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Effectiveness of steel wire mesh as a strengthening material for masonry walls: A review

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Abstract. The most prevalent and oldest type of structure is unreinforced masonry (URM) structures; URM walls are still a widely used construction material in India and many other developing countries due to their simplicity, ease of construction, economic sustainability, and ability to be built with locally available materials. URM walls are significantly weak while carrying lateral loads. The poor performance of URM walls during earthquakes has necessitated investigating an effective method for strengthening a newly built masonry building or retrofitting an old structure. Wire mesh, being cost-effective and easily available, satisfies the requirements to strengthen new and old URM buildings. The use of wire mesh to strengthen and retrofit the URM structure is simple to use, quick to construct, and inexpensive, especially in developing nations where heavy machinery and highly qualified labour are lacking. The current paper reviews the effectiveness of steel wire mesh as a reinforcing material for enhancing masonry strength. The finding gave encouraging results for the field application of wire mesh.

Keywords: compression test; in-plane loading; masonry; out of plane loading; steel wire mesh; strengthening

1. Introduction

Masonry walls are made up of bricks and binder mortar, both of which have unique qualities. The masonry wall's strength and responsiveness to various loads are determined by the adhesive action between bricks and mortar. The many forms of masonry walls are unreinforced masonry walls, unreinforced masonry infill walls, and grouted masonry walls as shown in Fig. 1. Amidst the many forms of masonry walls, the most prevalent and oldest form of structure is unreinforced masonry (URM) walls which act as a structural masonry and are used as main load-bearing walls without additional reinforcing components for gravity and lateral loads. URM walls are still widely used construction materials in India and many other developing nations due to their simplicity, durability, ease of construction, sound and thermal insulation, economic sustainability, and ability to be constructed with locally available materials. According to a Census 1991, 2001, 2011 by the

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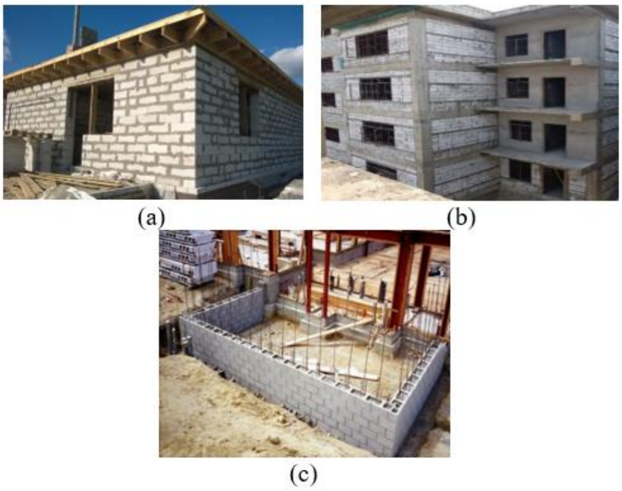

Fig. 1 Types of Masonry walls: (a) Unreinforced masonry walls, (b) Unreinforced masonry infill walls and (c) Grout-reinforced masonry walls

National Disaster Management Authority, Government of India; buildings made of contemporary materials (such as reinforced concrete and structural steel) make up only around 3.6% of the total stock of buildings, whereas materials such as mud bricks, burnt bricks, and stone, account for 84% of the country's housing material utilization.

URM structure are normally strong in compression and perform well under gravity load but are significantly weaker while carrying lateral loads. During an earthquake, URM structures suffered extensive damage, as presented in Fig. 2. and resume to be the most common source of human and economic misery, as observed during the 2015 Nepal earthquake (Dutta *et al*. 2016), 2015 Hindu Kush earthquake (Ismail and Khattak 2019), Sikkim earthquake (Dutta *et al*. 2015), Kashmir earthquake (Rossetto and Peiris 2009), and Bhuj earthquake (Jagadish *et al*. 2003).

The poor earthquake performance of URM structures has necessitated a seismic re-evaluation capability of the current URM structure and the investigation of a suitable strengthening approach for a freshly constructed structure or for retrofitting an older structure (Shermi and Dubey 2018). Over the last few decades, extensive investigation has been conducted to establish an efficient, cost-effective, and durable strengthening technology for susceptible non-engineered URM structures to improve their seismic performance. Some of the rehabilitation and retrofitting techniques over the last few decades include repairing and retrofitting using injection grouting (Schuller *et al*. 1994), retrofitting using shotcrete (ElGawady *et al*. 2006), strengthening by bed joints structural repointing (Valluzzi *et al*. 2005), improvement of masonry performance using elastic post-tensioning straps (Ahmet Turer *et al*. 2007), etc. Apart from the repair and retrofitting techniques considered, some of the most recent strengthening techniques of this decade include the implementation of fibre-reinforced polymer (FRP), engineered cementitious composite (ECC), and textile-reinforced mortar (TRM).

Ample investigation has been performed to strengthen URM's wall using FRP in the form of glass-fiber-reinforced polymer (GFRP) and carbon-fiber-reinforced polymer (CFRP), which increases the flexural and shear resistance along with an increase in the strengthened masonry's ductility (Anil *et al.* 2012, Doran *et al.* 2021, Elmalyh *et al.* 2020, Gattesco and Boem 2015, Sistani

Fig. 2 Failure of masonry wall during an earthquake (source: Tripathy and Singhal 2021, Asian News International)

Nezhad and Kabir 2017). However, using FRP has certain drawbacks related to its ineffectiveness in applying on wet surfaces and substrate materials, and poor performance at high temperatures. In addition, there are several disadvantages associated with epoxy adhesives, such as occupational hazards, damp incompatibility, lack of vapor permeability, thermal compatibility issues, lack of fire resistance, and poor adhesion to rough masonry surfaces (Kouris and Triantafillou 2018). To alleviate the problem FRP faces, it has been suggested that using inorganic matrices in place of resin provides improvement in terms of fire resistance, vapour permeability, coating compatibility with the substrate, and reinforcing reversibility (Xin and Ma 2021). Several authors have performed studies that incorporate ECC and TRM as a strengthening material to strengthen URM walls and overcome FRP limitations (Donnini *et al.* 2021, Ismail and Ingham 2016, Lin *et al.* 2014, Lin *et al.* 2016; Maalej *et al.* 2010, Giaretton *et al.* 2018). However, using ECC and TRM as a strengthening material to strengthen URM walls may not be economical in developing countries like India. The high construction level, cost, non-availability in the local market, and importing from the cheapest sources proves expensive. Materials such as ECC and TRM may find it difficult to be promoted in developing and underdeveloped areas.

