedding mesh in the joint is a straightforward method to enhance structural performance without compromising the aesthetic appearance or increasing the thickness of the walls, leading to a reduction in overall costs (Badonbok Lyngkhoi *et al*. 2023b). Reinforcing bed joints in masonry structures is a common practice aimed at preventing crack propagation and elevating values of cracking stress, compressive strength, or shear strength. Autoclaved aerated concrete (AAC), known for its low compressive and tensile strength, often requires reinforcement to limit crack development and enhance overall strength. Incorporating reinforcement into bed joints is a simple yet effective method not only for infill walls but also for load-bearing walls that predominantly carry vertical loads and stiffening walls (Jasinski and Lukasz Drobiec 2019).

Internal surface strengthening involves the application of reinforcement in bed-joint and/or bed-head joint. Badonbok Lyngkhoi, Warjri, and Marthong (2023c) detail the construction process for bed-joint (BJ) specimens, which includes laying the first course and installing reinforcement (Fig. 8). A U nail was employed to secure the mesh to the specimen bed joint. The reinforcement was then placed in the alternate course or bed joint, and the specimens were left exposed to the open air for approximately 12 days before being plastered on both faces. Similarly, the construction of bed-head joint (BHJ) specimens began with laying the first course and installing reinforcement on one block following the head and bed joint. Using a U nail, the mesh was affixed to the block. Upon completing the first course, the second course was constructed, and the mesh was installed at the bed and head joint in a single run without any overlap or interruptions. This process continued with the construction of the third course. When laying the fourth course, the mesh was attached to one block following the head and bed joint.

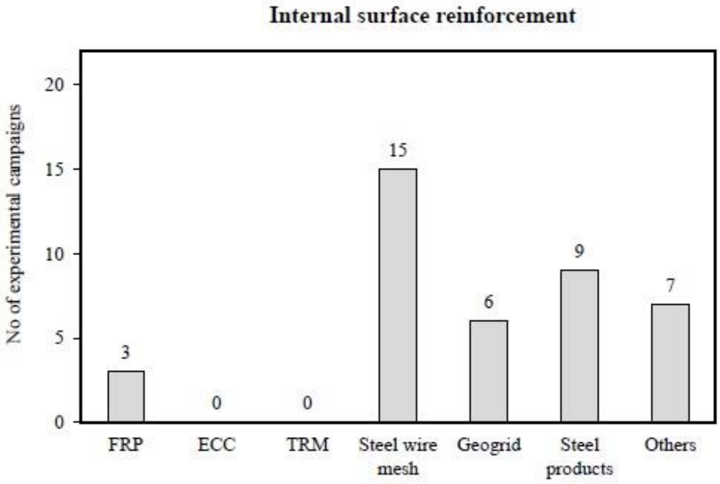
4.2 Bed joint and bed-head joint strengthening

