Strengthening of Confined Masonry Structures for In-plane Loads: a Review

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Abstract. Confined masonry is a load-bearing masonry structure where walls are confined with nominally reinforced concrete elements at key locations. This building typology is popularly used in many countries as it generally performs better than the unreinforced masonry and non-ductile RC infill masonry under seismic loads. However, the confined masonry buildings have also experienced damage during past earthquakes. Poor seismic performance is generally seen due to construction errors, design flaws or material deficiencies in the building design and construction process. To overcome the structural deficiencies researchers have used different strengthening techniques for confined masonry walls such as application of ferrocement overlay, steel bands, and fiber-reinforced polymers. There are several inherent advantages and disadvantages of these strengthening techniques in terms of efficiency, bonding with the substrate material, durability, ease in construction and economy. This article will review and discuss the in-plane strengthening of confined masonry walls with conventional and fiber-reinforced materials and will highlight the gap areas and scope for future research.

1. Introduction
Confined masonry system was introduced in Italy as an alternative to unreinforced masonry (URM) buildings, which were almost completely destroyed in the 1908 Messina earthquake. Confined masonry (CM) structure has always gained vital importance in the construction practices, as its performance is much better than the unreinforced masonry and non-ductile RC infill structures during seismic loads. The CM structures are more popularly known for the low rise residential buildings of South America, Central America, Asian countries and European countries.

Past studies have revealed the satisfactory performance of confined masonry buildings during the 1939 Chile earthquake, 1985 Llolleo earthquake. However, few major damages were observed in these structures during the seismic event such as in M7.5 Llolleo earthquake, it was reported that 6% of the confined masonry buildings sustained repairable damage and 2% of the confined masonry buildings sustained irreparable damage [1]. Likewise, in the Tehuacan earthquake 1999 (Figure 1a), major damages were seen in the three or more storey CM buildings. Moreover, in the 2010 Haiti earthquake, inadequate performance of CM buildings was observed due to poor construction practices and the use of substandard materials (Figure 1b). The damages in the CM wall arise due to the poor design, detailing and construction. To improve the performance of CM buildings, many researchers have investigated different methods of strengthening. Generally, two types of techniques have been used for the strengthening of CM walls, which includes the retrofitting with conventional composites and retrofitting with reinforced fiber composites.
2. Common failures in confined masonry

Generally, three types of in-plane failure modes are seen in confined masonry walls, which include diagonal shear failure, sliding shear failure and in-plane bending failure, as shown in figure 2. The diagonal shear failure mechanism is the most common failure for confined masonry walls resulting from the combination of vertical and horizontal loads (seismic loads). The shear failure happens when the principal tensile stresses become more than the masonry tensile strength. The diagonal shear failure of the CM wall is shown in figure 2a [4]. The inadequate number of tie-columns and poor workmanship may result in sliding shear failure and subsequently large damage to confined masonry walls (Figure 2b). In some cases, the bond failure at the mortar-brick interface or tensile cracking at the masonry units was also found to be the major cause of the damage [5].

![Figure 2](image)

Figure 2. Common failures in confined masonry (a) Diagonal shear failure; Yoshimura et al. [4] (b) Sliding shear Failure; Singhal [6] (c) In-plane bending Failure; Zabala et al. [7].

When the CM walls are subjected to compression stresses at one end and tensile stresses at the other end, the type of failure is known as an in-plane bending failure (Figure 2c) [7]. The wall having panel height much larger than the panel length is more susceptible to a flexural mode of failure. To mitigate these failures, strengthening techniques have been developed using various composites.

3. Strengthening techniques

Many techniques have been used for the retrofitting of the CM walls. These techniques majorly use the application of composite materials on the surface of the walls. Broadly, it includes the retrofitting of CM structures by conventional composites or by fiber-reinforced composites. Retrofitting by conventional composites have been majorly used for strengthening, as these are readily available at a cheaper price. A conventional composite includes steel welded wire mesh, which is generally placed on the surface of the wall with the help of anchors/nails as shown in figure 3a. A layer of mortar (plaster) is then applied to the mesh. This strengthening composite is commonly known as ferrocement or wire reinforced cementitious matrix. On the other hand, the fiber-reinforced polymer composites in the form of carbon, glass, and basalt have also been widely used by several researchers for the retrofitting of CM walls. These composite materials can effectively strengthen the CM walls for better seismic performance. Earlier, fibers were applied on the surface of the CM wall with the help of chemical epoxy and cementitious matrix as shown in figures 3b and 3c. However, the organic binder or epoxy has now been
replaced with the cementitious matrix due to its high durability, fire resistance and good compatibility with the substrate material (Figure 3c) [8], [9]. This type of strengthening technique is popularly known as fibre reinforced cementitious matrix (FRCM). Depending on the type of deficiencies, the fibers are applied either in a grid pattern or in a diagonal pattern. To overcome the failures like diagonal shear, flexure, interface, etc. these layouts are used. A typical example of the diagonal layout has been shown in figure 3c, in order to overcome the diagonal shear failure of CM wall specimen. Similar to solid CM walls, different techniques have been proposed to strengthen CM walls with door and window openings. In general, openings are confined by providing reinforcement along its periphery to mitigate failure of adjacent masonry piers and corners of opening.