New strengthening techniques and materials are being extensively researched and are in high demand for the simple reason that no one technique can address all the reasons for strengthening demand within a certain geographical bound. The use of low-cost welded wire mesh (WWM) to strengthen masonry walls has recently become highly popular since it adds a large amount of strength and ductility to the structure (Banerjee *et al.* 2018). In a developing nation like India, wire mesh may be utilized as a strengthening material for masonry structures since it is inexpensive and readily accessible. Strengthening using closely spaced wire mesh embedded in mortar is called ferrocement overlay. This technology is simple, quick to construct, and inexpensive, especially in developing nations where heavy machinery and highly qualified labour are lacking. Some of the advantages of employing wire mesh for reinforcement include: (1) wire mesh has high tensile strength, high modulus of elasticity, low weight, corrosion resistance, easy installation, minimum change in dimensions of the sections (Syiemiong and Marthong 2020) (2) Cost-competitive solution (3) Requirement of minimal skilled labour (4) No particular measure taken to guarantee the bonding between masonry (this process is advantageous over FRP) (Kaish *et al.* 2018).

Wire mesh in the form of ferrocement is a very old material that was first employed by Joseph Louis Lambot, a Frenchman, in 1848 when he built a ferrocement boat. The material has grown in popularity in developing countries due to its versatility and forgiving nature, ease of use, and low maintenance (Rafeeqi and Ayub, 2011). The fundamental advantage of ferrocement is that it eliminates the complicated formwork of reinforced cement concrete and the welding required for structural steelwork; Everything can be done by hand, and no expensive machines are needed. The

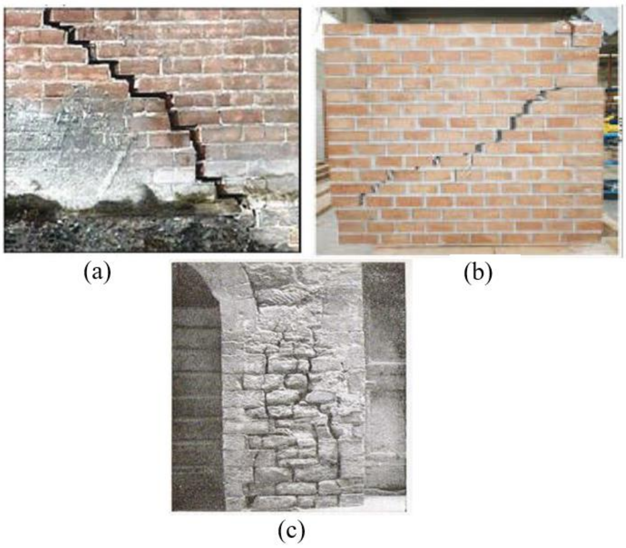

Fig. 3 The local failure mode of URM: (a) detachment failure, (b) detachment fractures alternate line of sliding, and (c) compression failure (source: Angelillo *et al*. 2014)

American Society published the first national specification for Testing and Materials (ASTM) in 1936 (Bernold 1992). Organizations like the American Association of State Highway and Transportation Officials (AASHTO) and the ACI (ACI detailing manual-1988) provide design guidelines that allow the use of WWM as structural reinforcement. The American Concrete Institute Committee presents a guide in ACI 549.1R-93 that covers materials for Ferro-cement and also the Indian standard codal specification (IS 13935: 2009) prescribed the use of galvanized steel wire fabric to repair and strengthened masonry walls.

Some research being investigated on the potential structural applications of steel wire mesh include (1) strengthening of structural elements (Abu Maraq *et al.* 2021, Kumar and Patel 2016, Mourad and Shannag 2012, Qeshta *et al.* 2014). (2) strengthening of masonry elements (Yardim and Lalaj, 2016). In a collaboration initiative between the Indian Institute of Technology Roorkee, India, and Nanyang Technological University, Singapore, the wire mesh retrofitting approach was recently employed to retrofit six school buildings in the Indian Himalayas (Kadam *et al.* 2014). The current paper reviews the findings concerning the possible utilization of steel wire mesh as a reinforcing material to enhance masonry buildings and masonry components.

2. Strengthening of un-reinforced masonry walls

2.1 Compression strengthening of URM

Under the action of load, URM walls commonly exhibit two modes of failure, namely local failure and structural failure. Under local failure, there are three locally visible failure modes. The first is detachment failure, as shown in Fig. 3(a). The second is the mixed mode of failure, wherein detachment fractures occur in alternating lines of sliding, as presented in Fig. 3(b). The third is compression failure associated with crushing of the material, as illustrated in Fig. 3(c). The first

Fig. 4 Strengthening of URM walls using wire mesh and plastering using mortar. (Source: Sandoval *et al*. 2021)

form of fracture is the most common and typically unimportant. The second and third modes of failure are frequently encountered when the load is critical or on the brink of collapse. The third mode of failure is the most hazardous since compression failure is generally sudden (Angelillo 2014). URM walls typically perform very well under compression. However, there are cases where walls operate near compression strength and their capacity is jeopardized because URM walls tend to collapse brittle.

Chourasia *et al*. (2019) investigated mesh materials such as WWM, hexagonal mesh, nylon mesh, plastic cement bag mesh, industrial geogrid mesh, and polypropylene band mesh to strengthen masonry prisms and wallets. The result indicates that the steel mesh provides effective confinement since the masonry prism reinforced with WWM has much higher compressive strength than other retrofitting materials. Hamdy *et al.* (2018) used GFRP sheets, GFRP strips, ferrocement, and steel bars to strengthen walls with the doors opening. It was observed that fully wrapping the masonry wall with ferrocement showed the highest increase in average ultimate load.

Sandoval *et al.* (2021) studied the effect of transverse connectors for the wire mesh strengthened hollow brick masonry and found that completely encasing both sides of the masonry with WWM and then plastering with mortar, as shown in Fig. 4. could increase the stiffness and axial strength by 3.2 and 2.3 times higher than URM panels. Further, the number of transverse connections guarantees that both layers of mortar work together to reduce buckling length and increase the axial compressive strength of the reinforced prisms.

Elsamny *et al*. (2016) rehabilitated damaged masonry wallets with openings using different layers of steel wire mesh with or without the addition of steel bars. The test result indicates an increase in performance was observed for rehabilitating damaged masonry wallets using steel wire