Ewing and Kowalsky (2004) used thin galvanized steel plates in mortar joints for masonry prism confinement, achieving a 40% increase in compressive strength. Penna *et al.* (2015) found an 18.6% shear strength boost in AAC masonry walls with steel flat-truss bed-joint reinforcement. Jasinski and Drobiec (2016) identified steel truss-type and basaltic mesh as optimal for AAC masonry compressive strength. In a subsequent study, Jasinski (2019) noted positive effects of smooth steel bars and truss-type reinforcement on brick walls. Halici *et al.* (2023) enhanced out-of-plane seismic performance in AAC walls with innovative steel cord-type bed-joint reinforcement, showing superior displacement and energy dissipation capacity. Turanli and Saritas (2011) studied the seismic performance of square wall panels by replacing steel with fiberglass plaster reinforcement mesh along horizontal mortar joints. The use of plaster mesh improved friction in these joints, leading to increased strength and enhanced energy absorption capacity. Sadek and Lissel (2013) studied bed joint reinforcement (steel, GFRP, geogrid) for CMU walls, highlighting GFRP and geogrid's benefits in improving seismic performance and strength. Recommending their use, especially geogrid in a grid shape, the study observed a 54.7% average increase in lateral capacity. Geogrid, being recyclable, corrosion-resistant, and cost-effective, stands out as a preferable choice over steel or GFRP reinforcement. Geofabrics, geogrids and geotextiles are novel geosynthetic composite materials applied in civil engineering for structural enhancement. In a study conducted by Sreekeshava *et al.* (2020), polyester geofabric used as bed joint reinforcement in masonry elements demonstrated a 25% increase in load-carrying capacity and a 30% strength boost compared to unreinforced specimens. Behera *et al*. (2020) evaluated diagonal strength in brick masonry panels using geotextile wrapping and geogrid reinforcement, noting enhanced diagonal and in-plane shear strength. Geogrid reinforcement showed a 43% increase in in-plane shear strength compared to a 29% increase with surface reinforcement. Giaretton *et al.* (2021) explored various meshes for horizontal reinforcement in adobe walls, finding that biaxial polypropylene geogrid exhibited superior tensile strength and bonding. Diagonal compression tests with geogrid reinforcement enabled ductile behavior, allowing significant deformations and energy dissipation through dispersed narrow cracks. Behera and Nanda (2022) investigated the efficacy of geogrid reinforcement in brick masonry buildings under in-plane loading and out-of-plane bending subjected to lateral cyclic loading. Unreinforced corner walls exhibited damage and collapse, while geogrid-reinforced walls showed no signs of damage, achieving a 68.52% increase in lateral strength. This highlights geogrid's cost-effective role in earthquake disaster mitigation for brick buildings. In another study, Xu *et al*. (2023) used glass fiber geogrids (GFGs) in horizonal mortar joints as a steel bar substitute to reduce joint thickness and thermal bridging. GFG effectively delayed AAC masonry wall cracking, enhancing seismic performance with comparable construction time and cost to traditional rebar installation. GFG's ease of cutting and installation makes it a robust choice for this application.

In contrast to the geogrid material, researchers such as Christy *et al.* (2013) investigated the effectiveness of steel wire mesh, particularly galvanized hexagonal woven wire mesh, in reinforcing alternate bed joints of clay and flyash brick masonry prisms. The study showed a 25% increase in load-carrying capacity for clay brick masonry and a 10% increase for flyash brick masonry with wire mesh. Campione *et al*. (2016) used stainless steel grids in horizontal mortar joints, ensuring optimal bonding and preventing sliding issues observed with continuous steel plates. This cost-effective method enhanced load-carrying capacity and proved easy to implement. Kanchidurai *et al*. (2019) improved masonry structural performance by embedding meshes on brick unit surfaces and within bed joints, utilizing cost-effective meshes for enhanced strength and ductile behavior. Cheng *et al*. (2020) reported increased energy dissipation capacity by reinforcing bed joints and mortar, enhancing ultimate bearing capacity. Marbaniang *et al*. (2022) and Warjri *et al*. (2022) recommended minimal strengthening for unreinforced masonry by incorporating steel



(a) Masonry unit types



(b) Reinforcing material types

Fig. 9 Experimental campaigns on internal surface reinforcement involving (a) Masonry unit types and (b) Reinforcing material types

welded wire mesh along bed joints during new wall construction due to observed sudden brittle failure and cost considerations.

Pioneering the study of bed-head joint reinforcement, Behera and Nanda (2021) conducted experiments on brick masonry using geogrid reinforcement in bed and bed-head joints. For geogrid bed-head joint reinforcement, cracks were supported in mortar bed joints, propagating through head joints. In the case of geogrid bed joint reinforcement, cracks distributed, leading to brick crushing with shear cracks along bed and head joints. Diagonal compression testing showed a 108% increase in crushing load for bed joints and a 20% increment for bed-head joints compared to unreinforced panels. Geogrid bed joint reinforcement exhibited a 45% increase in lateral strength for brick panels. Lyngkhoi *et al*. (2023a) investigated the behavior of AAC masonry walls

