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SI

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Externally Bonded Fiber-Reinforced Polymer Systems Design and Construction for Strengthening Masonry Structures—Guide

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Externally Bonded Fiber-Reinforced Polymer Systems Design and Construction for Strengthening Masonry Structures—Guide

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**38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701**

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Externally Bonded Fiber-Reinforced Polymer Systems Design and Construction for Strengthening Masonry Structures—Guide

Reported by ACI Committee 440

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Pedro F. Silva
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Jay Thomas
Houssam A. Toutanji
J. Gustavo Tumialan*
David White
Sarah E. Witt

*Co-chairs of the subcommittee who prepared this guide.

Note: The committee acknowledges the contribution of associate members Nestore Galati, Silvia Rocca, and Nancy Torres.

Consulting Members

P. N. Balaguru
Craig A. Ballinger
Lawrence C. Bank
Harald G. F. Budelmann
C. J. Burgoyne
Rami M. Elhassan

David M. Gale
Srinivasa L Iyer
Koichi Kishitani
Howard S. Kliger
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Kyuichi Maruyama

Antoine E. Naaman
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Mark A. Postma
Ferdinand S. Rostasy
Surendra P. Shah
Mohsen Shahawy

Yasuhsa Sonobe
Minoru Sugita
Luc R. Taerwe
Taketo Uomoto
Paul Zia

Fiber-reinforced polymer (FRP) systems can be used for strengthening masonry structures and masonry elements among other options such as external steel plates, section enlargement with reinforced concrete (RC) overlays or shotcrete, steel bracing, and internal steel reinforcement. FRP systems offer advantages over traditional strengthening techniques: they are lightweight, relatively easy to install, and are corrosion-resistant. Due to the char-

acteristics of FRP materials as well as the behavior of masonry members strengthened with FRP, specific guidance on the use of these systems is needed. This document offers a description of the unique material properties of FRP and committee recommendations on the engineering, construction, and inspection of FRP systems used to strengthen masonry. These guidelines are based on the knowledge gained from experimental research, analytical work, and field applications of FRP systems used to strengthen masonry structures.

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CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE, p. 3

- 1.1—Introduction, p. 3
- 1.2—Scope, p. 3

CHAPTER 2—NOTATION AND DEFINITIONS, p. 4

- 2.1—Notation, p. 4
- 2.2—Definitions, p. 5

CHAPTER 3—CONSTITUENT MATERIALS AND PROPERTIES, p. 6

- 3.1—Commercially available externally bonded FRP systems, p. 6
- 3.2—Constituent materials, p. 7
- 3.3—Physical properties, p. 8
- 3.4—Mechanical properties, p. 8
- 3.5—Time-dependent behavior, p. 9
- 3.6—Durability, p. 9
- 3.7—FRP system qualification, p. 10

CHAPTER 4—SHIPPING, STORAGE, AND HANDLING, p. 10

- 4.1—Shipping, p. 10
- 4.2—Storage, p. 10
- 4.3—Handling, p. 10

CHAPTER 5—INSTALLATION, p. 11

- 5.1—Contractor competency, p. 11
- 5.2—Temperature, humidity, and moisture considerations, p. 11
- 5.3—Equipment, p. 11
- 5.4—Substrate repair and surface preparation, p. 11
- 5.5—Mixing of resins, p. 12
- 5.6—Application of FRP systems, p. 12
- 5.7—Alignment of FRP materials, p. 13
- 5.8—Multiple plies and lap splices, p. 13
- 5.9—Curing of resins, p. 13
- 5.10—Temporary protection, p. 13

CHAPTER 6—INSPECTION, EVALUATION, AND ACCEPTANCE, p. 13

- 6.1—Inspection, p. 14
- 6.2—Evaluation and acceptance, p. 14

CHAPTER 7—MAINTENANCE AND REPAIR, p. 15

- 7.1—General, p. 15
- 7.2—Inspection and assessment, p. 15
- 7.3—Repair of strengthening system, p. 15
- 7.4—Repair of surface coating, p. 16

CHAPTER 8—GENERAL DESIGN CONSIDERATIONS, p. 16

- 8.1—Design philosophy, p. 16
- 8.2—Existing masonry strength, p. 16
- 8.3—Strengthening limits, p. 17
- 8.4—Design material properties, p. 17

