FRP Composites for Masonry Retrofitting

Review of Engineering Issues, Limitations, and Practical Applications

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Recently, FRP systems have received attention from the repair and rehabilitation industry as a viable methodology that can be employed to address strength, damage, and deterioration issues in masonry. The emerging FRP industry, which had originally focused on retrofitting of concrete structures, has eventually recognized an opportunity to employ high-strength composites to improve structural capacity or stabilize distress in masonry construction, especially walls.

Masonry structures are often in need of help. Because of its material characteristics and exposure conditions, masonry is often prone to damage or deterioration. Temperature changes and exposure to moisture and other environmental factors result in deterioration, weakening, and distress of masonry elements. In addition, masonry construction, especially in unreinforced historic applications, is especially vulnerable and often cannot resist demands due to external loads such as earthquakes, high wind pressures, soil pressure, deformation-driven stresses (e.g. foundation settlement), excessive vibration, etc. FRP materials, if used properly, can be used to address a number of these problems in service and to arrive at more-durable, ductile, and stronger masonry systems.

As with any other retrofitting method, however, the success of FRP technology for masonry depends on the availability of information and guidance related to design, construction, and inspection. Without them, proper application, understanding of benefits and limitations, as well as performance and durability in service cannot be ensured. Currently, there are no comprehensive guidelines for installation, material selection, and design in the US. However, Technical Committee 440 of the American Concrete Institute (ACI) is working on development of comprehensive design and detailing guidelines, which ACI plans to publish next year. When this document becomes available, it is expected that masonry strengthening with FRP composites will become more common. In the meantime, this article presents a summary of some of the more important and practical engineering and construction issues related to FRP applications for masonry structures.

Figure 1: Flexural strengthening with NSM GFRP Bars of a CMU wall in Kansas City, MO. The wall was damaged due to lateral displacement. Note the repaired crack at mid-height.

Masonry Retrofitting With FRP Composites

Retrofit of masonry structures with FRP can include seismic or wind upgrades, repair of deterioration, or rectification of design/construction errors. FRP can effectively be used as a flexural or shear strengthening element to upgrade structural capacity, or to restore the original capacity of damaged elements (most commonly walls) subject to out-of-plane and in-plane load (*Figures 1 and 2*). FRP can also be used to address existing distress in masonry construction. One example is "stitching" of wide cracks to re-establish masonry integrity when this cannot be achieved by solely "filling" cracks with a repair material (*Figure 3*). FRP can also be wrapped around masonry elements to provide confinement (*Figure 4*).

The advantage of FRP composites for masonry retrofitting include lower installation costs, improved corrosion resistance, flexibility of use, and minimum changes in member size (and in some cases appearance) after repair. Disturbance to occupants and loss of usable space are also minimal. Furthermore, for earthquake retrofits, seismic mass of the existing structure remains unchanged because there is little addition of weight.

Considerations for FRP Selection

FRP Retrofitting Systems

There are two FRP techniques that can be used for retrofitting masonry walls: externally-bonded FRP laminates and near-surface-mounted (NSM) FRP bars.

Laminates come in two forms: FRP sheets (fabrics) and pre-cured strips (plates). They both derive strength from high strength composite fiber, which is the main component of both systems. FRP sheets are typically woven from individual uni-, bi-, or multi-directionally oriented fibers into thin sheets resembling wallpaper without a binding matrix material. FRP sheets are typically applied by manual wet lay-up and are adhered with adhesive onto the prepared surface of the member that is being strengthened.

Pre-cured FRP laminates typically feature unidirectional fibers embedded in a resin matrix, pultruded in long, strip-like shapes. In this instance, a plant-manufactured strip is adhered to the substrate of the member with an epoxy or cement paste, similar to steel-plate retrofits.