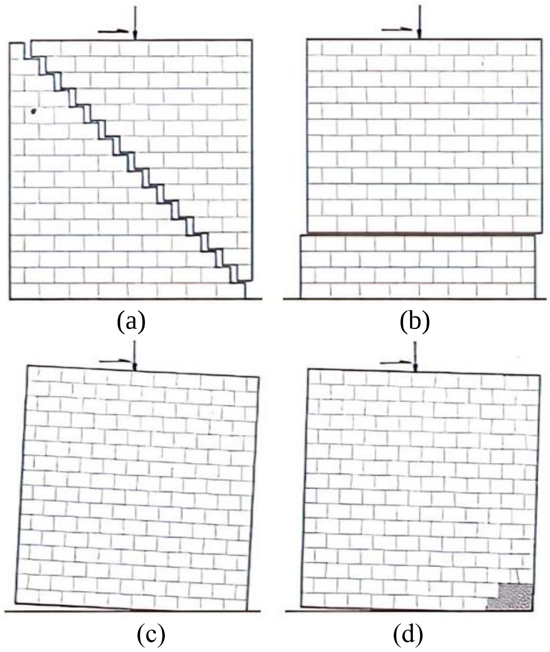

Fig. 5 In-plane failure modes of a laterally loaded URM wall: (a) shear failure, (b) sliding failure, (c) rocking failure and (d) toe crushing. (ElGawady *et al.* 2006)

mesh with or without steel rebar. Elsamny *et al*. (2017a) placed different numbers of steel wire mesh strips in the bed joints of the masonry wallets. The test results indicate increasing the number of steel wire mesh strips saw an increase in the load-carrying capacity of the masonry wallets with an increase in ductility. Elsamny *et al.* (2017b) reinforced brick masonry wallets with openings by connecting steel wire mesh strips plastered using cement mortar along both faces of the wall openings, with varying widths of steel wire mesh strips. It was discovered that an increase in load-carrying capacity and ductility was observed in the reinforced brick masonry wallets when the strips of steel wire mesh were increased. El-Salakawy and Hamdy (2021) used ferrocement layers and near-surface-mounted steel bars to preserve the load carrying capacity when an opening is made in the wall. The test results indicate that both the strengthening materials were able to enable openings in loaded walls

From the literature survey, it is evident that wire mesh proved effective for strengthening masonry walls. Applying wire mesh strips in the bed joint, applying strips of steel wire mesh, or fully wrapping the masonry using steel wire mesh has shown its effectiveness in rehabilitating and retrofitting masonry walls when subjected to compression loading, with an increased load-carrying capacity and ductility of the brick walls. Further, when the masonry wallets are fully covered with steel wire mesh, transverse connections serve a primary role in retaining mortar overlays operational and decreasing the buckling length.

2.2 In-plane strengthening of URM

Apart from the local failure experienced by the URM walls under the action of loading, URM walls can also fail through structural failure. In the event of structural failure, URM walls are prone to both out-of-plane and in-plane failure. The weak tensile strength between the brick and mortar is mainly responsible for URM masonry's out-of-plane failure. Due to its inherent weakness in out-of-plane action, the unreinforced masonry (URM) wall primarily relies on in-plane action to resist lateral loads. When the loading direction is along the face of the wall, the corresponding failure in the URM wall is referred to as in-plane failure. This form of failure is found in proper and well-designed buildings (Angelillo 2014). Common in-plane failure modes are diagonal shear failure, horizontal shear failure, and rocking failure, as presented in Fig. 5**.**

Yardim and Lalaj (2016) investigated different strengthening materials such as ferrocement jacketing, polypropylene fiber reinforced mortar jacket, and textile-reinforced mortar strengthened on one side or both sides of the wallet. Two layers of wire mesh were utilized on either side of the wallets for the ferrocement strengthened wallets. The ferrocement jacketed panels observed a higher stiffness and shear strength than other strengthened panels. Chourasia *et al*. (2019) investigated mesh materials such as WWM, hexagonal mesh, nylon mesh, plastic cement bag mesh, industrial geogrid mesh, and polypropylene band mesh to strengthen masonry prisms and wallets. The test results indicated that shear strength was highest for the plastic cement bag mesh wallets, followed by WWM wallets and industrial geogrid mesh wallets. Banerjee *et al*. (2018) strengthened masonry wallets using steel wire mesh and polypropylene band and observed that the shear strength contribution was more for the wire mesh strengthened masonry. Again, Banerjee *et al.* (2020a) strengthened masonry wallets using steel wire mesh and polypropylene band. Out of the two strengthening materials, the test result indicates that the wire mesh strengthened wallets contributed more toward the shear strength particularly the double-sided strengthened wallets, due to the confinement provided by the wire mesh. The author also observed that the half-scale wallets failed in the same way as the full-scale wallets, confirming the in-plane behaviour of the scaled-down model.

Amanat *et al.* (2007) rehabilitated infilled masonry using ferrocement and observed that the cracked frame was not repaired but only coated using Ferro-cement. However, the width of the crack opening was significantly smaller than the original frame; the failure load of the repaired frame was higher than that of the original frame. Kadam *et al.* (2014) strengthened single wythe thick and two wythes thick wallets reinforced using WWM and micro-concrete. The test results indicate the effectiveness of the strengthening techniques with the highest improvement in shear strength and ductility observed in one-wythe thick masonry wallets compared to two-wythe thick masonry wallets because of the increased reinforcement ratio in the one-wythe wallets. It was also observed that the two anchorage scenarios (uni-directional and bi-directionally anchored) have an effect on failure mode but have no impact on capacity enhancement. Shermi and Dubey (2018) investigated the effect of mortar type on masonry panels, reinforced using WWM of spacing (25 mm, 38 mm, and 50 mm). The results indicated that all the strengthened samples significantly increased the shear strength and ductility compared to URM; however, debonding was observed in the URM panels reinforced with 50 mm WWM and 1:4 cement sand mortar. Suraj and Unnikrishnan (2020) studied concrete block masonry wallets reinforced with different types and sizes of steel wire mesh, such as 12 mm, 25 mm, and hexagonal wire mesh. It was observed that the reinforced masonry wallets operate as a single composite material and resists cracking along masonry panel joints. The author concluded that using wire mesh with a spacing of 25 mm improves the procedure's effectiveness. Banerjee *et al.* (2020b) strengthened masonry wallets using steel wire mesh with different orientations. The test results indicate that the wallets that were completely covered with steel wire mesh experienced the greatest increase in strength compared to the other configurations; Ductility was greatest for fly-ash brick wallets covered by wire mesh. Further, out-of-plane distortion was seen for single-sided strengthened wallets. Sandoval *et al*. (2021) investigated the effect of

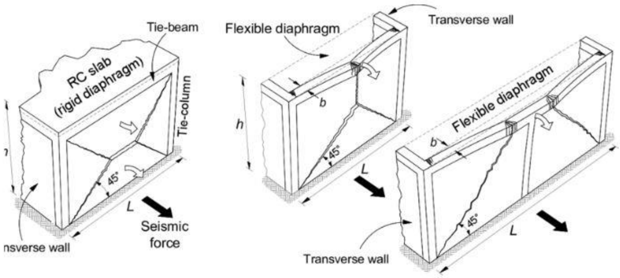

Fig. 6 The out-of-Plane failure mechanism of masonry wall (Source: http://achyutpaudel.com.np/)

transverse connectors for WWM strengthened hollow clay bricks masonry and discovered that masonry with more transverse connectors has higher shear strain, shear ductility, and energy dissipation capacity compared to masonry with fewer transverse connectors. It was also observed that the increased steel ratio offered by the WWM in the mortar promotes energy dissipation and considerably aids in the crack distribution along the sample. Furthermore, the effect of the transverse connection minimizes the effective length of buckling of the mortar overlay, resulting in improved performance. Tripathy and Singhal (2021) studied many parameters that influence the effectiveness of poor masonry. The test result shows that for a peculiar grade of cementitious matrix; when wire mesh size was changed from thin to thick, the thicker mesh showed a slightly higher deformation capacity. Further, based on the effect of the cementitious matrix, the cementitious matrix's ultimate deflection capacity was roughly the same as that of the mud mortar but the mud mortar had a greater deformation capacity. Warjri *et al.* (2022) experimentally investigated masonry wallets strengthened using different patterns and reinforcement percentages of WWM. The test results indicate that the smallest increases were observed when the WWM was placed on the bed joints and the highest increases were observed when the WWM was placed entirely on the wall surfaces.

