Strengthening of Masonry Walls with FRP Bars

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INTRODUCTION

Structural weakness or overloading, dynamic vibrations, settlements, and in-plane and out-of-plane deformations can cause failure of unreinforced masonry (URM) structures. URM buildings have features that, in case of overstressing, can threaten human lives. These include unbraced parapets, inadequate connections to the roof, floor and slabs, and the brittle nature of the URM elements. Organizations such as The Masonry Society (TMS) and the Federal Emergency Management Agency (FEMA) have determined that failures of URM walls result in more material damage and loss of human life during earthquakes than any other type of structural element. This was evident from the post-earthquake observations in Northridge, California (1994) and Izmit, Turkey (1999) (see Figure 1).

(a) Failure due to Out-of-Plane Loads   (b) Failure due to In-Plane Loads

Figure 1. Failure in URM Walls, Izmit Turkey, 1999

Under the URM Building Law of California, passed in 1986, approximately 25,500 URM buildings were inventoried throughout the state. Even though, this number is a relatively small percentage of the building inventory in California, it includes many cultural icons and historical resources. The building evaluation showed that 96% of the buildings needed to be retrofitted, which would result in approximately $4 billion in retrofit expenditures. To date, it has been estimated that only half of the owners have taken remedial actions, which may attributed to high retrofitting costs. Thereby, the development of effective and affordable retrofitting techniques for masonry elements is an urgent need.

For the retrofitting of the civil infrastructure, externally bonded Fiber Reinforced Polymer (FRP) laminates have been successfully used to increase the flexural and/or the shear capacity of reinforced concrete (RC) and masonry members. An alternative to the use of FRP laminates is the use near surface mounted (NSM) FRP bars. This technique consists of placing a bar in a groove cut into the surface of the member being strengthened. The FRP bar can be embedded in an epoxy-based or cementitious-based paste, which transfers stresses between the substrate and the FRP bar. The successful use of NSM FRP bars in the strengthening of concrete members (De Lorenzis et al., 2000) has been extended to URM walls, one of the building components most prone to failure during a seismic event.

The use of NSM FRP bars for increasing the flexural and the shear strength of deficient masonry walls, in certain cases, can be more convenient than using FRP laminates due to anchoring requirements or aesthetics requirements. Application of NSM FRP bars does not require any surface preparation work and requires minimal installation time compared to FRP laminates. Another advantage is the feasibility of anchoring these bars into members adjacent to the one being strengthened. For instance, in the case of the strengthening of a masonry infill with FRP bars, they can be easily anchored to columns and beams.

This article describes two applications of FRP bars for the strengthening of URM walls. In the first application, NSM FRP bars are used as flexural reinforcement to strengthen URM walls to resist out-of- plane forces. In the second application, a retrofitting technique denominated FRP Structural Repointing is described. In this technique the FRP bars are placed into the horizontal masonry joints to act as shear reinforcement to resist in-plane loads.

In both applications glass FRP (GFRP) bars were used to increase either the flexural or shear capacity. The GFRP bars are deformed by a helical wrap with a sand coating to improve the bond between the bar and the embedding paste (see Figure 2). The bars are produced using a variation of the pultrusion process using 100% vinylester resin and e-glass fibers. Typical fiber content is 75% by weight. The bars are commercially available in high volumes with stocking locations in several points throughout North America and Europe.
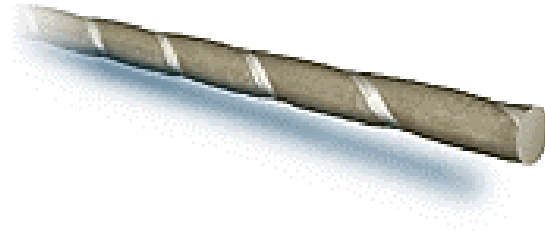

Figure 2. GFRP Bar

FLEXURAL STRENGTHENING

FRP bars can be used as a strengthening material to increase the flexural capacity of URM walls. The successful use of NSM bars for improving the flexural capacity of RC members led to extending their potential use for the strengthening of URM walls. The use of NSM FRP bars is attractive since their application does not require any surface preparation work and requires minimal installation time.

