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REVIEW OF STRENGTHENING TECHNIQUES FOR MASONRY USING FIBER REINFORCED POLYMERS

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1. Abstract

Various studies have been done over a number of years to develop strengthening techniques which will improve the performance of masonry structures. Many unreinforced masonry structures are seismically deficient and several research studies have been conducted to improve the seismic performance of these structures. Strengthening methods such as the addition of new structural elements, steel plate bonding, external post tensioning, steel bracing and many more have been applied with some degree of success. However, an innovative retrofitting technique using Fiber Reinforced Polymer (FRP) has gained recognition and acceptance. FRP materials have light weight, excellent durability, and high strength, yet are lightweight and are easy and quick to install. All these properties make FRP materials attractive for strengthening and rehabilitating of reinforced and unreinforced masonry structures. Different strengthening techniques are available to increase the flexural and shear strength and ductility of masonry structures using FRP materials. This paper reviews these strengthening techniques, their advantages, disadvantages and limitations.

Keywords: FRP, masonry, strengthening

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2. Introduction

Masonry is the worlds oldest construction system. It is estimated that more than 70% of the buildings worldwide are masonry buildings (marthysnoland1989). Its appeal and popularity stems from aesthetics, fire resistance, heat and sound insulation, mechanical properties and economic considerations. Masonry consists of four essential components: units, mortar, grout and accessories. Masonry units are made of fired clay or concrete blocks. Masonry mortar holds the units together. Masonry grout, which consists of fluid concrete surrounds deformed bar reinforcement and it, is used to structurally integrate masonry. Accessories consist of reinforcement, connectors and waterproofing materials. Majority of masonry units used in the United States are of fired clay (ASTM C62 or C216) or lightweight concrete (ASTM C90). Fired clay masonry generally have a density of about 120 lbs/ft^3 (2000 kg/m^3) and compressive strength ranging from 8000 to 30000 lb/in^2 (56 to 200 MPa). Lightweight concrete masonry on the other hand have a density of about 90 to 105 lbs/ft^3 (1500 to 1700 kg/m^3) and compressive strength of 1900 to 3000 lb/in^2 (13 to 20 MPa).

Masonry is a heterogeneous material due to the diversity of properties and types of materials used in building it. In general, masonry exhibits very low tensile strength. Masonry structures may require strengthening for a number of reasons. A redistribution of loads due to creep may occur within a structure whereby masonry carries more load (shrive-etal2001). This may arise as a result of structural deformation or stress redistribution elsewhere or within the structural element itself. A combination of load redistribution, environmental factors, aging, or accidental movements over time may lead to failure. Load bearing unreinforced masonry (URM) or under-reinforced walls subjected to seismic loads can fail by in-plane or out-of-plane mode.

In-plane failures are defined by diagonal tension crack pattern while out-of-plane failure is characterized by cracks along the mortar joints (ehsani-etal1999). The objective of a strengthening technique is to improve the ability of the structure to absorb inelastic deformation. The strengthening approach may be concentrated at joints by near surface mounted (NSM) or repointing techniques, or may be applied on the entire masonry wall or structure. The use of fiber reinforced polymer (FRP) for masonry is an innovative technique that can improve the structures load carrying capacity and integrity.

FRP consist of high resistance fiber impregnated with polymeric resins with high tensile strength, corrosion resistance and lightness. The fibers are main load carrying components in FRP while the resins transfer shear. FRP have high tensile strength, stiffness, corrosion resistance and are lightweight. However, some of the disadvantages include high cost, low impact resistance, and high electrical conductivity.

The three basic types of FRP manufactured are Glass, Aramid, and Carbon fiber reinforced polymer (GFRP, AFRP, and CFRP). FRP products used for strengthening or retrofitting are commercially available in form of laminates, meshes, tendons, and rods. According to ehsani-etal1999, they have been used to improve the strength and ductility of masonry structures. tumialan-nanni2002 concluded in their research that URM walls can improve the strength and ductility of masonry significantly by strengthening with FRP laminates. FRP have properties such as high strength and lightweight that make them very attractive for post-tensioning. The method consist of placing FRP tendons inside a steel tube or duct within holes drilled along the midplane of the wall or along grooves cut on both surfaces of a masonry wall. The post-tensioning system is anchored in self-activating dead end which is encased existing or new reinforced concrete elements at the top and bottom.

Post tensioning increases cracking moment and ultimate moment capacity of masonry walls. Repointing with FRP is performed by placing deformed FRP rods into masonry joints which are bonded to the walls with a paste or epoxy. Laboratory results have shown that FRP repointing technique when combined with laminates dramatically improve shear and bending moment capacities of masonry walls subjected to out of plane loading under cyclic or static load.

korany-drysdale2004 conducted an experimental program to investigate the effect of FRP rehabilitation technique to enhance the out-of-plane bending resistance of URM walls using carbon fiber rope as a reinforcing material. In this technique, braided carbon fiber rope was coated with an epoxy compound before installing in grooves cut vertically through joints between brick units. After the grooves were cleaned with compressed air, an epoxy primer was applied and the FRP reinforcement was installed. After installing the reinforcement, another layer of epoxy adhesive was applied to fully encapsulate the FRP rope. To maintain the existing faade, repointing mortar, similar in color and properties to the existing mortar was applied from outside. Fully reversing cyclic loading was applied to the wall after the repointing. The relevant conclusions of this investigation are; FRP reinforced walls showed significant increase in capacity, deformability and energy dissipation over unreinforced specimen, and no significant strength deterioration was observed under cyclic loading for FRP reinforced walls.

