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Guide for the Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Unreinforced Masonry Structures

Reported by ACI Committee 440

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Fiber-reinforced polymer (FRP) systems are an option to consider for strengthening unreinforced masonry (URM) structures. Traditional strengthening systems include external steel plates, reinforced concrete (RC) overlays, span shortening with steel subframing or bracing, and internal steel reinforcement. Relative to traditional systems, features of FRP systems include high tensile strength, light weight, ease of construction, and resistance to corrosion. This guide offers general information on FRP systems use, a description of their unique material properties, and recommendations for the design, construction, and inspection of FRP systems for strengthening URM structures. These guidelines are based on knowledge gained from a comprehensive review of experimental and analytical investigations and field applications.

Keywords: buildings; cracking; cyclic loading; detailing; earthquake resistance; fiber-reinforced polymers; fibers; flexure; masonry; shear; structural analysis;structural design; unreinforced.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Masonry is a generic term used to describe a type of construction where clay, or concrete masonry units, or natural stones are bonded together to form a load-bearing structure or a component in a structure. Non-load-bearing masonry includes partitions and veneers.

Although masonry is used in flexural applications such as retaining walls, roof and floor beams, and lintels, it is more frequently used in load-bearing walls primarily resisting compression loads. Reinforced and unreinforced masonry (URM) walls have been used in constructing structural load-bearing components. In buildings, masonry walls can serve effectively as part of the lateral load-resisting system to resist wind and earthquake loads. Infill masonry walls play a significant role in enhancing in-plane stiffness and shear resistance of both reinforced concrete (RC) and steel frames, if properly connected to the structural frame.

Unreinforced masonry structures have shown their vulnerability to major events such as earthquakes, severe wind, blast, and impact. In addition, factors such as change in occupancy, deterioration, or an increase in lateral-load demand, may create the need to perform structural retrofit. ACI 530 covers the design and construction of new masonry; the repair, retrofitting, and rehabilitation of masonry structures are not included in that code.

The repair and retrofit/rehabilitation of existing masonry structures have traditionally been accomplished using conventional materials and construction techniques. Externally bonded steel plates, RC overlays, grouted cell reinforcements, and post-tensioning are just some of the many traditional techniques available. Fiber-reinforced polymer (FRP) (ACI 440R) composites have emerged as an alternative to traditional materials for strengthening masonry structures. Fiber-reinforced polymer materials are lightweight and noncorrosive. They exhibit high tensile strength and elastic modulus (carbon FRP), and are impact resistant with electromagnetic transparency. These materials, which are available in a variety of forms, including flat sheets and plates and reinforcing bars and prestressing tendons of typically round cross section, provide the licensed design professional with flexibility in achieving desired performance. Fiber-reinforced polymer systems can be used in seismic, wind, or blast strengthening of URM structural elements.

Advantages of retrofitting masonry using FRP composites include easier handling and installation with resulting lower installation prices, and minimal changes to the structure's appearance. Disturbance to occupants and loss of usable space are also minimized. Dynamic properties of the existing structure remain unchanged because there is little weight addition or stiffness modification. Disadvantages of using FRP may include diminished performance at elevated temperatures, requirement for protective coatings, degradation of mechanical properties after long-term exposure to certain environmental conditions such as extensive moisture intrusion and frequent wet freezing-and-thawing cycles, and the relatively higher level of site supervision and inspection required.

1.2—Scope

This guideline provides information on the selection and design of FRP systems limited to externally bonded FRP laminates and near-surface-mounted FRP bars/strips for increasing the in-plane and out-of-plane strength of existing ungrouted, grouted, or partially grouted URM walls; infill walls are not included in this guide. The guide is applicable to URM structures made of clay bricks, concrete masonry units, and natural stones using conventional types of mortar.

For masonry with significant deterioration, questionable mortar bond, and cracking and/or element displacement, traditional procedures may be required as well as FRP strengthening. The evaluation for the need to apply traditional modes of strengthening is not covered in this guide.

CHAPTER 2—NOTATION AND DEFINITIONS

ACI provides a comprehensive list of notation and definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org. Definitions provided herein complement that resource.

2.1—Notation

A_f = cross-sectional area of FRP reinforcement, in.^{2} (mm^2)
$A_{f,bar}$ = area of one rectangular and/or circular FRP bar, in.^{2} (mm^2)
A_n = area of net mortared/grouted section, in.^{2} (mm^2)
a_b = smallest dimension of a FRP rectangular bar, in. (mm)
b_b = largest dimension of a FRP rectangular bar, in. (mm)
C_E = environmental reduction factor
c = distance from the fiber of maximum compressive strain to the neutral axis, in. (mm)
c_s = distance from the fiber of maximum compressive strain to the neutral axis at service limit state, in. (mm)
D = dead load effect
d_b = diameter of a FRP bar, in. (mm)
d_f = effective depth of FRP flexural reinforcement, in. (mm)
d_i = distance of force F_i measured from the extreme compression fiber, in. (mm)
E_f = tensile modulus of elasticity of FRP, psi (MPa)
E_s = tensile modulus of elasticity of steel, psi (MPa)
e = eccentricity of axial load, in. (mm)
F_i = force acting on the *i*-th FRP strip, lb (N)
f_a = axial compressive stress due to gravity loads, psi (MPa)
f'_{dt} = specified masonry diagonal tension strength, psi (MPa)
f_f = stress in the FRP reinforcement, psi (MPa)
f_{fe} = effective stress level in the FRP reinforcement, psi (MPa)
f_{fs} = stress in the FRP reinforcement at service, psi (MPa)
f_{fu} = design ultimate tensile strength of FRP, psi (MPa)
f_{fu}^* = ultimate tensile strength of the FRP material as reported by the manufacturer, psi (MPa)
$\overline{f_{fu}}$ = mean ultimate tensile strength of FRP reinforcement based on a population of 20 or more tensile tests per ASTM D3039/D3039M, psi (MPa)
f'_m = specified masonry compressive strength, psi (MPa)
f_{tm} = average value of the tensile strength of masonry, psi (MPa)
H = lateral earth pressure effect
h = effective height of the wall, in. (mm)
h_{eff} = height to resultant of lateral force, in. (mm)
k = coefficient accounting for the boundary conditions of the wall
L = length of the wall, in. (mm)
ℓ_d = development length, in. (mm)
M_n = nominal flexural strength, in.-lb (N-mm)
M_s = moment due to sustained loads, in.-lb (N-mm)
M_u = factored moment, in.-lb (N-mm)
n = number of plies of FRP laminates, and number of circular and rectangular bars, or both

P_n = nominal axial strength, lb (N)
P_s = axial load due to all sustained loads, lb (N)
P_u = factored axial load as a resultant of uniformly distributed load acting on the wall, lb (N)
p_{fm}, p_{fv} = force per unit width (per unit bar for NSM FRP systems), lb/in. (lb/bar) [N/mm (N/bar)]
R_n = nominal strength of a member
s_f = spacing of FRP reinforcement, in. (mm)
T_g = glass transition temperature, °F (°C)
t = nominal thickness of the wall, in. (mm)
t_b = effective depth of NSM FRP system, in. (mm)
t_f = nominal thickness of one ply of the FRP reinforcement, in. (mm)
V_{bjs} = nominal lateral strength corresponding to joint sliding, lb (N)
V_{dt} = nominal lateral strength corresponding to diagonal tension, lb (N)
V_f = FRP contribution to the nominal lateral strength for FRP-strengthened walls, lb (N)
V_n = nominal lateral strength of FRP-strengthened wall, lb (N)
V_n^{URM} = nominal lateral strength of URM, lb (N)
V_{tc} = nominal lateral strength corresponding to toe crushing, lb (N)
V_u = factored shear force, lb (N)
W = wind load effect
w_f = width of FRP laminate, in. (mm)
α = angle of inclination of diagonal strips, degrees
α_L = longitudinal coefficient of thermal expansion, in./in./°F (mm/mm/°C)
α_T = transverse coefficient of thermal expansion, in./in./°F (mm/mm/°C)
β_1 = ratio of the depth of the equivalent rectangular stress block to the depth of the neutral axis, in. (mm)
ε_{fe} = effective strain in FRP reinforcement, in./in. (mm/mm)
ε_{fu} = design rupture strain of the FRP reinforcement, in./in. (mm/mm)
ε_{fu}^* = ultimate rupture strain of the FRP reinforcement as reported by the manufacturer
$\overline{\varepsilon_{fu}}$ = mean rupture strain of FRP reinforcement based on a population of 20 or more tensile tests per D3039/D3039M, in./in. (mm/mm)
ε_{mu} = maximum usable masonry strain, in./in. (mm/mm)
ε_{bi} = strain level in the masonry substrate at the time of the FRP installation, in./in. (mm/mm)
γ = multiplier of f'_m to determine the intensity of an equivalent rectangular stress distribution for masonry
κ_m = bond-dependent coefficient for flexure
κ_v = bond-dependent coefficient for shear
ϕ = strength reduction factor
ω_f = FRP reinforcement index

2.2—Definitions

The following definitions clarify terms pertaining to the use of FRP in externally bonded systems for strengthening URM structures.

alkali-resistant (AR) glass—glass fiber formulated to resist degradation in alkaline conditions such as cementitious mixtures.

batch—quantity of material mixed at one time or in one continuous process.

binder—material forming the matrix of concretes, mortars, and sanded grouts; or chemical treatment applied to fibers to give integrity to mats, roving, and fabric.

catalyst—a substance that accelerates a chemical reaction and enables it to proceed under conditions more mild than otherwise required and that is not, itself, permanently changed by the reaction. (See also **initiator** and **hardener**.)

composite—engineering materials—for example, concrete or fiber-reinforced polymer—made from two or more constituent materials that remain distinct, but combine to form materials with properties not possessed by any of the constituent materials individually; the constituent materials are generally characterized as matrix and reinforcement or matrix and aggregate.

creep-rupture—breakage of a material under sustained loading at stresses less than the tensile strength.

cure of FRP systems—the process of causing irreversible change in the properties of a thermosetting resin by chemical reaction, typically accomplished by the addition of curing (cross-linking) agents or initiators, with or without heat and pressure.

curing agent—a catalytic or reactive agent that induces cross-linking in a thermosetting resin. (See also **hardener** and **initiator**.)

debonding—failure of cohesive or adhesive bond at the interface between a substrate and a strengthening or repair system.

degradation—a decline in the quality of the mechanical properties of a material.

delamination—a planar separation in a material that is roughly parallel to the surface of the material.

durability—the ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service for an extended period of time.

E-glass—a calcium-aluminosilicate glass that contains less than 2% alkali and may or may not contain boron. In electrical circuit board applications, the composition contains boron and less than 1% alkali. This glass is widely used as reinforcement in various resin-based components. Its high electrical resistivity makes it suitable for uses in electrical applications.

fabric—a two-dimensional network of woven, nonwoven, knitted, or stitched fibers.

fabric construction—the details of structure of fabric. Includes such information as style, width, type of knit or weave, threads per inch in warp and fill, and weight of goods.

fiber—a slender and greatly elongated solid material, generally with a length at least 100 times its diameter, that has properties making it desirable for use as reinforcement.

fiber, aramid—fiber in which chains of aromatic polyamide molecules are oriented along the fiber axis to exploit the strength of the chemical bond.

fiber, carbon—fiber produced by heating organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile (PAN), or pitch in an inert environment and at temperatures of 2700°F (1500°C) or greater.

fiber, glass—filament drawn from an inorganic fusion typically comprising silica-based material that has cooled without crystallizing. Types of glass fibers include alkali-lime (A-glass), alkali-resistant (AR-glass), general-purpose (E-glass), high-strength (S-glass), and boron-free (ECR-glass).

fiber content—the fiber present in a composite, usually expressed as a percentage volume fraction or weight fraction of the composite.

fiber fly—short filaments that break off dry fiber tows or yarns during handling and become airborne; usually classified as a nuisance dust.

fiberglass—(see **glass fiber-reinforced polymer**.)

fiber-reinforced polymer (FRP)—a general term for a composite material comprising a polymer matrix reinforced with fibers in the form of fabric, mat, strands, or any other fiber form. (See also **composite**.)

filament—see **fiber**.

filler—a finely divided, relatively inert material, such as pulverized limestone, silica, or colloidal substances, added to portland cement, paint, resin, or other materials to reduce shrinkage, improve workability, reduce price, or reduce density.

fraction, fiber volume—the ratio of the volume of fibers to the volume of the composite containing the fibers.

fraction, fiber weight—the ratio of the weight of fibers to the weight of the composite containing the fibers.

glass fiber-reinforced polymer (GFRP) —a composite material comprising a polymer matrix reinforced with glass fiber cloth, mat, or strands.

hardener—in a two-component adhesive or coating, the chemical component that causes the resin component to cure.

impregnate—to saturate fibers with resin or binder.

initiator—a chemical used to start the curing process for unsaturated polyester and vinyl ester resins. (See also **catalyst**.)

lamina—a single layer of fabric or mat reinforcing bound together in a cured resin matrix

laminate—multiple plies or lamina molded together.

layup—the process of placing reinforcing material and resin system in position for molding.

layup, wet—the process of placing the reinforcing material in the mold or its final position and applying the resin as a liquid.

length, development—the bonded length required to transfer the design strength of reinforcement at a critical section.

load, sustained—a constant load that in structures is due to dead load and long-term live load.

masonry substrate—the existing masonry, including any repair materials, to which the FRP system is applied.

matrix—the resin or binders that hold the fibers in FRP together, transfer load to the fibers, and protect them against environmental attack and damage due to handling.

monomer—an organic molecule of relatively low molecular weight that creates a solid polymer by reacting with itself or other compounds of low molecular weight.

near-surface-mounted (NSM) systems—an externally bonded FRP system in which FRP bars are bonded to grooves made in the masonry surface.

polyacrylonitrile (PAN)—a polymer fiber used to make high-modulus carbon fiber through pyrolysis.

pitch—viscid substance obtained as a residue of petroleum or coal tar and used as a precursor in the manufacture of some carbon fibers.

ply—see **lamina**.

polyester—one of a large group of synthetic resins, mainly produced by reaction of dibasic acids with dihydroxy alcohols; commonly prepared for application by mixing with a vinyl-group monomer and free-radical catalysts at ambient temperatures and used as binders for resin mortars and concretes, fiber laminates (mainly glass), adhesives, and the like. Commonly called "unsaturated polyester."

polymer—the product of polymerization; more commonly a rubber or resin consisting of large molecules formed by polymerization.

polymerization—the reaction in which two or more molecules of the same substance combine to form a compound containing the same elements and in the same proportions but of higher molecular weight.

polyurethane—reaction product of an isocyanate with any of a wide variety of other compounds containing an active hydrogen group; used to formulate tough, abrasion-resistant coatings.

pot life—time interval, after mixing of thermosetting resin and initiators, during which the mixture can be applied without degrading the final performance of the resulting polymer composite beyond specified limits.

prepreg—a sheet of fabric or mat containing resin or binder usually advanced to the B-stage and ready for final forming and cure.

resin—generally a thermosetting polymer used as the matrix and binder in FRP composites.

resin content—the resin in a fiber-reinforced polymer composite laminate, expressed as either a percentage of total mass or total volume.

resin, epoxy—a class of organic chemical bonding systems used in the preparation of special coatings or adhesives for concrete or as binders in epoxy-resin mortars, concretes, and fiber-reinforced polymer composites.

resin, thermosetting—a material that hardens by an irreversible cross-linking of monomers, typically when subjected to a chemical reaction.

roving—a parallel bundle of continuous yarns, tows, or fibers with little or no twist.

S-glass—a magnesium-aluminosilicate glass possessing tensile strength, modulus, and application temperature higher than E-glass. It is typically used as reinforcement in resin-based, high-performance and high-temperature composite applications.

sheet, FRP—a dry, flexible ply used in wet layup FRP systems. Fabrics are also called sheets.

shelf life—the length of time packaged materials can be stored under specified conditions and remain usable.

sizing—surface treatment applied to filaments to impart desired processing, durability, and bond attributes.

temperature, glass-transition—the midpoint of the temperature range over which an amorphous material (such as glass or polymer) changes from (or to) a brittle, vitreous state to (or from) a plastic state.

tow—an untwisted bundle of continuous filaments.

vinylester resin—a thermosetting reaction product of epoxy resin with a polymerizable unsaturated acid (usually methacrylic acid) that is then diluted with a reactive monomer (usually styrene).

volume fraction—see **fraction, fiber volume**.

witness panel—a small mockup manufactured under conditions representative of field application, to confirm that prescribed procedures and materials will yield specified mechanical and physical properties.

yarn—a twisted bundle of continuous filaments.

CHAPTER 3—CONSTITUENT MATERIALS AND PROPERTIES

The behavior of FRP-reinforced masonry structures depends on the physical and material properties of the existing masonry, as well as the FRP system. The physical and mechanical properties of the masonry should be investigated. The effects of factors such as loading history and duration, temperature, and moisture on the properties of FRP systems, are discussed in this chapter.

Fiber-reinforced polymer systems are available in a variety of forms such as wet layup, prepreg, and precured. Factors such as fiber volume, type of fiber, type of resin, fiber orientation, dimensional effects, and quality control during manufacturing, all play a role in establishing characteristics of the FRP system. The material characteristics described in this chapter are generic and do not apply to all commercially available products. Test methods according to ASTM standards should be used for material characterization; for test methods not included in ASTM standards, reference should be made to ACI 440.3R. Preconstruction quality assurance testing of the FRP strengthening system, hereby called FRP system or FRP reinforcement, is recommended.

3.1—Constituent materials

Constituent materials used in most commercially available FRP systems, including resins, primers, putties, saturants, adhesives, and fibers, have been developed for strengthening concrete structures. They are proven effective for strengthening masonry structures.

3.1.1 *Resins*—A wide range of polymeric resins, including primers, putty, fillers, saturants, and adhesives, are used in the manufacturing and installation of FRP systems. Common resins such as epoxies, vinyl esters, and polyesters have been formulated for use in a wide range of environmental conditions. Fiber-reinforced polymer system manufacturers use resins that have the following characteristics:

- Compatibility with and adhesion to the reinforcing fiber;
- Compatibility with and adhesion to the masonry;
- Compatibility with and adhesion to the FRP system—substrate interface;
- Resistance to environmental effects, including but not limited to moisture, salt water, temperature extremes, and chemicals normally associated with exposed masonry;
- Workability during installation;
- Resin pot life consistent with time needed for the application; and
- Development of appropriate mechanical properties for the FRP system.

3.1.1.1 *Primer*—Primer is used to penetrate the masonry surface, providing an improved adhesive bond for the saturating resin or adhesive.

3.1.1.2 *Putty fillers*—Putty is used to fill small surface voids in the substrate, such as bug holes, and to provide a smooth surface to which the FRP system can bond. Filled surface voids also prevent bubbles from forming during curing of the saturating resin.

3.1.1.3 *Saturating resin*—Saturating resin is used to impregnate the reinforcing fibers, fix them in place, and provide a shear load path to effectively transfer load between fibers. The saturating resin serves as the adhesive for wet layup systems, providing a shear load path between the previously primed substrate and the FRP system.

3.1.1.4 *Adhesives*—Adhesives are used to bond precured FRP laminate and near-surface-mounted (NSM) systems to the masonry. The adhesive provides a load path between the masonry and the FRP system. Adhesives are also used to bond together multiple layers of precured FRP laminates.

3.1.2 *Fibers*—Continuous glass, aramid, and carbon fibers are common reinforcements used in FRP systems. The fibers give the FRP system its strength and stiffness. A more detailed description of fibers is given in ACI 440R.

3.1.3 *Protective coatings*—Protective coating is used to protect the bonded FRP system from potentially damaging environmental and mechanical effects. Coatings are typically applied to the exterior surface of the FRP system after the adhesive or saturating resin has cured. Protection systems are available in a variety of forms that include:

- Polymer coatings, generally epoxies or polyurethanes;
- Acrylic coatings, either straight acrylic or acrylic cement-based; acrylic systems also come in different textures;
- Cementitious systems that may require roughening of the FRP surface by broadcasting sand into wet resin, and can be installed similarly as they would on a concrete surface; and
- Intumescent coatings that are polymer-based used, in some cases, to control flame spread and smoke generation.

Reasons for using protection systems with FRP systems installed on masonry surfaces include:

- *Ultraviolet light protection*—The resin used in the FRP system can be affected over time by exposure to ultraviolet light. To prevent degradation, there are a number of available coatings used to protect the FRP system such as acrylic coatings, cementitious surfacing, and aliphatic polyurethane coatings;
- *Vandalism*—Protective systems to resist vandalism should be hard and durable. Polyurethane coatings can offer protection against cutting and scraping. Cementitious overlays can provide more protection;

- *Impact, abrasion, and wear*—These protection systems are similar to those used for vandalism protection. Abrasion and wear, however, are different in that they result from continuous exposure rather than a one-time event and their performance is chosen for their hardness and durability;
- *Aesthetics*—Protective topcoats may be used to conceal the FRP system. These systems may be acrylic latex coatings that match the color of masonry or other colors and textures to match the existing structure;
- *Chemical resistance*—Exposure to harsh chemicals such as strong acids may damage the FRP system. In such environments, coatings with better chemical resistance such as urethanes and novolac epoxies may be used; and
- *Fire protection*—Coatings capable of reducing the spread of flames and smoke production should be employed when fire is a concern or as required by local building codes. Fiber-reinforced polymer materials are sensitive to high temperatures during a fire. When the temperature of the FRP system approaches the glass transition temperature of the resin (T_g), the strength, stiffness, and bond properties of the installed FRP system are reduced. In the case of FRP systems applied as external reinforcement to concrete or masonry members, exposure to high temperature produces a fast degradation of the bond between the FRP system and substrate. As a result, degradation of the strengthening effectiveness and debonding of FRP system may take place.

3.2—Physical properties

3.2.1 *Density*—Fiber-reinforced polymer materials have densities ranging from 75 to 130 lb/ft^3 (1.2 to 2.1 g/cm^3), which is four to six times less than that of steel, as indicated in Table 3.1 (ACI 440.2R).

3.2.2 *Coefficient of thermal expansion*—The coefficients of thermal expansion of unidirectional FRP materials differ in longitudinal and transverse directions, depending on the fiber type, resin type, and fiber content. Table 3.2 (ACI 440.2R) lists the longitudinal and transverse coefficients of thermal expansion for typical unidirectional FRP materials. Note that a negative coefficient of thermal expansion indicates the material contracts with increased temperature and expands with decreased temperature. For reference, concrete has a coefficient of thermal expansion that varies from 4×10^{-6} to 6×10^{-6}/°F (7×10^{-6} to 11×10^{-6}/°C) and is usually assumed to be isotropic (Mindess and Young 1981). Steel has an isotropic coefficient thermal expansion of 6.5×10^{-6}/°F (11.7×10^{-6}/°C).