Researchers have also explored the use of waste materials like plastic cement bag mesh for retrofitting of CM walls [10]. A mesh of waste plastic cement bag mesh was prepared and applied to the specimen. It was reported that the retrofitting through waste materials give a significant improvement in strength at a low cost. Further, modern materials such as engineered cementitious composite (ECC) was also used for the strengthening of confined masonry walls [11]. It was reported that the ECC overlay can significantly improve the in-plane strength of the CM wall. To evaluate different strengthening schemes, a repository of CM specimens available in the literature was created (Table 1). This repository consists of only single-story specimens strengthened for in-plane loads without any prior damage.

![WRCM][12]

(a) WRCM [12]

(b) FRP applied using epoxy [13]

(c) FRP applied using cementitious matrix[14]

**Figure 3.** Commonly used strengthening techniques.

### 4. Performance of various strengthening techniques

The result of various experimental studies showed that there was a huge influence of the retrofitting agent on the response of the CM wall. Based on the details collected in the repository, the performance of different strengthening schemes was compared using cracking load $\beta_c$, cracking drift $\lambda_c$, peak load $\beta_u$, and ultimate drift $\lambda_u$ for each strengthened and unstrengthened specimens (Table 2). The ultimate drift was considered at 80% of the peak load in the post-peak region. Further, the ultimate load and drift of strengthened specimens were compared with their respective control specimens by estimating ultimate load ratio $\beta_u/\beta_{uc}$ and ultimate drift ratio $\lambda_u/\lambda_{uc}$ (Table 2).

It was noted that the conventional strengthening techniques like wire reinforced cementitious matrix and the ferrocement were highly effective in enhancing the strength and deformation capacity of the CM wall. If these strengthening techniques are properly implemented along with the provision of suitable anchors then up to 150% improvement in the strength can be achieved (Table 2, Sl. No. 4). Further, it was reported that the larger diameter wire provides better deformation capacity and can sustain the peak
load up to larger drifts. However, the over-reinforcement may also lead to brittle failure of the strengthened wall.