In an experiment conducted by triantafillou1998 CFRP strips were applied to clay URM walls and the walls were subjected to out-of-plane bending with axial force, in-plane bending with axial force, and in-plane shear with axial force. The author concluded that CFRP improved the in-plane shear capacity of the walls in the case of low axial loads.

Three full-scale clay brick masonry walls were fitted with FRP laminates and tested under compression and cyclic loads by chuang-etal2003. The wall panels were supported on reinforced concrete beams that were bolted to a reaction floor. The beams acted as foundation for the walls. Two different FRP configurations consisting of intersecting diagonal strips and intersecting diagonal strips supported at the ends with vertical strips were used. One hydraulic jack was used to apply lateral loads to the specimen and another was used to apply vertical load to create a realistic loading condition. Horizontal displacement cycles of increasing amplitude were applied to the walls to simulate seismic loading. Test result showed that FRP strips significantly increased the in-plane strength, ductility and energy dissipation capacity of low rise masonry walls.

Post tensioning with CFRP tendons can improve serviceability, reduce crack sizes in damaged structures and increase cracking moment of resistance in masonry structures. shrive-etal2001 conducted an experiment on clay masonry walls. The walls were prestressed to a compression of 94.28 psi (0.65 MPa). The authors noted an increase in capacity and a closing up of horizontal cracks in the bed joints. They concluded that post tensioning can be used to close or control cracking in damaged structures and increase cracking moment of resistance in new structures.

quiroz2011 conducted a study on the seismic performance of four historical masonry towers reinforced with unbonded AFRP tendons. The towers, ranged in height from 105ft (32m) to 148ft (45m). Each tower was independently post-tensioned with four vertical unbonded tendons made of the same material located at each corner of the building. The tendons were made of Steel, Arapree Fiber Reinforced Polymer (AFRP), Technora Fiber Reinforced Polymer and Carbon Fiber Polymer (CFRP). A post-tensioned force of about 70% of the ultimate tensile strength was applied to steel tendons, while for FRP tendons, the applied post-tensioned force was limited to about 40%. The author, through parametric studies concluded that post-tensioning with fiber reinforced polymers considerably improved the lateral loading capacity and reduced the displacement of the towers.

In another study shrive-etal2001 applied FRP strips and sheets to one side of hollow, unreinforced concrete block to investigate the lateral load resistance and behavioral characteristics of unreinforced concrete block wall fitted with FRP. Different types of FRP (glass fiber sheets, carbon fiber sheets, and carbon fiber strips) oriented vertical and diagonally were used. The walls were subjected to cyclic and point loading. The results revealed an increase in hysteresis energy and strength. FRP strengthening can improve flexural strength and energy absorption characteristics of block walls.

tumialan-nanni2002 conducted an experiment to measure the improved performance and mode of failure of URM masonry wall panels strengthened with externally bonded laminates. Twelve walls built with 12 concrete blocks and 13 clay bricks measuring 24in (600mm) wide by 48 in (1200mm) high were strengthened with glass fiber reinforced polymer (GFRP) and aramid fiber reinforced polymer (AFRP). The FRP systems were installed by manual lay-up along the titudinal axis of the masonry panels. The walls were simply supported and loaded by hydraulic jack which transferred force through a steel beam to the wall by means of steel rollers. The load was applied in cycles of loading and unloading. The modes of failure observed included debonding, flexural and shear failure. After the formation of flexural cracks, debonding occurred due to shear transfer mechanism at the FRP laminate/masonry interface. Flexural failure developed after the formation of flexural cracks at the mortar joints while shear failure started due to the formation vertical cracks. The results showed that strengthening with FRP laminates can significantly increase the strength and ductility of URM walls.

FRP has also been proven to increase the axial capacity of masonry through confinement. In a study conducted by krevaikas-triantafillou2006, axial loads were applied monotonically to 42 unreinforced masonry square columns consisting of bricks measuring 4.5 in x 4.5 in (115 mm x 115 mm) for the first two specimen series, 6.79 in x 4.5 in (172.5 mm x 1155 mm) for the third specimen series and 9.05 in x 4.5 in (230 mm x 11 5mm) for the fourth series in seven rows with six bed joints and wrapped in CFRP sheets. The main objective was to record the axial stress-strain curve and the failure mode of the masonry specimens. Load cells attached to the specimens measured the loads while variable differential transducers attached to the specimens measured the displacements. The results showed that the confinement provided by FRP improved the load carrying capacity of the masonry columns considerably. In fact the masonry columns acted like FRP-confine concrete. Test result also showed that the specimens gained increase in strength and deformability.

aiello-valente2008, in a similar study, applied axial loads to rectangular full-core and hollow core columns made of clay bricks and limestone specimens measuring 9.84 in (250 mm) x 9.84 in (250mm) x 19.68 in (500 mm) . Some of the clay brick specimens were externally confined with two layers of GFRP sheets, some specimens were externally confined and reinforced with GFRP bars, and some with one layer of GFRP sheet. The limestone brick specimens were unconfined but reinforced with GFRP bars. The authors concluded that hollow-core column with FRP external confinement showed significant increase mechanical properties and this was more magnified in column specimens with both external FRP confinement and internal GFRP reinforcing bar.