Table 3 Summary of experimental studies employing internal surface reinforcement

Sl. no	References	Masonry unit	Masonry unit strength (MPa)	Mortar compressive strength (MPa)	Specimen size mm (l×h×t)	Reinforcing material	Orientation/ Pattern	Type of Test/ Loading	Increase in strength with respect to URM	Common Failure Mode
1	Turanli and Saritas (2011)	Adobe bricks	-	-	800 × 800 × 105	Fiberglass Plastic mesh	Bed-joint	Diagonal compression	136 %	Brittle failure
2	Sadek and Lissel (2013)	Hollow concrete blocks	13.7	-	1600 × 800 × 105	Steel, GFRP, Geogrid	Bed-joint	In-plane cyclic loading	13.3-85%	Shear and sliding failure
3	Christy *et al.* (2013)	Clay brick and Flyash brick	1.85 2.68	-	230 x 110 x 420	Chicken wire mesh	Bed-joint	axial compressive load	10-25%	Vertical cracks
4	Ewing and Kowalsky (2004)	Clay brick	34	1.72	254 x 551 x 191	Thin galvanized steel plates	Bed-joint	Compression	40%	vertical splitting cracks
5	Penna *et al.* (2015)	AAC block	3.48	-	2500 x 2000 x 300	Steel truss	Bed-joint	Vertical and diagonal compression tests	18.6%	Shear failure
6	Campione *et al*. (2016)	Clay brick	25.81	8.79	250 x 400 x 250	Steel wire mesh, Carbon FRP, Basalt FRP	Bed-joint	Monotonic compressive loading	16-38%, 16-43%, 34-61%	breaking of one or more steel grid
7	Jasinski and Lukasz Drobiec (2019)	AAC	4	6.1-11.9	1180 x 1212 x 180	Steel truss, Plastic mesh, Basalt meshes	Bed-joint	Diagonal compression, compression	27-50%, 2-19%	loss of adhesion between reinforcement and mortar
8	Jasiński (2019)	Clay bricks, Calcium silicate units, AAC blocks	28.8, 17.7, 3.65	9.67, 18.2, 6.1	1680 x 1415 x 250 4500 x 2450 x 180 4425 x 2424 x 180	Steel bars, steel truss, plastic mesh	Bed-joint	Shear test	25-34%	Diagonal crack through bed and head joints
9	Kanchidurai *et al.* (2019)	Clay bricks	12.6	13.46	480 × 480 × 140	GI expanded wire mesh (EWM), SS stainless steel mesh (SSM) SS poultry netting mesh (PNM)	Bed-joint	Diagonal compression	38%	Diagonal cracks
10	Sreekeshava *et al.* (2020)	Clay bricks	3.8	-	700 × 700 × 230	polyester geo-fabrics	Bed-joint	Uniaxial and Diagonal compression	25,30 %	Diagonal cracks
11	Cheng *et al.* (2020)	Gangue sintered brick	9.93	11.8	1000 × 1000 × 120	Carbon-glass fabric	Bed-joint	Diagonal compression	171.9%	Diagonal cracks
12	Behera *et al.* (2020)	Clay bricks	9.07	4.35	600 x 600 x 125	Geogrid	Bed-joint	Diagonal compression	43%	Diagonal cracks
13	Giaretton *et al.* (2021)	Adobe brick	0.66-0.89	-	1200 x 1200 x 280	Geogrid, 661 reinforcing steel mesh, Square grid chicken wire, Orange construction fencing	Bed-joint	Diagonal compression	16-18%	Diagonal cracks
14	Marbaniang *et al.* (2022)	Clay brick	8.4	12.98	600 × 480 × 120, 645×470×120	Welded wire mesh	Bed-joint	Four-point loading	17-139%	rupture of the WWM
15	Warjri *et al.* (2022)	Clay brick	8.4	12.98	600 × 600 × 120	Welded wire mesh	Bed-joint	Diagonal compression	16.07%	Slight ductile failure
16	Behera and Nanda (2022)	Clay bricks	9.07	4.35	600 x 600 x 125 850 x 850 x 760	Geogrid	Bed-joint	Diagonal compression sinusoidal loading test	112% 62.52%	Shear failure
17	Halici *et al.* (2023)	AAC block	2.59	-	3600 x 2500 x 150	Steel truss, steel cord	Bed-joint	Quasi-static IP and OOP displacement cycles	23.4-29.7%	-
18	Xu *et al.* (2023a)	AAC block	5.23	6.59	1225 × 1810 × 200	Glass fiber geogrids, steel	Bed-joint	Reciprocating load tests	74.79%	Shear failure