3.2.3 *Effect of high temperature*—At temperatures near and above the T_g, the elastic modulus, creep resistance, and strength of a polymer decrease due to changes in its molecular structure. The T_g depends on a range of factors including the type, degree of cure, and moisture content of the polymer. In FRP composite materials used in masonry repair, commonly used fibers such as glass, carbon, and aramid maintain their mechanical integrity at temperatures in excess of those tolerated by polymer resins. Due to a reduction in force transfer between fibers and across adhesively bonded interfaces, however, the effectiveness of the composite strengthening system is diminished at temperatures near and above the T_g of the resin(s) used in the system.

Table 3.1—Typical densities of materials, lb/ft^3 (g/cm^3)

Steel	GFRP	CFRP	AFRP
490 (7.9)	75 to 130 (1.2 to 2.1)	90 to 100 (1.5 to 1.6)	75 to 90 (1.2 to 1.5)

Table 3.2—Typical coefficient of thermal expansion for FRP materials*

Direction	Coefficient of thermal expansion, $\times 10^{-6}$/°F ($\times 10^{-6}$/°C)		
	GFRP	CFRP	AFRP
Longitudinal, α_L	3.3 to 5.6 (6 to 10)	–0.6 to 0 (–1 to 0)	–3.3 to –1.1 (–6 to –2)
Transverse, α_T	10.4 to 12.6 (19 to 23)	12 to 27 (22 to 50)	33 to 44 (60 to 80)

*Typical values for fiber-volume fractions ranging from 0.5 to 0.7.

3.3—Mechanical properties

3.3.1 *Tensile behavior*—When loaded in direct tension, FRP materials do not exhibit any plastic behavior, or yielding, before rupture. The tensile behavior of FRP materials consisting of one type of fiber material is characterized by a linear elastic stress-strain relationship until failure, which is sudden and without warning.

The tensile strength and stiffness of a FRP material depends on several factors. Because the fibers in a FRP material are the main load-carrying constituent, fiber type, fiber orientation, fiber quantity, and method and conditions that the composite is manufactured affect the tensile properties of the FRP material. Due to the primary role of the fibers as tensile reinforcement and methods of application, the properties of a FRP system are sometimes reported based on the net-fiber area (Method 2 of 440.3R). In other examples, such as in pre-cured laminates, the reported properties are based on the gross-laminate area (Method 1 of 440.3R).

The gross-laminate area of a FRP system is calculated using the total cross-sectional area of the cured FRP system, including all fibers and resin. The gross-laminate area is typically used for reporting precured laminate properties where the cured thickness is constant and the relative proportion of fiber and resin is controlled.

The net-fiber area of a FRP system is calculated using the known area of fiber, neglecting the total width and thickness of the cured system; thus, resin is excluded. For example, the net-fiber area is typically used for reporting properties of wet layup FRP systems that use fiber sheets or fabrics and field-installed resins. The wet layup installation process results in controlled fiber content and a variable resin content.

Fiber-reinforced polymer system properties reported using the gross-laminate area have higher relative thickness dimensions and lower relative strength and modulus values, whereas system properties reported using the net-fiber area have lower relative thickness dimensions and higher relative strength and modulus values. Regardless of the basis for the

reported values, the tensile strength ($f_{fu}A_f$) and axial stiffness (A_fE_f) remain constant. Properties reported based on the net-fiber area are not the properties of the bare fibers. The properties of a FRP system should be characterized as a composite, recognizing not only the material properties of the individual fibers, but also the efficiency of the fiber-resin system, the fabric architecture, and the method used to create the composite. The mechanical properties of all FRP systems, regardless of form, should be based on the testing of laminate samples with known fiber content.

The tensile properties of a particular FRP system, however, should be obtained from the FRP system manufacturer. Manufacturers should report an ultimate tensile strength, which is defined as the mean tensile strength of a sample of test specimens minus three times the standard deviation ($f_{fu}^* = \overline{f_{fu}} - 3\sigma$) and, similarly, report a guaranteed ultimate rupture strain ($\varepsilon_{fu}^* = \overline{\varepsilon_{fu}} - 3\sigma$). This approach provides a 99.87% probability that the ultimate tensile properties will exceed these statistically-based design values (Mutsuyoshi et al. 1990). Young's modulus should be calculated as the chord modulus between 0.003 and 0.006 strains, in accordance with ASTM D3039/D3039M. A minimum number of 20 replicate test specimens should be used to determine the mean ultimate tensile properties. The manufacturer should provide a description of the method used to obtain the reported tensile properties, including the number of tests, mean values, and standard deviations.

3.3.2 *Compressive behavior*—Externally bonded FRP systems should not be used as compression reinforcement because of insufficient test results validating its use in this type of application. While reliance on externally bonded FRP systems to resist compressive stresses is not recommended, the following section is presented to fully characterize the behavior of FRP materials.

Coupon tests on FRP laminates used for repair on concrete have shown that the compressive strength of the FRP system is lower than the tensile strength (Wu 1990). The mode of failure for FRP laminates subjected to longitudinal compression can include transverse tensile failure, fiber microbuckling, or shear failure. The mode of failure depends on the type of fiber, the fiber-volume fraction, and the type of resin. Compressive strengths of 55, 78, and 20% of the tensile strength have been reported for GFRP, carbon fiber-reinforced polymer (CFRP), and aramid fiber-reinforced polymer (AFRP), respectively (Wu 1990). In general, compressive strengths are higher for materials with higher tensile strengths, except in the case of AFRP, where the fibers exhibit nonlinear behavior in compression at a relatively low level of stress.

The compressive modulus of elasticity is usually smaller than the tensile modulus of elasticity of FRP materials. Test reports on samples containing a 55 to 60% volume fraction of continuous E-glass fibers in a matrix of vinyl ester or isophthalic polyester resin have indicated a compressive modulus of elasticity of 5000 to 7000 ksi (34,000 to 48,000 MPa) (Wu 1990). The compressive modulus of elasticity is approximately 80% for GFRP, 85% for CFRP, and 100% for AFRP of the tensile modulus of elasticity for the same product (Ehsani 1993).

3.4—Time-dependent behavior

3.4.1 *Creep rupture*—Fiber-reinforced polymer materials subjected to a constant tensile load over time can suddenly fail after a time period called the endurance time. As the ratio of the sustained tensile stress to the short-term strength of the FRP laminate increases, endurance time decreases. The creep rupture time may also decrease under adverse environmental conditions, such as high temperature, ultraviolet-radiation exposure, high alkalinity, wetting-and-drying cycles, or freezing-and-thawing cycles.

In general, carbon fibers are the least susceptible to creep rupture, aramid fibers are moderately susceptible, and glass fibers are most susceptible. Creep rupture tests have been conducted on 0.25 in. (6 mm) diameter FRP bars reinforced with glass, aramid, and carbon fibers. The FRP bars were tested at different load levels at room temperature. Results indicated that a linear relationship exists between creep-rupture strength and the logarithm of time for all load levels. The ratios of stress level at creep-rupture after 500,000 hours, which is about 50 years, to the initial ultimate strength of the GFRP, AFRP, and CFRP bars were extrapolated to be 0.3, 0.47, and 0.91, respectively (Yamaguchi et al. 1997). Similar values have been determined by Malvar (1998).

Recommendations on sustained stress limits imposed to avoid creep-rupture are given in Section 9.6 of this guide. As long as the sustained stress in the FRP is below the creep rupture stress limits, the strength of the FRP is available for nonsustained loads.

3.4.2 *Fatigue*—Fatigue of the FRP system is not an issue in URM structures that are typically strengthened with FRP systems because the systems are intended to resist loads with low cycle counts, such as earthquake, hurricane, and blast loads. Guidance on the fatigue performance for FRP composites can be found in ACI 440.2R.

3.5—Durability

Many FRP systems exhibit reduced mechanical properties after exposure to certain environmental factors, including high temperature, humidity, and chemical exposure (Karbhari 2007). The type of FRP strengthening technique may also affect the long-term durability performance of the strengthened system. The exposure environment, duration of the exposure, resin type and formulation, fiber type and volume fraction, and resin-curing method are some of the factors that influence the extent of the reduction in mechanical properties. Unless otherwise indicated, the tensile properties (ASTM D7565/D7565M) reported by the manufacturer are generally based on testing conducted in a laboratory environment and do not reflect the effects of environmental exposure.

3.6—Fiber-reinforced polymer system qualification

Fiber-reinforced polymer systems should be qualified for use on a project based on independent laboratory test data of the FRP constituent materials and the laminates made with them, structural test data for the type of application being considered, and durability data representative of the anticipated environment. Test data provided by the FRP system

manufacturer demonstrating that the proposed FRP system meets all mechanical and physical design requirements including tensile strength, durability, resistance to creep, bond to substrate, and T_g, should be considered, but not used as the sole basis for qualification.

Untested FRP systems should not be considered for use. Mechanical properties of FRP systems should be determined from tests on laminates manufactured in a process representative of their field installation according to the procedures in ASTM D7565/D7565M.

The specified material-qualification programs should require laboratory testing to measure the repeatability and reliability of critical properties. Testing five batches of FRP materials is recommended. Independent structural testing can be used to evaluate a system's performance for the specific application.

CHAPTER 4—SHIPPING, STORAGE, AND HANDLING

4.1—Shipping

The user of FRP constituent materials is advised to observe federal and state packaging and shipping regulations. Packaging, labeling, and shipping for thermosetting resin materials are controlled by the Code of Federal Regulations (CFR 49). Many materials are classified as corrosive, flammable, or poisonous in Subchapter C (CFR 49) under Hazardous Materials Regulations.

4.2—Storage

4.2.1 *Storage conditions*—To preserve the properties and maintain safety in the storage of FRP system constituent materials, materials should be stored in accordance with the manufacturer's recommendations. The storage of FRP system constituent materials should consider exposure to ultraviolet light (UV), extreme temperatures, and seawater spray or other environmental conditions that can be deleterious to the FRP. Certain constituent materials, such as reactive curing agents, hardeners, initiators, catalysts, and cleaning solvents, have safety-related requirements and should be stored as recommended by the manufacturer and Occupational Safety and Health Administration (OSHA). Catalysts and initiators, which are usually peroxides, should be stored separately.

4.2.2 *Shelf life*—The properties of uncured resin components can change with time, temperature, or humidity. Such conditions can affect the reactivity of the mixed system and the uncured and cured properties. The manufacturer sets a recommended shelf life within which the properties of the resin-based materials should continue to meet or exceed stated performance criteria. Any component material that has exceeded its shelf life, deteriorated, or been contaminated should not be used. Fiber-reinforced polymer materials deemed unusable should be disposed of as specified by the manufacturer and acceptable to state and federal environmental control regulations.

4.3—Handling

4.3.1 *Material safety data sheet*—Material safety data sheets (MSDS) for all FRP constituent materials and components should be obtained from the manufacturers and accessible at the job site.

4.3.2 *Information sources*—Detailed information on the handling and potential hazards of FRP-constituent materials can be found in information sources, such as ACI and International Concrete Repair Institute (ICRI) reports, company literature and guides, OSHA guidelines, and other government documents. ACI 503R is specifically noted as a general guideline for the safe handling of epoxy and other resin adhesive compounds.

4.3.3 *General handling hazard*—Thermosetting resins describe a generic family of products that includes unsaturated polyesters, vinyl esters, epoxy, and polyurethane resins. Materials used with them are generally described as hardeners, curing agents, peroxide initiators, fillers, and flexibilizers. There are precautions to observe when handling thermosetting resins and their component materials. General hazards that may be encountered when handling thermosetting resin materials are:

- Skin irritation, such as burns, rashes, and itching;
- Skin sensitization, which is an allergic reaction similar to that caused by poison ivy, building insulation, or other allergens;
- Breathing organic vapors from cleaning solvents, monomers, and diluents;
- With a sufficient concentration in air, explosion or fire of flammable materials when exposed to heat, flames, pilot lights, sparks, static electricity, cigarettes, or other sources of ignition;
- Exothermic reactions of mixtures of materials causing fires or personal injury; and
- Nuisance dust caused by grinding or handling of the cured FRP materials (consult manufacturer's literature for specific hazards).

The complexity of thermosetting resins and associated materials makes it essential that labels and MSDS are read and understood by those working with these products. Document CFR 16, Part 1500, regulates labeling of hazardous substances and includes thermosetting-resin materials. Document ANSI Z-129.1 provides further guidance regarding classification and precautions.

4.3.4 *Personnel safe handling and clothing*—Disposable suits and gloves are suitable for handling fiber and resin materials. Disposable rubber or plastic gloves are recommended and should be discarded after each use. Gloves should be resistant to resins and solvents. Safety glasses or goggles should be used when handling resin components and solvents. Respiratory protection, such as dust masks or respirators, should be used when fiber fly, dust, or organic vapors are present, or during mixing and placing of resins if required by the FRP system manufacturer.

4.3.5 *Workplace safe handling*—The workplace should be well ventilated. Surfaces should be covered as needed to protect against contamination and resin spills. Each FRP system constituent material has different handling and storage requirements to prevent damage. Consult with the material system manufacturer for guidance. Some resin systems are potentially dangerous during the mixing of the

components. Consult the system manufacturer's literature for proper mixing procedures and MSDSs for specific handling hazards. Ambient cure resin formulations produce heat when curing, which in turn accelerates the reaction. Uncontrolled reactions, including fuming, fire, or violent boiling, may occur in containers holding a mixed mass of resin; therefore, containers should be monitored.

4.3.6 *Clean-up and disposal*—Clean-up often involves the use of flammable solvents. When using flammable solvents, appropriate precautions should be observed. There are also clean-up solvents available that do not present flammability concerns. All waste materials should be contained and disposed of as prescribed by the prevailing environmental authority.

CHAPTER 5—INSTALLATION

Procedures for installing FRP systems have been developed by the system manufacturers and often differ between systems. In addition, installation procedures can vary within a system, depending on the type and condition of the structure. This chapter presents general guidelines for installation of FRP systems. Contractors trained in accordance with the installation procedures developed by the system manufacturer should install FRP systems. Deviations from the procedures developed by the FRP system manufacturer should not be allowed without getting the manufacturer's approval.

5.1—Contractor competency

The FRP system installation contractor should demonstrate competency for surface preparation and application of the FRP system to be installed. Contractor competency can be demonstrated by providing evidence of training and documentation of related work previously completed by the contractor, surface preparation and installation of the FRP system on portions or mock-ups of the structure. The FRP system manufacturer or its authorized agent should train the contractor's application personnel in the installation procedures of its system. Near-surface-mounted FRP systems require less training for surface preparation and installation than surface-mounted FRP systems.

5.2—Temperature, humidity, and moisture considerations

Temperature, relative humidity, and surface moisture at the time of installation can affect performance of the FRP system. Studies on these effects have been undertaken on concrete systems (Myers and Ekenel 2005). Conditions observed before and during installation include surface temperature of the masonry, air temperature, relative humidity, and corresponding dew point.

Primers, saturating resins, and adhesives generally should not be applied to cold or frozen surfaces. When the surface temperature of the masonry surface falls below a minimum level as specified by the FRP system or adhesive manufacturer, improper saturation of the fibers and improper curing of the resin constituent materials can occur, compromising the integrity of the FRP system. An auxiliary heat source can be used to raise the ambient and surface temperature during installation. The heat source should be clean and not contaminate the surface or the uncured FRP system.

Resins and adhesives generally should not be applied to damp or wet surfaces unless they are suitable for such applications. Fiber-reinforced polymer systems should not be applied to masonry surfaces that are subject to moisture vapor transmission. The transmission of moisture vapor from a masonry surface through the uncured resin materials typically appears as surface bubbles and can compromise the bond between the FRP system and the substrate.

5.3—Equipment

As different FRP systems may be used for strengthening URM, special equipment requirements may be specific to the selected system. In general, the advantage of FRP strengthening is associated with light weight, ease, and speed of application; therefore, special equipment requirements are limited. Equipment may include a resin impregnator, resin sprayer, and grinding and grooving tools. All equipment should be maintained, clean, and in good operating condition.

The contractor should have personnel trained in the operation of all equipment. Personal protective gear, such as gloves, masks, eye guards, and coveralls, should be worn as required by manufacturer's specifications.

Equipment and material supplies in sufficient quantities should be available to allow continuity in installation and quality control tasks. Safe and convenient access to surfaces to be strengthened to ensure proper FRP application and close inspection should be provided.

5.4—Substrate repair and surface preparation

The behavior of masonry members strengthened or retrofitted with FRP systems is highly dependent on masonry substrate and proper preparation and profiling of the masonry surface. An improperly prepared surface can result in debonding or delamination of the FRP system before achieving the design load transfer. The general guidelines presented in this chapter should be applicable to all externally bonded FRP systems. Specific guidelines for a particular FRP system should be obtained from the FRP system manufacturer.

5.4.1 *Substrate repair*—All problems associated with the condition of the original masonry and the masonry substrate that can compromise the integrity of the FRP system should be addressed before surface preparation begins. The FRP system manufacturer should be consulted to verify the compatibility of materials used for repairing the substrate with the FRP system.

5.4.2 *Surface preparation*—Surface preparation requirements depend on the FRP system used to strengthen a masonry element. Specific guidelines regarding procedures for surface preparation for each FRP system should be obtained from the system manufacturer.

5.4.2.1 *Surface preparation for externally bonded FRP laminates*—Surface preparation can involve sandblasting to roughen the surface, grinding of excess mortar in the joints, and application of epoxy primers and putty fillers. Particular care should be taken to ensure that the surface is dry and clean from dust and laitance, and to avoid unintentional

damage to the substrate by using excessive force. Epoxy primers formulated for concrete substrates may not be appropriate for use on concrete masonry units (CMUs) due to their low viscosity and the porous nature of CMU. Before using epoxy primers on CMU, consult with the FRP system manufacturer regarding the specific primer that is recommended. Generally, the epoxy primers used for concrete substrates are suitable for clay brick masonry units. Masonry built with extruded brick units, having less porosity, may require the use of an epoxy primer. Putty filler applied to the entire surface has experimentally been shown to notably improve bonding between the FRP laminates and masonry (Tumialan et al. 2003a). Mortar joints should be filled with adequate putty to ensure smoothness of the surface with no unevenness between mortar joints and masonry units.

5.4.2.2 *Surface preparation for NSM FRP bars*—Near-surface-mounted systems are typically installed in grooves cut into the masonry surface. The soundness of the masonry surface should be checked before installing the bar (both circular and rectangular bars can be used). The inside faces of the groove should be cleaned to ensure adequate bond with masonry. The resulting groove should be free of laitance or other compounds that may interfere with the bond. More information on groove dimensions is reported in Section 11.2.2. The moisture content of the parent masonry should be evaluated and determine to be suitable for bonding properties of the adhesive. Care should also be taken to ensure that the grooves are completely filled with the adhesive. The adhesive should be compatible with masonry and NSM FRP bars.

5.5—Resin mixing

Mixing of resins should be done in accordance with the FRP system manufacturer's recommended procedure. All resin components should be at a proper temperature and mixed in the correct ratio until there is a uniform and complete mixing of the components. Resin components are often contrasting colors, so full mixing is achieved when color streaks are eliminated. Resins should be mixed for the prescribed mixing time and visually inspected for uniformity of color. The material manufacturer should supply recommended batch sizes, mixture ratios, mixing methods, and mixing times.

Mixing equipment can include small electrically powered mixing blades or specialty units, or resins can be mixed by hand stirring, if allowed by the manufacturer. Resin mixing should be in sufficiently small quantities to ensure that all mixed resin can be used within the resin's pot life. Mixed resin that exceeds its pot life should not be used because the viscosity will continue to increase and will adversely affect the resin's ability to penetrate the surface or saturate the fiber sheet.

5.6—Application of constituent materials

Fumes can accompany the application of some resins. Fiber-reinforced polymer system should be selected with consideration for their impact on the installation environment, including emission of volatile organic compounds and toxicology.

5.6.1 *Primer and putty*—If required, primer should be applied to all areas on the masonry surface where the FRP system is to be placed. Primer should be placed uniformly on the prepared surface at the manufacturer's specified rate of coverage. The applied primer should be protected from dust, moisture, and other contaminants before applying the FRP system.

Putty should be used in an appropriate thickness and sequence with the primer as recommended by the FRP system manufacturer. The system-compatible putty, which is typically a thickened epoxy paste, should be used only to fill voids and smooth surface discontinuities before the application of other materials. Rough edges or trowel lines of cured putty should be ground smooth before continuing the installation.

Before applying the saturating resin or adhesive, the primer and putty should be allowed to cure as per the FRP system manufacturer recommendations. If the putty and primer are fully cured, additional surface preparation may be required before application of the saturating resin or adhesive according to the procedures specified by the FRP system manufacturer.

5.6.2 *Wet layup systems*—Wet layup FRP systems are typically installed by hand using dry fiber sheets and fabrics with a saturating resin and installed as per the manufacturer's recommendations. The procedure consists of applying dry fiber sheets and fabrics and resin directly to the member being strengthened. The saturating resin is applied uniformly to all prepared surfaces where the system is placed. Alternatively, the fibers can be impregnated in a separate operation using a resin-impregnating machine before placement of the FRP system on the masonry surface.

The reinforcing fibers are gently pressed into the uncured saturating resin in a manner recommended by the FRP system manufacturer. Entrapped air between layers is released by using rib rollers and pressing the fabric against the substrate. Rib rollers are specialized hand tools that use metal or plastic rollers with combs or ribs to facilitate saturation of the fibers with resin. Sufficient saturating resin is needed to achieve full saturation of the fibers.

Successive layers of saturating resin and fiber materials are placed before the complete cure of the previous layer of resin. If previous layers are cured, interlayer surface preparation, such as light sanding or solvent application recommended by the system manufacturer, may be required.

5.6.3 *Precured systems*—Precured systems include strips, plates, bars, and open grid forms. They are typically installed with an adhesive. Adhesives are applied uniformly to the prepared surfaces where precured systems are to be placed, except in certain instances of confinement where adhesion of the FRP system to the substrate may not be required.

Precured laminate surfaces to be bonded should be clean and prepared in accordance with the system manufacturer's recommendation. The precured plates are placed on or into the wet adhesive in a manner recommended by the system manufacturer.

5.6.4 *Near-surface-mounted systems*—Near-surface-mounted systems are precured systems that consist of installing rectangular or circular FRP bars into grooves cut onto the

masonry surface and bonding in place using an adhesive. Grooves should be dimensioned to ensure adequate adhesive around the bars (Chapter 11). There are many application methods and types of adhesive that have been successfully used in the field for NSM systems. Adhesive type and installation method should be selected as recommended by the system manufacturer.