Furthermore, ludovico-etal2008, investigated the effects of FRP confinement as a strengthening technique by applying axial loads to clay brick masonry columns measuring 8.66 in (220 mm) x 8.66 in (220 mm x 19.68 in (500 mm). Four series of three specimens were tested. Some of the specimen series were wrapped with CFRP sheets and the other series were wrapped with GFRP sheets. Results obtained from this research showed that both GFRP and CFRP confinements led to significant gains in compressive strength and ductility of the masonry columns under axial loads.

Extensive researches have been conducted on other strengthening techniques for improving the behavior of masonry structures with the aid of FRP. The modern strengthening techniques include:

3. Strengthening Techniques

3.1. **(Externally Bonded FRP Systems).** FRP laminates are used to strengthen existing structures such as masonry in flexure and shear. FRP may be bonded to the tension side of masonry walls or concrete beams, girders and slabs to provide additional flexural strength or to the sides of beams and girders to provide additional shear capacity. FRP is used for masonry strengthening to increase in-plane and out-of- plane capacity, and restore capacity of cracked masonry. Investigation of the plate bonding technology of FRP was first performed at the Swiss Federal Laboratory for Material Testing and Research. All FRP materials are composites of two different materials namely fiber and resin. The fibers provide strength and stiffness and the resins transfer stress from fiber to fiber and protect the fibers. FRP laminates are produced by impregnating the fibers with a resin and pultruding the uncured composite through a die into a continuous uniform plate.

Table 1. Mechanical Properties of fibers used in FRP system (ACI 440, 2002)

Fiber	**Tensile modulus (106 psi)**	**Tensile strength (ski)**	**Strain to failure (%)**
EGlass	10.5	500.0	4.8
Carbon (PAN)	34	530.0	1.4
Carbon (PITCH)	55	275.0	0.5

FRP laminates come either as a wet lay-up or precured system. The wet lay-up FRP system is made of dry unidirectional or multidirectional fiber sheets impregnated with resin on site. Precured FRP system consists of a variety of composite shapes that are manufactured off site. Adhesive, primer and putty are normally used to bond the precured shapes to the substrate. The primer penetrates the surface of the substrate providing a better surface for the adhesive bond or the resin while the putty seals off surface voids to provide a smoother for the FRP to bond. The precured FRP system has unidirectional and multidirectional laminate as well. Typical mechanical properties of FRP fibers are presented in Table 1.

Prior to installation of the FRP laminate, the masonry surface is cleaned to remove surface contaminants, mill and scale in accordance with ACI 546R and ICI 0370. Uneven areas are leveled with putty. The sanded side of the laminate is wiped with acetone to remove any residue. Structural adhesive is applied to both the substrate and the laminate surfaces. The laminate is carefully placed on the substrate with a hard rubber roller as shown in Figure 1. Excess adhesive is removed from the sides before the laminate cures. Structural performance of FRP could be affected by debonding in zones of high flexural and shear stresses.

4. Near Surface Mounted (NSM) FRP Systems

This technique involves inserting FRP bars or strips in specially constructed grooves in the masonry cover layer. The method consist of cutting grooves or slots having a diameter of one and half times the bar diameter in bed joints, cleaning and filling with epoxy or cement based mortar as shown in Figures 6a and 6b.. The FRP bars are inserted in the groove and fully encapsulated with mortar comprising of: epoxy resin liquid compound and cement and cementitious materials with a compressive strength of 5800 psi (40MPa) as shown in Figures 6c and 6d. To avoid tilting or twisting of the strengthened wall, FRP reinforcement should be placed symmetrically on both faces of the wall. According to rizkalla-etal2003, NSM FRP systems are three times more efficient than externally bonded FRP systems. The two types of debonding failure that can occur with NSM FRP bars are debonding due to splitting of the epoxy cover and debonding due to cracking of the concrete surrounding the epoxy adhesive (Rizkalla et al.2003). High

Figure 1. Strengthening of CMU wall with FRP laminates (tumialan-nanni2002)

tensile stresses at the FRP-epoxy interface can lead to splitting of the epoxy cover and cracking of the concrete surrounding the epoxy adhesive can occur when the tensile stresses at the concrete-epoxy interface reaches the tensile strength of the concrete. However, the tensile stresses can be reduced by increasing the thickness of the epoxy cover, or by using adhesives of high tensile strength. By widening the groove, the induced tensile stresses at the concrete-epoxy interface can be minimized (rizkalla-etal2003).

Test results produced by tumialan-nanni2002 revealed that masonry walls strengthened with NSM FRP bars showed an increase of 4 to 14 times of the original masonry capacity with an increase in shear capacity as well.

5. Center Core Technique

This technique involves drilling continuous straight vertical grooves through head joints and brick units and horizontally at bed joints. The groove is about 1 inch deep and as wide as the mortar thickness. After core drilling the groove, the debris is removed by a vacuum. After cleaning, an epoxy primer is applied and the grooves are partially filled with an epoxy adhesive. The FRP reinforcing rod is then installed and another layer of epoxy adhesive is pumped in to fully encapsulate the reinforcement. Lateral ties are used to connect the rods to the roof. This technique is illustrated in Figures 7 and 8 below.

To maintain the existing facade, repointing mortar of similar color and properties is applied from the outside. The grout migrate into adjacent voids during pumping, which strengthens the inner and outer bricks thereby producing a homogenous structural element. According to elgawady-etal2004, the reinforced homogeneous vertical beam increases the wall capacity to resist in-plane and out-of-plane loading.