CHAPTER 9—WALL STRENGTHENING FOR OUT-OF-PLANE LOADS, p. 18

- 9.1—General, p. 18
- 9.2—Nominal flexural strength of FRP-strengthened masonry walls subjected to out-of-plane loads, p. 19
- 9.3—Serviceability, p. 20
- 9.4—Creep rupture stress limits, p. 21

CHAPTER 10—WALL STRENGTHENING FOR IN-PLANE LOADS, p. 21

- 10.1—General, p. 21
- 10.2—Nominal shear strength of FRP-strengthened masonry walls subjected to in-plane loads, p. 22
- 10.3—FRP contribution to shear strength, p. 23
- 10.4—Nominal flexural strength of FRP-strengthened walls subjected to in-plane loads, p. 23
- 10.5—Wall strengthening for shear and flexure, p. 24

CHAPTER 11—STITCHING OF CRACKED MASONRY, p. 24

- 11.1—General, p. 24
- 11.2—Design considerations, p. 25

CHAPTER 12—CONFINEMENT OF COLUMNS, p. 25

- 12.1—General, p. 25
- 12.2—Pure axial compression, p. 25
- 12.3—Combined axial compression and bending, p. 27

CHAPTER 13—DETAILING, p. 28

- 13.1—Development length, p. 28
- 13.2—Lap splices, p. 28
- 13.3—Groove dimensions for NSM systems, p. 28
- 13.4—Spacing limits, p. 29
- 13.5—Anchorage of FRP reinforcement, p. 29
- 13.6—Load path continuity, p. 30

CHAPTER 14—CONSTRUCTION DOCUMENTS, p. 31

- 14.1—Engineering requirements, p. 31
- 14.2—Drawings and specifications, p. 31
- 14.3—Submittals, p. 31

CHAPTER 15—DESIGN EXAMPLES, p. 31

- 15.1—Increasing the flexural capacity of an unreinforced CMU wall subjected to out-of-plane loads, p. 32
- 15.2—Increasing the shear and flexural capacities of an unreinforced CMU wall subjected to in-plane loads, p. 38
- 15.3—Increasing the flexural capacity of a reinforced masonry wall subjected to out-of-plane loads, p. 46
- 15.4—Restoring the strength of a cracked URM wall, p. 55
- 15.5—Increasing the axial capacity of a URM column subjected to axial loads, p. 61

CHAPTER 16—REFERENCES, p. 68

- Authored documents, p. 69

APPENDIX A—MATERIAL PROPERTIES OF CARBON, GLASS, AND ARAMID FIBERS, p. 70

APPENDIX B—SUMMARY OF STANDARD TEST METHODS, p. 71

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Masonry is a type of construction where clay units, concrete masonry units, or natural stones are laid in and bound together by mortar to form a building structure or a component in a structure. Masonry elements can be load-bearing or non-load-bearing. Masonry elements include walls, columns, pilasters, and beams.

Historically, most masonry, until the mid-twentieth century, was unreinforced. Due to damage of unreinforced masonry (URM) in the 1933 Long Beach, CA, earthquake, it was prohibited in seismically active regions, and reinforced masonry (RM) became more prevalent. During the nineteenth century, most of the URM building construction consisted of load-bearing mass-masonry walls. These walls are multi-wythe brick walls connected with brick headers, typically three or four wythes thick at the lowest stories and two wythes thick at the upper stories. From the late 1890s until the mid-1900s, URM was used in many transitional façades. These types of façades consist of steel or reinforced concrete frames that are filled with backup walls supported on spandrel beams, and an outer wythe that in many cases extends the entire building height and is supported only at grade. URM masonry elements were designed to rely on the strength of masonry alone to resist loads.

RM elements use steel reinforcement in grouted cells or embedded in horizontal mortar joints to resist tensile and shear stresses. RM construction became more common in the United States since the 1960s with the development of codes for structural masonry. However, there are examples of older RM structures built in the years following the 1933 Long Beach earthquake as a response to the poor performance of many URM buildings during this earthquake.

Unreinforced structures such as URM are particularly vulnerable to earthquakes and high winds, and many times strengthening is required to resist loads due to these events. Deterioration, change of use, structural modifications, and other factors may also necessitate strengthening of masonry structures or elements. The repair and retrofit/rehabilitation of existing masonry structures have traditionally been accomplished using conventional materials and construction techniques. Externally bonded steel plates, reinforced concrete overlays, installation of steel bars in grouted cells, and post-tensioning are just some of the many traditional techniques available. Fiber-reinforced polymer (FRP) composites have emerged as an alternative to traditional materials for strengthening masonry structures (ACI 440R). FRP materials are lightweight and resistant to corrosion. They exhibit high tensile strength and elastic modulus (carbon FRP), are impact-resistant and have electromagnetic transparency. These materials, which are available in a

variety of forms including flat sheets and plates, reinforcing bars, and prestressing tendons of typically round cross section, provide the licensed design professional with flexibility in achieving desired performance.