5.6.5 *Protective coatings*—Coatings should be compatible with the FRP system and applied in accordance with the manufacturer's recommendations. Typically, the use of solvents to clean the FRP surface before installing coatings is not recommended due to the deleterious effects that solvents can have on the polymer resins. The FRP system manufacturer should approve any use of solvent-wipe preparation of FRP surfaces before applying the protective coatings.

Coatings should be periodically inspected and maintenance provided to ensure their effectiveness. Inspections should be performed periodically in conjunction with other regular inspections of the structure or at a frequency that is based on the exposure conditions and facility use.

5.7—Alignment of FRP materials

The FRP fiber reinforcement ply orientation and ply stacking sequence should be specified. Small variations in angle, as little as 5 degrees, from the intended direction of fiber alignment can cause a substantial reduction in strengthening performance (Yang et al. 2002). Deviations in ply orientation should only be made if approved by the licensed design professional.

Sheet and fabric materials should be handled in a manner to maintain the fiber straightness and orientation. Kinks, folds, or other forms of severe waviness in the fiber reinforcement layer should be reported to the licensed design professional; refer to Section 6.2.2 for allowable fiber misalignment.

5.8—Multiple plies and lap splices

Multiple plies can be used, provided all plies are fully impregnated with the resin system, the resin shear strength is sufficient to transfer the shearing load between plies, and the bond strength between masonry and FRP system is sufficient to transfer design forces. Lap splices should be staggered. Lap splice details, including lap length, should be based on the results of tests performed in accordance with ACI 440.3R (L.3), until ASTM tests become available. Due to the unique characteristics of some FRP systems, multiple plies and lap splices are not always possible.

5.9—Resins curing

Curing of resins is a time-temperature-dependent phenomenon. Ambient-cure resins can take several days to reach full cure. Temperature extremes or fluctuations can retard or accelerate the resin curing time. The FRP system manufacturer may offer several prequalified grades of resin to accommodate various ambient conditions.

Elevated cure systems require the resin to be heated to a specific temperature for a specified period of time. Various combinations of time and temperature within a defined envelope provide full cure of the system.

Resins should be cured according to the system manufacturer's recommendation. Field modification of resin chemistry should not be permitted without consulting the system manufacturer.

5.10—Temporary protection

Adverse temperatures, direct contact by rain, dust, dirt, excessive sunlight, high humidity, or vandalism can damage a FRP system during installation and cause improper cure of the resins. Temporary protection, such as tents and plastic screens, may be required during installation and until the resins have cured. If temporary shoring is required, the FRP system should be fully cured before removing the shoring and allowing the structural member to carry the design loads. In the event of suspected damage to the FRP system during installation, the licensed design professional should be notified and the FRP system manufacturer consulted.

CHAPTER 6—INSPECTION, EVALUATION, AND ACCEPTANCE

Quality assurance and quality control (QA/QC) programs and criteria are to be developed and maintained by the FRP system manufacturers, the installation contractors, and others associated with the project. The quality-control program should be comprehensive and cover all aspects of strengthening procedures. The degree of quality control and the scope of testing, inspection, and record-keeping depend on the size and complexity of the project.

Quality assurance is achieved through a set of inspections and applicable tests to document the acceptability of the installation. Project specifications should include a requirement to provide a quality-assurance plan for the installation and curing of all FRP materials. The plan should include:

- Personnel safety issues;
- Application and inspection of the FRP system;
- Location and placement of splices;
- Curing provisions;
- Means to ensure dry surfaces;
- Quality-assurance samples;
- Cleanup; and
- Required submittals listed in Section 12.3.

6.1—Inspection

Fiber-reinforced polymer systems and all associated work should be inspected as required by the applicable local codes. In the absence of such requirements, inspection should be conducted by or under the supervision of a licensed design professional or a qualified inspector. Inspectors should be knowledgeable of and trained in the installation of FRP systems. The qualified inspector should require compliance with design drawings and project specifications. During installation of the FRP system, the scope of the inspection should include:

- Date and time of installation;
- Ambient temperature, relative humidity, and general weather observations;
- Surface temperature of masonry;
- Surface preparation methods and resulting profile;

- Qualitative description of surface cleanliness;
- Type of auxiliary heat source, if applicable;
- Fiber or precured laminate batch number(s) and approximate location in structure;
- Batch numbers, mixture ratios, mixing times, and qualitative descriptions of the appearance of all mixed resins, including primers, putties, saturants, adhesives, and coatings mixed for the day;
- Observations of progress of cure of resins;
- Conformance with installation procedures;
- Pulloff test results according to ASTM D4541/D4541M done or supervised by a licensed design professional or owner's independent testing agency;
- Fiber-reinforced polymer properties from tests of field sample panels or witness panels, if required;
- Location and size of any delaminations or air voids; and
- General progress of work.

The inspector should provide the licensed design professional or owner with the inspection records and witness panels. The installation contractor should retain sample cups of mixed resin and maintain a record of the placement of each batch.

6.2—Evaluation and acceptance

Fiber-reinforced polymer systems should be evaluated based on conformance with the design drawings and specifications, and the manufacturer's installation recommendations. Nonconformance of the FRP system should be reported to the licensed design professional for further evaluation. The FRP system material properties, installation within specified placement tolerances, presence of delaminations, cure of resins, and adhesion to substrate should be evaluated. The evaluation should also consider fiber orientation, ply orientation, width and spacing, corner radii, and lap splice lengths of the installed FRP system.

Witness panel and pulloff tests are used to evaluate the installed FRP system. In-place load testing can also be used where applicable to confirm the installed behavior of the FRP-strengthened member (Nanni and Gold 1998).

6.2.1 *Materials*—Before starting the project, the FRP system manufacturer should submit certification of specified material properties and identification of all materials to be used. Additional material testing can be conducted if deemed necessary based on the complexity and intricacy of the project. Evaluation of delivered FRP materials can include tests for tensile strength, gel time, pot life, and adhesive strength. These tests are usually performed on material samples sent to a laboratory, according to the quality-control test plan. Tests for pot life of resins and curing hardness are usually conducted on-site. Materials that do not meet minimum requirements as specified by the licensed design professional should be rejected.

Witness panels can be used to evaluate the tensile strength and modulus, lap splice strength, and T_g of the FRP system installed and cured on-site using installation procedures similar to those used to install and cure the FRP system. During installation, flat panels of the specified dimensions and thickness can be fabricated on-site according to a predetermined sampling plan. After curing on-site, the panels can then be sent to a laboratory for testing. Witness panels can be retained or submitted to an approved laboratory for testing of tensile strength (ASTM D7205/D7205M), and T_g (ASTM D4065). Strength and elastic modulus of the FRP system is determined in accordance with the requirements of Section 3.3.1 of this guide and ACI 440.3R (L.2) or CSA-S806-02. ASTM standard tests should be used as they become available. The properties to be evaluated by testing should be specified by the licensed design professional. The licensed design professional may waive or alter the frequency of testing.

During installation, sample cups of mixed resin should be prepared according to the specified sampling plan and retained for testing to determine the level of cure (Section 6.2.4).

6.2.2 *Fiber orientations*—Fiber or precured-laminate orientation should be evaluated by inspection using a level or a straightedge. Fiber waviness—a localized appearance of fibers that deviate from the general straight-fiber line in the form of kinks or waves—should be evaluated for wet layup systems.

Fiber or precured laminate misalignment of more than 5 degrees from that specified on the design drawings (approximately 1 in./ft [80 mm/m]) should be reported to the licensed design professional for evaluation. The licensed design professional should calculate the capacity of the system considering this misalignment to determine if the design criteria are still satisfied. If the design criteria cannot be satisfied, remedial action may be warranted.

6.2.3 *Delaminations*—The cured FRP system should be evaluated for delaminations or air voids between multiple plies or between the FRP system and the masonry surface. Inspection methods should be capable of detecting delaminations of 2 in.^{2} (1300 mm^2) or greater. Methods such as acoustic sounding, for example, hammer sounding, ultrasonics, and infrared thermography can be used to detect delaminations.

The effect of delaminations or other anomalies on the structural integrity and durability of the FRP system should be evaluated by the licensed design professional. Delamination size, location, and quantity relative to the overall application area should be considered in the evaluation.

General acceptance guidelines for wet layup systems are:

- Small delaminations less than 2 in.^{2} (1300 mm^2) each are permissible as long as the delaminated area is less than 5% of the total laminate area and there are no more than 10 such delaminations per 10 ft^2 (1 m^2);
- Large delaminations, greater than 25 in.^{2} each (16,000 mm^2), compromise the structural performance of the installed FRP and should be repaired by selectively cutting away the affected sheet and applying an overlapping sheet patch of equivalent plies; and
- Delaminations less than 25 in.^{2} (16,000 mm^2) each may be repaired by resin injection or ply replacement, depending on the size and number of delaminations and their locations.

For precured FRP systems, each delamination should be evaluated and repaired in accordance with the licensed design professional's direction. Upon completion of repairs, the laminate should be re-inspected to verify the repair was properly installed.

6.2.4 *Cure of resins*—The relative cure of FRP systems can be evaluated by laboratory testing of witness panels or resin-cup samples using ASTM D3418. The relative cure of the resin can also be evaluated on the project site by physical observation of resin tackiness and hardness of work surfaces or hardness of retained resin samples. The FRP system manufacturer should be consulted to determine the specific resin-cure verification requirements. For precured systems, adhesive-hardness measurements should be made in accordance with the manufacturer's recommendation.

6.2.5 *Adhesion strength*—Tension adhesion testing of cored samples should be conducted using the method in ASTM D4541. Sampling frequency should be specified. Due to the low tensile strength of masonry units, the evaluation of tension adhesion tests should be based primarily on the failure mode. Tension adhesion tests should exhibit failure of the masonry substrate. Failure between the FRP system and the masonry substrate or interlaminar failure between layers of the FRP system should be reported to the engineer and evaluated for acceptance.

6.2.6 *Cured thickness*—Small core samples, typically 0.5 in. (13 mm) diameter, may be taken to visually ascertain the cured laminate thickness or number of plies at locations approved by the licensed design professional. Cored samples required for adhesion testing also can be used to ascertain the laminate thickness or number of plies. The sampling frequency should be specified by the licensed design professional. Taking samples from high-stress areas or splice areas should be avoided. For aesthetic reasons, the cored hole can be filled and smoothed with a repair mortar or the FRP system putty. If required by the licensed design professional, a 4 to 8 in. (100 to 200 mm) overlapping FRP sheet patch of equivalent plies may be applied over the filled and smoothed core hole immediately after taking the core sample. The FRP sheet patch should be installed in accordance with the manufacturer's installation procedures.

CHAPTER 7—MAINTENANCE AND REPAIR

7.1—General

As with any FRP system, the owner should periodically inspect and assess the performance of the FRP system used for strengthening of masonry members. Inspections should be performed periodically in conjunction with other regular inspections of the structure or at a frequency that is determined based on the exposure conditions and use of the facility. The causes of any damage or deficiencies detected during routine inspections should be identified and addressed before performing any repairs or maintenance.

7.2—Inspection and assessment

7.2.1 *General inspection*—A visual inspection should be performed to observe any changes in color, debonding, peeling, blistering, cracking, crazing, deflections, and other anomalies. In addition, ultrasonic, acoustic sounding, for example, hammer tap, or thermographic tests may reveal signs of progressive debonding and delamination. More information on inspection methods is available in ACI 440R.

7.2.2 *Assessment*—Test data and observations are used to assess any damage and the structural integrity of the strengthening system. The assessment should include repair recommendations and suggestions for reducing the incidence of future damage.

7.3—Repair of strengthening system

The repair method of the strengthening system depends on causes of the damage, the type of material, the form of degradation, and the level and extent of damage. Before repairing the FRP system, causes of the damage should be identified.

Minor damage should be repaired, including localized FRP laminate cracking or abrasions that affect the structural integrity of the laminate. Minor damage can be repaired by bonding FRP patches over the damaged area. The FRP patches should possess the same characteristics, such as thickness and ply orientation, as the original laminate. The FRP patches should be installed in accordance with the material manufacturer's recommendation. Minor delaminations can be repaired by epoxy-resin injection. Major damage, including peeling and debonding of large areas, may require removal of the affected area and replacement of the FRP laminate.

7.4—Repair of surface coating

In the event that the surface-protective coating should be replaced, the FRP laminate should be inspected for structural damage or deterioration. Consult the system manufacturer for repair of the surface coating.

CHAPTER 8—GENERAL DESIGN CONSIDERATIONS

8.1—Design philosophy

The design methodology presented in Chapters 9 and 10 is based on limit state design principles to provide acceptable safety levels.

To evaluate the nominal strength of a FRP-strengthened masonry member, all possible failure modes with associated strains and stresses in each material should be assessed.

Material properties such as compressive and tensile strength, elastic modulus in compression, and shear strength of existing masonry, should preferably be determined by in-place tests or laboratory tests of extracted samples. If these are unavailable, the material properties of existing masonry may be obtained from available guidelines, including ASCE 41-06, ACI 530, or historical records found in the literature. Dimensions of the masonry elements should be obtained from the existing drawings or field measurements.

If there are uncertainties regarding existing material strengths or substrate conditions, the engineer may wish to incorporate more conservative strength-reduction factors than those discussed in this guide.

This guide can be used to design a FRP strengthening system for existing individual masonry walls. The engineer designing the FRP strengthening system for individual wall(s) should evaluate the effect wall strengthening has on the overall structure. If appropriate, a global analysis of the overall structure should be performed (Moon et al. 2006; ASCE 41-06).

In strengthening of URM members, the relationship between each element and the entire structure is of particular relevance. Specifically, the in-plane rigidity of floor diaphragms and the effectiveness of the connections between the floor diaphragms and the walls as well as among intersecting walls themselves can be critical to the global behavior of the building. For example, post-earthquake observations of damage have shown out-of-plane wall failures due to the lack of in-plane rigidity of floor diaphragms and inadequate connectivity between walls and diaphragms. Conversely, in cases where the proper connection was ensured by anchors into the walls or by retrofit measures such as RC ring beams or steel ties at each floor level, out-of-plane failures were prevented and the seismic actions could mobilize in-plane strength of the walls (Magenes and Calvi 1997).

8.2—Strengthening limits

For concrete structural members, FRP strengthening limits are imposed to guard against failure of the strengthened element should the FRP reinforcement become ineffective due to fire, substrate degradation, vandalism, or impact damage (ACI 440.2R). These limitations ensure that the concrete member, typically a gravity-load-carrying element, can resist sustained loads typically expressed as dead loads and a portion of the live loads without the contribution of the FRP system.

In the case of masonry elements, FRP systems are usually installed to increase the strength of URM walls subjected to special loading events such as earthquake, wind, hurricane, and blast loads. These loads are rare and typically not sustained. The probability of simultaneous occurrence of damage to FRP, for example from vandalism or exposure to high temperatures and high short-term loads, like from earthquake or wind, is low; therefore, a strengthening limit for these applications is unnecessary.

There are two cases, however, in which the strengthening limits should be considered. These cases include masonry walls resisting out-of-plane loads due to earth pressure and walls that are part of the primary lateral load-carrying system resisting in-plane loads from wind. For walls resisting out-of-plane loads due to earth pressures, the strength of the existing wall should be sufficient to meet the limitation given in Eq. (8-1)

$$(\phi R_n)_{existing,\ out\text{-}of\text{-}plane} \geq (0.9D + 1.0H)_{new} \qquad (8\text{-}1)$$

For cases of walls that are part of the primary lateral-load-carrying system, the in-plane strength of the wall should be sufficient to meet the limitation given in Eq.(8-2)

$$(\phi R_n)_{existing,\ in\text{-}plane} \geq (0.9D + 1.0W)_{new} \qquad (8\text{-}2)$$

8.3—Design material properties

Unless otherwise stated, material properties reported by the system's manufacturer, such as tensile strength, typically do not consider long-term exposure to environmental conditions and, therefore, should be considered as initial properties. Because long-term exposure to various types of environments can reduce the tensile properties and creep-rupture and fatigue endurance of FRP laminates, the material properties used in design equations should be reduced based on the environmental exposure condition. Equations (8-3) through (8-5) give the tensile properties that are used in all design equations. The design tensile strength is determined using the environmental reduction factor given in Table 8.1 for the appropriate fiber type and exposure condition.

Table 8.1—Environmental reduction factors for various FRP systems and exposure conditions

Exposure conditions	Fiber type	Environmental reduction factor C_E
Interior exposure (for example, partitions)	Carbon	0.95
	Glass	0.75
	Aramid	0.85
Exterior exposure (including internal side of exterior walls)	Carbon	0.85
	Glass	0.65
	Aramid	0.75
Aggressive environment (basement walls)	Carbon	0.85
	Glass	0.50
	Aramid	0.70

$$f_{fu} = C_E f_{fu}^* \qquad (8\text{-}3)$$

Similarly, the design rupture strain should also be reduced for environmental-exposure conditions.

$$\varepsilon_{fu} = C_E \varepsilon_{fu}^* \qquad (8\text{-}4)$$

Fiber-reinforced polymer materials consisting of one type of fiber oriented predominantly in one direction are practically linearly elastic until failure. Their modulus of elasticity does not vary significantly with environmental exposure and loading history and can be computed according to Eq. (8-5).

$$E_f = \frac{f_{fu}}{\varepsilon_{fu}} \qquad (8\text{-}5)$$

Constituent materials affect the durability and resistance to environmental exposure of a FRP system. The environmental-reduction factors given in Table 8.1 are estimates based on the relative durability of each fiber type. As more research information is developed and becomes available, these values may be refined. Durability test data for FRP systems with and without protective coatings may be obtained from the FRP manufacturer of the system under consideration. As Table 8.1 illustrates, if the FRP system is located in a relatively benign environment, such as indoors, the reduction factor is closer to unity. If the FRP system is located in an aggressive environment where prolonged exposure to high humidity, freezing-and-thawing cycles, salt water, or alkalinity is expected, a lower reduction factor should be used. The reduction factor can reflect the use of a protective coating if the coating has been shown through testing to lessen the effects of environmental exposure and the coating

is maintained for the life of the FRP system; in such a case, the environmental reduction factor should never be larger than the values provided in Table 8.1 (ACI 440.2R) for the interior exposure conditions.

The relative durability of NSM systems versus surface-applied laminates may be better. Given the lack of data, however, this guide conservatively recommends use of the same C_E factors for both applications.

8.4—Effective strain and stress in the FRP reinforcement at the strength limit state

Debonding of the FRP system can occur if the force in the FRP system at the strength limit state cannot be sustained by the masonry substrate. For a typical FRP system that is linear elastic until failure, the level of strain in the FRP system will dictate the level of stress developed in the system. To prevent debonding, a limitation is placed on the strain level developed in the FRP laminate. The maximum strain and corresponding stress that FRP systems can attain before debonding from the masonry substrate are defined as effective strain ε_{fe} and effective stress f_{fe}.

8.4.1 *Effective strain for flexure-controlled failure modes*—The effective strain ε_{fe} and effective stress f_{fe} used for the design of flexural out-of-plane and in-plane FRP strengthening of masonry walls (Sections 9.4, 10.5, and 10.6) can be computed according to Eq. (8-6) and (8-7), respectively

$$\varepsilon_{fe} = \kappa_m \varepsilon_{fu}^* \leq C_E \varepsilon_{fu}^* \tag{8-6}$$

$$f_{fe} = E_f \varepsilon_{fe} \tag{8-7}$$

where κ_m is a bond reduction coefficient calibrated using available experimental data (Albert et al. 2001; Hamilton and Dolan 2001; Tumialan 2001; Bajpai and Duthinh 2003; Tumialan et al. 2003a,b; Turco et al. 2003; Galati et al. 2006), defined as in Eq. (8-8).

$$\kappa_m = \begin{cases} 0.45 & \text{for surface-mounted FRP systems} \\ 0.35 & \text{for NSM FRP systems} \end{cases} \tag{8-8}$$

Based on current knowledge and experimental data, Eq. (8-8) is applicable only when the total force per unit width (per bar for NSM systems) that the FRP system transfers to the masonry substrate satisfies the limitation given in Eq. (8-9).

$$p_{fm} = \begin{cases} n t_f f_{fe} \leq 1500 \text{ lb/in. for surface-mounted FRP systems} \\ A_{f,bar} f_{fe} \leq 10{,}000 \text{ lb/bar for NSM FRP systems} \end{cases} \text{(in.-lb)}$$
$$p_{fm} = \begin{cases} n t_f f_{fe} \leq 260 \text{ N/mm for surface-mounted FRP systems} \\ A_{f,bar} f_{fe} \leq 44{,}500 \text{ N/bar for NSM FRP systems} \end{cases} \text{(SI)} \tag{8-9}$$

8.4.2 *Effective strain for shear-controlled failure modes*—The effective strain ε_{fe} and effective stress f_{fe} to be used for the design of shear in-plane FRP strengthening of masonry walls (Sections 10.4 and 10.6) can be computed according to Eq. (8-10) and (8-11), respectively

$$\varepsilon_{fe} = \kappa_v \varepsilon_{fu}^* \leq C_E \varepsilon_{fu}^* \tag{8-10}$$

$$f_{fe} = E_f \varepsilon_{fe} \tag{8-11}$$

The bond reduction coefficient for shear-controlled failure modes κ_v depends on the FRP reinforcement index ω_f, defined in Eq. (8-12).

$$\omega_f = \frac{1}{1000} \frac{A_f E_f}{A_n \sqrt{f'_m}} \quad \text{for in.-lb units}$$
$$\omega_f = \frac{1}{85} \frac{A_f E_f}{A_n \sqrt{f'_m}} \quad \text{for SI units} \tag{8-12}$$

For shear-controlled failure modes, the bond reduction coefficient is again calibrated based on experimental data (Tinazzi and Nanni 2000; Tumialan et al. 2001b; Morbin and Nanni 2002; Valluzzi et al. 2002; Grando et al. 2003; Zhao et al. 2003; Santa Maria et al. 2004, 2006; Senescu and Mosalam 2004; Stratford et al. 2004). The coefficient for shear-controlled failure modes is equal for both FRP laminates and NSM FRP systems and is given in Eq. (8-13).

$$\kappa_v = \begin{cases} 0.40 & \text{for } \omega_f \leq 0.20 \\ 0.64 - 1.2\omega_f & \text{for } 0.20 < \omega_f \leq 0.45 \\ 0.10 & \text{for } \omega_f > 0.45 \end{cases} \tag{8-13}$$

Similar to flexure-controlled failure modes, Eq. (8-13) is applicable only when the force per unit width (per bar for NSM systems) that the FRP system transfers to the masonry substrate satisfies the limitation given in Eq. (8-14).

$$p_{fv} = \begin{cases} n t_f f_{fe} \leq 1500 \text{ lb/in. for surface-mounted FRP systems} \\ A_{f,bar} f_{fe} \leq 10{,}000 \text{ lb/bar for NSM FRP systems} \end{cases} \text{(in.-lb)}$$
$$p_{fv} = \begin{cases} n t_f f_{fe} \leq 260 \text{ N/mm for surface-mounted FRP systems} \\ A_{f,bar} f_{fe} \leq 44{,}500 \text{ N/bar for NSM FRP systems} \end{cases} \text{(SI)} \tag{8-14}$$

It is recognized that in Eq. (8-6) and (8-10), the κ values will always control over the C_E values. The κ values, however, have been set as a lower bound from experimental data. It is expected that further experimental data may result in higher κ values in the future. Limitation involving the C_E value is presented to establish the design philosophy that will remain consistent. Furthermore, if experimental data for a particular application is available, the designer may wish to incorporate different C_E or κ values. In this case, it is recommended to follow the limitations given by Eq. (8-6) and (8-10).