The literature survey concludes that steel wire mesh proved effective for rehabilitation and retrofitting masonry wallets under in-plane loading compared to other low-cost strengthening materials. Externally bonding the steel wire mesh to the masonry wallets using different orientations shows good results. Still, when fully wrapped using the steel wire mesh on both sides of the masonry wallets, the confinement produced by the steel wire mesh had better results in terms of shear strength and ductility. It was also observed that using steel wire mesh with a higher percentage ratio showed a slightly higher deformation capacity; this case was also prevalent in one-wyte wallets showing the highest shear strength than the two-wyte wall because of the higher percentage of steel ratio. However, using wire mesh with a spacing of 25 mm improves the procedure's effectiveness. Furthermore, de-bonding is an important issue faced by the wallets reinforced using steel wire mesh where the full capacity of the wire mesh could not be utilized. The literature survey observed that the anchorage plays an important role wherein the strength of the masonry with more transverse connectors was higher. The transverse connections effect minimizes the effective length of buckling of the mortar overlay, resulting in improved performance.

2.3 Out of plane strengthening of URM

Another common structural failure mechanism is the out-of-plane failure of the URM wall, which results from poor design or modification of the original construction (Angelillo 2014). During an earthquake, when the loading direction is perpendicular to the wall face, the corresponding failure in the URM wall is referred to as out-of-plane failure; depending upon the geometry of the URM wall, i.e., whether the wall is too high or too long, the URM walls may have a vertical or a horizontal out-of-plane failure, out-of-plane failure is characterized by delamination or complete fracture of the wall, as presented in Fig. 6. In comparison to in-plane failure, out-of-plane failure causes more severe consequences. Considering the topic's importance, several studies performed to upgrade the URM wall's performance against out-of-plane failure have been gathered and discussed.

Banerjee *et al.* (2019) compared the effectiveness in enhancing the flexural behaviour using steel wire mesh and PP band. The test result indicated that the effectiveness was observed in the steel wire mesh in terms of flexural capacity when compared to PP band. The enhancement in strength and energy dissipation capability was observed for the wallets reinforced on both sides of the wallets. However, wallets reinforced only on the tension and compression face of the wallets show an improvement in ductility.

Kadam *et al.* (2015) reinforced URM walls using WWM and micro-concrete. The test result indicates that unidirectionally and bidirectionally anchored WWM wallets were identical and flexural cracks initiated the failure, which the WWM later restrained. It was also observed that the URM wallets' flexural capacity depends on the direction of loading, whereas the flexural capacity of reinforced wallets is independent of the loading direction since the reinforcement dictates it. Shermi and Dubey (2017) investigated the effect of mortar type on masonry panels, reinforced using WWM of spacing (25mm, 38mm, and 50mm). The results indicated that wallets constructed with 1:6 cement-sand ratio behaved more ductile than wallets constructed with 1:5 cement-sand ratio with the WWM influencing the ultimate failure mode. Further, the specimens reinforced with 38 mm wire mesh behave twice more ductile than specimens reinforced with 25 mm and 50 mm WWM. Padalu *et al.* (2018) investigated the impact of the shear span to depth ratio on reinforced wallets. Firstly, the series-A masonry wallets, i.e., (shear span to depth ratio 1.17); when the wallets were reinforced with 25 mm grid spacing of WWM, the failure was triggered by shear sliding or diagonal shear fractures. However, when the wallets were reinforced with WWM grid spacing of 50 mm, most of the samples failed due to flexural failure, resulting in WWM rupture. Further, in the series-B masonry wallets, i.e. (shear span to depth ratio 2.24), flexural failure was seen in most samples, when the wallets were reinforced with 25 mm or 50 mm grid spacing of WWM. Second, it was discovered that the strength of reinforced wallets is determined not only by the reinforcement ratio but also by the direction of loading. Banerjee *et al.* (2020b) strengthened masonry using steel wire mesh with different orientations and observed that when subjected to loads orthogonal to the bed joint, the flexural strength showed the highest improvement when the face of the masonry wallets was completely covered. Further, all the cases saw a reduced improvement in flexural strength when subjected to load parallel the bed joint except for when the wallets were fully covered with steel wire mesh.

Syiemiong and Marthong (2020) investigated the influence of different types of mortar which bonded masonry wallets reinforced using WWM. the failure mode indicates that the URM wallets are not affected by the strength of the mortar. However, the mortar composition influenced the first crack load and the inclusion of the WWM resulted in the full mobilization of the mortar strength, with the strengthened specimens failing in a ductile manner. Syiemiong and Marthong 2021 further extended the research and observed that there is a significant variation in ductility between the reinforced wallets bonded using a weak mortar and medium/strong mortar. However, from a practical point of view, the effect of the kind of mortar mixes on the flexural strength of masonry wallets should be regarded as minor. The author concluded that the use of WWM with a spacing of

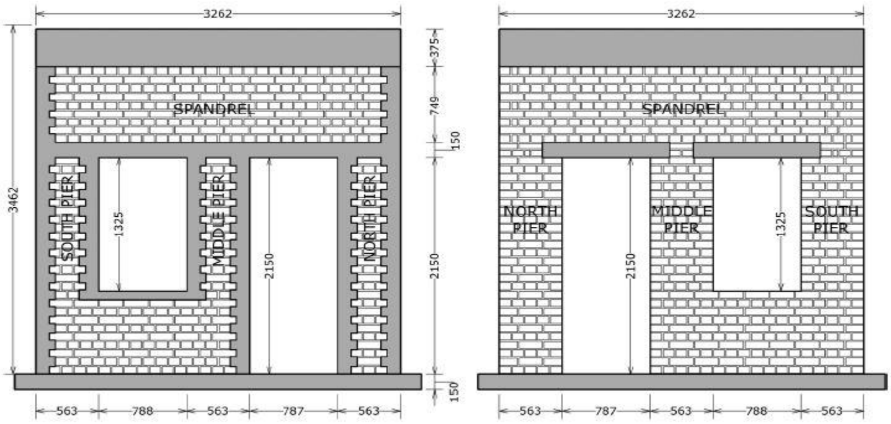

Fig. 7 Confined masonry walls and Unreinforced masonry walls (source: Ashraf *et al*. 2012)

30 mm and a mortar grade (1:3) effectively improves the strength of low-strength hollow concrete block masonry, with no debonding of the WWM. Tripathy and Singhal (2021) studied many parameters that influence the effectiveness of poor masonry. The test result indicates that the flexural strength of all reinforced masonry walls increases, regardless of the quality of the cement matrix. Depending on the size of the wire mesh, specimens reinforced with thin wire mesh experienced substantial deformation prior to failure. Conversely, specimens reinforced with thick wire mesh might be associated with masonry shear failure or wire mesh debonding failure indicating that the sample might be over-reinforced. Marbaniang *et al.* (2022) strengthened masonry wallets using WWM applied using different orientations. The test results indicate that the strengthened specimens failed due to rupture of WWM when the specimens were loaded perpendicular to the bed joint whereas a sudden brittle failure was observed for the specimens loaded parallel to the bed joint. It was also observed that for the fully covered wallets, the WWM's contribution was independent of loading direction, whereas other strengthening orientations did not show the same results.