NSM bars are rectangular or round pultruded elements that contain high-strength fiber embedded in a pre-cured matrix. NSM FRP bars are placed in grooves cut on the masonry surface, typically in joints (if practical), which allows for minimal alteration of appearance. The grooves are partially filled with an epoxy

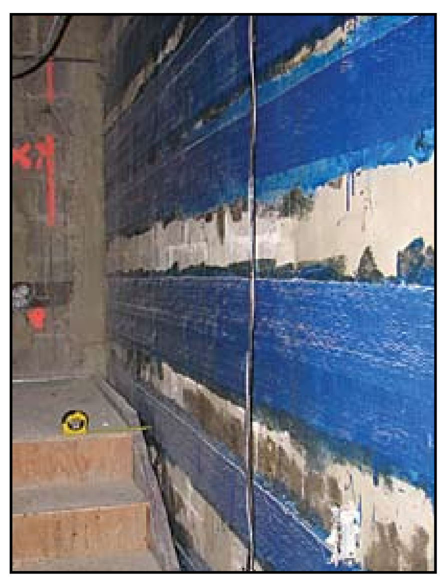

Figure 2: Shear strengthening of CMU Walls with GFRP laminates due to construction errors in Princeton, NJ. Original shear reinforcement in several locations of the wall was either omitted or placed too far apart.

Figure 3: Crack stitching of a brick wall with NSM CFRP Bars in Boston, MA. The wall was severely cracked due to foundation settlement.

or cement-based paste. The bar is then placed into the groove and lightly pressed to force the paste to flow around the bar.

From the structural point of view, NSM and laminate systems can be engineered to achieve similar objectives. They differ in installation techniques and in the impact on wall aesthetics. If the goal is to preserve wall appearance, NSM bars should probably be used since they can be concealed in the masonry.

Moisture migration through the wall should also be considered when selecting the type of FRP system: the laminates, typically placed on the exposed "face" of masonry, will change the wetting and drying characteristics of the element (usually the wall), while the NSM bars, typically placed in mortar joints, will have little impact on the wall's appearance and moisture characteristics.

Type of Fibers

Three types of fibers are commonly used in FRP composites for infrastructure applications: carbon, aramid and glass fibers. In the order listed, these fibers exhibit an ultimate strain ranging from 1 to 4%, with no yielding occurring prior to failure. Ultimate strength ranges from approximately 300 to 900 ksi, and elastic moduli range from 10,000 to 40,000 ksi.

In many instances, glass FRP (GFRP) is preferred for strengthening of masonry. The lower elastic modulus of GFRP, as compared to carbon FRP (CFRP), is not as limiting in masonry strengthening applications as it might be in concrete structures because it is more compatible with the low elastic modulus of masonry. In addition, GFRP material costs are substantially less than carbon or aramid materials. Also, experimental data from shear-strengthening of masonry walls have shown that use of CFRP systems do not offer significant improvement in structural performance over similar GFRP systems.

Use of CFRP systems, however, is preferable for applications where masonry elements will be subjected to sustained stresses, such as in retaining walls. CFRP systems are more suitable for these applications since they have better resistance to creep than other fibers. Also, in exterior applications, CFRP is generally a better option because of its superior durability in moist environments compared to GFRP.

Aramid is not commonly used in masonry. The material properties for aramid are sensitive to moisture change, which is common in masonry construction.

Embedding Paste in NSM FRP Applications

When compared to a latex-modified cement paste, epoxy pastes provide superior bond of FRP to the masonry substrate. Therefore, this kind of paste is typically used for NSM masonry strengthening when preservation of wall appearance is not a requirement. A cement-based paste is recommended for strengthening of walls where no change in appearance of the masonry wall is desired. This kind of paste can produce repairs that are visually compatible with existing mortar. Thus, for strengthening of historic masonry buildings, the paste can be mixed to match the original mortar in color and texture. Due to comparatively inferior bond properties of cement pastes, a reduction in bond-development strengths between FRP and masonry should be accordingly considered in design; this may result in an increase in the number of bars or in larger development lengths.