Strengthening Procedure

The NSM technique consists of the installation of FRP reinforcing bars in slots grooved in the masonry surface. An advantageous aspect of this method is that it does not require sandblasting and puttying. The strengthening procedure can be summarized as: (1) grooving of slots having a width of approximately one half times the bar diameter and cleaning of surface, (2) application of embedding paste (epoxy-based or cementitious-based paste) (see Figure 3a), (3) encapsulation of the bars in the joint (see Figure 3b), and (4) finishing. If hollow masonry units are present, special care must be taken to avoid that the groove depth exceeds the thickness of the masonry unit shell, and that local fracture of the masonry occurs. In addition, if an epoxy-based paste is used, strips of masking tape or other similar adhesive tape can be attached at each edge of the groove to avoid staining of the masonry surface (see Figure 3).

(a) Application of Embedding Paste   (b) Encapsulation of FRP Bar

Figure 3. Installation of NSM FRP Bars

Depending on the kind of embedding material, cementitious-based or epoxy-based, a mortar gun used for tuckpointing or an epoxy gun can be used. The guns can be hand, air or electric powered, being the latter two, the most efficient in terms of efficiency. Figure 4a illustrates the application of an epoxy-based paste using an air powered gun. Figure 4b shows the application of a cementitious-based paste with an electric powered gun.

(a) Air Powered Gun　　　　　　　　　　　　(b) Electric Powered Gun

Figure 4. Guns for Installation of Embedding Paste

Experimentation

The test results of three masonry specimens, constructed with concrete blocks, are presented. Their dimensions were 3.75x24x48 in. The masonry specimens were strengthened with #3 GFRP bars having a tensile strength of 110 ksi and modulus of elasticity of 5900 ksi. The strengthening layout intended to represent URM wall strips with GFRP bars at different spacing. Thus, Wall R1 was strengthened with one GFRP bar (spacing = 24 in.), Wall R2 with two GFRP bars (spacing = 12 in.). In order to compare the performance of FRP bars and laminates, Wall L1 was strengthened with one 3 in. wide GFRP laminate. The amount of strengthening reinforcement was equivalent to that of Wall R1 in terms of axial stiffness. The load capacity of an URM wall was estimated to be equal to 800 lbs. The walls were tested under simply supported conditions (see Figure 5).

Figure 5. Test Setup

Wall R1 failed due to debonding of the embedding material from the masonry. Initial flexural cracks were primarily located at the mortar joints. A cracking noise during the test revealed a progressive cracking of the embedding material. Since the tensile stresses at the level of the

mortar joints were being taken by the FRP reinforcement, a redistribution of stresses occurred. As a consequence, cracks developed in the masonry units oriented at 45° (see Figure 6a) or in the head mortar joints. Some of these cracks followed the epoxy paste and masonry interface causing their debonding and subsequent wall failure. Wall R2 failed due to shear (see Figure 6b). Similarly to Wall R1, cracking started in the mortar joints at the maximum bending region. In general, initial cracking was delayed and the crack widths were thinner as the amount of FRP reinforcement increased.
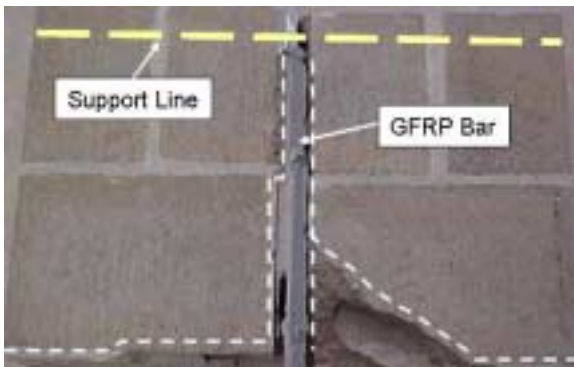
(a) Debonding Failure (Wall R1)   (b) Shear Failure (Wall R2)