[c]0.5

Figure 2. Air-Powered Gun

[c]0.5

Figure 3. Electric Powered Gun

[c]0.5

Figure 4. Application of Embedding Paste

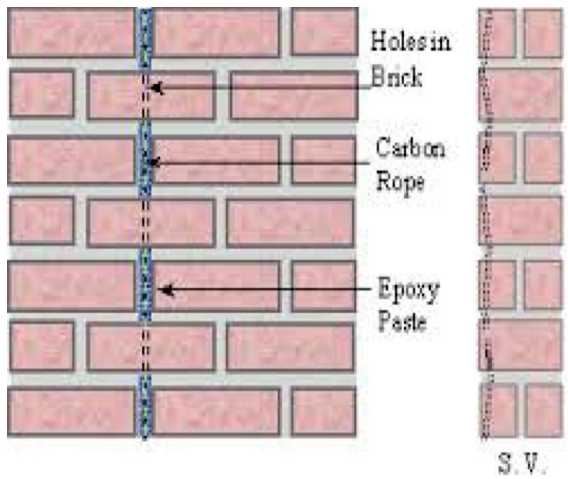


Figure 7. Installation of FRP rod as vertical reinforcement (korany-drysdale2004)

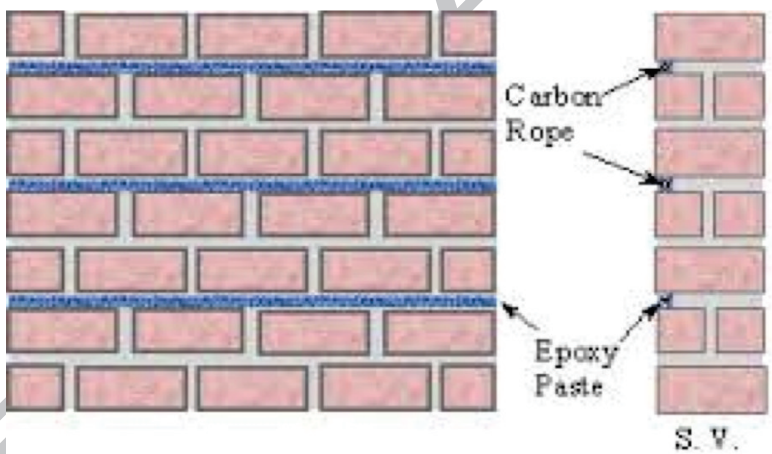


Figure 8. Installation of FRP rod as horizontal reinforcement (korany-drysdale2004)

Research conducted by citetkorany-drysdale2004 showed that this technique produced significant increase in capacity, deformability and energy dissipation over unreinforced specimens. Also, no strength deterioration was observed under cyclic loading in their study. The additional advantage of the system is that it does not alter the wall surface appearance or the function of the building. However the main drawback of the technique is that it creates zones of varying stiffness and strength properties according to elgawady-etal2004.

6. Cement Based Matrix Grid System

Studies by aldea-etal2005 have shown that the use of cement based matrix grid (CMG) can improve the performance of masonry by increasing its strength and ductility. CMG system offers good compatibility and bond with the substrate, provides a breathable system which allows air and moisture transfer through the matrix, allows for ease of installation through the use of trowel.

CMG system is a composite that consists of a series of layers of cement based matrix and alkali resistant glass coated reinforcing grid as shown in Figure 11b. The grid may consist of bi-directional aramid (AR) glass coated open grid which is made of machine strands connected perpendicularly at a spacing of about one inch as shown in Figure 11a.

The CMG strengthening techniques may be performed by pre-wetting the masonry wall with water and applying about 1/4 inch of mortar mixed with a fortifier by trowel on to the wall. The CMG fabric sheet is firmly hand pressed in to the wet binder to ensure adequate support and embedment into the wall. A second layer of mortar is applied by troweling additional 1/4 inch layer of mortar. To ensure interlocking and prevent debonding, the first CMG fabric sheet is installed with the primary fibers oriented horizontally. Another layer of CMG fabric sheet with the primary fibers aligned vertically is installed and covered by a smooth mortar layer.

7. Strengthening with FRP strips

This method involves using strips of composite material, glass fibers and epoxy resin matrix to reinforce masonry by applying the strips in layers

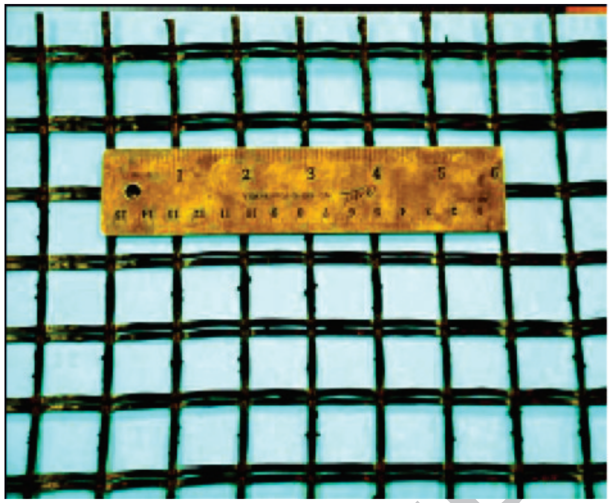
[b]0.5 

Figure 9. Structural Reinforcing Grid

[b]0.5 

Figure 10. Cement Based Matrix

Figure 11. Cement Based Matrix Grid System aldea-etal2005 (Aldea et al., 2005)

from one corner of the wall to the other with or without connectors. The strips are oriented in the principal direction of tensile strength and different configurations may evolve as a result. A sample arrangement is shown in Figure 16.