Table 3 Continued-

19	Behera and Nanda (2021)	Clay brick	9.1	4.4	600 × 600 × 125	Uni-axial geogrid	Bed joint, Bed-head joint	Diagonal compression	108% 20%	Shear failure, Failure along bed and head joint
20	(Badonbok Lyngkhoi *et al.* 2023c)	AAC block	3.05	14.37	570 x 660 x 100	Chicken wire mesh, Welded wire mesh	Bed joint, Bed-head joint	Compression	20.41-31.61%, 29.49-48.21%	Vertical cracks, Crushing
21	Lyngkhoi *et al.* (2023a)	AAC block	3.05	12.3	570 x 660 x 100	Chicken wire mesh, Welded wire mesh	Bed joint, Bed-head joint	Axial compression	20.41-58.71%, 29.49-85.28%	Compression failure,
22	Lyngkhoi *et al.* (2023b)	AAC block	3	12.3	315 x 330 x 100	Chicken wire mesh, Welded wire mesh	Bed joint, Bed-head joint	Direct shear test	2.23 - 23.33%, 22.92-50.69%	Brittle failure, Ductile failure

under axial compression loading by incorporating steel wire mesh (one chicken wire mesh M1 and two welded wire mesh M2, M3) at the masonry bed joint and bed-head joint. Strengthened specimens exhibited ductile failure, restraining crack propagation. Bed-head joint strengthening proved effective, especially for M2 and M3 specimens, serving as a seismic band. The proposed scheme enhances seismic resistance, with bed-head joint strengthening, though labor-intensive, outperforming bed joint strengthening. All three steel wire mesh types (M1, M2, M3) are suitable, with M2 and M3 showing superior performance. In a related study, Lyngkhoi *et al.* (2023a) assessed the shear characteristics of AAC masonry triplet assemblages by embedding steel wire mesh in both the masonry bed joint (BJ) and bed-head joint (BHJ). The reinforcement improved shear strength in BJ configurations by 2.23% to 23.33% and in BHJ configurations by 22.92% to 50.69%. Notably, BHJ configurations demonstrated intact, cohesive failure even after block breakage, presenting a significant advantage over unreinforced and BJ configurations.

A summary of experimental studies involving internal surface reinforcement is presented in Table 3, with Fig. 9 illustrating the corresponding experimental campaigns, highlighting the diverse masonry unit types and reinforcing materials employed.

4.3 Concluding remark

Previous studies have indicated that incorporating internal bed-joint reinforcement emerges as a promising strategy for enhancing the overall seismic performance of masonry walls. Most strengthening methods commonly employ full wall-surface strengthening, requiring thorough surface preparation for successful application. Additionally, external surface strengthening can adversely affect the aesthetic appearance of a building. Exploring alternatives, strengthening the bed joints emerges as a straightforward solution to enhance structural performance. European codes (CEN, 2005, 2004) suggest employing a limited amount of steel welded wire mesh for horizontal bed joint reinforcement to improve the integrity of masonry. This approach not only enhances stability but also contributes to increased strength against flexural and shear forces, ensuring higher levels of serviceability. Implementing horizontal bed joint reinforcement has demonstrated its effectiveness in decreasing the likelihood of out-of-plane collapse, even in scenarios following in-plane damage (Vicente *et al.* 2012). This strategy remains valuable in enhancing structural resilience. The benefits of utilizing internal reinforcement for upgrading unreinforced masonry (URM) walls comprise cost-effectiveness, minimal disturbance to the occupants of the structure, no observable modification to the original masonry aesthetics as the reinforcement remains concealed, straightforward and prompt installation, and no apparent increase in structural weight. Additionally, it provides protection against external factors for the reinforcement and allows for the application of prestressing, enhancing the strength and ductility of the structure.