Advantages of repair or strengthening masonry using FRP composites include easier handling and installation than other strengthening methods with resulting lower installation prices, and minimal dimensional changes to the structure. Disturbance to occupants and loss of usable space are commonly minimized. Dynamic properties of the existing structure remain unchanged because there is little weight addition or stiffness modification.

Disadvantages of using FRP may include inferior performance at elevated temperatures, requirements for protective coatings, degradation of mechanical properties after long-term exposure to certain environmental conditions such as extensive moisture intrusion and frequent freezing-and-thawing cycles, and the relatively higher level of site supervision and inspection required during construction. These disadvantages can typically be addressed by using protection systems suitably designed for the environment as well as testing to confirm the long-term design properties of FRP systems. In addition, due to different textures and uneven surfaces across masonry units and mortar joints, additional effort may be needed to properly prepare the masonry substrate to achieve adequate bond of the FRP system.

1.2—Scope

This guide provides recommendations for the selection and design of FRP systems limited to externally bonded FRP laminates and near-surface-mounted (NSM) FRP bars/strips for increasing or restoring the in-plane and out-of-plane strength of undamaged or damaged URM and RM walls and columns. Infill walls are not included in this guide.

The guide is applicable to masonry structures made of clay bricks, concrete masonry units, and natural stones using conventional types of mortar. The effectiveness of FRP systems is highly dependent on the adequate surface preparation of the masonry substrate. Masonry elements have different textures and uneven surfaces due to units and mortar joints that can affect the effectiveness of FRP systems if the masonry surface is not properly prepared.

For masonry with significant deterioration, questionable mortar bond, as well as cracking, element displacement, or both, traditional repair procedures may be required to be used in combination with FRP strengthening. Procedures and requirements for traditional methods for repair and strengthening of masonry are not covered in this guide. *Assessment and Retrofit of Masonry Structures* (Hamid and Schuller 2019) provides background and guidance for other methods for repair and strengthening.

Before starting the project, the licensed design professional should determine the design basis code (DBC) under which the evaluation, repair, and rehabilitation will be implemented. The DBC will establish the extent of the repairs and rehabilitation, evaluation methods, and design loads. The DBC is the code legally adopted by jurisdiction, under which the assessment, repairs, and rehabilitations