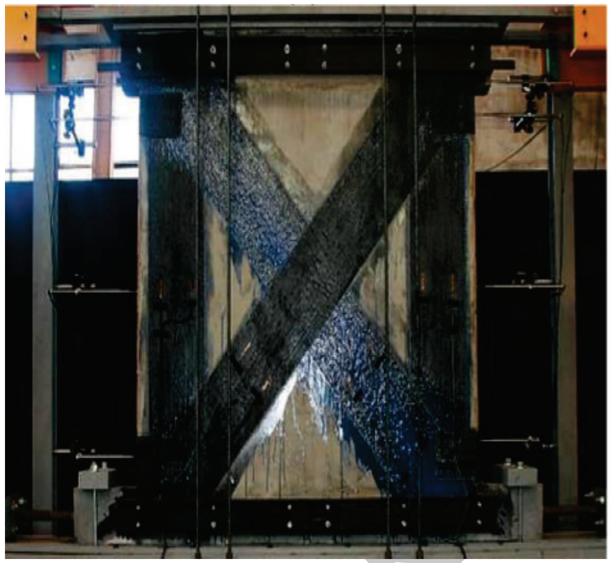
[b]0.5 

FIGURE 12

[b]0.5 

FIGURE 13

FIGURE 14. *
FRP strips with different configurations

8. Micro-reinforcement of masonry joints

Micro-reinforcement of masonry joints is accomplished by mixing polymer fibers or polypropylene fibers with cement and water. Used as mortar joints, the mixture can reduce cracks induced in ordinary mortar and can improve flexibility and toughness. Tests conducted by lanivschi2012 have shown that compression strength of micro-reinforced mortar increased by about 15%.

8.1. **Macro-reinforced masonry joint.**

This method involves constructing with two layers of mortar sandwiched with resin coated glass fiber (boslijkov2006). An improvement of about 15% in compressive strength was also observed in laboratory tests performed on macro-reinforced walls by lanivschi2012.

9. Post- Tensioning using FRP Tendons

Post tensioning is an effective method for increasing the out of plane strength of URM walls. Post-tensioning modifies the stress behavior of URM in bending. According to ingham-griffith2011, URM wall does not bend instantly. This modifies the material properties which also result in an increase in the shear strength of the wall . Post tensioning may be applied externally, internal application by drilling vertical cores through the middle of a URM wall and then inserting FRP tendons located inside a duct along the cores is less intrusive and preferred. FRP's are light weight and have high strength. These properties are very suitable for post-tensioning applications. CFRP tendons whose fibers are aligned in the longitudinal of the tendon have strength in the range of 290075 psi - 362594 psi (2000-2500 MPa) while Aramid FRP tendons have a variety of strengths depending on the manufacturer GFRP is not as strong with strength in the range 159541 psi

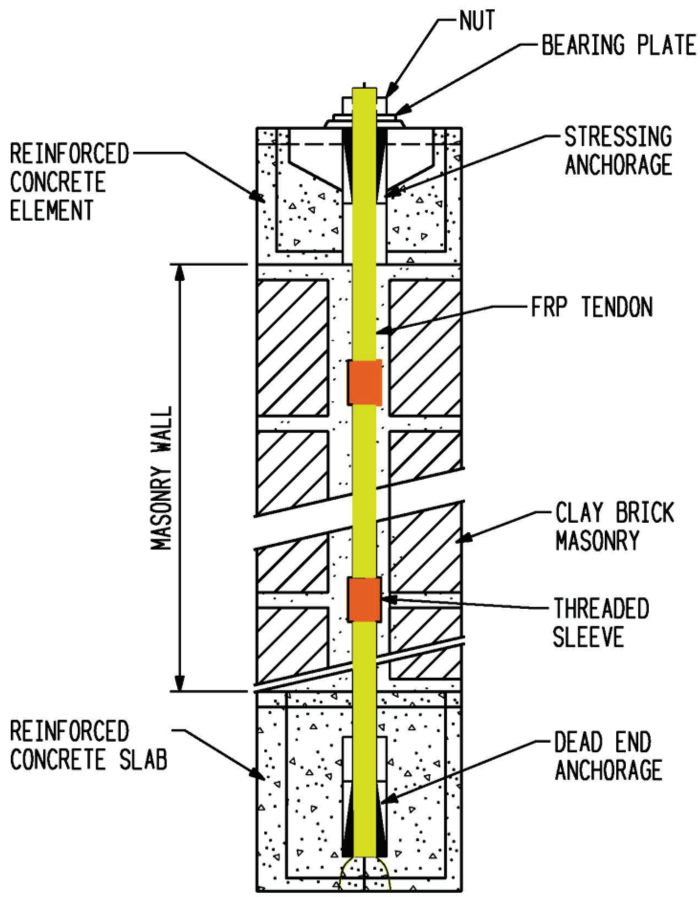


FIGURE 17. Section through a Post-tensioned Masonry Wall (VSL1990)

- 188549 psi (1100 - 1300 MPa) (sayed-shrive1998). The system utilizes CFRP tendons because of high strength and durability.

First the CFRP rods are fed through stressing anchorage and duct located in predrilled holes in the middle of a URM wall into a self-activating dead-end anchorage. The holes are grouted and the tendons are subsequently stressed to a maximum of 75% of their tensile strength. A typical masonry tendon is illustrated in Figure 17 and a field installation is shown in Figure 18.