CHAPTER 9—WALL STRENGTHENING FOR OUT-OF-PLANE LOADS

9.1—Background information

A number of research projects have been conducted to study the use of FRP systems for flexural strengthening of masonry walls. Ehsani and Saadatmanesh (1996) investigated

the flexural behavior of URM walls strengthened with GFRP sheets. The specimen dimensions were 8.5 in. wide, 4 in. high, and 57 in. long (216 mm wide, 100 mm high, and 1450 mm long). Specimens were subjected to four-point bending. Tension failure was observed when a low composite reinforcement ratio was used. When the number of plies was increased, the masonry failed in compression. It was observed that the flexural capacity was increased up to 24 times compared with the unreinforced control specimen. According to test results, effects of the mortar strength appeared to be negligible and both specimens with the higher composite reinforcement ratio failed by masonry crushing.

Velazquez-Dimas et al. (2000) reported test results of half-scale URM walls tested under out-of-plane cyclic loading. The test specimens had a width of 48 in. (1220 mm) and a height of 56 in. (1420 mm), with a slenderness ratio (span length divided by the specimen thickness) of 28. Two of the walls were strengthened on both faces with GFRP strips. Understanding that the balanced condition represents simultaneous failure of masonry and rupture of composite laminate, one wall had reinforcement equivalent to the balanced ratio, while the other wall had three times the balanced reinforcement. The specimen with balanced reinforcement showed extensive composite delamination at failure. The specimen with the higher reinforcement ratio failed due to high shear stresses along the lower brick course. Substantial increases in strength and deformation capability were achieved. The retrofitted walls resisted pressures up to 24 times the weight of the wall and deflected as much as 5% of the wall height. To avoid very stiff behavior and improve the hysteretic response, it was recommended to limit the reinforcement ratio to two times the balanced condition.

Hamilton and Dolan (2001) investigated the flexural behavior of URM walls strengthened with different composite materials. The walls were built with standard 8 in. (200 mm) concrete masonry units, with an overall dimension of 2 x 6 ft (0.61 x 1.83 m). The use of high-strength composite materials such as CFRP and AFRP, with vertical fiber orientation, led to modes of failure such as FRP delamination and shear in the masonry. To use the composite material more efficiently, two alternatives were recommended. The first alternative was to increase spacing of the material until observing the laminate rupture. The second alternative was to use less-expensive materials, such as GFRP. These more efficient alternatives resulted in four failure modes: debonding, laminate rupture, masonry shear, and face shell pullout. It was reported that debonding from the masonry substrate caused failure for most of the test specimens. Hamoush et al. (2001) investigated the influence of two different surface preparation methods, sand blasting and wire brush, on the behavior of 4 ft x 6 ft x 8 in. (1.2 m x 1.8 m x 0.2 m) specimens strengthened using GFRP strips placed along the horizontal and vertical directions subjected to a distributed load. They concluded that adding more than one layer of FRP reinforcement improved the structural performance of the wall. When only one layer of FRP reinforcement was used, its distance from the support had a minor influence on the wall behavior.

Successful use of NSM bars for improving the flexural capacity of RC members led to extending this technique to URM walls. When installed to masonry walls, NSM bars are typically placed in horizontal masonry bed joints. As an example, masonry panels of concrete masonry units were tested by Tumialan et al. (2002). One specimen was strengthened with one No. 10 (No. 3) GFRP bar, the second with two No. 10 (No. 3) GFRP bars, and the third was strengthened with an externally bonded GFRP laminate (width = 3 in. [7.6 mm]) to provide the same axial stiffness as the first specimen. The wall strengthened with one GFRP bar failed due to debonding of the epoxy paste from the masonry. Initial flexural cracks formed at the mortar bed joints perpendicular to the reinforcement, and originated secondary cracks at the epoxy paste-masonry interface causing debonding and subsequent wall failure. The wall strengthened with two bars failed due to masonry shear, while the specimen with the GFRP laminate failed due to debonding. As expected, Specimens 1 and 3 exhibited similar behavior in terms of load-carrying capacity and ultimate deflection. This experimental program was used as a validation for the strengthening of two URM concrete walls at an educational facility in Kansas City, MO, where the walls exhibited cracking in the bed joints at the midheight region. By using epoxy strengthened with short fibers, Bajpai and Duthinh (2003) were able to prevent debonding of NSM glass FRP bars and consistently rupture the bars in flexural tests of masonry walls. This method resulted in higher wall strength and more brittle behavior.

The load-carrying capacity of flexural walls strengthened with FRP laminates is a function of the axial load level (Triantafillou 1998). Moreover, FRP composites are highly effective in the case of walls that can be treated as simply supported—for example, walls having a large slenderness ratio. For a wall with low slenderness ratio built between rigid supports, when the out-of-plane deflection increases, the wall is restrained from free rotation at its extremities. This action induces an in-plane compressive force that, depending on the degree of support fixity, can increase the URM wall ultimate capacity by several times. This mechanism is known as arching. Due to arching, the increase of flexural capacity in walls strengthened with FRP laminates may be considerably less than expected. Laboratory and field experimentation have shown that the contribution of FRP to the flexural capacity of fixed-end walls is less than in the case of simply supported conditions, as crushing masonry units at the boundary regions controls ultimate behavior (Tumialan et al. 2003a; Galati 2002).

A wide experimental campaign has been conducted by Galati et al. (2004) on URM walls strengthened using FRP laminates and NSM bars. Twenty-five specimens had dimensions of 23.6 x 47 x 3.7 in. (600 x 1200 x 95 mm); 12 were built using concrete masonry units and 13 using clay bricks. Glass fiber-reinforced polymer and AFRP strips having widths ranging between 3 and 12 in. (75 and 300 mm) have been installed. In addition, 15 specimens were strengthened using GFRP and CFRP NSM bars; their width was 3.7 in. (95 mm) for clay specimens and ranged between 3.6 and 5.6 in.

(92 and 143 mm) for concrete specimens. All of the specimens had dimensions of 24 x 48 in. (610 x 1220 mm). Four-point bending tests have been conducted to assess the effectiveness of the strengthening method. The test results showed three types of failure modes: shear, debonding, and flexural. For large amounts of reinforcement, shear failure resulted to be the controlling mode; for other reinforcement ratios, either FRP rupture or debonding was observed. Based on the experimental data obtained in their study on FRP laminates, this guide recommends maximum usable strains equal to $0.45\varepsilon_{fu}$ for non-puttied surfaces, and $0.65\varepsilon_{fu}$ for puttied surfaces. They also proposed maximum usable strains depending on the cross section shape of NSM bars and type of adhesive. A similar investigation has been conducted by Tan and Patoary (2004) on clay brick plates simply supported on the four sides. Thirty plates with dimensions of 39 x 39 x 4 in. (1000 x 1000 x 110 mm) have been subjected to out-of-plane loads with different loading paths. The study has also analyzed the influence of surface preparation and the effectiveness of mechanical anchorages using steel bars or GFRP bolts. It was concluded that the combination of surface grinding and fiber bolt anchorage system resulted in the greatest increase of wall strength. Bidirectional GFRP fabrics provided larger strength increases than carbon or glass fiber sheets bonded with appropriate adhesive.

Parretti et al. (2004) validated a system consisting of GFRP grids embedded in polyurea resin for the strengthening of natural masonry walls. Both ultimate capacity and member ductility were improved with respect to the original, unstrengthened wall, even though the geometry and compressive strength of the masonry were such that GFRP rupture was never the obtained failure mode.

9.2—General considerations

9.2.1 *Assumptions*—The following assumptions are considered:

1. The strains in the FRP reinforcement and masonry are directly proportional to their distance from the neutral axis, that is, a plane section before loading remains plane after loading;

2. The maximum usable compressive strain in concrete masonry is 0.0025, while for clay and natural stone masonry, a value of 0.0035 can be assumed;

3. The tensile behavior of the FRP reinforcement is linear elastic up to failure;

4. The contributions of both masonry in tension and FRP reinforcement in compression are neglected;

5. There is no relative slip between external FRP reinforcement and masonry until debonding failure occurs; and

6. The wall behaves as a simply supported element or very nearly so, and the influence of wall arching mechanisms can be neglected. Arching mechanisms can potentially develop in a wall with a height-to-thickness ratio (h/t) less than 8 and built between stiff supports. In such a case, the FRP contribution should not be added to the out-of-plane capacity corresponding to arching mechanism. The influence of arching in the out-of-plane behavior decreases for walls with h/t larger than 14. This guide recommends that Tables 7-5 and 7-10 of ASCE 41-06, developed for seismic design, can be used to determine h/t for which URM walls do not need to be analyzed for out-of-plane loads and, therefore, do not require strengthening.

9.2.2 *Shear strength*—When externally bonded FRP systems are used to increase the out-of-plane flexural strength of a masonry wall, the wall should be checked to verify it has adequate shear strength (Section 9.3.2) to resist the design shear forces. If the shear strength of the existing masonry is inadequate, where shear controls the design, supplementary methods for shear strengthening could be implemented to increase the shear strength. These methods can involve grouting of hollow units near the supports, and lateral bracing.

9.3—Existing wall strength

To determine whether FRP strengthening is needed, the existing out-of-plane strength of the wall should be evaluated first. Unreinforced masonry walls should be analyzed for out-of-plane seismic forces and wind pressures, or both, and earth pressures as isolated elements spanning between floor levels and spanning horizontally, or both, between columns or pilasters (ACI 530; ASCE 41-06) and the applicable local building code, or both.

9.3.1 *Flexural and axial strength*—Assuming that the wall behaves as a simply supported element, the nominal out-of-plane flexural strength of the unreinforced and unstrengthened wall M_n can be determined as the bending moment calculated based on the masonry modulus of rupture or flexural tensile strength. The flexural tensile strength can be obtained by in-place testing following one of the test methods recommended by ASCE 41-06 (Chapter 7). In the absence of test results, the flexural tensile strength of an URM wall can be conservatively estimated using the lower-bound flexural tensile strength values shown in Table 7-1 of ASCE 41-06, which depend on the condition of the masonry. If the masonry is in good condition and built after 1960, the flexural tensile strength can be estimated using the modulus of rupture shown in Table 3.1.8.2.1 of ACI 530. The nominal axial strength P_n should be determined in accordance with the ACI 530 provisions using appropriate compressive strengths, determined by in-place testing, historical records for old masonry, or f'_m values shown in Table 7-1 of ASCE 41-06. The design strength should be obtained as the nominal strength multiplied by the strength reduction factor ϕ as determined from a reliability-based calibration study that accounts for uncertainties in materials, fabrications, construction details, and geometric properties. In the event that such a detailed reliability study is not available, it is recommended that a strength reduction factor ϕ of 0.6 as suggested by ACI 530 be used.

9.3.2 *Shear strength*—The shear strength can be obtained by in-place testing following one of the test methods recommended by ASCE 41-06 (Chapter 7). In the absence of test results, the shear strength of a URM wall can be conservatively estimated using the lower-bound shear strength values shown in Table 7-1 of ASCE 41-06, which depend on the condition of the masonry. Based on engineering judgment,

the shear strength of masonry proved to be in good condition and built after 1960 can be estimated using the shear strength computed according to Section 3.2.4 of ACI 530. The design strength should be obtained as the nominal strength multiplied by the strength reduction factor ϕ, as determined from a statistical analysis of the as-built masonry materials. In the event that such a detailed materials investigation is not made, a strength reduction factor ϕ of 0.8 as suggested by ACI 530-08 should be used.

9.4—Nominal flexural strength of FRP-reinforced masonry walls subjected to out-of-plane loads

The strength design method requires that the flexural strength of the FRP-strengthened wall exceeds the factored moment, as indicated by Eq. (9-1).

$$\phi M_n \geq M_u \tag{9-1}$$

The Committee recommends the use of a strength reduction factor of ϕ = 0.6 as required by ACI 530 for URM walls subjected to flexural load, axial load, or a combination thereof. The use of a URM ϕ-factor is justified by the reduced ductility and potential for a brittle failure of FRP-strengthened walls.

Assuming that the factored axial load P_u acts at $t/2$ (t = thickness of wall), the nominal flexural strength M_n of the FRP-strengthened masonry wall can be determined from Eq. (9-2) using strain compatibility, internal force equilibrium, and the controlling mode of failure.

$$M_n = A_f f_{fe}\left(d_f - \frac{\beta_1 c}{2}\right) + P_u\left(\frac{t}{2} - \frac{\beta_1 c}{2}\right) \tag{9-2}$$

where f_{fe} represents the effective stress to be calculated according to Eq. (8-7) with the strain level ε_{fe} as defined in Eq. (9-3).

9.4.1 *Failure modes*—The following failure modes can control the out-of-plane behavior of URM walls strengthened with externally bonded FRP systems (Tumialan et al. 2003b; Galati et al. 2006):

- Crushing of the masonry in compression
- Debonding of the FRP system from the masonry substrate

Crushing of the masonry is an acceptable failure mode provided that strength and serviceability criteria are satisfied. If no mechanical anchorage is provided, FRP debonding is the most common failure mode in masonry walls strengthened with FRP systems (Tumialan et al. 2003b; Galati et al. 2005, 2006). The design protocols for flexural strengthening in this guide consider that either masonry crushing or debonding govern the flexural behavior of FRP-strengthened walls. Debonding occurs at the masonry-FRP interface and typically starts from flexural cracks at the maximum bending moment region and propagates toward the supports. As the tensile strength of masonry is lower than that of the epoxy used to bond the FRP system, the failure typically occurs in the masonry substrate. To prevent debonding, a bond-dependent coefficient is introduced to limit the strain level in the FRP reinforcement according to the provisions given in Section 8.4.1.

9.4.2 *Strain level in the FRP reinforcement*—The maximum strain level that can be achieved in the FRP reinforcement is determined by the strain developed in the FRP system at the ultimate limit state by either crushing of the masonry or FRP system debonding. The maximum strain or effective strain level in the FRP reinforcement may be calculated as

$$\varepsilon_{fe} = \varepsilon_{mu}\left(\frac{t-c}{c}\right) \leq \min(\kappa_m \varepsilon_{fu}^*,\ C_E \varepsilon_{fu}^*) \tag{9-3}$$

9.4.3 *Stress level in the FRP reinforcement*—The effective stress level in the FRP reinforcement is the maximum level of stress that can be developed in the FRP reinforcement before reaching the ultimate limit state. This effective stress can be calculated from the strain level in the FRP system, assuming perfectly elastic behavior as given in Eq. (8-7).

9.4.4 *Flexural strength computation*—Strain compatibility and equilibrium of forces are used to calculate the member flexural strength. The calculation described herein follows a simple trial-and-error method. This procedure requires the assumption of the neutral axis depth c. After assuming the neutral axis depth, the strain in the FRP can be calculated using Eq. (9-3). If the left side term in the equation controls, crushing of the masonry is the governing failure mode. If the second term controls, FRP system debonding or FRP rupture is the governing failure mode. If the equilibrium condition is not satisfied, the depth of the neutral axis should be revised and the procedure repeated. As an alternative, the flexural capacity can be computed (Section 13.1) by assuming a failure mode and calculating the corresponding neutral axis depth and area of FRP reinforcement (Bank 2006).

When FRP debonding is the governing failure mode, the effective stress in the FRP reinforcement can be computed from Eq. (8-7) assuming perfectly elastic behavior. When crushing of the masonry is the governing failure mode, the coefficients γ and β_1 defining the equivalent rectangular stress block approach, are each equal to 0.80, as reported in ACI 530. If FRP system rupture or debonding occurs before crushing of the masonry, methods considering a nonlinear stress-strain distribution can be used to estimate γ and β_1. These methods may include the use of a parabolic representation of the nonlinear compressive behavior of the masonry or other more elaborated methods such as Todeschini's method appropriately modified for the use with masonry (Galati et al. 2005). Alternative values of γ and β_1, both equal to 0.70, can provide reasonably accurate results (Tumialan et al. 2003b).

9.5—Serviceability

The serviceability of a masonry member, for example, deflections and crack widths, under service loads should satisfy applicable provisions of ACI 530. If deflection and crack width requirements are not satisfied before strengthening, supplementary strengthening or stiffening methods, or both, might need to be implemented to satisfy these

Table 9.1—Sustained plus cyclic service load stress limits in FRP reinforcement

Fiber type		
Carbon	Glass	Aramid
$0.55f_{fu}$	$0.20f_{fu}$	$0.30f_{fu}$

requirements. Fiber-reinforced polymer systems can be moderately effective in reducing deflections and crack widths; however, they are primarily effective in increasing strength.

The effect of FRP reinforcement on the in-service performance of a masonry member can be evaluated using the transformed section analysis. The strain level in the FRP reinforcement at service conditions should be compared with the limitations described in Section 9.6 for the case of sustained or cyclic load conditions.

Calculation of the stress level in the FRP reinforcement at service is required for masonry walls that resist sustained loads, such as retaining walls. The in-service stress in the FRP reinforcement can be estimated using Eq. (9-4), where M_s and P_s represent the moment and axial load due to all sustained loads, respectively. In the case of retaining walls, this load should include the entire lateral load due to earth and hydrostatic pressure and, depending on the service condition, a fraction or all lateral loads due to surcharge. The stress at service may be computed as

$$f_{fs} = \begin{cases} \dfrac{M_s - P_s\left(\frac{t}{2} - \frac{c_s}{3} \pm e\right)}{A_f\left(t - \frac{c_s}{3}\right)} & \text{for surface-mounted FRP systems} \\[2ex] \dfrac{M_s - P_s\left(\frac{t}{2} - \frac{c_s}{3} \pm e\right)}{A_f\left(t_b - \frac{c_s}{3}\right)} & \text{for NSM FRP systems} \end{cases} \quad (9\text{-}4)$$

where c_s is the neutral axis depth at service conditions.

The stress in the FRP reinforcement should not exceed the limits presented in Section 9.6.

9.6—Creep rupture stress limits

Masonry walls can be used as structural members to resist sustained lateral loads. For instance, concrete masonry walls are commonly used as retaining walls. To avoid creep-rupture of the FRP systems under sustained loads, the in-service stress calculated from Eq. (9-4) should not exceed the values shown in Table 9.1 (ACI 440.1R-06). As the stress levels will be within the elastic response range, or very nearly so, the stresses can be estimated using elastic analysis.

CHAPTER 10—WALL STRENGTHENING FOR IN-PLANE LOADS

10.1—Background information

Schwegler (1995) investigated strengthening methods for masonry shear walls with FRP laminates. The objective of this study was to determine how to increase the system ductility, generate uniform crack distribution, and increase load-carrying capacity. Carbon fiber-reinforced polymer laminates were bonded diagonally to the masonry walls and mechanically anchored to the adjoining RC slabs. The test results showed that the strengthened wall exhibited 50% to 300% increases in ultimate strength and displacement, respectively, as compared with the same wall without any strengthening system applied to the surface. By comparing walls strengthened on one versus two faces, it was observed that in the case of the one-face application, the capacity was half of the two-face strengthening, without any other major effect on the in-plane load-carrying capacity. In all the strengthened walls, fine cracks were observed perpendicular to the FRP laminates with constant spacing and small width.

Hartley et al. (1996) tested two full-sized 8 in. (203 mm) concrete block walls, 8 ft (2.44 m) high and 20 ft (6.1 m) long to investigate the feasibility of using unidirectional CFRP sheets to repair damage caused by differential foundation settlement. In the study, settlement loads were first applied to induce characteristic step cracking. Carbon fiber-reinforced polymer was then applied to one surface, and the wall retested. Strength gains of over 50% were recorded. The results suggested that CFRP was suitable for rehabilitating concrete block walls damaged by foundation settlement.

Al-Chaar and Hasan (1999) experimentally investigated the behavior of masonry bearing and shear walls subjected to seismic forces provided by an earthquake simulator. The FRP composite retrofit applied to one side of the URM walls enhanced the in-plane load capacity of these walls. Seismic rehabilitation of URM walls with FRP was investigated at the U.S. Army Corps of Engineers (Marshall et al. 1999). A large number of concrete and clay masonry walls were tested using several different FRP systems, such as laminates, grids, and NSM bars.

The U.S. Army Corps of Engineers (Marshall and Sweeney 2002) Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), in partnership with the Market Development Alliance of the FRP Composites Industry, investigated FRP composite systems to strengthen both lightly reinforced and URM walls to better withstand damage during earthquakes. A total of 107 masonry walls, 64 clay brick walls, and 43 CMU walls, with FRP applied to one side only, were tested using a variety of different FRP configurations. The walls were tested in shear tension, in-plane shear, and in-plane rocking. Both E-glass and carbon fabrics were evaluated, as well as NSM shapes. The testing objective was to determine failure modes, mechanisms, and strengths using a variety of FRP configurations to optimize material placement. The performance of buildings in earthquakes is characterized by both the strength of the structure and its ability to survive large deformations without collapsing. In the ERDC-CERL tests, the ability to strengthen the walls using FRP was demonstrated. Placement of the FRP composites were shown to increase the strength and change the failure mode of masonry walls in shear. The configurations that performed best on clay brick walls were carbon full-coverage and both carbon and glass X-frame. The X-frame configuration consisted of an 8 in. (200 mm) wide strip of FRP placed vertically at each edge of the test specimen with two diagonal 8 in. (200 mm) strips

starting from the corners to form an X across the center of the specimen. Full coverage and NSM CFRP rectangle performed best on CMU. The NSM CFRP configuration was rectangular shapes 5/8 in. (16 mm) wide by 1/8 in. (3 mm) thick with a roughened surface to enhance bond with the adhesive. The grooves were cut 4 in. (100 mm) from the outer edges and were approximately 1/4 in. (6 mm) wide and 1 in. (25 mm) deep. It was found in this investigation that because of its stiffness, carbon FRP failed in sudden bond failure.