The research review shows that steel wire mesh outperformed alternative low-cost reinforcing materials for rehabilitation and retrofitting masonry structures under out-of-plane loading. The use of steel wire mesh enhances the flexural strength and ductility of clay, fly ash, and hollow concrete block masonry structures; the addition of the steel wire mesh resulted in the complete mobilization of the mortar strength, with the reinforced specimens collapsing slowly and in a ductile manner. Externally connecting the steel wire mesh to the masonry surface using different orientations produces good results. However, fully wrapping the masonry wallets with steel wire shows good improvement in terms of strength and ductility. It was concluded that anchorage could be provided at regular intervals to improve performance, avoid the de-bonding failure, and transform the failure to the ductile failure of strengthened masonry wallets. Flexural failure is most prevalent in one-wyte thick wallets, whereas the thicker two-wyte wallets fail due to shear or flexure depending upon the direction of loading, implicating the importance of the direction of loading.

2.4 Cyclic loading conditions

In the event of an earthquake, the masonry structure is subjected to a repeated and continuous

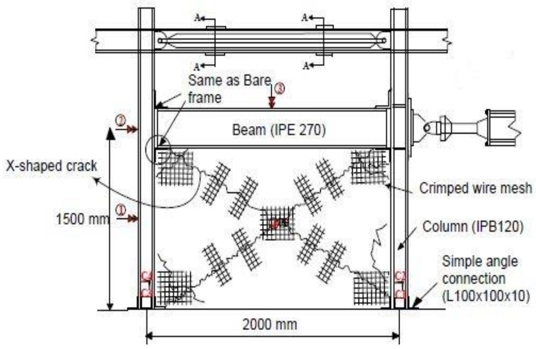

Fig. 8 Repaired Infill. (Source: Ghobadi *et al.* 2019)

application of loading that causes material degradation and ultimately leads to fatigue. The behavior of masonry structures and the efficiency of employing steel wire mesh for rehabilitation and strengthening under such loading conditions have been gathered and discussed.

Sathiparan *et al.* (2016) investigated several mesh-type materials for retrofitting URM panels, including polymer mesh, steel mesh, industrial geo-grid, polypropylene band, and plastic carry bags. The test findings show that all mesh-type materials may increase the residual strength, stiffness, and energy dissipation of the URM, with steel mesh retrofitted URM panels having the greatest residual strength among all retrofitted panels.

Ashraf *et al*. (2012) retrofitted URM wallets and confined masonry wallets with an opening in the form of a door and windows, (Fig. 7). The test result indicates that the URM wallets retrofitted with grout injection and ferrocement overlay improves the lateral strength and effective stiffness by 110% and 68%, respectively. Though, the energy dissipation capability of both wallets was unaffected. However, the seismic performance of retrofitted URM wallets was equivalent to that of confined masonry wallets that had not been altered.

El-Diasity *et al.* (2015) retrofitted confined masonry wallets using GFRP and ferrocement and tested under in-plane cyclic loading. The test result indicates that the retrofitting techniques enhanced the lateral resistance of the confined wallets by 25% to 32% and the overall energy dissipation by 33% to 85%. It was observed that the updated X- diagonal connection layouts and full coverage could aid in the prevention of diagonal shear failure and transition to a rocking failure mode for the undamaged wallets. Ghobadi *et al.* (2019) examine the function of infill in bare steel frame and the rehabilitation process for earthquake-damaged masonry by fixing crimped wire mesh with hook-driven nails. According to the test findings, the rehabilitation method as shown in Fig. 8. would be able to restore the damaged structure load performance; the damaged infill's energy dissipation was efficiently recovered and its undesirable asymmetric cyclic behavior was corrected. Furthermore, the diagonal tension failure mode was modified to corner crushing.

Carrillo *et al*. (2020) investigated confined masonry walls made with multi-hollow clay brick, reinforced with WWM and hooked end steel fibers, and tested under reverse cyclic loaded. The test findings show that the strengthened wall has higher lateral strength (about 20%), and a lesser reduction in lateral drift (up to 0.4%) than the un strengthened wall. The failure mode of the WWM strengthened wall was dictated by sliding shear along the base of the wall. De Silva and Abeygunawardana (2020) retrofitted wallets with and without openings using different ferrocement belt configurations and tested them against reverse cyclic loading. From the test results, it was observed that the retrofitted wallets saw an improvement in the in-plane and ductility capabilities; the increase in ductility was in the range of 310 % - 500 % for all the strengthened specimens.

Ashraf *et al*. (2011) studied the cyclic stress of a life-size damaged masonry building retrofitted with ferrocement cladding and cement mortar injection. According to the test findings, the damage was shifted from a combined compression- shear-flexural mode to a more stable flexural rocking mode. The load-carrying capacity and lateral stiffness were enhanced by 107% and 129%. Further, the deformation capacity and ductility both drop by 26% and 15% respectively with no substantial difference in the energy dissipation capacity. Ali Shah *et al*. (2017) investigated the behavior of a full-size confined masonry building under reverse cyclic loading before and after retrofitting with ferrocement cladding. The test results indicate that before retrofitting, a combination of shear-flexure failure was observed. However, the dominant mode of deformation for the retrofitted building was global and local rocking. Lateral stiffness, load-carrying capacity, and deformation capacity all rose by 12%, 4%, and 49%, respectively, while ductility decreased by 8%. Banerjee *et al.* (2021) strengthened a scale-down single-story box-shaped masonry structure made up of clay and fly ash bricks using steel wire mesh and PP band. The test results demonstrate that when the building model was reinforced with steel wire mesh, the confinement of the steel wire mesh increases the strength of the clay and fly-ash building models by 1.31 and 1.9 times, respectively, and withstood 2 and 1.2 times more input energy. Xin and Ma (2021) repaired 1/3 scale masonry walls using ferrocement overlay combined with grout injection. The test results indicate that the repaired process changed the failure mode from diagonal shear failure to a flexural dominant failure mode. It was also observed that the ultimate resistance and residual strength were increased by 6% and 13%; the overall ductility increased by 2.72 times.