Figure 18. Construction of a masonry wall post-tensioned with CFRP tendons (cintec2012)

The anchorage used for steel tendons can cause a CFRP tendon to shatter. According to shrive-etal2001, the sharp ridges on the wedge of a standard anchorage is designed to dig into and grip steel tendons but this may cause the carbon fiber tendon to shatter in the anchorage. To avoid this, a split wedge anchorage system (shown in Figure 19) is used. It consists of a barrel that is contoured inside, wedges with an external angled surface that matches the inside of the contoured barrel and a sleeve to distribute compressive stresses from the wedges to the FRP tendon to prevent sudden failure (campbell-etal2000). Self activating dead end can be encased in an in-situ concrete beam at the bottom. The stressing anchorage is placed in prefabricated concrete element or steel plates at the top.

10. Design philosophy

Different failure modes of URM reinforced with FRP have been reported and they are often described as debonding or rupture of the composite,

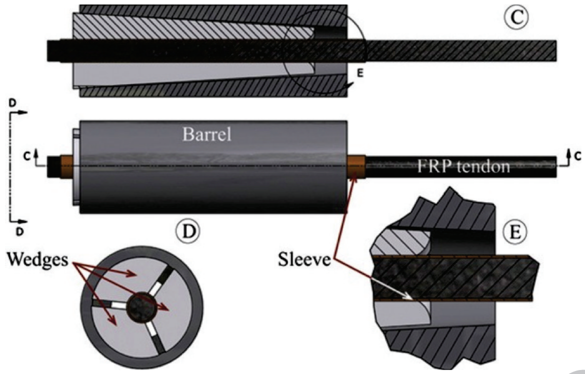


FIGURE 19. Wedge Anchorage System schmidt-etal2012

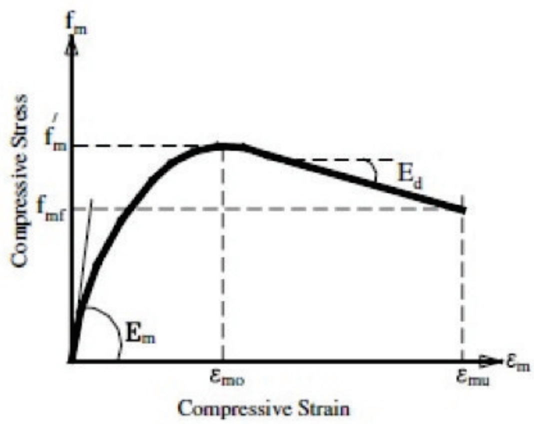


FIGURE 20. Stress-strain curve for brick-mortar blocks in compression (mosallam2007)

brittle failure, or ductile failure involving crushing of the masonry. An analytical procedure that ensures safety from sudden and catastrophic failure is imperative. The design of URM structures reinforced with FRP are based on limit states design principles. The design of URM structures reinforced with FRP is based on strength, and then checked for serviceability criteria, creep rupture and fatigue endurance. Serviceability criteria, creep rupture or fatigue endurance may actually control the design.

Due to the linear elastic behavior of FRP materials, sudden and brittle flexural or shear failure may occur. As a result, design guidelines of the

Masonry Institute which stipulates conservative strength reduction factors are carefully followed.

11. Flexural Capacity Based on Strengthening With FRP Laminate

The flexural strengthening of URM with FRP laminate is governed by three limit states, namely;

a) Crushing of the masonry in compression
b) Debonding of the FRP laminate
c) Rupture of the FRP laminate

Research studies conducted by velazquez1998,Hamilton-etal1999 and roko-etal1999 have suggested that the predominant limit state is debonding of the FRP laminate. However, shear failure may also occur if a substantial quantity of FRP laminate is used for strengthening. roko-etal1999 observed that debonding is closely related with porosity of the masonry unit which is a function of the initial rate of absorption of the epoxy bonding agent used. For example, molded bricks epoxy better than extruded bricks due to the nature of their surfaces which in turn leads to a reduction in bond strength between FRP laminate and masonry surface.

To calculate the flexural capacity of a masonry wall strengthened with FRP, the strain compatibility, internal force equilibrium and mode of failure must be considered. The ultimate capacity of a FRP strengthened masonry wall is estimated based on the assumption that no premature failure will occur. Therefore failure is governed by either rupture of the laminate or crushing of the masonry.

An analytical approach to check the out-of-plane flexural capacity of a red brick wall strengthened with FRP as described by mosallam2007 is presented below.

The principles used for the analysis of the cross-section of a URM wall are:

(1) Stresses and strains are related by the material properties of masonry and CFRP.
(2) Plain section before bending remains plane after bending, therefore a linear strain distribution is assumed along the section.
(3) The area of the FRP laminates is large enough for the failure of the specimen to be due to masonry crushing instead of FRP rupture.
(4) Tensile strength of the brick mortar is ignored.
(5) Tensile resistance of the FRP laminate in the transverse direction is ignored.

12. Stress-Strain Relations

12.1. **Brick-Mortar Block.** The uniaxial stress strain behavior and other characteristics of brick-mortar blocks under uniaxial compression have been studied by several laboratory tests and are presented in Figure 20.