Cracked URM concrete block walls were repaired by Gergely and Young (2001) using CFRP laminates attached to both sides of the specimens and subjected to cyclic out-of-plane loads, and in-plane loads. The symmetric laminates significantly increased the flexural and shear capacity of damaged walls. The specimens failed as a result of severe shear damage in the concrete masonry blocks. Experimental and analytical studies showed that the repaired walls behaved similarly to traditional composite sandwich panels.

Concrete masonry walls strengthened with FRP laminates in the horizontal direction only and tested with in-plane loading along the wall diagonal, have been observed to fail due to sliding shear along an unstrengthened joint (Tumialan et al. 2001a). This mode of failure is undesirable if there are adjacent columns such as in the case of infill walls, but may be controlled by placing FRP bars in the vertical direction to act as dowels.

As in the case of URM walls strengthened for flexure with FRP laminates, the masonry topology has been observed to be one of the factors influencing the in-plane wall behavior. Thus, in the case of clay brick masonry walls strengthened with laminates for shear, the FRP strengthening has been observed to be more efficient than in the case of concrete masonry (Grando et al. 2003). This can be attributed to characteristics of the parent material such as height of masonry courses—for example, smaller in the case of brick masonry—and better mortar-masonry unit bond characteristics. Grando et al. (2003) also reported that the in-plane capacity of clay masonry walls strengthened on one and two faces doubled, when doubling the FRP reinforcement.

Valluzzi et al. (2002) reported experimental results on clay brick masonry specimens having dimensions of 20 x 20 x 4.7 in. (0.51 x 0.51 x 0.12 m). The investigation considered variables such FRP laminate types (CFRP and GFRP); strengthening configurations (single-side versus double-side strengthening) and square grid and diagonal. Single-side-strengthened specimens failed due to splitting of masonry. Crack growth was larger on the unstrengthened sides due to reinforcement eccentricity. In some cases, the maximum loads were lower than those of the control panels. The double-side strengthened specimens failed due to delamination or rupture of the FRP laminate. In general, the diagonal strengthening configuration was observed to be more effective than the grid configuration; also, GFRP laminates were more effective at increasing the shear capacity.

Unreinforced masonry walls built with clay tile units are commonly used as inner walls in building envelopes. From the early 1900s to the 1960s, structural clay tiles were commonly used in infill walls throughout the U.S. This masonry typology is still widely used in other parts of the world where failure of this kind of wall has been reported to cause a large amount of loss of human life and material damage. In that context, Bastidas et al. (2002) investigated the strengthening with GFRP laminates of nonstructural masonry walls built with clay tiles. This investigation included diagonal compression tests of 26 specimens of 3.5 x 27.5 x 27.5 in. (90 x 700 x 700 mm) and 3.5 x 47 x 47 in. (90 x 1200 x 1200 mm), strengthened with different layouts of GFRP laminates. In addition, a full-scale wall was tested to validate the technology. The strengthening configurations included vertical and horizontal laminate strips, combinations of both, and diagonal laminates (cross-pattern). The test results showed that GFRP reinforcement increased the shear strength as well as the ductility of the system. The cross-pattern layout on both sides of the wall proved to be the most effective configuration. It was observed that areas of high load concentration, such as corners, should be filled with grout to avoid the fracture of the brittle clay tile units and premature failure of the wall. An infill clay tile masonry wall surrounded by an RC frame was built to validate the effectiveness of the GFRP reinforcement in larger specimens. The wall was 7.2 ft (2.2 m) high x 9.8 ft (3.0 m) long x 3.5 in. (90 mm) thick. Based on the results obtained from the testing of the small specimens, the wall was strengthened with 1.0 in. (25 mm) wide diagonal strips. The GFRP strips were applied on both sides of the wall to ensure symmetrical behavior during the in-plane cyclic loading. A significant global reduction of damage levels was observed for the strengthened masonry wall when compared with results reported by the same authors on similar URM walls. Also, global stability and overall seismic behavior were greatly improved with the GFRP reinforcement for in-plane loading.

Strengthening by FRP structural repointing, that is, placement of NSM bars in bed joints, can also remarkably increase the shear capacity of URM walls. This was evident from the results of tests conducted on concrete masonry walls loaded along the diagonal (Tumialan et al. 2001b). The maximum increase in shear capacity was 80%, registered in walls strengthened with GFRP bars placed at every bed joint. Strengthened walls showed stability after failure, that is, no loose material was observed, potentially reducing the risk of partial or total collapse. Due to reinforcement eccentricity, which caused the crack growth on the unstrengthened side to increase at a higher rate than the strengthened side, walls with FRP reinforcement on one side tilted toward the direction of the strengthened face. Walls with reinforcement staggered on both wall faces exhibited the largest displacement capacity. In-place tests were performed by Corradi et al. (2002) on FRP retrofitted masonry walls damaged by recent earthquakes. Both CFRP and GFRP unidirectional laminates were used to retrofit the masonry panels, followed by in-plane tests. The tests confirmed that the shear capacity of the masonry panels was significantly increased by the FRP materials.

Fiber-reinforced polymer structural repointing has also been used to improve the in-plane structural performance of masonry infill walls (Tumialan et al. 2003c). Full-scale specimens were subjected to in-plane cyclic load. The

specimens were surrounded by an RC frame and a stand-alone RC support. The infill walls were built with concrete masonry blocks following a running bond pattern. The dimensions of the infill masonry walls were 8 ft 8 in. long and 8 ft high (2.64 x 2.44 m). The RC frames consisted of columns and a beam with cross sections of 12 x 12 in. (305 x 305 mm). The RC frame was designed to have sufficient ductility and strength; in this way, the behavior of the lateral force-resisting system would be controlled by the infill masonry wall and not by the frame. The results indicated that FRP-strengthened specimens could reach lateral drifts of 0.7% without losing lateral load-carrying capacity.

With the objective to find alternative embedding materials to the epoxy-based paste, Turco et al. (2003) investigated the in-plane behavior of concrete masonry walls strengthened with GFRP bars embedded in two different materials: epoxy-based paste and latex-modified cementitious paste. The in-plane test results showed that the performance of walls with both materials yielded similar results. The use of less expensive pastes, such as the latex-modified ones, makes the FRP structural repointing technique more appealing, as the structural performance is not reduced and the appearance of the filled joints is similar to conventional mortar joints. A study on the shear behavior of walls strengthened with FRP laminates was reported by Gu et al. (2003) confirming the effectiveness of this technique to improve both shear capacity and ductility of tested specimens.

Moon et al. (2003, 2007) tested under lateral loads a full-size two-story URM brick building that was strengthened using several FRP techniques. On one three-wythe wall, GFRP was epoxy-bonded vertically on the inside face, while NSM glass rods were epoxy-bonded into horizontal bed joints on the exterior face. This two-way retrofit increased the lateral strength, caused cracks to be well distributed, and produced a ductile-type failure mode with broad hysteresis loops and considerable energy dissipation. The four FRP systems used in this project included: precured structural thin grids embedded in trowel applied epoxy adhesive; wet layup unidirectional glass fabrics with an epoxy matrix; epoxy adhesive-applied NSM GFRP rods; and finally, glass grids in cementitious trowel-applied matrix. Application of GFRP systems on the other multi-wythe walls worked well in in-plane shear retrofit because header bricks every sixth course generally maintained continuity between wythes. Moon et al. (2006) concluded that the full three-dimensional behavior of the structural system should be considered, including flange effects, to properly design FRP retrofit systems. Each FRP system enhanced the performance of the URM building.

Stratford et al. (2004) reported the results of an experimental campaign on clay bricks and concrete masonry walls externally bonded using GFRP laminates under axial load and shear. The analysis of test results points out significant strength increases provided by the external reinforcement; the experiments have also shown that if proper anchorage is provided to FRP laminates, the wall could also attain a ductile failure mode. The use of CFRP laminates was investigated by To-Nan et al. (2006) on 5.4 x 5.2 ft (1640 x 1570 mm) walls subjected to in-plane cyclic loads; the CFRP laminates have been placed along the wall diagonals. It was pointed out that the presence of the CFRP strengthening provided a more ductile behavior of the strengthened walls compared with the URM wall and increased their energy dissipation capacity.

Marcari et al. (2007) investigated the behavior of tuff masonry panels having dimensions of 5.2 x 4.9 x 1.7 ft (1570 x 1480 x 530 mm) and subjected to shear-compression load. The main objectives were to assess the influence of different types of fibers—for example, CFRP versus GFRP—and FRP layout—for example, cross versus grid layout). The analysis of test results showed the shear strength of the wall panels was considerably improved by FRP laminates. In some cases, the original failure mode changed from shear to a shear/flexural mode; consequently, substantial gains in lateral strength were achieved up to the threshold of the value corresponding to as-built flexural capacity. In cases when such transition did not occur, strength increases proportional to the axial stiffness of the external reinforcement were measured. It was also underlined that the elastic stiffness of FRP-strengthened panels was not substantially modified by the external reinforcement and that the large increases of lateral strength were attained without significantly modifying the inelastic deformation capacity of FRP-strengthened panels. The use of GFRP laminates to improve the seismic behavior of tuff walls was also assessed by means of shake-table tests on a two story structure (Bergamo et al. 2006); shear strengthening by means of diagonal strips and flexural strengthening by means of vertical strips were designed for the tested structure. The results pointed out that the GFRP strengthening improved the seismic performance of the structure by reducing the crack opening related to rocking mechanism and allowing for a more energy dissipating behavior.

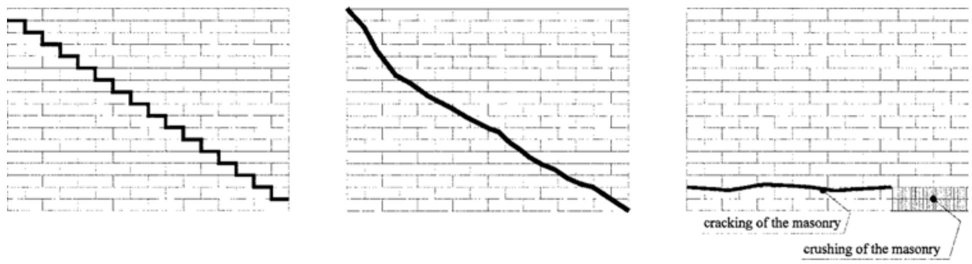
10.2—General considerations

Experimental tests have confirmed the effectiveness of FRP systems to increase the in-plane lateral strength of masonry walls (El-Gawady et al. 2005; Gergely and Young 2001; Marcari et al. 2007; Moon et al. 2007; Shrive 2006; Triantafillou 1998; Zhao et al. 2003). The design lateral strength of FRP-strengthened masonry walls should exceed the required shear strength, computed according to the load factors required by ASCE 7-05.

10.3—Existing wall strength

The behavior of URM walls under in-plane loads depends on several parameters related to geometric properties, including height, thickness, slenderness, and bond pattern; mechanical properties, for example, strength of the masonry units and mortar; and loading and support conditions. In general, the following failure modes can be recognized: joint sliding, diagonal tension, and toe crushing (Fig. 10.1).

Joint sliding and diagonal tension are shear-controlled failure modes. Joint sliding occurs on the bed joints and can develop either along a horizontal plane, generally near or at the wall base, or along a stair-stepped diagonal crack. Sliding does not reduce the axial load capacity of the wall, although the sliding distance should be controlled so that the



(a) Joint sliding *(b) Diagonal tension* *(c) Toe crushing*

Fig. 10.1—Failure modes.

structure does not slide off the foundation. It does, however, reduce the out-of-plane flexural load capacity of the wall. In earthquakes, sliding can be a pseudo-ductile mode, which dissipates considerable energy through friction. Bed-joint sliding is preferred to diagonal tension, as the latter is a brittle failure mode. Diagonal tension is characterized by diagonal cracks that can propagate through both mortar joints and masonry units, depending on their relative strength and on the level of axial stress.

Unlike joint sliding and diagonal tension, toe-crushing is a flexure-controlled failure mode, characterized by the formation of flexural cracks at the heel and crushing of the toe when the compression stresses reach the compressive strength of the masonry. In a steel-reinforced wall, toe crushing is often a ductile failure mode. In a URM structure, toe crushing together with a large axial load plus the increased axial force caused by steel or FRP retrofit can result in loss of vertical load capacity and wall collapse. Under such axial loads, P-Δ effects should be considered as required by ACI 530. For slender walls characterized by large material shear capacity and subjected to small compressive stresses, a rigid body rotation about the toe, that is, rocking, could occur after flexural cracking (FEMA 306). Yet, the overall response of the entire structural system should be considered (Moon et al. 2006). As the toe crushing strength generally exceeds that of the other failure modes, typically rocking does not control the design and, therefore, relevant checks will not be discussed in this guide.

The nominal lateral strength of URM walls should be computed as follows:

$$V_n^{URM} = \min(V_{bjs}, V_{dt}, V_{tc}) \tag{10-1}$$

where V_{bjs} is the nominal lateral strength corresponding to joint sliding, V_{dt} is the nominal lateral strength corresponding to diagonal tension, and V_{tc} is the nominal lateral strength corresponding to toe crushing.

To determine whether FRP strengthening is needed, the existing in-plane strength of the wall should be evaluated first. The design lateral strength should be obtained as the nominal lateral strength multiplied by the strength reduction factor ϕ, equal to 0.8 for shear-controlled failure modes (for example, joint sliding or diagonal tension) or equal to 0.6 for flexure-controlled failure mode (that is, toe crushing) in compliance with the provisions for URM walls specified by ACI 530. The shear and flexural tensile strength of masonry can be obtained by in-place testing following one of the test methods recommended by ASCE 41-06 (Chapter 7). In the absence of test results, the shear and flexural tensile strength can be conservatively estimated using the lower-bound values shown in Table 7-1 of ASCE 41-06, based on the conditions of the masonry and by consulting local building codes, or both. Alternatively, the shear and flexural tensile strength of masonry built after 1960 and proven to be in good condition may be estimated in accordance with ACI 530 provisions for URM if, in the judgment of the licensed design professional, the use of the ACI 530 provisions in place of the lower bound values from Table 7-1 of ASCE 41-06 can be justified.

10.4—Nominal shear strength of FRP-reinforced masonry walls subjected to in-plane loads

The strength design method requires that the shear strength of the FRP-strengthened wall exceeds the factored shear demand as indicated by Eq. (10-2).

$$\phi V_n \geq V_u \tag{10-2}$$

The design strength should be obtained as the nominal strength multiplied by the strength reduction factor ϕ equal to 0.8 as required by ACI 530 for URM walls subject to in-plane shear loads.

Unreinforced masonry walls requiring shear strengthening are those walls whose failure mode is due to either stepped joint sliding or diagonal tension as discussed in Section 10.3. A typical FRP strengthening scheme performed either with wet layup or NSM systems is indicated in Fig. 10.2(a) and (b), respectively. This guide discusses the most commonly used placement layouts of FRP for shear strengthening. Other layouts, including fibers placed diagonally, have been used, but they are not covered in the scope of this guide (Marcari et al. 2007).

Extending the FRP systems a distance ℓ_d (Chapter 11) beyond the wall, as shown in Fig. 10.2, or otherwise anchoring is a good detailing practice but it is not required by the shear design methodology. This is because the design method is based on the assumption that FRP debonding governs the behavior of the FRP-strengthened wall. Bonding the FRP into boundary elements such as beams or columns can help reduce the risk of wall overturning due to out-of-plane excitations. In several situations, however, extension

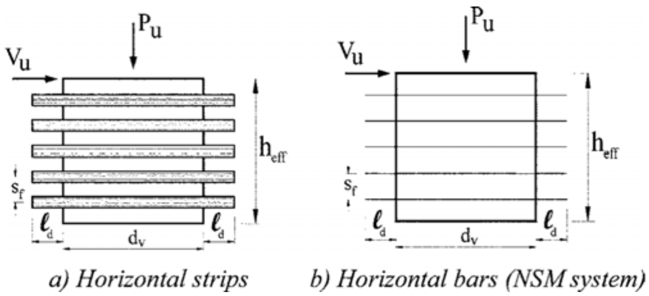


Fig. 10.2—Fiber-reinforced polymer strengthening of shear-controlled walls.

Table 10.1—Limitations for FRP use

Masonry type	Wall construction	FRP strengthening layout
Hollow unit masonry wall	t = 8 in. (200 mm) or less Ungrouted or partially grouted walls with grouted cells spaced greater than 48 in. (1.20 m)	FRP on one face of wall is acceptable
	t = 8 in. (200 mm) or less Fully or partially grouted walls with grouted cells spaced at 48 in. (1.20 m) or less	FRP on two faces of wall is required
	t = 10 to 12 in. (250 to 300 mm) Ungrouted or partially grouted walls with grouted cells spaced greater than 60 in. (1.50 m)	FRP on two faces of wall is required
	t = 10 to 12 in. (250 to 300 mm) Fully or partially grouted walls with grouted cells spaced at 60 in. (1.50 m) or less	Use of FRP is not recommended
	t greater than 12 in. (300 mm) Ungrouted or grouted	Use of FRP is not recommended
Solid unit masonry wall	Single-wythe walls with t = 4 in. (100 mm) or less	FRP on one face of wall is acceptable
	Double-wythe walls with t = 8 in. (200 mm) or less	FRP on two faces of wall is required
	Multi-wythe walls with t > 8 in. (200 mm)	Use of FRP is not recommended

of FRP may not be practical due to existing field conditions. For example, intersecting walls, slabs, or columns with dimensions larger than the wall thickness can preclude extending the FRP beyond the wall. In such cases, other mechanical anchors should be considered.

The in-plane performance of FRP-strengthened walls is highly dependent on the type of masonry construction and the FRP strengthening layout. Experimental investigations have shown that FRP systems can significantly increase the shear capacity of URM walls when the original shear strength of the wall is not large (for example, single-wythe or ungrouted walls). Contrarily, when the shear strength of the URM wall is large (for example, multi-wythe or grouted walls), the contribution of FRP has been observed to be marginal in some situations. Test results also indicate that the FRP layout influences the wall's structural performance. For instance, in thick walls, FRP placed on the two wall sides has been shown to be more effective than FRP placed on one side. In the absence of project specific experimental evidence, this guide recommends FRP strengthening layouts based on the masonry construction as shown in Table 10.1, where the wall thicknesses are given in nominal dimensions.

The nominal shear strength of the FRP-strengthened wall can be computed by adding the FRP contribution V_f (Prota et al. 2008) to the nominal strength of the URM wall, computed according to the provisions given in Section 10.3; V_n^{URM} as

$$V_{n,s} = V_n^{URM} + V_f \tag{10-3}$$

The nominal lateral strength of the FRP-strengthened wall is the minimum of the nominal shear strength given in Eq. (10-3) and the nominal lateral strength corresponding to toe crushing of the URM wall.

The FRP contribution to the shear strength V_f can be determined as

$$V_f = \begin{cases} p_{fv} w_f \dfrac{d_v}{s_f} \text{ for surface-mounted FRP systems} \\ p_{fv} \dfrac{d_v}{s_f} \text{ for NSM FRP systems} \end{cases} \tag{10-4}$$

where p_{fv} is computed according to Eq. (8-14), w_f is the width of the FRP laminates, s_f is the center-to-center spacing between each strip, and d_v is the effective masonry depth for shear calculations given by

$$d_v = \min(H, L) \tag{10-5}$$

10.5—Nominal flexural strength of FRP-reinforced walls subjected to in-plane loads

The strength design method requires that the flexural strength of the FRP-strengthened wall exceeds the factored flexural demand, as indicated by Eq. (10-6)

$$\phi M_n \geq M_u \tag{10-6}$$

The design strength should be obtained as the nominal strength multiplied by the strength reduction factor ϕ equal to 0.6, as required by ACI 530 for URM walls under combination of axial load and bending.

Unreinforced masonry walls requiring flexural strengthening are those walls whose failure mode is due to toe crushing, as discussed in Section 10.3. A typical FRP strengthening scheme is depicted in Fig. 10.3 for a wet layup system. The effectiveness of this scheme as flexural reinforcement is highly dependent on the continuation of the load path by anchoring the wall at its base, which can be achieved either by extending or anchoring the FRP reinforcement or installing steel dowels. Suggested details for load path continuation, as well as requirements for minimum anchorage length ℓ_d, are given in Chapter 11.

Assuming that the factored axial load P_u acts at L/2 (L = length of the wall), the nominal moment capacity M_n of a FRP-strengthened masonry wall subjected to in-plane

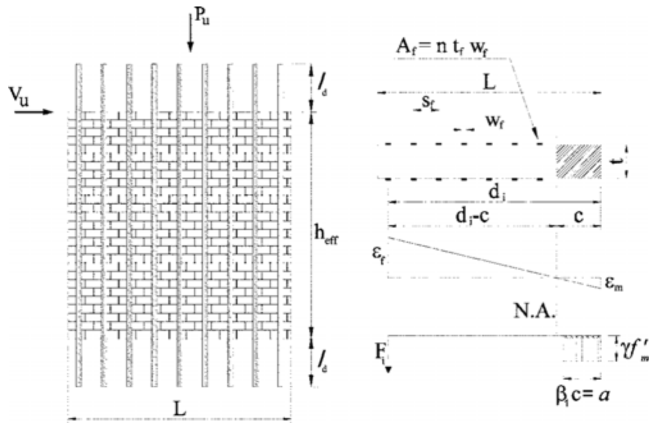


Fig. 10.3—Fiber-reinforced polymer strengthening of flexure-controlled masonry wall.

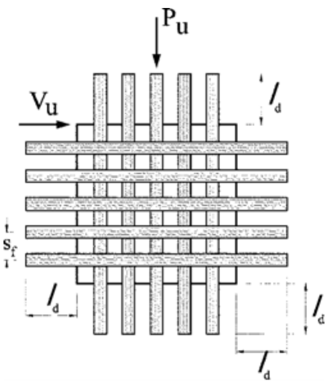


Fig. 10.4—Possible FRP scheme for both shear and flexural strengthening of URM walls.

loading can be calculated from Eq. (10-7) according to the assumptions and provisions given in Section 9.4.

$$M_n = \sum_i F_i\left(d_i - \frac{\beta_1 c}{2}\right) + P_u\left(\frac{L}{2} - \frac{\beta_1 c}{2}\right) \qquad (10\text{-}7)$$

where F_i is the force acting on the i-th FRP strip located at a distance d_i from the extreme compression fiber as indicated in Fig. 10.3. In cases where P_u does not act at $L/2$, Eq. (10-7) should account for the eccentricity of the axial load by inserting an appropriate value instead of $L/2$.