The literature survey demonstrates the use of steel wire mesh to rehabilitate or retrofit masonry structures under cyclic loading. It was observed that strengthening the masonry walls by applying ferrocement belts resulted in a performance improvement. When steel wire mesh was used to reinforce confined and unreinforced masonry walls, the seismic capacity of URM wallets was equivalent to that of confined masonry wallets that had not been altered. It was also observed that connecting X- diagonal layouts and full covering the confined masonry walls could aid in the prevention of diagonal shear failure and transition to a rocking failure mode for the undamaged wallets. Further, when the full-size confined masonry building was retrofitted with ferrocement cladding. The damage process also changed from a combined bending-shear-compression mode to a stable bending-rocking mode.

3. Conclusions

The poor performance of URM during earthquakes has necessitated a reassessment of the current URM structure's earthquake capabilities and the investigation of an appropriate strengthening approach for strengthening a newly built masonry building or retrofitting an existing old structure. New strengthening techniques and materials are being extensively researched and are in high demand for the simple reason that no one technique can address all the reasons for strengthening demands within a certain geographical bound. Wire mesh, being cost-effective and easily available, can be used to repair and retrofit URM buildings. The use of wire mesh to repair and retrofit URM building technology is simple to use, quick to construct, and inexpensive, especially in developing nations where heavy machinery and highly qualified labour are lacking.

A brief review on the main issue on the potential utilization of steel wire mesh to rehabilitate and retrofit masonry structures has been compiled. The behaviour of masonry rehabilitated and retrofitted incorporating steel wire mesh under compression, in-plane, out-of-plane, and cyclic loading conditions have been discussed. The test results reported gave an encouraging for field application of WWM as a cost-effective strengthening material. Though commendable and extensive research has been carried out in the field of masonry construction throughout the world in recent years, but little research has been directed specifically to new low strength masonry units. i.e the Autoclaved Aerated Concrete (AAC). It is, therefore, essential to examine the structural behaviour of such low-strength masonry buildings to similarly enhance the knowledge and add to the prevailing wealth of information on masonry buildings. The study of feasible and cost-effective strengthening strategies for such low-strength masonry buildings is likewise necessitated.

References

Abu Maraq, M.A., Tayeh, B.A., Ziara, M.M. and Alyousef, R. (2021), "Flexural behavior of RC beams strengthened with steel wire mesh and self-compacting concrete jacketing - Experimental investigation and test results", *J. Mater. Res. Tech.*, **10**, 1002-1019. https://doi.org/10.1016/j.jmrt.2020.12.069.

ACI 549.1R-93 (1993), Guide for design, construction & repair of Ferrocement, ACI, Michigan, USA.

ACI detailing manual-1988 (1988), ACISP-66, American Concr. Inst., Detroit, Michigan.

Ali Shah, S.M., Shahzada, K., Gencturk, B. and Memon, S.A. (2017), "Retrofitting of full-scale confined masonry building using ferro-cement overlay", *J. Perform. Constr. Fac.*, **31**(5), 04017079. https://doi.org/10.1061/(asce)cf.1943-5509.0001060.

Amanat, K.M., Alam, M.M.M. and Shahria Alam, M. (2007), "Experimental investigation of the use of ferrocement laminates for repairing masonry in filled RC frames", *J. Civil Eng.*, **35**(2), 71-80.

Angelillo, M. (2014), *Mechanics of Masonry Structures*, **551**. https://doi.org/10.1007/978-3-7091-1774-3

Anil, Ö., Tatayolu, M. and Demirhan, M. (2012), "Out-of-plane behavior of unreinforced masonry brick walls strengthened with CFRP strips", *Constr. Build. Mater.*, **35**, 614-624. https://doi.org/10.1016/j.conbuildmat.2012.04.05.

Ashraf, M., Khan, A.N., Ali, Q., Shahzada, K. and Naseer, A. (2011), "Experimental behavior of full scale URM building retrofitted with ferrocement overlay", *Adv. Mater. Res.*, **255-260**, 319-323. https://doi.org/10.4028/www.scientific.net/AMR.255-260.319.

Ashraf, M., Khan, A.N., Naseer, A., Ali, Q. and Alam, B. (2012), "Seismic behavior of unreinforced and confined brick masonry walls before and after ferrocement overlay retrofitting", *Int. J. Architect. Heritage*, **6**(6), 665-688. https://doi.org/10.1080/15583058.2011.599916.

Banerjee, S., Nayak, S. and Das, S. (2018), "Enhancing shear capacity of masonry wallet using PP-band and steel wire mesh", *Proceedings of the IOP Conference Series: Materials Science and Engineering*, **431**(7). https://doi.org/10.1088/1757-899X/431/7/072004.

Banerjee, S., Nayak, S. and Das, S. (2019), "Enhancing the flexural behaviour of masonry wallet using PP band and steel wire mesh. *Constr. Build. Mater.*, **194**, 179-191. https://doi.org/10.1016/j.conbuildmat.2018.11.00.

Banerjee, S., Nayak, S. and Das, S. (2020a), "Improving the in-plane behavior of brick masonry wallet using PP band and steel wire mesh", *J. Mater. Civil Eng.*, **32**(6), 04020132. https://doi.org/10.1061/(asce)mt.1943-5533.0003159.

Banerjee, S., Nayak, S. and Das, S. (2020b), "Shear and flexural behaviour of unreinforced masonry wallets with steel wire mesh", *J. Build. Eng.*, **30**. https://doi.org/10.1016/j.jobe.2020.101254.

Banerjee, S., Nayak, S. and Das, S. (2021), "Seismic performance enhancement of masonry building models strengthened with the cost-effective materials under bi-directional excitation", *Eng. Struct.*, **242**. https://doi.org/10.1016/j.engstruct.2021.112516.

Bernold, L.E. and Chang, P. (1992), "Potential gains through welded-wire fabric reinforcement", *J. Constr.*

Eng. Management, **118**(2), 244-257. https://doi.org/https://doi.org/10.1061/(ASCE)0733-9364(1992)118:2(244).

Carrillo, J., Pincheira, J.A. and Flores, L.E. (2020), "Quasi-static cyclic tests of confined masonry walls retrofitted with mortar overlays reinforced with either welded-wire mesh or steel fibers", *J. Build. Eng.*, **27**, 1-10. https://doi.org/10.1016/j.jobe.2019.100975.

Chourasia, A., Singhal, S. and Parashar, J. (2019), "Experimental investigation of seismic strengthening technique for confined masonry buildings", *J. Build. Eng.*, **25**.https://doi.org/10.1016/j.jobe.2019.100834.