The stress strain curve for the brick-mortar consists of a parabolic portion up to the maximum compressive strength f'm and a linear portion that descended to the ultimate compressive strain ϵ_{mu}.

fattal-etal1976 and triantafillou1998 gave the parameters of the stress-strain curve as follows:

$$f'_m = 4500 \text{ psi } (31 \text{ MPa}); \epsilon_{mo} = 0.002; \epsilon_{mu} = 0.0035; E_m = 2.8x10^6 \text{ psi } (19.28 \text{ GPa}) \text{ and } f_{mf} = 0.5 f'_m$$

13. CFRP Laminate

The relationship between stress and strain for FRP is linear and a typical curve for FRP laminate in tension is shown in Figure 21.

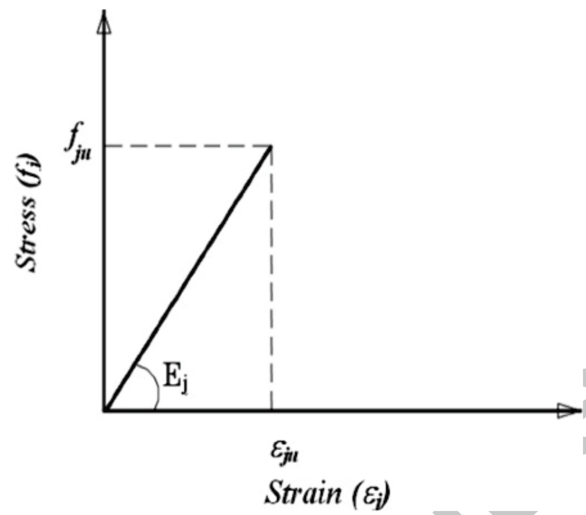


Figure 21. Stress-Strain Curve for FRP Laminate mosallam2007

13.1. **Distribution of Stresses and Strain.** For the analysis of brick-mortar block reinforced with FRP, it is assumed that the brick will crack under ultimate tensile strain. After the brick fails, all the tensile loads will be carried by the FRP laminate. Figure 21 shows the cross section of a rectangular beam subjected to bending and the strain diagram with a stress block. A parabolic stress distribution similar to the flexural analysis of reinforced concrete members is used in calculating the flexural capacity of the FRP strengthened masonry.

Since there is compatibility of strains between the brick and the FRP laminate which is bonded to the tension face of the brick, the FRP laminate strain ϵ_j in tension, can be determined from the strain diagram. From figure 22 the relationship between the depth of the neutral axis c, the ultimate masonry block strain ϵ_μ and the FRP strain ϵ_j is given by:

$$0.0035/c = \epsilon_j/h - c$$
$$\epsilon_j = 0.0035(h - c/c)$$
$$\epsilon_j = 0.0035(h/c - 1) \quad (1)$$

The rectangular stress block parameters are required to perform the analysis. These parameters bound the equivalent compressive block and are determined from the following equations (mosallam2007):

$$\beta = 2\left[1 - \frac{\int_0^{\epsilon_{mu}} f_m \epsilon_m d\epsilon_m}{\epsilon_{mu} \int_0^{\epsilon_{mu}} f_m d\epsilon_m}\right] = 0.88 \quad (2)$$

$$\gamma = \frac{\int^{\epsilon_{mu}} f_m d\epsilon_m}{\beta f'_m \epsilon_{mu}} \quad (3)$$

mosallam2007, by integrating the stress-strain curve for the brick-mortar blocks in compression provided them as follows:

$$\beta = 0.88 \text{ and } \gamma = 0.8$$
$$a = \beta c \quad (4)$$
$$c = a/\beta = a/0.88 \quad (5)$$

substituting c

$$\epsilon_j = 0.00308h/a - 0.00305 \quad (6)$$

Bending will induce forces acting on the section and these forces are shown in Figure 22. The forces are derived as follows:

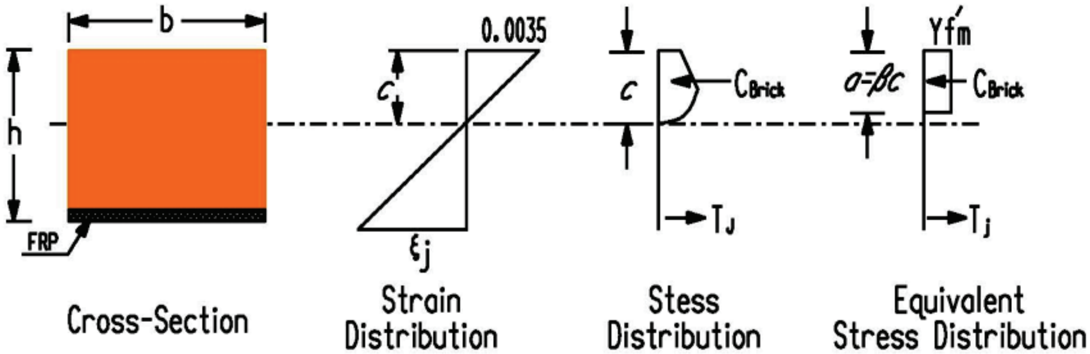


Figure 22. Cross-section with strain diagram and stress block

Brick-mortar block compression; $$C = \gamma f_m^t ab \quad (7)$$

Substituting; $$C = 0.8 \times 4500ab = 3600ab \quad (8)$$

FRP tension; $T = A_j f_j = A_J E_J \epsilon_J$

$$T = 2.8X10^6 A_j(0.00308h/a - 0.00305)$$

From Equilibrium; $C = T$ from which a is obtained.
By calculating a, the FRP strain ϵ_j can be obtained.