The nominal lateral strength corresponding to flexural failure of the FRP-strengthened wall can be obtained as

$$V_n = \frac{M_n}{k \cdot h_{eff}} \qquad (10\text{-}8)$$

where k is the coefficient that accounts for the boundary condition of the wall, k ($k = 0.5$ and $k = 1.0$ for a fixed-fixed and fixed-free wall, respectively), and h_{eff} is the wall height (Step 9, Section 13.2).

The nominal lateral strength of the FRP-strengthened wall is the minimum of the nominal lateral strength corresponding to flexural failure given in Eq. (10-8) and the nominal lateral strength corresponding to shear failure of the URM wall (that is, minimum between joint sliding and diagonal tension).

Similar considerations and identical procedures may be repeated in case of NSM FRP systems installed on the wall as an alternative to the wet layup system of Fig. 10.3.

10.6—Wall strengthening for shear and flexure

In some cases, the existing situation could require an increase in the lateral strength of the wall with respect to both shear and flexural failure modes. The objective can be achieved according to the principles given in Sections 10.4 and 10.5. A typical FRP scheme that could be used for this purpose is depicted in Fig. 10.4 for a wet layup system. When the URM wall is strengthened for both shear and flexure, the nominal lateral strength of the FRP-strengthened wall is the minimum of the strength corresponding to its shear (Section 10.4) and flexural (Section 10.5) failure. For the former, the nominal shear strength of the FRP-strengthened wall can be computed according to Eq. (10-3) in which the masonry contribution is that provided by ACI 530 for steel reinforced masonry.

Similar considerations may be repeated when NSM FRP systems replace the wet layup system. The installation of NSM systems in two directions, however, may not be practical from a constructibility stand point.

CHAPTER 11—DETAILING

11.1—General requirements

Chapter 11 provides guidance for detailing externally bonded and NSM FRP systems. Detailing will typically depend on the geometry of the structure, the quality of the substrate, and the levels of load that are to be sustained by the FRP system.

References relating to detailing issues presented herein are very limited and care should be taken in detailing and design of anchorages. In many cases, the following recommendations are empirical and should be implemented with caution.

11.2—Fiber-reinforced polymer debonding

11.2.1 *Externally bonded FRP systems*—For FRP systems installed according to Chapter 5, the weak link in the masonry/FRP interface is the masonry. The quality and tensile strength of the substrate will limit the overall effectiveness of the bonded FRP system.

Debonding of a properly installed FRP laminate can result from a lack of bonded area of the FRP laminate to the substrate. The masonry cannot maintain the interfacial shear and normal stresses, and the FRP laminate debonds from the substrate with a relatively thin layer of masonry attached to it.

11.2.2 *NSM FRP systems*—For NSM systems, the minimum dimension of the grooves should be at least $1.5d_b$ (d_b = FRP bar diameter) when an epoxy-based paste is used to embed the bar (De Lorenzis and Nanni 2001; Hassan and Rizkalla 2003). When a rectangular bar with a large aspect ratio is used, the limit may lose significance due to constructibility. In such a case, a minimum groove size of $3.0a_b$ x $1.5b_b$ is suggested, where a_b is the smallest bar dimension.

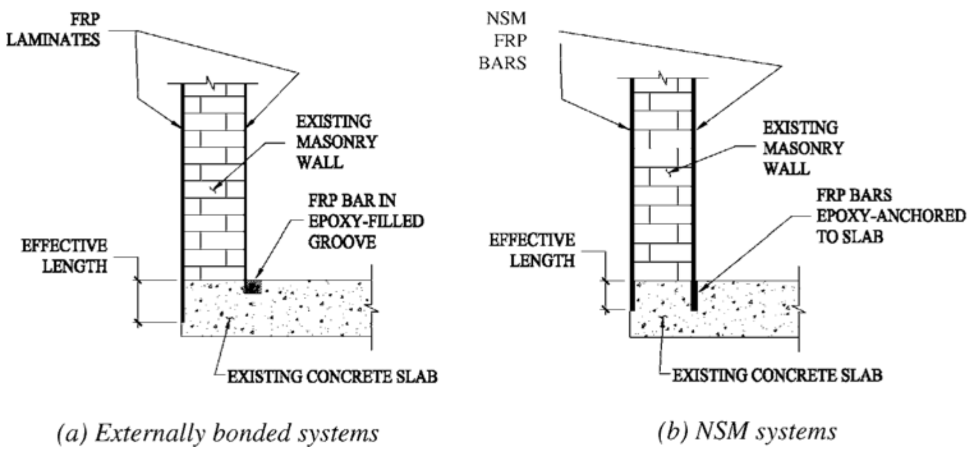


Fig. 11.1—Recommended anchorage details for externally bonded systems.

The minimum clear groove spacing for NSM FRP bars should be greater than twice the depth of the NSM groove to avoid overlapping of the tensile stresses around the NSM bars. Furthermore, a clear edge distance of four times the depth of the NSM groove should be provided to minimize the edge effects, which could accelerate debonding failure (Hassan and Rizkalla 2003). If final appearance of masonry requires cement-based mortar joints, the groove depth may be deeper to accommodate the cement mortar over top the resin paste adhesive. Turco et al. (2003) assessed the use of cementitious grouts to embed FRP bars. They concluded that a square groove with a least dimension of $2.5d_b$ could be adequate. Due to limited experimental data, however, the committee has no recommendation for the groove dimensions for cementitious grouts at this time.

11.2.3 *Development length*—For proper development length, ℓ_d expressed in in. (mm), of externally bonded FRP systems, the Committee recommends using Eq. (11-1) (CNR-DT 200/2004)

$$\ell_d = \begin{cases} \sqrt{\dfrac{E_f t_f}{50 f_{tm}}} & \text{in in.-lb units} \\ \sqrt{\dfrac{E_f t_f}{2 f_{tm}}} & \text{in SI units} \end{cases} \qquad (11\text{-}1)$$

where t_f is the thickness the FRP system and f_{tm} is the average tensile strength of the masonry. Instead of specific data, when f_{tm} is unknown it may be assumed equal to $0.1f'_m$.

The development length of NSM FRP systems should be provided by the manufacturer and substantiated by testing independent of the manufacturer.

11.3—Spacing limits

11.3.1 *Out-of-plane flexural reinforcement*—While the horizontal clear spacing of vertical strips as high as $5.5t$ (for modern clay brick masonry walls) has been shown to be effective (Willis et al. 2009), it is recommended that the maximum clear spacing of externally bonded strips be limited to $3t$ to account for the fact that strengthening is typically performed on existing masonry. For NSM bars, the maximum center-to-center spacing should be limited to $3t$.

11.3.2 *In-plane shear reinforcement*—Based on the reinforcement spacing requirements for reinforced masonry walls subject to in-plane loading (ACI 530), the maximum clear reinforcement spacing for externally bonded strips (or the maximum center-to-center spacing for NSM bars) should be 16 in. (400 mm).

11.4—Anchorages of FRP reinforcement

Termination of the FRP reinforcement in a manner that will minimize the potential for premature debonding is recommended. Some typical termination details are shown in Fig. 10.1. Other termination details may also be possible depending on the configuration of the masonry element being strengthened. It is important to note that the details shown in Fig. 10.1 do not necessarily establish load path continuity between the masonry wall and adjoining concrete element. Additional details are discussed in Section 11.6, which may be used when continuity needs to be established.

11.4.1 *Externally bonded FRP systems*—For external faces (left face, Fig. 11.1(a)) it may be possible to extend the FRP system beyond the edge of the masonry wall by at least the effective length defined in ACI 440.2R using the appropriate concrete compressive strength. When FRP laminates are applied to interior faces (right face, Fig. 11.1(a)) it is recommended that the fabric be wrapped around a circular FRP bar embedded in the boundary element in the near-surface-mounted approach. The dimensions of the square groove should be in accordance with Section 11.2.2 considering the FRP bar diameter and thickness of the FRP sheet. The minimum recommended FRP bar diameter is 0.5 in. (12 mm). When pultruded FRP laminates are used on inside faces, it will not be possible to wrap the ends. In this case, it is recommended that a slot be cut into the boundary element and the FRP inserted as would be the case in the near-surface mounted approach (similar to right face, Fig. 11.1(b)).

Care should be taken to avoid air voids and that the epoxy resin completely fills the groove. Care should also be taken to avoid cutting or otherwise damaging embedded slab

reinforcement that is critical to the performance of the overall structure.

11.4.2 *NSM FRP systems*—For exterior faces (left face, Fig. 11.1(b)) it may be possible to extend the FRP bars beyond the base of the masonry wall by at least the effective length, and groove dimensions, defined in ACI 440.2R using the appropriate concrete compressive strength. Although practically more difficult, the same is recommended for internal faces (right face, Fig. 11.1(b)). Care should be taken to avoid air voids and that the epoxy resin completely fills the groove. Care should also be taken to avoid cutting or otherwise damaging embedded slab reinforcement that is critical to performance of overall structure.

11.5—Alternate forms of anchoring

If adhesively bonded anchorage methods similar to those described in Section 10.4 are not possible, the following alternatives may be considered for externally bonded FRP systems.

11.5.1 *Embedded mechanical anchoring*—It has been shown experimentally that various forms of embedded mechanical anchors, including fiber anchors, are effective in anchoring ends of externally bonded FRP systems. Research, however, is still limited and it is recommended that the performance of any embedded mechanical anchorage system be substantiated through testing.

11.5.2 *External steel anchors*—External steel anchors similar to that illustrated in Fig. 11.2 are minimally invasive and can be used, provided that they do not interfere with external finishes. The width of the external steel anchor should at least be the same as the FRP laminates or the full width of the wall if a continuous FRP laminate is used. The external steel anchor should be bonded to the FRP using an adhesive suitable for FRP-to-steel joints, and should extend beyond the edge of the FRP by at least the anchorage length of the FRP-to-masonry interface defined by Section 12.3. Care should be taken to ensure a good bond between the steel and the FRP system and to prevent the possibility of galvanic corrosion if carbon fibers are used. For external faces (right face, Fig. 11.2) a bent steel shape (for example, plate, angle or channel) may be used and anchored to the concrete boundary with expansion or epoxy anchors. The steel member and anchors should be designed to resist the maximum axial tensile force that can be resisted by the FRP system. For internal faces (left face, Fig. 11.2) a steel angle is required. Prying of the angle due to the forces transferred by the FRP laminates should be taken into consideration when sizing the angle.

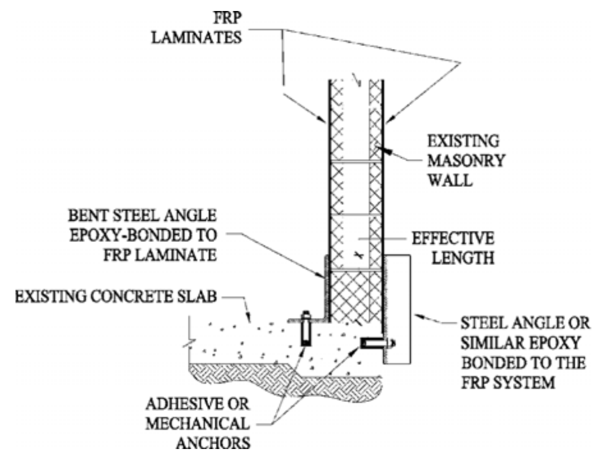


Fig. 11.2—Typical external steel anchor detail.

11.6—Load path continuity

The resistance of a masonry building subject to in-plane loads is defined by the inter-connectivity between the individual structural components. A structurally adequate connection between the different components creates a continuous load path for the loads. In masonry buildings, the load path is achieved by connecting the walls to the roof and floor diaphragms, and to the slabs or foundations. Thereby, load path continuity should be provided when a FRP-strengthened wall will be part of the lateral load-resisting system of a building structure. In addition, the increased loads due to the application of FRP systems may result in other failure mechanisms such as bed-joint sliding or rocking, for the case of in-plane loading, which may not be resisted by FRP systems. In such cases, internal steel bar anchors are an alternative that can be used to provide load path continuity at the wall base. Internal steel bar anchors do require disruption of the masonry wall and grouting of masonry cells, but they can be installed without impacting the exterior dimensions of the wall. These anchors should be located and spaced similarly to the FRP reinforcement and should be designed to provide adequate development length and embedment for the steel bar used.

A variety of wall-to-floor and wall-to-roof details exist. The applicability of each of those details depends on the type of floor or roof structure and the magnitude of the loads. These details may also include the use of screw or bolt connections with angles.

Many other methods outside the scope of this guide can be used to ensure load path continuity. The use of a particular method depends on the application and it should be evaluated on a case-by-case basis.

11.7—Splices

Splices of FRP laminates should be provided only as permitted on drawings or in specifications, or as approved by the licensed design professional, following recommendations from the system manufacturer.

The fibers in FRP systems should be continuous and oriented in a direction that resists the largest tensile forces. Fiber continuity is maintained with a lap splice. For FRP systems, a lap splice should be made by overlapping the fibers along their length. The required overlap, or lap-splice length, depends on the tensile strength and thickness of the FRP system and on the bond strength between adjacent layers of FRP laminates. Sufficient overlap should be provided to promote the failure of the FRP laminate before debonding of the overlapped FRP laminates. The required overlap for a FRP system should be provided by the material manufacturer and substantiated through testing, by an independent testing agency.

For unidirectional FRP laminates, lap splices are required only in the direction of the fibers. Lap splices are not required in the direction transverse to the fibers. Fiber-reinforced polymer laminates consisting of multiple unidirectional sheets oriented in more than one direction or multidirectional fabrics require lap splices in more than one direction to maintain the continuity of the fibers and the overall strength of the FRP system.

CHAPTER 12—DRAWINGS, SPECIFICATIONS, AND SUBMITTALS

12.1—Engineering requirements

In 2009, federal, state, and local codes do not specifically address the structural design of externally bonded FRP systems. Other applicable code requirements, however, may influence the selection, design, and installation of the FRP system. For example, code requirements related to fire or potable water may influence the selection of the coatings used with the FRP system. All design work should be performed under the guidance of a licensed design professional familiar with the properties and applications of FRP systems and applicable building code requirements.

12.2—Drawings and specifications

This guide recommends the licensed design professional document calculations summarizing the assumptions and parameters used to design the FRP strengthening, prepare design drawings, and draft project specifications. The design and installation of the FRP systems requires close coordination between the licensed design professional and FRP system manufacturer. The drawings and specifications should show, at a minimum, the following information specific to externally applied FRP systems:

- Fiber-reinforced polymer system to be used;
- Location of the FRP system relative to the existing structure;
- Dimensions and orientation of each ply, laminate, or NSM bar;
- Number of plies and bars and the sequence of installation;
- Location of splices and lap length;
- General notes listing design loads and strains in the FRP systems;
- Material properties of the FRP systems and masonry substrate;
- Masonry surface preparation requirements, including groove dimensions for NSM bars, and maximum irregularity limitations;
- Installation procedures, including surface temperature and moisture limitations, and application time limits between successive installation procedures for the FRP materials such as plies for laminates;
- Curing procedures of FRP systems;
- Protective coatings and sealants if required;
- Shipping, storage, handling, and shelf-life guidelines; and
- Quality control and inspection procedures, including acceptance criteria.

12.3—Submittals

Specifications should require the FRP system manufacturer; installation contractor; inspection agency, if required; and all those involved with the project to submit product information and evidence of their qualifications and experience to the licensed design professional for review.

12.3.1 *Fiber-reinforced polymer system manufacturer*—Submittals required of the FRP system manufacturer should include:

- Product data sheets indicating the physical, mechanical, and chemical characteristics of the FRP system and all its constituent materials;
- Tensile properties of the FRP system including the method of reporting properties (net fiber or gross laminate), test methods used, and the statistical basis used for determining the properties;
- Installation instructions, maintenance instructions, and general recommendations regarding each material to be used. Installation procedures should include surface preparation requirements;
- Manufacturer's Material Safety Data Sheets (MSDS) for all materials to be used; and
- Quality-control procedure for tracking FRP materials and material certifications.

12.3.2 *Fiber-reinforced polymer system installation contractor*—Submittals required from the FRP system installation contractor include:

- Documentation from the FRP system manufacturer of having been trained to install the proposed FRP system or project references;
- Evidence of competency in surface preparation techniques; and
- Quality-control procedures including the daily log or inspection forms used by the contractor.

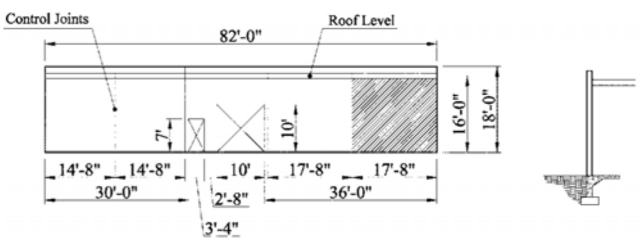
12.3.3 *Fiber-reinforced polymer system inspection agency*—If an independent inspection agency is used, submittals required of that agency should include:

- A list of inspectors to be used on the project and their qualifications;
- Sample inspection forms; and
- A list of previous projects inspected by the inspector or proof of training.

CHAPTER 13—DESIGN EXAMPLES

13.1—Increasing the flexural capacity of a wall subjected to out-of-plane loads

An existing warehouse has a roof built with steel open web joists and beams supported by steel interior columns and load-bearing masonry walls along the building perimeter. An elevation view of the shorter direction of the building is shown in Fig. 13.1. Determine the out-of-plane flexural strength of the wall panel shown shaded in Fig. 13.1(a) and design the required GFRP strengthening system to resist the applied loads.



(a) Elevation view *(b) Section*

Fig. 13.1—Schematic of the masonry wall (1 in. = 25.4 mm).

The ungrouted masonry wall has a 12 in. (300 mm) nominal thickness as shown in Fig. 13.2(a); a Type N mortar was used during the construction. Factored shear and bending moment diagrams are depicted in Fig. 13.2(b). The applied factored axial load is P_u = 576 lb/ft (8406 N/m).

Table 13.1 summarizes the masonry geometrical and mechanical properties while Table 13.2 shows the FRP mechanical properties as reported by the manufacturer.

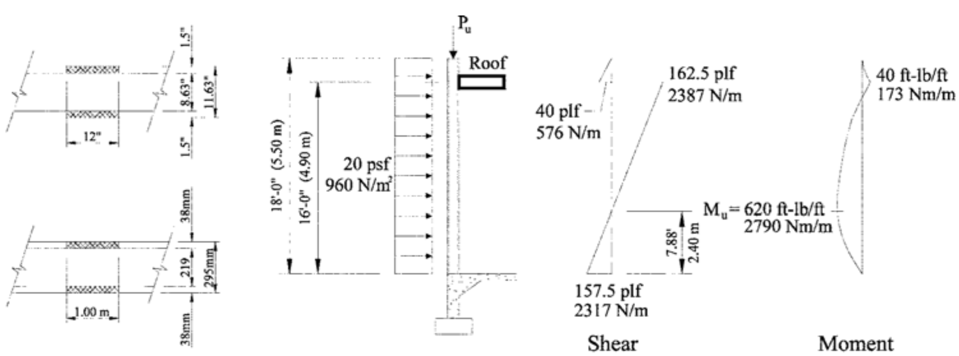
The values stated in either in-lb or SI units are to be regarded separately. The values stated in each system are not exact equivalents; therefore, each system should be used independently.

Table 13.1—Masonry geometrical and mechanical properties

Height of the wall H	18 ft	5.50 m
Wall thickness t	11.63 in.	295 mm
Section area A_n	36 in.^{2}/ft	76,000 mm^2/m
$I/(t/2)$, S	160 in.^{3}/ft	8.570×10^6 mm^3/m
Masonry compressive strength f'_m	1500 psi	10 MPa
Masonry compressive strain ε_{mu}	0.0025	0.0025

Table 13.2—Manufacturer's reported FRP system properties

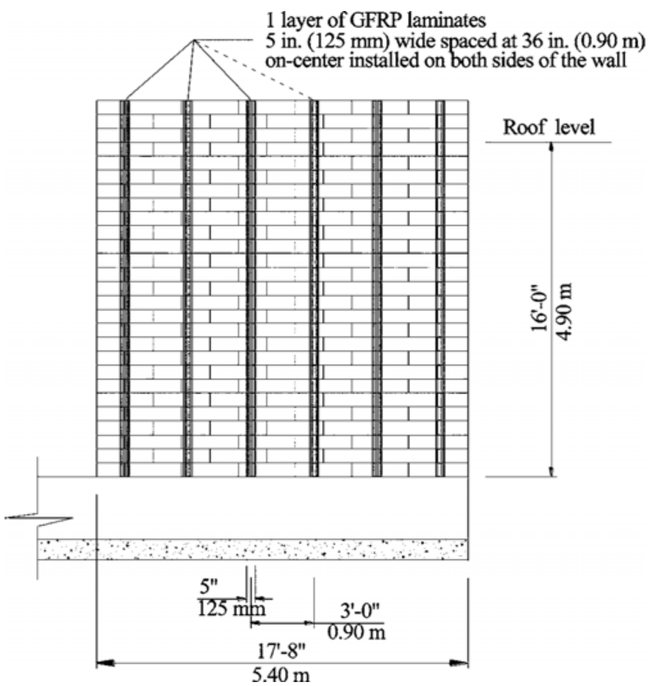
Reinforcement type	f_{fu}^*, ksi (MPa)	E_f, ksi (MPa)	ε_{fu}^*	Thickness t_f, in. (mm)	Area $A_{f,bar}$, in.^{2} (mm^2)
GFRP laminate	220 (1517)	10,500 (72,000)	0.021	0.014 (0.356)	—
GFRP bar	120 (827)	5920 (41,000)	0.02	—	0.05 (32)



(a) Wall thickness *(b) Shear and bending moment diagrams*

Fig. 13.2—Wall thickness and external loading.