**Table 1.** Details of confined masonry specimens.

| No. | Reference               | A_c (mm × mm) | Composite | Φ (mm) | S_c | Remarks                        |
|-----|-------------------------|---------------|-----------|--------|-----|--------------------------------|
| 1   | Alcocer et al. [15]     | 2500 × 2500   | C         | -      | -   |                                 |
| 2   |                         | 2500 × 2500   | WRCM      | 4.88   | 300 |                                 |
| 3   |                         | 2500 × 2500   | WRCM      | 6.35   | 300 |                                 |
| 4   |                         | 2500 × 2500   | WRCM      | 3.43   | 450 |                                 |
| 5   | El-Diasity et al. [14]  | 2000 × 1820   | C         | -      | -   | Opening - 760 × 780mm          |
| 6   |                         | 2000 × 1820   | C-W       | -      | -   | Opening - 680 × 1410mm         |
| 7   |                         | 2000 × 1820   | C-D       | -      | -   |                                 |
| 8   |                         | 2000 × 1820   | FCM       | 1.6    | 15  | Full wall cover                |
| 9   |                         | 2000 × 1820   | FCM       | 1.6    | 15  |                                 |
| 10  |                         | 2000 × 1820   | FCM       | 1.6    | 15  |                                 |
| 11  |                         | 2000 × 1820   | GFRP      | 0.013  | -   | At diagonals                   |
| 12  |                         | 2000 × 1820   | GFRP      | 0.013  | -   |                                 |
| 13  |                         | 2000 × 1820   | FCM-W     | 1.6    | 15  | Full wall cover                |
| 14  |                         | 2000 × 1820   | FCM-D     | 1.6    | 15  |                                 |
| 15  | Dimas et al. [16]       | 3000 × 2100   | C-W       | -      | -   | Opening -1200 × 1000mm         |
| 16  |                         | 3000 × 2100   | GFRP-W    | 1.0    | -   | Vertical cover                 |
| 17  | Zhou et al. [13]        | 1860 × 1500   | C         | -      | -   |                                 |
| 18  |                         | 1860 × 1500   | C-W       | -      | -   | Opening - 600 × 450 mm         |
| 19  |                         | 1860 × 1500   | BFRP      | 0.121  | -   | Solid wall                     |
| 20  |                         | 1860 × 1500   | BFRP-W    | 0.121  | -   | Opening - 600 × 450 mm         |
| 21  | Shakib et al. [12]      | 2580 × 2590   | C         | -      | -   |                                 |
| 22  |                         | 2580 × 2590   | CFRP      | -      | -   | Grid pattern                   |
| 23  |                         | 2580 × 2590   | CFRP      | -      | -   | Diagonal pattern               |
| 24  |                         | 2580 × 2590   | PFS       | -      | -   | Fiber density 0.9 g/cm³        |
| 25  | Deng and Yang [11]      | 2370 × 1370   | C-LMS     | -      | -   |                                 |
| 26  |                         | 2370 × 1370   | C-LMS     | -      | -   |                                 |
| 27  |                         | 2370 × 1370   | C-HMS     | -      | -   |                                 |
| 28  |                         | 2370 × 1370   | C-HMS     | -      | -   |                                 |
| 29  |                         | 2370 × 1370   | ECC-LMS   | -      | -   | One side strengthening         |
| 30  |                         | 2370 × 1370   | ECC-LMS   | -      | -   | One side strengthening         |
| 31  |                         | 2370 × 1370   | ECC-LMS   | -      | -   | One side strengthening         |
| 32  |                         | 2370 × 1370   | ECC-LMS   | -      | -   | One side strengthening         |
| 33  |                         | 2370 × 1370   | ECC-LMS   | -      | -   | Both side strengthening        |
| 34  |                         | 2370 × 1370   | ECC-LMS   | -      | -   | Both side strengthening        |
| 35  |                         | 2370 × 1370   | ECC-LMS   | -      | -   | Both side strengthening        |
| 36  |                         | 2370 × 1370   | ECC-HMS   | -      | -   | Both side strengthening        |

A_c – Area of specimen; Φ – Diameter of reinforcement; S_c – Reinforcement spacing; C – control specimen; W – Window opening; D – Door opening; WRCM – strengthening with wire reinforced cementitious matrix; BFRP – strengthened with basalt fiber reinforced polymer; R – Repaired; GFRP – strengthened with glass fiber reinforced polymer; CFRP – retrofitting by carbon fiber reinforced polymer; PFS – retrofitted with poly-propylene fiber shotcrete; ECC – strengthening with engineered cementitious composites; LMS – low mortar strength; HMS – high mortar strength.

Similarly, the use of modern material for strengthening showed a significant increase in the strength of the CM wall specimens. The specimen strengthened with GFRP composite on full wall surface exhibited an approximately 80% increase in strength when compared to the control specimen. Moreover, for the ultimate drift, retrofitting with the CFRP composite was found highly effective. It was seen that an increment of more than 150% in the drift can be achieved when CFRP composite is used in a diagonal
The strengthening with ECC exhibited a significant improvement in the strength, but there was no improvement in the deformation capacity. However, it is highly advantageous to use ECC as a strengthening composite, as it shows an approximately 250% rise in the strength of the CM structure when applied on both sides of the wall. Further, in comparison to other strengthening methods, the application of ECC for strengthening is relatively quicker and easier as it does not require a highly skilled manpower.

Table 2. Influence of composite material on CM wall specimen.