The ultimate strain is calculated from: $$\epsilon_{ju} = f_{ju}/E_J \quad (9)$$

If the ultimate strain is greater than the allowable strain, then failure is due to masonry crushing instead of FRP fracture and the ultimate moment can be calculated as:

$$M_u = \text{ Ultimate flexural capacity } = \gamma f_m^t ab(h - a/2) = A_j f_{ju}(h - a/2) \quad (10)$$

14. Example for illustration of the procedure

A wall section is shown in Figure 22. The material properties are $f_m' = 3.629$ ksi for masonry, $\gamma = 0.8, \beta = 0.88, f_{ju} = 180.7$ ksi for the FRP laminate. The modulus of elasticity is $E_j = 15060$ ksi for the FRP laminate.

Section Data. $b = 104$ in, $t_p = 0.046$ in (2 ply thickness), $d = 4$ in

Calculate neutral axis depth:

h =4 in + 0.046in/2 = 4.023 in

$a = \beta c = 0.88c$

$C = \gamma f_m' ab = 0.8 \times 3.629 \times a \times 104 = 301.93a$

$T = A_j f_j = A_j E_j \epsilon_j$

$T = 2 \times 0.023 \times 104 \times 15060 \times \epsilon_j = 72047.04\epsilon_j$

From strain compatibility,

$$\epsilon_j = 0.0035(h/c - 1) = (0.00308h/a - 0.0035)$$

$$T = 892.723/a - 252.17$$

From equilibrium:

$C = T$

$301.93a = 892.723/a - 252.17$

$a = 1.352$ in

Check FRP for allowable strain

$\epsilon_j = (0.00308h/a - 0.0035) = (0.00308 \times 4.023/1.352 - 0.0035) = 0.0057$

ultimate strain $\epsilon_u = f_{ju}/E_j = 180.7/15060 = 0.120$

Since allowable strain $\epsilon_j, <$ ultimate ϵ_u, failure is due to masonry crushing rather than FRP fracture.

Ultimate moment capacity:

$M_u = \gamma f'_m ab(h - a/2) = A_j f_j u(h - a/2)$

$M_u = 0.8 \times 3.629 \times 1.35 \times 104 \times (4.023 - 1.35/2) = 1364.68$ kip-in

Ultimate uniform load, $w_u = 8M_u/L^2 = 8 \times 1364.68/104^2 = 1.01$ kip/in

Ultimate load capacity, $P_u = w_u \times L = 1,01$ kip/in $\times 104in = 105.14$ kip

Ultimate pressure $P_u = \frac{105.14\text{kips}}{(104\text{in})(104\text{in})} = 1399.79$ psf.

The ultimate out-of-plane capacity of a similar wall specimen is 136 psf. Consequently, strengthening with FRP increased the out-of-plane capacity 10.29 times. This increase is due to the FRP composite which caused the strength and ductility of the wall to increase.

15. Summary

The efficiency, advantage, disadvantage of the techniques discussed are summarized in Table 15. The summary is based on extensive literature survey.

to —X[2,l,p] —X[2,l,p]—X[2,l,p]—X[3,l,p]—X[3,l,p]— [Technique Summary]Technique Summary

Technique | Advantage Disadvantage

In-plane Out of Plane

Technique | Advantage Disadvantage

Externally Bonded FRP System Increases lateral resistance. Improves lateral displacement Improves Flexural strength. Improves ductility. Increases strain capacity. Improves stability Provides additional flexural and shear strength. Enhances ductility of columns in high seismic zones due induced confinement. Ease of handling and installation Premature failure due to debonding. Poor performance at high temperature. Sensitivity to ultra violet rays. Linear stress-strain curve with no yield. plateau. High initial cost. Unprotected against wear, harsh environmental conditions and impact loads

Near Surface Mounted FRP Systems Improves out-of-plane bending resistance. Improves lateral resistance Increases post-cracking flexural strength and ductility of URM walls. Flexural strength increase of 4 to 14 times the original masonry capacity can be achieved. Significant increase in shear capacity and axial strain can be attained. Provides greater anchoring capacity than externally bonded FRP systems. Precludes delamination type failures. No surface preparation work required. Requires minimal installation time. Minimal impact upon aesthetics of the structure. Offers protection from fire and ultra violet rays. Debonding failure due to splitting of epoxy cover from high tensile stresses may occur. Debonding failure due to cracking of concrete surrounding the epoxy adhesive likely

Center Core Technique Doubles resistance of unreinforced masonry Improves lateral resistance Does not alter architectural appearance. No effect on building function. No space reduction Creates zones with varying stiffness and strength

Cement Based Matrix Grid System N/A N/A Increases wall bearing capacity. Polymer grids increase strength and stiffness of URM wall Grid slippage or tensile failure may occur

FRP strip strengthening technique. Improves strength, ductility and energy dissipation capacity Improves lateral load resistance to 4 times unreinforced wall capacity Minimizes displacement

Micro-reinforcement of masonry joints N/A N/A Improves mortar toughness and flexibility Increases compressive strength N/A

Macro-reinforced masonry joint N/A N/A Improves mortar toughness and flexibility Increases compressive and tensile strength Improves ductility N/A

Post-tensioning Improves lateral resistance Improves lateral resistance Increases cracking moment resistance and ultimate moment resistance No added mass No effect on building function High losses Potential for corrosion of anchorage system

N/A - Data not available

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