PROCEDURE	CALCULATION IN in.-lb
STEP 1: Compute the as-built tensile strength f_b.	
Determine f_r from Table 7.1 of ASCE 41 (in general, f_r can be determined according to ASCE 41 and/or the applicable local building code)	f_r = 20 psi
Assume $\phi = 0.6$	$\phi f_r = 0.6 \times 20$ psi = 12 psi
Compute $f_b = \frac{M_u}{S} - \frac{P_u}{A_n}$	$f_b = \frac{12 \text{ in./ft} \times 620 \text{ ft-lb/ft}}{160 \text{ in.}^3\text{/ft}} - \frac{576 \text{ lb/ft}}{36 \text{ in.}^2\text{/ft}} = 30.5 \text{ psi} > \phi f_r$ The masonry wall cannot sustain the applied load and needs to be strengthened. The selected strengthening system is the GFRP laminate shown in Table 13.2.
STEP 2: Compute the nominal flexural strength M_n.	
The required nominal flexural strength is calculated as follows $M_n = \frac{M_u}{\phi}$	$M_n = \frac{12 \text{ in./ft} \times 620 \text{ ft-lb/ft}}{0.6} = 12{,}400$ in.-lb/ft
STEP 3: Compute the design mechanical properties of the FRP system.	
Assuming an environmental reduction factor C_E equal to 0.65, the FRP design tensile strength and strain can be determined from Eq. (8-3) and (8-4) $f_{fu} = C_E f_{fu}^*$ $\varepsilon_{fu} = C_E \varepsilon_{fu}^*$	$f_{fu} = 0.65 \times 220{,}000$ psi = 143,000 psi $\varepsilon_{fu} = 0.65 \times 0.021 = 0.01365$
The bond reduction factor for flexure-controlled failure mode applicable to FRP laminates is assumed, from Eq. (8-8), equal to $\kappa_\mu = 0.45$. Therefore $f_{fe} = \kappa_m f_{fu}^* \leq C_E f_{fu}^*$ $\varepsilon_{fe} = \kappa_m \varepsilon_{fu}^* \leq C_E \varepsilon_{fu}^*$	$f_{fe} = 0.45 \times 220{,}000$ psi = 99,000 psi < 143,000 psi $\varepsilon_{fe} = 0.45 \times 0.021 = 0.00945 < 0.01365$
STEP 4: Determine the area of FRP reinforcement required.	
An assumption has to be made regarding the failure mode. As shown in Section 9.4.1, the failure mode can be caused by crushing of the masonry or debonding of the FRP system. Assume that the failure mode is controlled by debonding of the FRP system (such an assumption is later verified in Step 5). Assuming the stress block parameters $\gamma = \beta_1 = 0.7$ as suggested in Section 9.4.4, the two equilibrium equations can be written as follows: $\gamma \cdot f'_m \cdot \beta_1 \cdot c \cdot b - P_u = A_f \cdot f_{fe}$ $M_n = A_f \cdot f_{fe} \cdot t/2 + \gamma \cdot f'_m \cdot \beta_1 \cdot c \cdot b(t/2 - \beta_1 \cdot c/2)$ Replacing A_f obtained from the first equation $A_f = \frac{\gamma \cdot f'_m \cdot \beta_1 \cdot c \cdot b - P_u}{f_{fe}}$ (a) into the second equation, the following second-order equation in the unknown c (neutral axis position) can be found $\alpha \cdot c^2 + \beta \cdot c + \delta = 0$	
where $\alpha = (1/2)\gamma \cdot f'_m \cdot \beta_1^2 \cdot b$ $\beta = -\gamma \cdot f'_m + \beta_1 \cdot b \cdot t$ $\delta = M_n + (1/2)P_u \cdot t$	$\alpha = (1/2)(0.7)(1500 \text{ psi})(0.7)^2(12 \text{ in.}) = 3087$ lb/in. $\beta = -(0.7)(1500 \text{ psi})(0.7)(12 \text{ in.})(11.63 \text{ in.}) = -102{,}576.6$ lb $\delta = 12{,}400 \text{ in.-lb} + (1/2)(576 \text{ lb})(11.63 \text{ in.}) = 15{,}749.4$ in.-lb
The neutral axis dept c can then be found by taking the only solution with physical meaning as follows $c = \frac{-\beta - \sqrt{\beta^2 - 4\alpha\delta}}{2\alpha}$	$c = \frac{102{,}576.6 \text{ lb} - \sqrt{(-102{,}576.6 \text{ lb})^2 - 4(3087 \text{ lb/in.})(15{,}749.4 \text{ in.-lb})}}{2(3087 \text{ lb/in.})} = 0.15$ in.
The area of FRP reinforcement required can finally be computed by replacing c into Eq. (a).	$A_{f,required} = \frac{(0.7)(1500 \text{ psi})(0.7)(0.15 \text{ in.})(12 \text{ in.}) - (576 \text{ lb})}{99{,}000 \text{ psi}} = 0.0078 \text{ in.}^2\text{/ft}$

PROCEDURE	CALCULATION IN in.-lb
STEP 5: Failure mode.	
As we assumed that the failure mode was governed by debonding of the FRP system, we should now verify that the compressive strain in the masonry, ε_m, does not exceed, ε_{mu}, as indicated by Eq. (9-3) rewritten as follows $\varepsilon_m = \varepsilon_{fe}\left(\frac{c}{t-c}\right) \le \varepsilon_{mu}$ In the previous equation we neglected the initial strain in the masonry due to the applied loads before strengthening.	$\varepsilon_m = (0.00945)\left(\frac{0.15\text{ in.}}{11.63\text{ in.} - 0.15\text{ in.}}\right) = 0.00012 << \varepsilon_{mu} = 0.0025$ Fiber-reinforced polymer debonding is confirmed to be the governing failure mode.
STEP 6: Compute the area of FRP reinforcement to be installed.	
The width of the FRP reinforcement required can be determined as $w_{f,required} = \frac{A_{f,required}}{t_f}$  *Fig. 13.3—Fiber-reinforced polymer reinforcement layout for out-of-plane loads.*	$w_{f,required} = \frac{0.0078\text{ in.}^2\text{/ft}}{0.014\text{ in.}} = 0.56\text{ in./ft}$ Place one layer of a 5 in. wide GFRP laminate spaced at 36 in. on center (Fig. 13.3). $A_{f,installed} = \frac{12\text{ in./ft}}{36\text{ in.}}(5\text{ in.})(0.014\text{ in.}) = 0.023\text{ in.}^2\text{/ft} > A_{f,required}$
STEP 7: Maximum spacing requirement.	
For externally bonded FRP systems, the maximum spacing between FRP laminates should meet the requirement of Section 11.3.1 translated into the following equation $s_{f,max} < 3t + w_f$	$s_{f,max} < 3(11.63\text{ in.}) + 5\text{ in.} = 40\text{ in.}$ The maximum spacing requirement is satisfied.
STEP 8: Check the maximum force in the FRP system.	
According to Section 8.4.1, the maximum force per unit width in the FRP reinforcement should meet the requirement of Eq. (8-9) $p_{fm} = n \cdot t_f \cdot f_{fe} < 1500\text{ lb/in.}$	$p_{fm} = (1)(0.014\text{ in.})(99{,}000\text{ psi}) = 1386\text{ lb/in.} < 1500\text{ lb./in.}$ The maximum force per unit width requirement is satisfied.

PROCEDURE	CALCULATION IN in.-lb
STEP 9: Check the out-of-plane shear strength of the existing wall.	
The out-of-plane design shear strength ϕV_n of the existing masonry wall is calculated according to ACI 530 as $\phi V_n = \phi \cdot \min\begin{cases} 3.8A_n\sqrt{f'_m} \\ 300A_n \\ 56A_n + 0.45P_u \end{cases}$ larger than the factored shear force V_u equal to 162.5 lb/ft as indicated in Fig. 13.2(b).	$\phi V_n = (0.8)\cdot\min\begin{cases} 3.8\cdot(12\text{ in.}\times 2\times 1.5\text{ in.})\sqrt{1500\text{ psi}} = 5298\text{ lb/ft} \\ 300\cdot(12\text{ in.}\times 2\times 1.5\text{ in.}) = 10{,}800\text{ lb/ft} \\ 56\cdot(12\text{ in.}\times 2\times 1.5\text{ in.}) + 0.45\cdot 576\text{ lb/ft} = 2275\text{ lb/ft} \end{cases}$ $\phi V_n = 1820$ lb/ft $\phi V_n > V_u$ OK
STEP 10: Determine the development length to anchor the FRP system.	
The appropriate development length is calculated according to Eq. (11-1) as follows $\ell_d = \sqrt{\frac{E_f t_f}{50 f_{tm}}}$ On the exterior face of the wall, the FRP system is installed as indicated in Fig. 13.3. On the interior side, the FRP system is anchored as indicated in Fig. 11.2 using a steel angle epoxy bonded to the FRP laminate.	$\ell_d = \sqrt{\frac{(10{,}500{,}000\text{ psi})(0.014\text{ in.})}{50(0.1\times 1500\text{ psi})}} = 4.42$ in., assume 5 in.

PROCEDURE	CALCULATION IN SI UNITS
STEP 1: Compute the as-built tensile strength f_b.	
Determine f_r from Table 7.1 of ASCE 41 (in general, f_r can be determined according to ASCE 41 and/or the applicable local building code) Assume $\phi = 0.6$ Compute $f_b = \frac{M_u}{S} - \frac{P_u}{A_n}$	$f_r = 0.14$ MPa $\phi f_r = 0.6 \times 0.14 \text{ MPa} = 0.084 \text{ MPa}$ $f_b = \frac{2{,}790{,}000 \text{ N·mm/m}}{8.570 \times 10^6 \text{ mm}^3\text{/m}} - \frac{8406 \text{ N/m}}{76{,}000 \text{ mm}^2\text{/m}} = 0.215 \text{ MPa} > \phi f_r$ The masonry wall cannot sustain the applied load and needs to be strengthened. The selected strengthening system is the GFRP laminate shown in Table 13.2.
STEP 2: Compute the nominal flexural strength M_n.	
The required nominal flexural strength is calculated as follows $M_n = \frac{M_u}{\phi}$	$M_n = \frac{2790 \text{ Nm/m}}{0.60} = 4650 \text{ Nm/m}$
STEP 3: Compute the design mechanical properties of the FRP system.	
Assuming an environmental reduction factor C_E equal to 0.65, the FRP design tensile strength and strain can be determined from Eq. (8-3) and (8-4) $f_{fu} = C_E f_{fu}^*$ $\varepsilon_{fu} = C_E \varepsilon_{fu}^*$ The bond reduction factor for flexure-controlled failure mode applicable to FRP laminates is assumed, from Eq. (8-8), equal to $\kappa_\mu = 0.45$. Therefore $f_{fe} = \kappa_m f_{fu}^* \leq C_E f_{fu}^*$ $\varepsilon_{fe} = \kappa_m \varepsilon_{fu}^* \leq C_E \varepsilon_{fu}^*$	$f_{fu} = 0.65 \times 1517 \text{ MPa} = 986 \text{ MPa}$ $\varepsilon_{fu} = 0.65 \times 0.021 = 0.01365$ $f_{fe} = 0.45 \times 1517 \text{ MPa} = 683 \text{ MPa} < 986 \text{ MPa}$ $\varepsilon_{fe} = 0.45 \times 0.021 = 0.00945 < 0.001365$
STEP 4: Determine the area of FRP reinforcement required.	
An assumption has to be made regarding the failure mode. As shown in Section 9.4.1, the failure mode can be caused by crushing of the masonry or debonding of the FRP system. Assume that the failure mode is controlled by debonding of the FRP system (such an assumption is later verified in Step 5). Assuming the stress block parameters $\gamma = \beta_1 = 0.7$ as suggested in Section 9.4.4, the two equilibrium equations can be written as follows: $\gamma \cdot f'_m \cdot \beta_1 \cdot c \cdot b - P_u = A_f \cdot f_{fe}$ $M_n = A_f \cdot f_{fe} \cdot t/2 + \gamma \cdot f'_m \beta_1 \cdot c \cdot b(t/2 - \beta_1 \cdot c/2)$ Replacing A_f obtained from the first equation $A_f = \frac{\gamma \cdot f'_m \cdot \beta_1 \cdot c \cdot b - P_u}{f_{fe}}$ (a) into the second equation, the following second-order equation in the unknown c (neutral axis position) can be found: $\alpha \cdot c^2 + \beta \cdot c + \delta = 0$ where $\alpha = (1/2)\gamma \cdot f'_m \cdot \beta_1^2 \cdot b$ $\beta = -\gamma \cdot f'_m + \beta_1 \cdot b \cdot t$ $\delta = M_n + (1/2)P_u \cdot t$ The neutral axis dept c can then be found by taking the only solution with physical meaning as follows $c = \frac{-\beta - \sqrt{\beta^2 - 4\alpha\delta}}{2\alpha}$ The area of FRP reinforcement required can finally be computed by replacing c into Eq. (a).	$\alpha = (1/2)(0.7)(10 \text{ MPa})(0.7)^2(1000 \text{ mm}) = 1715 \text{ N/mm}$ $\beta = -(0.7)(10 \text{ MPa})(0.7)(1000 \text{ mm})(295 \text{ mm}) = -1{,}445{,}500 \text{ N}$ $\delta = 4{,}650{,}000 \text{ N·mm} + (1/2)(8406 \text{ N})(295 \text{ mm}) = 5{,}889{,}885 \text{ N·mm}$ $c = \frac{1{,}445{,}500 \text{ N} - \sqrt{(-1{,}445{,}500 \text{ N})^2 - 4(1715 \text{ N/mm})(5{,}889{,}885 \text{ N·mm})}}{2(1715 \text{ N/mm})} = 4$ mm $A_{f,required} = \frac{(0.7)(10 \text{ MPa})(0.7)(4 \text{ mm})(1000 \text{ mm}) - (8406 \text{ N})}{683 \text{ MPa}} = 16 \text{ mm}^2\text{/mm}$

<table>
<tr><th>PROCEDURE</th><th>CALCULATION IN SI UNITS</th></tr>
<tr><td colspan="2">STEP 5: Failure mode.</td></tr>
<tr><td>As we assumed that the failure mode was governed by debonding of the FRP system, we should now verify that the compressive strain in the masonry, ε_m, does not exceed ε_{mu} as indicated by Eq. (9-3) rewritten as follows

$\varepsilon_m = \varepsilon_{fe}\left(\frac{c}{t-c}\right) \le \varepsilon_{mu}$

In the previous equation we neglected the initial strain in the masonry due to the applied loads before strengthening.</td><td>$\varepsilon_m = (0.00945)\left(\frac{4\ \text{mm}}{295\ \text{mm} - 4\ \text{mm}}\right) = 0.00012 << \varepsilon_{mu} = 0.0025$

Fiber-reinforced polymer debonding is confirmed to be the governing failure mode.</td></tr>
<tr><td colspan="2">STEP 6: Compute the area of FRP reinforcement to be installed.</td></tr>
<tr><td>The width of the FRP reinforcement required can be determined as

$w_{f,required} = \frac{A_{f,required}}{t_f}$

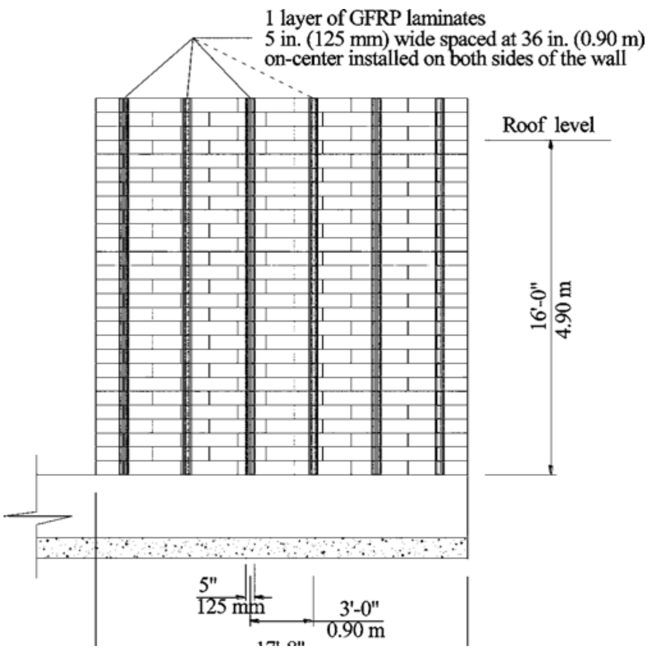


Fig. 13.3—Fiber-reinforced polymer reinforcement layout for out-of-plane loads.</td><td>$w_{f,required} = \frac{16\ \text{mm}^2/\text{mm}}{0.356\ \text{mm}} = 45\ \text{mm/m}$

Place one layer of a 125 mm wide GFRP laminate spaced at 900 mm on center (Fig. 13.3).

$A_{f,installed} = \frac{1000\ \text{mm/m}}{900\ \text{mm}}(125\ \text{mm})(0.356\ \text{mm}) = 49\ \text{mm}^2/\text{m} > A_{f,required}$</td></tr>
<tr><td colspan="2">STEP 7: Maximum spacing requirement.</td></tr>
<tr><td>For externally bonded FRP systems, the maximum spacing between FRP laminates should meet the requirement of Section 11.3.1 translated into the following equation

$s_{f,max} < 3t + w_f$</td><td>$s_{f,max} < 3(295\ \text{mm}) + 125\ \text{mm} = 1010\ \text{mm}$

The maximum spacing requirement is satisfied.</td></tr>
<tr><td colspan="2">STEP 8: Check the maximum force in the FRP system.</td></tr>
<tr><td>According to Section 8.4.1, the maximum force per unit width in the FRP reinforcement should meet the requirement of Eq. (8-9)

$p_{fm} = n \cdot t_f \cdot f_{fe} < 1500$ lb/in.</td><td>$p_{fm} = (1)(0.356\ \text{mm})(683\ \text{MPa}) = 243\ \text{N/mm} < 260\ \text{N/mm}$

The maximum force per unit width requirement is satisfied.</td></tr>
</table>

PROCEDURE	CALCULATION IN SI UNITS
STEP 9: Check the out-of-plane shear strength of the existing wall.	
The out-of-plane design shear strength ϕV_n of the existing masonry wall is calculated according to ACI 530 as $\phi V_n = \phi \cdot \min\begin{cases} 0.3A_n\sqrt{f'_m} \\ 2A_n \\ 0.4A_n + 0.45P_u \end{cases}$ larger than the factored shear force V_u equal to 2387 N/m as indicated in Fig. 13.2(b).	$\phi V_n = (0.8) \cdot \min\begin{cases} 0.3 \cdot (76{,}000\text{ mm}^2/\text{m})\sqrt{10\text{ MPa}} = 72{,}100\text{ N/m} \\ 2 \cdot (76{,}000\text{ mm}^2/\text{m}) = 152{,}000\text{ N/m} \\ 0.4 \cdot (76{,}000\text{ mm}^2/\text{m}) + 0.15 \cdot 8406\text{ N/m} = 31{,}661\text{ N/m} \end{cases}$ $\phi V_n = 25{,}329$ N/m $\phi V_n > V_u$ OK
STEP 10: Determine the development length to anchor the FRP system.	
The appropriate development length is calculated according to Eq. (11-1) as follows $\ell_d = \sqrt{\frac{E_f t_f}{50 f_{tm}}}$ On the exterior face of the wall, the FRP system is installed as indicated in Fig. 13.3. On the interior side, the FRP system is anchored as indicated in Fig. 11.2 using a steel angle epoxy bonded to the FRP laminate.	$\ell_d = \sqrt{\frac{(41{,}000\text{ MPa})(0.356\text{ mm})}{2(0.1 \times 10\text{ MPa})}} = 85$ mm, assume 120 mm

The 12 in. (300 mm) UMR wall can be strengthened to support a 620 ft-lb/ft (2790 Nm/m) moment by bonding nine 5 in. (125 mm) wide GFRP laminates at 3 ft (0.90 m) on centers (Fig. 13.3). Each strip extends 18 ft (5.50 m) to the roof level. The first of the nine strips is placed 16 in. (400 mm) from the end of the 17 ft 8 in. (5.40 m) wide wall. They should be bonded to both wall surfaces to account for load reversal under seismic loading.

13.2—Increasing the lateral capacity of a wall subjected to in-plane loads

The same warehouse analyzed in the previous example is subjected to a factored lateral in-plane force equal to V_u = 20 kip (90 kN) acting at the level of the roof H_{roof} = [16 in. – 0 in. (4.90 m)], as indicated in Fig. 13.1(a). Design the shear strengthening using the reinforcement type indicated as GFRP bars in Table 13.2 of Section 13.1 for the wall panel shown shaded in Fig. 13.1(a). Additional information is provided in Table 13.3. Figure 13.4 shows the strengthening systems used to enhance the wall capacity for in-plane and out-of-plane (Section 13.1) loads.

The values stated in either in.-lb or SI units are to be regarded separately. The values stated in each system are not exact equivalents; therefore, each system should be used independently of the other.

Table 13.3—Additional masonry mechanical and geometrical properties and loading information

Lower-bound masonry shear strength, v_{tl}	15 psi	0.10 MPa
Superimposed dead load, P_D	280 lb/ft	4000 N/m
Factor accounting for boundary conditions, α	1.00	1.00
Lower-bound axial compressive force due to gravity load, Q_G	400 lb/ft	5800 N/m
Spacing of every other course of masonry unit where the NSM FRP reinforcement is to be installed, s	16 in.	400 mm

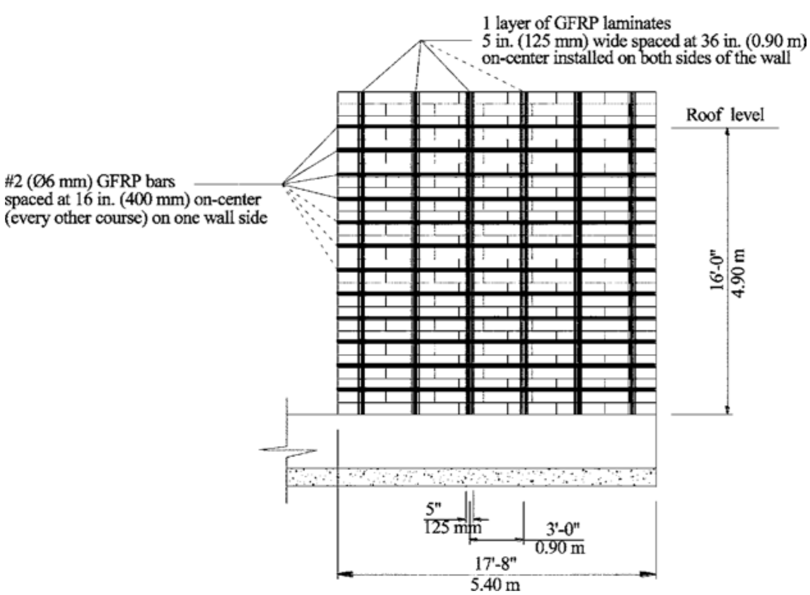


Fig. 13.4—Schematic of the strengthened wall for in-plane loads.