De Silva, S. and Abeygunawardana, N.T. (2020), "Performance of ferro-cement strengthened unreinforced masonry walls against reverse cyclic loading", *Engineer: J. Institution of Engineers, Sri Lanka*, **52**(4), 11. https://doi.org/10.4038/engineer.v52i4.7345.

Donnini, J., Maracchini, G., Lenci, S., Corinaldesi, V. and Quagliarini, E. (2021), "TRM reinforced tuff and fired clay brick masonry: Experimental and analytical investigation on their in-plane and out-of-plane behavior", *Constr. Build. Mater.*, **272**. https://doi.org/10.1016/j.conbuildmat.2020.121643.

Doran, B., Ulukaya, S., Unsal Aslan, Z., Karslioglu, M. and Yuzer, N. (2021), "Experimental investigation of CFRP strengthened unreinforced masonry walls with openings", *Int. J. Archit. Heritage*, **16**(12), 1-14. https://doi.org/10.1080/15583058.2021.1918286.

Dutta, S.C., Mukhopadhyay, P.S., Saha, R. and Nayak, S. (2015), "2011 Sikkim earthquake at eastern himalayas: Lessons learnt from performance of structures", *Soil Dyn. Earthq. Eng.*, **75**, 121-129. https://doi.org/10.1016/j.soildyn.2015.03.020.

Dutta, S.C., Nayak, S., Acharjee, G., Panda, S.K. and Das, P.K. (2016). "Gorkha (Nepal) earthquake of April 25, 2015: Actual damage, retrofitting measures and prediction by RVS for a few typical structures", *Soil Dyn. Earthq. Eng.*, **89**, 171-184. https://doi.org/10.1016/j.soildyn.2016.08.010.

El-Diasity, M., Okail, H., Kamal, O. and Said, M. (2015), "Structural performance of confined masonry walls retrofitted using ferrocement and GFRP under in-plane cyclic loading", *Eng. Struct.*, **94**, 54-69. https://doi.org/10.1016/j.engstruct.2015.03.035.

ElGawady, M., Lestuzzi, P. and Badoux, M. (2006), "Retrofitting of masonry walls using shotcrete", *Proceedings of the NZSEE Conference*, **45**, 45-54.

Elmalyh, S., Bouyahyaoui, A., Cherradi, T., Rotaru, A. and Mihai, P. (2020), "Shear strength of unreinforced masonry walls retrofitted with CFRP", *Adv. Sci. Tech. Eng. Syst.*, **5**(2), 351-359. https://doi.org/10.25046/AJ050246.

Elsamny, M.K., Abd-Elhamed, M.K. and Mahmoud, M.H. (2016), "Rehabilitation of brick walls with openings using steel wire mesh", *Int. J. Sci. Eng. Res.*, **7**(12).

Elsamny, M.K., Abd-Elhamed, M.K. and Elmokrany, A.A. (2017a), "Experimental study of brick walls with opening strengthened during construction by using steel wire mesh embedded into bed joint mortar between bricks", *Int. J. Eng. Res. Tech.*, **6**(1), 49-59.

Elsamny, M.K., Ezz-Eldeen, H.A. and Elmokrany, A.A. (2017b), "Strengthening of brick walls with openings during construction by steel wire mesh around openings on both sides of wall", *IOSR J. Mech. Civil Eng.*, **14**(3), 131-139. https://doi.org/10.9790/1684-140305131139.

El-Salakawy. T. and Hamdy, G. (2021), "Experimental and numerical investigation of strengthening of openings in masonry walls using steel bars and steel wire mesh", *Eur. J. Environ. Civil Eng.*, https://doi.org/10.1080/19648189.2021.1997828.

Gattesco, N. and Boem, I. (2015). "Experimental and analytical study to evaluate the effectiveness of an in-plane reinforcement for masonry walls using GFRP meshes", *Constr. Build. Mater.*, **88**, 94-104. https://doi.org/10.1016/j.conbuildmat.2015.04.01.

Ghobadi, M.S., Jazany, R.A. and Farshchi, H. (2019), "In situ repair technique of infill masonry walls in steel frames damaged after an earthquake", *Eng. Struct.*, **178**, 665-679. https://doi.org/10.1016/j.engstruct.2018.10.022.

Giaretton, M., Dizhur, D., Garbin, E., Ingham, J.M. and da Porto, F. (2018), "In-plane strengthening of clay brick and block masonry walls using textile-reinforced mortar", *J. Compos. Constr.*, **22**(5), 04018028. https://doi.org/10.1061/(asce)cc.1943-5614.0000866.

Hamdy, G., El-Salakawy, T. and El-Gendy, A. (2018), "Strengthening loaded masonry walls to enable making openings – experimental and numerical investigation", *Int. J. Sci. Eng. Res.*, **9**(11), 1149-1161.

IS 13935 (2009), Indian Standard Code of Evaluation, Repair and Strengthening of Masonry Building. Bureau of Indian Standards, New Delhi.

Ismail, N. andIngham, J.M. (2016), "In-plane and out-of-plane testing of unreinforced masonry walls strengthened using polymer textile reinforced mortar", *Eng. Struct.*, **118**, 167-177. https://doi.org/10.1016/j.engstruct.2016.03.041.

Ismail, N. and Khattak, N. (2019), "Observed failure modes of unreinforced masonry buildings during the 2015 Hindu Kush earthquake", *Earthq. Eng. Eng. Vib.*, **18**(2), 301-314. https://doi.org/10.1007/s11803-019-0505-x.

Jagadish, K.S., Raghunath, S. and Nanjunda Rao, K.S. (2003), "Behaviour of masonry structures during the Bhuj earthquake of January 2001", *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, **112**(3), 431-440. https://doi.org/10.1007/BF02709270.

Kadam, S.B., Singh, Y. and Li, B. (2014), "Strengthening of unreinforced masonry using welded wire mesh and micro-concrete - Behaviour under in-plane action", *Constr. Build. Mater.*, **54**, 247-257. https://doi.org/10.1016/j.conbuildmat.2013.12.033.

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

Kaish, A.B.M.A., Jamil, M., Raman, S.N., Zain, M.F.M. and Nahar, L. (2018), "Ferrocement composites for strengthening of concrete columns: A review", *Constr. Build. Mater.*, **160**, 326–340. https://doi.org/10.1016/j.conbuildmat.2017.11.054.

Kouris, L.A.S. and Triantafillou, T.C. (2018). "State-of-the-art on strengthening of masonry structures with textile reinforced mortar (TRM)", *Constr. Build. Mater.*, **188**, 1221-1233. https://doi.org/10.1016/j.conbuildmat.2018.08.039.

Kumar, V. and Patel, P.V. (2016), "Strengthening of axially loaded circular concrete columns using stainless steel wire mesh (SSWM) – Experimental investigations", *Constr. Build. Mater.*, **124**, 186-198. https://doi.org/10.1016/j.conbuildmat.2016.06.109.