are designed and constructed. Depending on the jurisdiction and project conditions, the DBC can either be the International Existing Building Code (IEBC) or a local existing building code. This guideline does not cover code compliance requirements. Refer to **ACI 562** for guidance on how to determine the DBC.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_c = cross-sectional area of masonry in compression member, in. ² (mm ²)	f_{fe} = effective stress level in the FRP reinforcement; stress attained at section failure, psi (MPa)
A_e = cross-sectional area of effectively confined masonry section, in. ² (mm ²)	f_{fs} = stress in the FRP reinforcement at service, psi (MPa)
A_f = area of FRP external reinforcement, in. ² (mm ²)	f_{fu} = design ultimate tensile strength of FRP, psi (MPa)
$A_{f,bar}$ = area of one rectangular or circular FRP bar, in. ² (mm ²)	f_{fu}^* = ultimate tensile strength of the FRP material as reported by the manufacturer, psi (MPa)
A_n = net cross-sectional area of member, in. ² (mm ²)	$\overline{f_{fu}}$ = mean tensile strength of FRP reinforcement based on a population of 20 or more tensile tests per ASTM D3039/D3039M , psi (MPa)
A_s = area of non-prestressed steel reinforcement, in. ² (mm ²)	f_m = compressive stress of masonry, psi (MPa)
a_b = smaller cross-section dimension for rectangular FRP bars, in. (mm)	f_m' = specified compressive strength of masonry, psi (MPa)
b_b = larger cross-section dimension for rectangular FRP bars, in. (mm)	f_s = stress in the steel reinforcement, psi (MPa)
b_c = short side dimension of compression member, in. (mm)	f_{tm} = average value of the tensile strength of masonry, psi (MPa)
b_m = width of masonry wall, in. (mm)	f_y = specified yield strength of non-prestressed steel reinforcement, psi (MPa)
C_E = environmental reduction factor	h = effective height of wall or column, in. (mm)
c = distance from extreme compression fiber to the neutral axis, in. (mm)	h_c = long side dimension of compression member, in. (mm)
c_s = distance from extreme compression fiber to the neutral axis at service, in. (mm)	h_{eff} = height to resultant of lateral force, in. (mm)
d = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)	k = coefficient to calculate the depth to the neutral axis at service
d_b = diameter of an FRP bar, in. (mm)	ℓ_{df} = development length of FRP, in. (mm)
d_f = effective depth of FRP flexural reinforcement, in. (mm)	ℓ_w = length of the wall, in. (mm)
d_i = distance from centroid of the i -th layer of longitudinal FRP reinforcement to the extreme compression fiber, in. (mm)	M_n = nominal flexural strength, in.-lb (N-mm)
d_v = effective masonry depth for shear calculations, in. (mm)	M_s = moment due to sustained loads at section, in.-lb (N-mm)
E_f = tensile modulus of elasticity of FRP, psi (MPa)	M_u = factored moment at section, in.-lb (N-mm)
E_m = modulus of elasticity of masonry in compression, psi (MPa)	n = number of plies of FRP reinforcement
E_s = tensile modulus of elasticity of steel, psi (MPa)	P_n = nominal axial compressive strength of a masonry section, lb (N)
E_2 = slope of linear portion of stress-strain model for FRP-confined masonry, psi (MPa)	P_s = axial load due to all service loads, lb (N)
e = eccentricity of axial load, in. (mm)	P_u = factored axial load, lb (N)
F_i = force in the i -th layer of longitudinal FRP reinforcement, lb (N)	p_{fm}, p_{fv} = force per unit width for surface-mounted FRP systems, lb/in. (N/mm), or force per unit bar for NSM FRP systems, lb/bar (N/bar)
f_a = axial compressive stress due to gravity loads, psi (MPa)	R_n = nominal strength of a masonry member
f_{cm}' = compressive strength of confined masonry, psi (MPa)	r = least radius of gyration of a section, in. (mm)
f_f = stress in FRP reinforcement, psi (MPa)	r_c = radius of edges of a prismatic cross section confined with FRP, in. (mm)
f_{fd} = design stress of externally bonded FRP reinforcement, psi (MPa)	S_{DL} = dead load effects
	S_H = lateral earth pressure effects
	S_{LL} = live load effects
	s_f = center-to-center spacing of FRP reinforcement, in. (mm)
	T_g = glass-transition temperature, °F (°C)
	t = nominal thickness of the wall, in. (mm)
	t_f = nominal thickness of one ply of FRP reinforcement, in. (mm)
	V_f = nominal shear strength provided by FRP reinforcement, lb (N)
	V_n = nominal shear strength, lb (N)
	V_u = factored shear force at section, lb (N)
	w_f = width of FRP reinforcing plies, in. (mm)

α	=	angle of application of primary FRP reinforcement direction relative to longitudinal axis of member, 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_{bi}	=	strain in masonry substrate at time of FRP installation (tension is positive), in./in. (mm/mm)
ϵ_{cmu}	=	ultimate axial compressive strain of confined masonry, in./in. (mm/mm)
ϵ_{fd}	=	debonding strain of externally bonded FRP reinforcement, in./in. (mm/mm)
ϵ_{fe}	=	effective strain in FRP reinforcement attained at failure, in./in. (mm/mm)
ϵ_{fu}	=	design rupture strain of FRP reinforcement, in./in. (mm/mm)
ϵ_{fu}^*	=	ultimate rupture strain of FRP reinforcement as reported by the manufacturer
ϵ_{fu}	=	mean rupture strain of FRP reinforcement based on a population of 20 or more tensile tests per ASTM D3039/D3039M , in./in. (mm/mm)
ϵ_m	=	compressive strain in masonry, in./in. (mm/mm)
ϵ_m'	=	compressive strain of unconfined masonry corresponding to f_m' , in./in. (mm/mm); it may be taken as 0.002
ϵ_{mu}	=	maximum usable compressive strain in masonry, in./in. (mm/mm)
ϵ_t'	=	transition strain in stress-strain curve of FRP confined masonry, in./in. (mm/mm)
ϕ	=	strength-reduction factor
γ	=	multiplier of f_m' to determine the intensity of an equivalent rectangular stress distribution for masonry
κ_a	=	efficiency factor for FRP reinforcement in determination of f_{cm}' (based on geometry of cross section)
κ_b	=	efficiency factor for FRP reinforcement in determination of ϵ_{cmu}' (based on geometry of cross section)
κ_m	=	bond-dependent coefficient for flexure
κ_v	=	bond-dependent coefficient for shear
κ_{vc}	=	efficiency factor for FRP reinforcement in determination of f_{cm}' (based on vertical spacing of FRP reinforcement)
κ_ϵ	=	efficiency factor equal to 0.55 for FRP strain to account for the difference between observed rupture strain in confinement and rupture strain determined from tensile tests
ρ_g	=	ratio of area of longitudinal steel reinforcement to cross-sectional area of a compression member ($A_s/(b_c h_c)$)
ρ_s	=	ratio of steel reinforcement
τ_b	=	average bond strength for near-surface-mounted FRP bars, psi (MPa)
ω_f	=	FRP reinforcement index
ψ_f	=	FRP strength-reduction factor