Also, in older masonry and in heavily loaded masonry, the designer should consider that "hard-filling" epoxy might result in masonry spalling at the joints due to stiffness incompatibility of the paste versus the balance of the bedding mortars.

Considerations for Design and Construction

Usable Design Strength

FRP composites have large tensile strengths; they are much stronger than steel bars of comparable area. However, behavior (failure modes) of masonry walls strengthened with FRP is typically controlled by debonding of the FRP from the masonry. The debonding failure mechanism, regardless of whether the element is loaded in flexure or in shear, almost always precludes utilization of the full tensile strength of the FRP. Because of these bond limitations, the usable FRP design strengths in conventional masonry applications are typically in the range of 30% to 40% of the ultimate tensile strength of the FRP. In addition, due to a linear stress-strain behavior to failure of the composites, FRP strengthening applications offer less ductility than steel-strengthened sections with a similar reinforcement ratio.

Fire Resistance

A major consideration in the selection of FRP as repair material is related to the potential loss of FRP effectiveness due to extraordinary events. The most typical such risk is damage due to fire, but loss from vandalism and impact should also be considered. Increased temperatures will cause an epoxy adhesive to flow plastically, causing a loss of shear load transfer from substrate to FRP and within the FRP. Typically, the critical temperatures (known as "glass-transition temperature") for the epoxies are in the range of 120°F to 200°F; in fact, for exterior masonry applications, only adhesives on the higher end of that range should be considered, because solar gain can push wall temperatures well above the ambient temperature, into the 120°F to 160°F range. Conventional fireproofing systems cannot protect the adhesive in these relatively low temperature ranges. An additional concern is the potential for FRP to contribute to smoke generation and flame spread; governing building code requirements should be evaluated.

Because of these concerns, there are practical limits to how much reasonable strength increase can be supplied by FRP to resist sustained loads. For example, in FRP strengthening applications for concrete elements, strength-increase limitations are introduced through

Figure 4: Strengthening with CFRP laminates of a 17th century masonry cathedral tower in Peru. Vertical reinforcement provides flexural strength. Hoop reinforcement provides confinement to restrain lateral expansion under earthquake forces.

design. Basically, unstrengthened candidate members must be capable of resisting the expected service loads, in case the FRP is lost. For example, for concrete elements that carry gravity-loads, the design requirement is that they must be capable of continuing to carry dead loads and a portion of the design live loads without the FRP (the reduction from the full live load reflects low probability that the full design live load will coincide with a fire). Essentially, the elements must possess certain "threshold" strength even before FRP application, and this inherently reduces the amount of design strength that can be added by FRP. For masonry elements, however, FRP systems are most frequently used to increase the capacity of walls subject to rare and extreme lateral loads, like in wind or seismic events. In such situations, the threshold strength limitations can be relaxed due to very low probability of say simultaneous seismic and fire events. This is beneficial because a large number of unreinforced masonry elements would likely not meet stringent threshold strength requirements (especially regarding existing flexural strength), and therefore would not be suitable candidates for FRP strengthening.

On the other hand, in masonry walls subject to sustained lateral loads, such as earth pressure on retaining walls, FRP loss could have catastrophic consequences if the FRP contribution to strength is not limited to ranges that still maintain a positive (larger than 1.0) factor of safety in case FRP is lost. For all FRP applications, however, the designer should carefully evaluate the consequences of the FRP system becoming ineffective. In the end, project conditions may reveal that FRP strengthening is not feasible unless fire suppression systems are installed as part of the repair.

Accessibility of Wall Faces

Strengthening of masonry walls for seismic and wind loads may require FRP placement on both sides of the wall, to provide flexural resistance against both inward and outward loads. Thus, for some exterior walls that are part of the building envelope, placing FRP on both wall sides may not be possible due to field constraints (e.g. presence of the backup wall of a cavity wall system). In these cases, internal grouting of steel bars might be more appropriate. Similar constraints may exist for brick walls in historical buildings. In this case, even though both wall sides are accessible, the exterior side may be "untouchable" because the FRP would disrupt the façade appearance unless outside-face bars are concealed in the bed joints.