In the method of internal reinforcement, the reinforcing materials are embedded within the wall during the construction process (Meybodian *et al*. 2020). Consequently, this approach is not suitable for retrofitting purposes. Implementing this approach in existing structures involves additional labor, potentially escalating costs and rendering it impractical. Proper embedding of the horizontal reinforcement mesh within the mortar joint is crucial to ensure effective bonding and the success of the strengthening procedure (Giaretton *et al*. 2021). Furthermore, the drawbacks arise from the invasive nature of the technique, necessitating meticulous application and posing challenges in anchoring the reinforcement to adjacent structural elements. The presence of reinforcement leads to an increase in the thickness of the horizontal mortar joint. As mortar has higher thermal conductivity than the block, a thicker mortar layer intensifies the thermal bridging effect, leading to increased energy loss. Consequently, a material with comparable tensile properties and ductility to reinforcement is necessary to dimmish the thickness of mortar joints (Xu *et al*. 2023).

5. Conclusions

This paper summarizes a comprehensive state-of-the-art review on the retrofitting and strengthening of unreinforced masonry walls. Subsequently, the effectiveness of various strengthening techniques such as external surface reinforcement, near-surface reinforcement and internal surface reinforcement systems is evaluated. Based on the results obtained from different studies, the following concluding remarks can be made:

- Among the various reinforcement methods, external surface reinforcement systems are widely used for unreinforced masonry under various load conditions. Full wrapping and strip wrapping are popular methods for reinforcing both old and new constructions. While retrofitting with external overlays enhances in-plane and out-of-plane behavior, it may not be suitable for historical monuments. Despite improving shear and flexural behavior, challenges like premature debonding limit the use of high-strength composites. The method also alters the appearance of the masonry structure, impacting its aesthetic characteristics. Reinforcing materials externally applied to one or both faces of walls can be economically impractical for large-scale construction.
- Near surface and internal surface reinforcement systems offer cost-effective alternatives to traditional external surface methods for reinforcing masonry structures. These approaches optimize the use of reinforcing materials, reducing the risk of debonding failures and providing enhanced protection against external damage.
- Internal surface reinforcement, although promising for new constructions, faces challenges in existing structures due to labor-intensive work, potentially raising costs and making it impractical. Additionally, in developing countries, new masonry constructions often lack seismic-resistant codes, with challenges such as lack of awareness, insufficient structural knowledge, and authorities neglecting effective implementation of earthquake-resistant measures. This contributes to the persistence of non-engineered construction and inadequate strengthening practices.

- Hence, near surface reinforcement technique finds widespread acceptance, especially in situations where preserving the aesthetic appearance of a structural element is crucial. This makes it a viable option for the rehabilitation or retrofitting of existing and historic URM buildings. NSM offers advantages over external methods, such as higher axial strain at debonding, fire and environmental protection, minimal aesthetic impact, and reduced construction time. This makes NSM a cost-effective and minimally invasive option for seismic retrofitting compared to conventional methods. Its appeal lies in superior performance, particularly in terms of premature debonding and minimal interference with the building's architecture, making it one of the most favorable seismic improvement methods for URM buildings.
- In recent decades, extensive research has focused on developing efficient, cost-effective, and durable strengthening technologies for vulnerable non-engineered URM structures to improve their seismic performance. While global research on masonry construction has been substantial, few studies specifically target low-cost buildings using new locally-produced, low-strength masonry units like autoclaved aerated concrete (AAC). Investigating the structural behavior of these buildings is crucial to expand knowledge. Additionally, there's a need to explore cost-effective strengthening techniques including near surface reinforcement and materials such as steel welded wire mesh, PP-band, geogrid, and barbed wire, to meet the requirements of low-strength masonry structures.

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