| No. | $\beta^c$ (kN) | $\beta^u$ (kN) | $\lambda^c$ (%) | $\lambda^u$ (%) | $\lambda^{uc}$ | $\lambda^{uc}$ |
|-----|----------------|----------------|-----------------|-----------------|--------------|--------------|
| 1.  | 82.5           | 112.5          | 0.42            | 0.76            | -            | -            |
| 2.  | 160.0          | 237.5          | 0.60            | 1.28            | 2.11         | 1.68         |
| 3.  | 167.5          | 215.0          | 0.40            | 1.39            | 1.91         | 1.83         |
| 4.  | 207.5          | 292.5          | 0.58            | 0.79            | 2.60         | 1.04         |
| 5.  | 210.0          | 290.0          | 0.109           | 0.550           | -            | -            |
| 6.  | 152.5          | 254.0          | 0.109           | 0.896           | -            | -            |
| 7.  | 130.0          | 207.0          | 0.055           | 1.420           | -            | -            |
| 8.  | 345.0          | 365.0          | 0.329           | 0.760           | 1.26         | 1.38         |
| 9.  | 335.0          | 378.5          | 0.329           | 0.790           | 1.31         | 1.44         |
| 10. | 376.0          | 376.0          | 0.219           | 0.640           | 1.30         | 1.16         |
| 11. | 315.0          | 373.0          | 0.219           | 0.745           | 1.29         | 1.35         |
| 12. | 525.0          | 525.0          | 0.659           | 0.796           | 1.81         | 1.45         |
| 13. | 227.5          | 325.0          | 0.055           | 1.049           | 1.28         | 1.17         |
| 14. | 177.5          | 272.5          | 0.164           | 1.145           | 1.32         | 0.81         |
| 15. | 58.9           | 82.2           | 0.084           | 0.695           | -            | -            |
| 16. | 62.5           | 110.0          | 0.122           | 0.793           | 1.34         | 1.14         |
| 17. | 192.0          | 234.0          | 0.087           | 0.660           | -            | -            |
| 18. | 184.0          | 217.0          | 0.073           | 0.356           | -            | -            |
| 19. | 218.0          | 322.0          | 0.146           | 1.359           | 1.38         | 2.06         |
| 20. | 204.0          | 266.0          | 0.126           | 0.800           | 1.23         | 2.25         |

| No. | $\beta^c$ (kN) | $\beta^u$ (kN) | $\lambda^c$ (%) | $\lambda^u$ (%) | $\lambda^{uc}$ | $\lambda^{uc}$ |
|-----|----------------|----------------|-----------------|-----------------|--------------|--------------|
| 5.  | 163.4          | -              | 0.876           | -               | -            | -            |
| 6.  | 190.7          | -              | 1.241           | -               | -            | -            |
| 7.  | 217.8          | -              | 0.731           | -               | -            | -            |
| 8.  | 243.6          | -              | 1.462           | -               | -            | -            |
| 9.  | 317.9          | -              | 1.95            | 0.33            | -            | -            |
| 10. | 436.8          | -              | 2.29            | 0.35            | -            | -            |
| 11. | 417.9          | -              | 1.92            | 0.60            | -            | -            |
| 12. | 441.4          | -              | 1.81            | 0.35            | -            | -            |
| 13. | 588.9          | -              | 3.60            | 0.50            | -            | -            |
| 14. | 577.6          | -              | 3.03            | 0.41            | -            | -            |
| 15. | 416.1          | -              | 1.91            | 0.63            | -            | -            |
| 16. | 635.0          | -              | 2.61            | 0.39            | -            | -            |

$\beta^c$ – Cracking load; $\beta^u$ – Ultimate load; $\lambda^c$ – Cracking drift; $\lambda^u$ – Ultimate drift (at 80% of peak load in the post-peak zone); $\lambda^{uc}$ – Ultimate load ratio; $\lambda^{uc}$ – Ultimate drift ratio.

5. Conclusions

This article provides preliminary review of various strengthening techniques used for the CM walls with and without openings. It was seen that strengthening techniques were significantly beneficial for the improvement of the overall strength and deformation capacity of the confined masonry walls. A comparative study was done to evaluate various techniques for the strengthening of CM walls. The specific increase of strength was particularly seen when conventional techniques like wire reinforced cementitious matrix and modern techniques like FRP, FRCM and ECC were used. It was seen that different layout of strengthening enhanced the performance differently and can mitigate different types of failures. The comparative analysis showed that the engineered cementitious composite (ECC) was most effective in improving the in-plane capacity of CM walls, whereas the carbon-fiber reinforcement laid in a diagonal pattern significantly improved the deformation capacity when compared with other strengthening schemes. The application of ECC overlay for strengthening is much simpler but the availability of material especially suitable polyvinyl alcohol (PVA) fibres is scarce in local market. Further, the use of ECC did not show any improvement in the deformation capacity. However, based on the test results, the strengthening using wire reinforced cementitious matrix (WRMC) is a better choice as it had shown improvement in both deformation and in-plane capacity and the required material is easily available.

The developed repository clearly indicates that the limited studies have been done till date on the strengthening and rehabilitation of the CM structures. A more detailed analytical and experimental investigation is required to understand the behaviour of strengthened CM walls and to develop the methodology for designing the strengthening scheme to achieve the desired performance level.
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