Figure 6. Specimens after Failure

Figure 7 illustrates the Moment vs. Deflection curves for the test specimens. The flexural strength and stiffness of the FRP strengthened walls increased as the amount of reinforcement increased. It is observed that increments of 4 and 14 times the original masonry capacity were achieved for Walls R1 and R2, respectively.
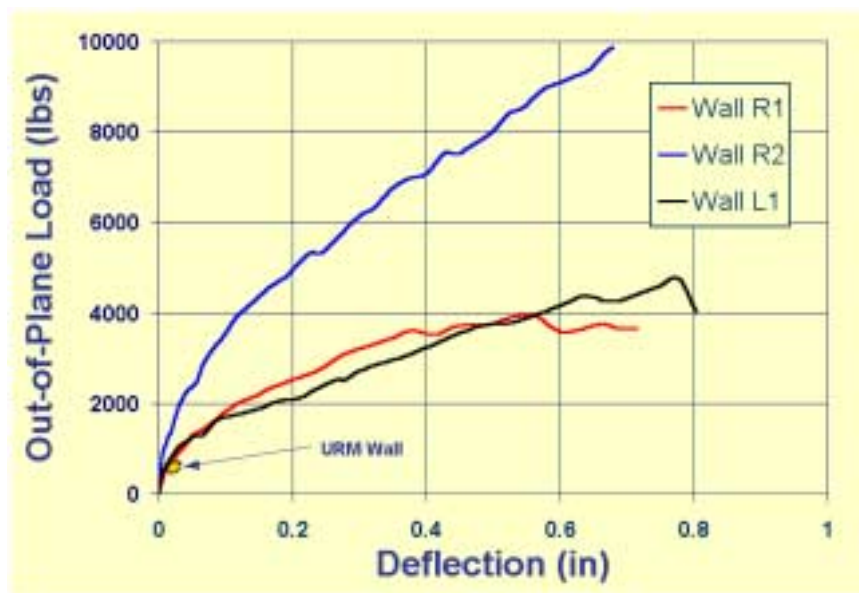

Figure 7. Moment vs. Deflection Curves

SHEAR STRENGTHENING

The technique denominated FRP structural repointing is basically a variant of the NSM technique. It consists of placing FRP bars in the mortar joints. Repointing is a traditional retrofitting technique commonly used in the masonry industry, which consists of replacing missing mortar in the joints. The term "structural" is added because this method does not merely consist of filling the joints as the traditional technique, but allows for restoring the integrity and/or upgrading the shear and/or flexural capacity of walls.

Strengthening Procedure

FRP structural repointing offers advantages compared to the use of FRP laminates. The method itself is simpler since the surface preparation is reduced, sandblasting and puttying is not required. In addition, the aesthetics of masonry can be preserved. In this technique, the diameter size of the FRP bars is limited by the thickness of the mortar joint, which usually is not larger than $^{3}/_{8}$ inches. The strengthening procedure consists of: (1) cutting out part of the mortar using a grinder, (2) filling the bed joints with a epoxy-based or cementitious-based paste (see Figure 8a), (3) embedding the bars in the joint (see Figure 8b), and (4) retooling.

(a) Application of Embedding Paste   (b) Installation of GFRP Bars

Figure 8. Strengthening by Structural Repointing

To ensure a proper bonding between the epoxy-based paste and masonry, dust must be removed from the grooves by means of an air blower prior to filling the bed joints. A masking tape or another suitable adhesive tape can be used to avoid staining. Stack bond masonry allows to install FRP bars in the vertical joints, if required (see Figure 8b). In this case since the faceshell thickness of the masonry units does not limit the grove depth, this can be deeper.

Experimentation

Three masonry walls built with 6x8x16 in. concrete blocks were tested. The walls were strengthened with #2 GFRP bars having a diameter of 0.25 in., a tensile strength of 120 ksi and