PROCEDURE	CALCULATION IN in.-lb
STEP 1: Compute the shear capacity due to bed-joint sliding, V_{bjs}.	
The nominal shear capacity of the unreinforced masonry wall for bed-joint sliding is found according to the provisions of ASCE 41 as follows $V_{bjs} = v_{mL}A_n$ where $v_{mL} = 0.75\dfrac{0.75v_{tL} + \dfrac{P_D}{A_n}}{1.5}$ In general, the nominal shear capacity of the URM wall for bed-joint sliding can be determined according to ASCE 41 and/or the applicable local building code.	V_{bjs} = (9.5 psi)(636 in.^{2}) = 6042 lb $v_{mL} = 0.75\dfrac{0.75(15\text{ psi}) + \dfrac{280\text{ lb/ft} \times 17.7\text{ ft}}{2(1.5\text{ in.} \times 212\text{ in.})}}{1.5} = 9.5\text{ psi}$
STEP 2: Compute the shear capacity due to diagonal tension, V_{dt}.	
The nominal shear capacity of the URM wall for diagonal tension is found according to the provisions of FEMA 356 as follows $V_{dt} = f'_{dt} \cdot A_n\left(\dfrac{L}{h_{eff}}\right)\sqrt{1 + \dfrac{f_a}{f'_{dt}}}$ where f'_{dt} may be replaced by v_{mL} calculated in the previous step; L is length of the wall assumed equal to 17 ft 8 in. (Fig. 13.1(a)); h_{eff} is the height to resultant of lateral force equal to 16 ft 0 in. (Fig. 13.1(a)); and f_a represents the axial compressive stress due to gravity load, computed as $f_a = \dfrac{P_D}{A_n}$	$V_{dt} = (9.5\text{ psi})(636\text{ in.}^2)\left(\dfrac{17.7\text{ ft}}{16\text{ ft}}\right)\sqrt{1 + \dfrac{7.8\text{ psi}}{9.5\text{ psi}}} = 9020\text{ lb}$ $f_a = \dfrac{280\text{ lb/ft} \times 17.7\text{ ft}}{636\text{ in.}^2} = 7.8\text{ psi}$
STEP 3: Compute the shear capacity due to toe crushing, V_{tc}.	
The nominal shear capacity of the URM wall for toe crushing is found according to the provisions of ASCE 41 as follows $V_{tc} = \alpha \cdot Q_G\left(\dfrac{L}{h_{eff}}\right)\left(1 - \dfrac{f_a}{0.7f'_m}\right)$ where L and h_{eff} are as defined in the previous step, and f_a is calculated as follows $f_a = \dfrac{Q_G}{A_n}$ In general, the nominal shear capacity of the URM wall for toe crushing can be determined according to ASCE 41 and/or the applicable local building code.	$V_{tc} = (1.00)(7080\text{ lb})\left(\dfrac{17.7\text{ ft}}{16\text{ ft}}\right)\left(1 - \dfrac{11.1\text{ psi}}{0.7 \times 1500\text{ psi}}\right) = 7749\text{ lb}$ $f_a = \dfrac{400\text{ lb/ft} \times 17.7\text{ ft}}{636\text{ in.}^2} = 11.1\text{ psi}$
STEP 4: Compute the as-built shear capacity, ϕV_n^{URM}.	
As indicated in Section 10.3, the nominal shear capacity or nominal lateral strength of the URM wall V_n^{URM} is obtained as the minimum of Eq. (10-1) $V_n^{URM} = \min(V_{bjs}, V_{dt}, V_{tc})$ Assuming ϕ = 0.8, the design lateral strength can be computed as ϕV_n^{URM}.	V_n^{URM} = min(6042 lb, 9020 lb, 7749 lb) = 6042 lb ϕV_n^{URM} = 0.8(6042 lb) = 4834 lb As $\phi V_n^{URM} < V_u$, the wall needs strengthening for in-plane loads
STEP 5: Compute the design mechanical properties of the NSM FRP system.	
Assuming an environmental reduction factor C_E equal to 0.65, the FRP design tensile strength and strain can be determined from Eq. (8-3) and (8-4) $f_{fu} = C_E f_{fu}^*$ $\varepsilon_{fu} = C_E \varepsilon_{fu}^*$	f_{fu} = (0.65)(120,000 psi) = 78,000 psi ε_{fu} = (0.65)(0.02) = 0.013

PROCEDURE	CALCULATION IN in.-lb
STEP 6: Compute the effective strain and stress for shear-controlled failure mode.	
To determine the effective strain in the FRP reinforcement, compute the area of FRP reinforcement as follows $A_f = \frac{H_{roof}}{s}A_{f,bar}$	$A_f = \frac{12\text{ in./ft} \times 16\text{ ft}}{16\text{ in.}}0.05\text{ in.}^2 = 0.6\text{ in.}^2$
The value of ω_f is defined in Eq. (8-12) $\omega_f = \frac{1}{1000}\frac{A_f E_f}{A_n\sqrt{f'_m}}$	$\omega_f = \frac{1}{1000}\frac{(0.6\text{ in.}^2)(5{,}920{,}00\text{ psi})}{(636\text{ in.}^2)\sqrt{1500\text{ psi}}} = 0.144$
According to Section 8.4.2, the effective strain and stress in the FRP reinforcement can be found from Eq. (8-10) and (8-11) as a function of κ_v (Eq. (8-13)) $\kappa_v = \begin{cases} 0.40 & \text{for } \omega_f \leq 0.20 \\ 0.64 - 1.2\omega_f & \text{for } 0.20 < \omega_f \leq 0.45 \\ 0.10 & \text{for } \omega_f > 0.45 \end{cases}$	$\kappa_v = 0.40$
$\varepsilon_{fe} = \kappa_v\varepsilon_{fu}^* \leq C_E\varepsilon_{fu}^*$ $f_{fe} = E_f\varepsilon_{fe}$	$\varepsilon_{fe} = (0.40)(0.02) = 0.008 < 0.013$ $f_{fe} = (5{,}920{,}000\text{ psi})(0.008) = 47{,}360\text{ psi}$
STEP 7: Compute the FRP contribution to the shear strength, V_f.	
The total force per bar that the FRP system can transfer to the masonry substrate is given by Eq. (8-14) as follows: $p_{fv} = A_{f,bar}f_{fe} \leq 10{,}000$ lb/bar	$p_{fv} = (0.05\text{ in.}^2)(47{,}360\text{ psi}) = 2368\text{ lb/bar} < 10{,}000\text{ lb/bar}$
The NSM FRP contribution to the shear strength can be determined from Eq. (10-4) as follows $V_f = p_{fv}\frac{d_v}{s_f}$	$V_f = (2368\text{ lb})\frac{212\text{ in.}}{16\text{ in.}} = 31{,}376\text{ lb}$
where $d_v = \min(H, L)$; and s_f represents the spacing of the NSM FRP reinforcement equal to the spacing of every other course of masonry unit, s.	$d_v = \min(18\text{ ft}, 17\text{ ft } 8\text{ in.}) = 17\text{ ft } 8\text{ in.}$
STEP 8: Compute the nominal shear strength of the FRP-strengthened wall.	
According to Eq. (10-3), the nominal shear strength of the FRP-strengthened wall is $V_{n,s} = V_n^{URM} + V_f$	$V_{n,s} = (6042\text{ lb}) + (31{,}376\text{ lb}) = 37{,}418\text{ lb}$

PROCEDURE	CALCULATION IN in.-lb
STEP 9: Compute the nominal flexural strength of the FRP-reinforced wall under in-plane loads.	
As the design lateral strength determined in the previous step is larger than the lateral strength due to toe crushing of the unreinforced wall computed in Step 3, a check needs to be performed to ensure that the FRP reinforcement designed in Section 13.1 will prevent the rupture of the wall due to toe crushing. To this extent, the FRP reinforcement designed in Section 13.1 should effectively be anchored as suggested in Section 11.4. The maximum lateral force $V_{n,f}$ that the wall can sustain before flexural failure is computed as follows $V_{n,f} = \frac{M_n}{k \cdot H_{roof}}$ where M_n is the nominal moment capacity computed according to Eq. (10-7) using a trial-and-error procedure that allows the determination of the neutral axis depth, c = 12.76 in., and gives M_n = 3975 in.-kip. By installing an extra layer of GFRP vertical reinforcement 5 in. wide spaced at 36 in. on-center on both sides of the wall (Fig. 13.5), the neutral axis depth results in c = 24.06 in. and M_n = 7483 in.-kip.	$V_{n,f} = \frac{3975 \text{ in.-kip}}{1.0 \times 192 \text{ in.}} = 20.703 \text{ kip} < V_{n,s}$ computed in Step 8 (not good) $V_{n,f} = \frac{7483 \text{ in.-kip}}{1.0 \times 192 \text{ in.}} = 38.974 \text{ kip} > V_{n,s}$ computed in Step 8 (OK)

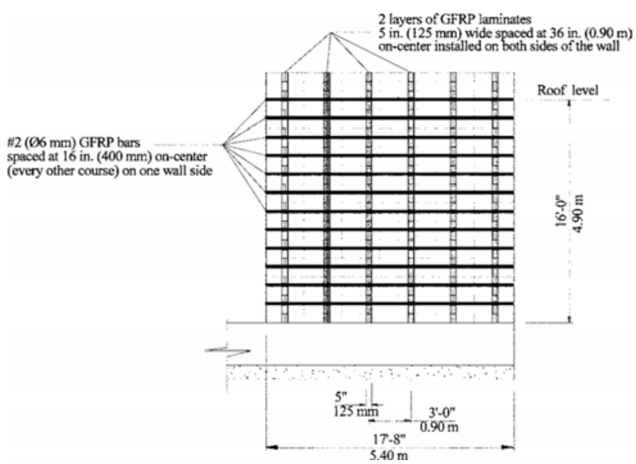
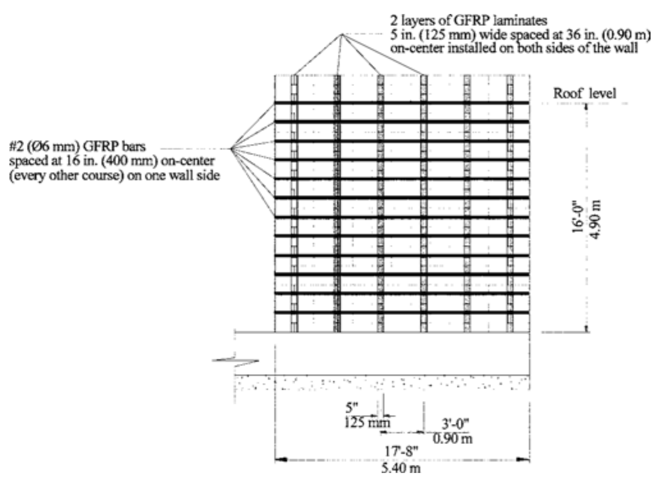


Fig. 13.5—Schematic of the strengthened wall for in-plane loads with the additional layer of vertical reinforcement.

PROCEDURE	CALCULATION IN in.-lb
STEP 10: Compute the design lateral strength of the FRP-strengthened wall.	
The nominal lateral strength of the FRP-strengthened wall is obtained as the minimum of the nominal shear strength as determined in Step 8 and the nominal lateral strength corresponding to flexural failure of the FRP-strengthened wall as determined in Step 9 $V_n = \min(V_{n,s}, V_{n,f})$ As failure is controlled by the shear strength, the strength reduction factor is taken equal to 0.8 (Section 10.4).	$V_n = \min(37.418 \text{ kip}, 38.974 \text{ kip}) = 37.418$ kip $\phi V_n = (0.8)(37.418 \text{ kip}) = 29.934 \text{ kip} > V_u = 20$ kip

PROCEDURE	CALCULATION IN SI UNITS
STEP 1: Compute the shear capacity due to bed-joint sliding, V_{bjs}.	
The nominal shear capacity of the unreinforced masonry wall for bed-joint sliding is found according to the provisions of ASCE 41 as follows $V_{bjs} = v_{mL}A_n$ where $v_{mL} = 0.75\dfrac{0.75v_{tL} + \dfrac{P_D}{A_n}}{1.5}$ In general, the nominal shear capacity of the URM wall for bed-joint sliding can be determined according to ASCE 41 and/or the applicable local building code.	$V_{bjs} = (0.064\text{ MPa})(410{,}400\text{ mm}^2) = 26{,}266\text{ N}$ $v_{mL} = 0.75\dfrac{0.75(0.10\text{ MPa}) + \dfrac{4000\text{ N/m} \times 5.40\text{ m}}{2(38\text{ mm} \times 5400\text{ mm})}}{1.5} = 0.064\text{ MPa}$
STEP 2: Compute the shear capacity due to diagonal tension, V_{dt}.	
The nominal shear capacity of the URM wall for diagonal tension is found according to the provisions of FEMA 356 as follows $V_{dt} = f'_{dt} \cdot A_n\left(\dfrac{L}{h_{eff}}\right)\sqrt{1 + \dfrac{f_a}{f'_{dt}}}$ where f'_{dt} may be replaced by v_{mL} calculated in the previous step, L is length of the wall assumed equal to 5.4 m (Fig. 13.1(a)); h_{eff} is the height to resultant of lateral force equal to 4.88 m (Fig. 13.1(a)); and f_a represents the axial compressive stress due to gravity load, computed as $f_a = \dfrac{P_D}{A_n}$	$V_{dt} = (0.064\text{ MPa})(410{,}400\text{ mm}^2)\left(\dfrac{5.40\text{ m}}{4.90\text{ m}}\right)\sqrt{1 + \dfrac{0.053\text{ MPa}}{0.064\text{ MPa}}} = 39{,}137\text{ N}$ $f_a = \dfrac{4000\text{ N/m} \times 5.40\text{ m}}{410{,}400\text{ mm}^2} = 0.053\text{ MPa}$
STEP 3: Compute the shear capacity due to toe crushing, V_{tc}.	
The nominal shear capacity of the URM wall for toe crushing is found according to the provisions of ASCE 41 as follows $V_{tc} = \alpha \cdot Q_G\left(\dfrac{L}{h_{eff}}\right)\left(1 - \dfrac{f_a}{0.7f'_m}\right)$ where L and h_{eff} are as defined in the previous step, and f_a is calculated as follows $f_a = \dfrac{Q_G}{A_n}$ In general, the nominal shear capacity of the URM wall for toe crushing can be determined according to ASCE 41 and/or the applicable local building code.	$V_{tc} = (1.00)(5800\text{ N/m} \times 5.40\text{ m})\left(\dfrac{5.40\text{ m}}{4.90\text{ m}}\right)\left(1 - \dfrac{0.079\text{ MPa}}{0.7 \times 10\text{ MPa}}\right) = 34{,}126\text{ N}$ $f_a = \dfrac{5800\text{ N/m} \times 5.40\text{ m}}{410{,}400\text{ mm}^2} = 0.076\text{ MPa}$
STEP 4: Compute the as-built shear capacity, ϕV_n^{URM}.	
As indicated in Section 10.3, the nominal shear capacity or nominal lateral strength of the URM wall V_n^{URM} is obtained as the minimum of Eq. (10-1) $V_n^{URM} = \min(V_{bjs}, V_{dt}, V_{tc})$ Assuming $\phi = 0.8$, the design lateral strength can be computed as ϕV_n^{URM}.	$V_n^{URM} = \min(26{,}266\text{ N}, 39{,}137\text{ N}, 34{,}126\text{ N}) = 26{,}266\text{ N}$ $\phi V_n^{URM} = 0.8(26{,}266\text{ N}) = 21{,}013\text{ N}$ As $\phi V_n^{URM} < V_u$, the wall needs strengthening for in-plane loads
STEP 5: Compute the design mechanical properties of the NSM FRP system.	
Assuming an environmental reduction factor C_E equal to 0.65, the FRP design tensile strength and strain can be determined from Eq. (8-3) and (8-4) $f_{fu} = C_E f_{fu}^*$ $\varepsilon_{fu} = C_E \varepsilon_{fu}^*$	$f_{fu} = (0.65)(827\text{ MPa}) = 538\text{ MPa}$ $\varepsilon_{fu} = (0.65)(0.02) = 0.013$

PROCEDURE	CALCULATION IN SI UNITS
STEP 6: Compute the effective strain and stress for shear-controlled failure mode.	
To determine the effective strain in the FRP reinforcement, compute the area of FRP reinforcement as follows $A_f = \frac{H_{roof}}{s}A_{f,bar}$ The value of ω_f is defined in Eq. (8-12) $\omega_f = \frac{1}{85}\frac{A_f E_f}{A_n\sqrt{f'_m}}$ According to Section 8.4.2, the effective strain and stress in the FRP reinforcement can be found from Eq. (8-10) and (8-11) as a function of κ_v (Eq.(8-13)) $\kappa_v = \begin{cases} 0.40 \text{ for } \omega_f \le 0.20 \\ 0.64 - 1.2\omega_f \text{ for } 0.20 < \omega_f \le 0.45 \\ 0.10 \text{ for } \omega_f > 0.45 \end{cases}$ $\varepsilon_{fe} = \kappa_v \varepsilon^*_{fu} \le C_E \varepsilon^*_{fu}$ $f_{fe} = E_f \varepsilon_{fe}$	$A_f = \frac{4900 \text{ mm}}{400 \text{ mm}} 32 \text{ mm}^2 = 392 \text{ mm}^2$ $\omega_f = \frac{1}{85}\frac{(392 \text{ mm}^2)(41{,}000 \text{ MPa})}{(410{,}400 \text{ mm}^2)\sqrt{10 \text{ MPa}}} = 0.146$ $\kappa_v = 0.40$ $\varepsilon_{fe} = (0.40)(0.02) = 0.008 < 0.013$ $f_{fe} = (41{,}000 \text{ MPa})(0.008) = 328 \text{ MPa}$
STEP 7: Compute the FRP contribution to the shear strength, V_f.	
The total force per bar that the FRP system can transfer to the masonry substrate is given by Eq. (8-14) as follows: $p_{fv} = A_{f,bar} f_{fe} \le 10{,}000$ lb/bar The NSM FRP contribution to the shear strength can be determined from Eq. (10-4) as follows $V_f = p_{fv}\frac{d_v}{s_f}$ where $d_v = \min(H, L)$; and s_f represents the spacing of the NSM FRP reinforcement equal to the spacing of every other course of masonry unit, s.	$p_{fv} = (32 \text{ mm}^2)(328 \text{ MPa}) = 10{,}496 \text{ N/bar} < 44{,}500 \text{ N/bar}$ $V_f = (10{,}496 \text{ N})\frac{5400 \text{ mm}}{400 \text{ mm}} = 141{,}696 \text{ N}$ $d_v = \min(5.50 \text{ m}, 5.40 \text{ m}) = 5.40 \text{ m}$
STEP 8: Compute the nominal shear strength of the FRP-strengthened wall.	
According to Eq. (10-3), the nominal shear strength of the FRP-strengthened wall is $V_{n,s} = V_n^{URM} + V_f$	$V_{n,s} = (26{,}266 \text{ N}) + (141{,}696 \text{ N}) = 167{,}962 \text{ N}$

PROCEDURE	CALCULATION IN SI UNITS
STEP 9: Compute the nominal flexural strength of the FRP reinforced wall under in-plane loads.	
As the design lateral strength determined in the previous step is larger than the lateral strength due to toe crushing of the unreinforced wall computed in Step 3, a check needs to be performed to ensure that the FRP reinforcement designed in Section 13.1 will prevent the rupture of the wall due to toe crushing. To this extent, the FRP reinforcement designed in Section 13.1 should effectively be anchored as suggested in Section 11.4. The maximum lateral force $V_{n,f}$ that the wall can sustain before flexural failure is computed as follows $V_{n,f} = \dfrac{M_n}{k \cdot H_{roof}}$ where M_n is the nominal moment capacity computed according to Eq. (10-7) using a trial-and-error procedure that allows the determination of the neutral axis depth, c = 324 mm, and gives M_n = 449,115 N·m. By installing an extra layer of GFRP vertical reinforcement 125 mm wide spaced at 0.90 m on-center on both sides of the wall (Fig. 13.5), the neutral axis depth results in c = 611 mm and M_n = 845,465 N·m.  *Fig. 13.5—Schematic of the strengthened wall for in-plane loads with the additional layer of vertical reinforcement.*	$V_{n,f} = \dfrac{449{,}155\ \text{N·m}}{1.0 \times 4.90\ \text{m}} = 91{,}656\ \text{N} < V_{n,s}$ computed in Step 8 (not good) $V_{n,f} = V_{n,f} = \dfrac{845{,}465\ \text{N·m}}{1.0 \times 4.90\ \text{m}} = 172{,}544\ \text{N} > V_{n,s}$ computed in Step 8 (OK)
STEP 10: Compute the design lateral strength of the FRP-strengthened wall.	
The nominal lateral strength of the FRP-strengthened wall is obtained as the minimum of the nominal shear strength as determined in Step 8 and the nominal lateral strength corresponding to flexural failure of the FRP-strengthened wall as determined in Step 9 $V_n = \min(V_{n,s}, V_{n,f})$ As failure is controlled by the shear strength, the strength reduction factor is taken equal to 0.8 (Section 10.4).	V_n = min(167,962 N, 172,544 N) = 167,962 N ϕV_n = (0.8)(167,962 N) = 134,370 N > V_u = 90,000 N

CHAPTER 14—REFERENCES

14.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this guide was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

440R	Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures
440.1R	Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars
440.2R	Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures
440.3R	Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures
503R	Use of Epoxy Compounds with Concrete
530/530.1	Building Code Requirements for Masonry Structures

American Society of Civil Engineers

7-05	Minimum Design Loads for Buildings and Other Structures
41-06	Seismic Rehabilitation of Existing Buildings

ASTM International

D3039/D3039M	Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
D3418	Standard Test Method for Transition Temperatures of Polymers by Differential Scanning Calorimetry
D4065	Standard Practice for Plastics: Dynamic Mechanical Properties: Determination and Report of Procedures
D4541/D4541M	Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers
D7205/D7205M	Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars
D7565/D7565M	Standard Test Method for Determining Tensile Properties of Fiber Reinforced Polymer Matrix Composites Used for Strengthening of Civil Structures

Canadian Standards Association

S806	Design and Construction of Building Components with Fiber-Reinforced Polymers

Federal Emergency Management Agency (FEMA)

306	Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings—Basic Procedures Manual
356	Prestandard and Commentary for the Seismic Rehabilitation of Buildings

These publications may be obtained from these organizations:

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
www.concrete.org

American Society of Civil Engineers
1801 Alexander Bell Dr.
Reston, VA 20191
www.asce.org

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428
www.astm.org

Canadian Standards Association
5060 Spectrum Way, Suite 100
Mississauga, ON
L4W 5N6 Canada
www.csa.ca

Federal Emergency Management Agency
FEMA Distribution Center
PO Box 430
Buckeystown, MD 21717
www.fema.gov

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