In shear strengthening applications, the requirement for one or two-faced FRP placement may depend on wall construction. It is often acceptable to place FRP on only one face in hollow block walls of up to 8 inches thick. In thicker hollow walls, FRP should be placed on both faces. For 8-inch thick solid (brick or grouted) walls, FRP should be placed on both faces. Experimental results have shown that two-sided FRP shear strengthening is not effective in solid walls with thicknesses larger than 10 inches. Therefore, FRP use in such applications is not recommended unless substantiated by testing.

Influence of Boundary Conditions

The potential effects of boundary conditions on the behavior of masonry wall systems need to be evaluated before proposing the use of FRP strengthening. Specifically, in walls that are built between stiff supports, or are "infill" construction in a structural frame, FRP may not be effective due to additional resisting mechanisms or due to premature failures, such as crushing of masonry units at the wall boundaries.

Flexural FRP strengthening is highly effective for walls that can be treated as simply-supported elements, such as walls with large height-to-thickness (h/t) ratios, or walls with "flexible" boundaries where rotation of the wall ends is not constrained. However, for walls built between stiff supports and with low slenderness ratios (typically h/t below 12), analyzing a wall as a simply-supported element is not correct. Short walls with end restraints can develop arching action with thrust forces at supports, resulting in a larger inherent capacity that can potentially eliminate the need for strengthening. However, if it is analytically shown that even an "arching" wall requires strengthening, the designer should account for the occurrence of premature failures, like crushing in the thrust zones, which cause premature bonding failures and may severely limit the benefit of the FRP.

Load-Path Continuity

Resistance of a masonry building subjected to lateral loads depends on inter-connectivity between individual structural components along the load path. In masonry buildings, the load path is achieved by connecting walls to roof and floor diaphragms, or to slabs or foundation walls. Therefore, load-path continuity must be addressed when an FRP-strengthened wall will be part of the lateral load resisting system.

There are a variety of details that can be used to provide load-path continuity; these typically involve use of steel dowels grouted in the wall and anchored to the slabs, or steel shapes connected to walls and diaphragms. Care should be taken to develop a good connection between the steel and FRP system and to electrically isolate metal elements from the FRP, if conductive fibers like carbon are used, to prevent galvanic corrosion. This can often be achieved by "sandwiching" a glass fiber sheet between carbon and steel.

Surface Preparation

Surface preparation for installation of FRP laminates is typically more extensive than that of FRP bars. Surface preparation can involve sandblasting to roughen the surface, grinding of excess mortar in the joints, and application of epoxy primers and fillers. Use of epoxy primers is not practical for surface preparation of masonry with large porosity, such as in masonry built with molded bricks or concrete masonry units (CMU). In these situations, the epoxy used to bond the fibers to the substrate may be directly applied to the substrate. However, masonry built with extruded brick units, with less porosity, may require the use of an epoxy primer. For some substrates, it has been experimentally shown that epoxy fillers applied to the substrate surface notably improve bonding between the laminates and masonry.

The surface preparation required for installation of NSM FRP bars is minimal. Surface preparation typically requires grooving of masonry or mortar, and cleaning with pressurized air or water. If an epoxy-based paste is used to embed the bar, the recommended groove width is 1.5 times the bar diameter. A width of 2.5 times the diameter is more adequate when a cement-based paste is used.

Summary and Conclusions

A new tool for retrofitting of masonry structures is emerging. With proper planning, design, and construction considerations, FRP systems can be successfully used in a wide variety of structural and historic preservation applications of masonry construction. Currently, however, guidance on a number of critical issues related to engineering, material selection, and field application is incomplete; therefore, FRP is still far from being considered a mainstream tool. Until comprehensive guides become available, this article offers discussion on several critical engineering and practical issues that can help engineering professionals more comfortably embark on projects that utilize FRP technology in masonry applications.▪

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