Lin, Y.W., Biggs, D., Wotherspoon, L. and Ingham, J.M. (2014), "In-plane strengthening of unreinforced concrete masonry wallettes using ECC shotcrete. *J. Struct. Eng.*, **140**(11), 04014081. https://doi.org/10.1061/(asce)st.1943-541x.0001004.

Lin, Y., Lawley, D., Wotherspoon, L. and Ingham, J.M. (2016), "Out-of-plane testing of unreinforced masonry walls strengthened using ECC shotcrete. *Structures*, **7**, 33-42. https://doi.org/10.1016/j.istruc.2016.04.005.

Maalej, M., Lin, V.W.J., Nguyen, M.P. and Quek, S.T. (2010), "Engineered cementitious composites for effective strengthening of unreinforced masonry walls", *Eng. Struct.*, **32**(8), 2432-2439. https://doi.org/10.1016/j.engstruct.2010.04.017.

Marbaniang, D.F., Warjri, T. and Marthong, C. (2022), "Out-of-plane bending of masonry wall embedding with welded wire mesh (WWM) in different orientations", *Innov. Infrastruct. Solutions*, **7**(1), 10-14. https://doi.org/10.1007/s41062-021-00676-w.

Mourad, S.M. and Shannag, M.J. (2012), "Repair and strengthening of reinforced concrete square columns using ferrocement jackets", *Cement Concrete Compos.*, **34**(2), 288-294. https://doi.org/10.1016/j.cemconcomp.2011.09.010.

Padalu, P.K.V.R., Singh, Y. and Das, S. (2018), "Experimental investigation of out-of-plane behaviour of URM wallettes strengthened using welded wire mesh", *Constr. Build. Mater.*, **190**, 1133-1153. https://doi.org/10.1016/j.conbuildmat.2018.09.176.

Qeshta, I.M.I., Shafigh, P., Jumaat, M.Z., Abdulla, A.I., Ibrahim, Z. and Alengaram, U.J. (2014), The use of wire mesh-epoxy composite for enhancing the flexural performance of concrete beams", *Mater. Design*, **60**, 250-259. https://doi.org/10.1016/j.matdes.2014.03.075.

Rafeeqi. S.F.A. and Ayub. T. (2011), "Investigation of versatility of theoretical prediction models for plain concrete confined with ferrocement", *Asian J. Civil Eng.*, **12**(3), 337-352.

Rossetto, T. and Peiris, N. (2009), "Observations of damage due to the Kashmir earthquake of October 8, 2005 and study of current seismic provisions for buildings in Pakistan", *Bull. Earthq. Eng.*, **7**(3), 681-699.

https://doi.org/10.1007/s10518-009-9118-5.
Sandoval, O.J., Takeuchi, C., Carrillo, J. and Barahona, B. (2021), "Performance of unreinforced masonry panels strengthened with mortar overlays reinforced with welded wire mesh and transverse connectors", *Constr. Build. Mater.*, **267**. https://doi.org/10.1016/j.conbuildmat.2020.121054.
Sathiparan, N., Nissanka, N.A.A.C. and Priyankara, R.L.S. (2016), "A comparative study of meshtype retrofitting for unreinforced masonry under in-plane loading", *Arabian J. Sci. Eng.*, **41**(4), 1391-1401. https://doi.org/10.1007/s13369-015-1937-x.
Schuller, M.P., Atkinson, R.H. and Borgsmillerr, J.T. (1994), "Injection grouting for repair and retrofit of unreinforced masonry", *Proceedings of the IB2MAC - 10h International Brick and Block Masonry Conference*, **303**, 549-558.
Seismic Retrofitting of Deficient Buildings and Structures (2014), *National Disaster Management Guidelines*, Government of India.
Shermi, C. and Dubey, R.N. (2017), "Study on out-of-plane behaviour of unreinforced masonry strengthened with welded wire mesh and mortar", *Constr. Build. Mater.*, **143**, 104-120. https://doi.org/10.1016/j.conbuildmat.2017.03.002.
Shermi, C. and Dubey, R.N. (2018), "In-plane behaviour of unreinforced masonry panel strengthened with welded wire mesh and mortar", *Constr. Build. Mater.*, **178**, 195-203. https://doi.org/10.1016/j.conbuildmat.2018.04.081.
Sistani Nezhad, R. and Kabir, M.Z. (2017), "Experimental investigation on out-of-plane behavior of GFRP retrofitted masonry panels", *Constr. Build. Mater.*, **131**, 630-640. https://doi.org/10.1016/j.conbuildmat.2016.11.118.
Standard specification for highway bridges (1985), American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C.
Suraj, S. and Unnikrishnan, S. (2020), Strengthening of concrete block masonry walls using steel wire mesh", *Lecture Notes in Civil Eng.*, **46**, 749-762. https://doi.org/10.1007/978-3-030-26365-2_69.
Syiemiong, H. and Marthong, C. (2020), "Flexural behavior of low strength masonry wallettes strengthened with welded wire mesh", *Materials Today: Proceedings*, **43**, 1774-1779. https://doi.org/10.1016/j.matpr.2020.10.452.
Syiemiong, H. and Marthong, C. (2021), "The effect of mortar grade on the out-of-plane behaviour of low-strength masonry wall strengthened with welded wire mesh", *Constr. Build. Mater.*, **279**. https://doi.org/10.1016/j.conbuildmat.2021.122393
Tripathy, D. and Singhal, V. (2021), "Strengthening of weak masonry assemblages using wire reinforced cementitious matrix (WRCM) for shear and flexure loads", *Constr. Build. Mater.*, **277**, 122223. https://doi.org/10.1016/j.conbuildmat.2020.122223.
Turer. A., Korkmaz. S.Z. and Korkmaz. H.H. (2007), "Performance improvement studies of masonry houses using elastic post-tensioning straps", *Earthq. Eng. Struct. D.*, **36**, 683-705.
Valluzzi, M.R., Binda, L. and Modena, C. (2005), "Mechanical behaviour of historic masonry structures strengthened by bed joints structural repointing", *Constr. Build. Mater.*, **19**(1), 63-73. https://doi.org/10.1016/j.conbuildmat.2004.04.036.
Warjri, T., Marbaniang, D. F., & Marthong, C. (2022), "In-plane behaviour of masonry walls embedding with steel welded wire mesh overlay with mortar", *J. Struct. Integrity Maint.*, **7**(3), 177-187. https://doi.org/10.1080/24705314.2022.2048241.
Xin, R. and Ma, P. (2021), "Experimental investigation on the in-plane seismic performance of damaged masonry walls repaired with grout-injected ferrocement overlay", *Constr. Build. Mater.*, **282**, 122565. https://doi.org/10.1016/j.conbuildmat.2021.122565
Yardim, Y. and Lalaj, O. (2016), "Shear strengthening of unreinforced masonry wall with different fiber reinforced mortar jacketing", *Constr. Build. Mater.*, **102**, 149-154. https://doi.org/10.1016/j.conbuildmat.2015.10.095.