modulus of elasticity of 5900 ksi. One URM wall, Wall R0, was selected as control specimen. Wall R2 was strengthened with GFRP bars at every horizontal joint. Wall L2 was strengthened with GFRP laminates; the amount of FRP was equivalent to that of Wall R2 in terms of axial stiffness. Thus, Wall L2 was strengthened with four horizontal 4 in. wide GFRP strips. The specimens, tested in a close loop fashion, were loaded along one diagonal of the specimen. Figure 9 illustrates the test setup.
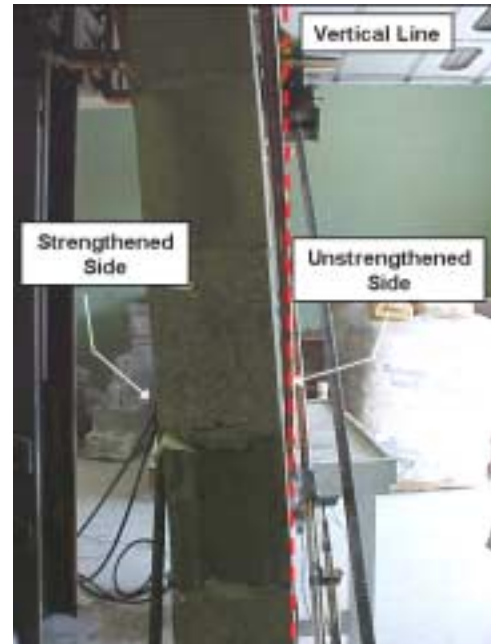

Figure 9. Test Setup

The tests results showed that in the control Wall R1 the failure was brittle, controlled by bonding between the masonry units and mortar. When the tensile strength of masonry is overcome, the wall cracks along the diagonal, following the mortar joints (stepped crack vertical/horizontal). In the strengthened Wall R2 failure occurs when the shear cracks widen and GFRP bars are not able to carry tensile stresses due to debonding at the top and bottom epoxy/block interface (see Figure 10a). The shear capacity was increased in about 80%. The strengthened walls showed stability (i.e. no loose material was observed) after failure. This fact can reduce risk of injuries due to partial or total collapse of walls also subjected to out-of-plane loads. In addition, due to the reinforcement eccentricity, Wall R2 tilted to the direction of the strengthened face (see Figure 10b). In addition, due to the reinforcement eccentricity, which caused the crack growth on the unstrengthened side to increase at a higher rate than the strengthened side, Wall 2 tilted to the direction of the strengthened face (see Figure 10b). Data showing the crack opening is presented elsewhere (Tumialan et al., 2001). Failure in Wall L2 was due to sliding shear along an unstrengthened joint.
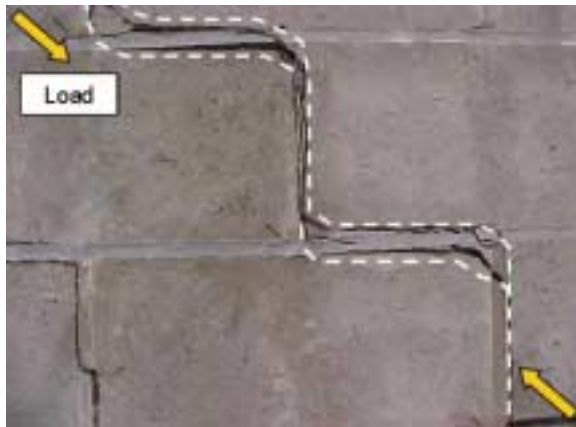
(a) Debonding of epoxy/block interface	(b) Tilting of Wall R2

Figure 10. Specimens after Failure

From Figure 11 it is observed that the walls strengthened with FRP bars (Wall R2) and FRP laminates (Wall L2) had similar shear capacity; however, the pseudo-ductility was less in the Wall L2, which can be attributed to the occurrence of the sliding shear failure.

Figure 11. In-Plane Load vs. Shear Strain

J.G. Tumialan and A. Nanni, "Strengthening of Masonry Walls with FRP Bars,"
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FINAL REMARKS

Experimental results of two different applications of NSM FRP bars for the strengthening of masonry walls were presented. Each of them showed promising potential of FRP bars for the retrofitting of masonry. In general, strength and pseudo-ductility can be substantially increased by strengthening masonry walls with NSM FRP bars. Thus:

- Masonry walls strengthened with NSM FRP bars exhibited similar performance to walls strengthened with FRP laminates.
- For flexural strengthening, increments ranging between 4 and 14 times of the original masonry capacity may be achieved.
- Remarkable increases in shear capacity were achieved by strengthening URM walls by FRP structural repointing.

ACKNOWLEDGEMENTS

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