

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

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

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.

Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

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*Chair of the subcommittee that prepared this report.

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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.

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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 frame, 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
$\overline{\epsilon_{fu}}$	=	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 impart 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

laminated—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 material 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/ft³ (1.2 to 2.1 g/cm³), 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 $6 \times 10^{-6}/^{\circ}\text{F}$ (7×10^{-6} to $11 \times 10^{-6}/^{\circ}\text{C}$) and is usually assumed to be isotropic (Mindess and Young 1981). Steel has an isotropic coefficient thermal expansion of $6.5 \times 10^{-6}/^{\circ}\text{F}$ ($11.7 \times 10^{-6}/^{\circ}\text{C}$).

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

Table 3.1—Typical densities of materials, lb/ft³ (g/cm³)

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, $\times 10^{-6}/^{\circ}\text{F}$ ($\times 10^{-6}/^{\circ}\text{C}$)		
	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.

effectiveness of the composite strengthening system is diminished at temperatures near and above the T_g of the resin(s) used in the system.

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 ($f_{fu}^* = \bar{f}_{fu} - 3\sigma$) and, similarly, report a guaranteed ultimate rupture strain ($\epsilon_{fu}^* = \bar{\epsilon}_{fu} - 3\sigma$). 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. FRP 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 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 mm²) 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 mm²) 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 ft² (1 m²);
- Large delaminations, greater than 25 in.² each (16,000 mm²), 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 mm²) 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 that repairs are properly installed.