2.2—Definitions

Please refer to the latest versions of ACI Concrete Terminology and **TMS 402/602** for a comprehensive list of definitions. Definitions provided herein complement those resources.

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

aramid fiber-reinforced polymer—composite material comprising a polymer matrix reinforced with aramid fiber cloth, mat, or strands.

carbon fiber—fiber produced by heating organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile, or pitch, in an inert environment.

carbon fiber-reinforced polymer—composite material comprising a polymer matrix reinforced with carbon fiber cloth, mat, or strands.

catalyst—substance that accelerates a chemical reaction and enables it to proceed under conditions milder than otherwise required and that is not, itself, permanently changed by the reaction.

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

cross linking—formation of covalent bonds linking one polymer molecule to another.

E-glass—family of glass fibers used in reinforced polymers with a calcium aluminum borosilicate composition and a maximum alkali content of 2.0%.

fabric—two-dimensional network of woven, nonwoven, knitted, or stitched fibers; yarns; or tows.

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

fiber fly—short filaments that break off dry fiber tows or yarns during handling and become airborne.

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

fire retardant—additive to the resin or a surface coating used to reduce the tendency of a resin to burn.

full cure—period at which components of a thermosetting resin have reacted sufficiently for the resin to produce specified properties.

glass fiber—filament drawn from an inorganic fusion typically comprising silica-based material that has cooled without crystallizing.

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

impregnate—to saturate fibers with resin or binder.

initiator—chemical used to start the curing process for unsaturated polyester and vinyl ester resins.

interlaminar shear—force tending to produce a relative displacement along the plane of the interface between two laminae.

intumescent coating—covering that swells, increasing volume and decreasing density, when exposed to fire imparting a degree of passive fire protection.

lamina—single layer of fiber reinforcement.

laminate—multiple plies or lamina molded together.

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

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

phenolic resin—thermosetting resin produced by the condensation reaction of an aromatic alcohol with an aldehyde (usually a phenol with formaldehyde).

pitch—viscid substance obtained as a residue of petroleum or coal tar.

polyacrylonitrile—synthetic semi-crystalline organic polymer-based material that is spun into a fiber form for use as a precursor in the manufacture of some carbon fibers.

polyester—one of a large group of synthetic resins, mainly produced by reaction of dibasic acids with dihydroxy alcohols.

postcuring—application of elevated temperatures to material containing thermosetting resin to increase the degree of polymer crosslinking and enhance the final material properties.

prepreg—sheet of fabric or mat pre-impregnated with resin or binder that is partially cured and ready for final forming and curing.

pultrusion—continuous process for manufacturing fiber-reinforced polymer composites in which resin-impregnated fiber reinforcements (roving or mats) are pulled through a shaping and curing die, to produce composites with uniform cross sections.

putty—thickened polymer-based resin used to prepare the masonry substrate.

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

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

saturating resins (or saturants)—polymer-based resin used to impregnate the reinforcing fibers, fix them in place, and transfer load between fibers. The saturating resin also serves as the means of adhering a wet layup system to the substrate.

shelf life—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.

storage modulus—measure of the stored energy in a viscoelastic material undergoing cyclic deformation during dynamic mechanical analysis.

tow—untwisted bundle of continuous filaments.

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

volatile organic compound—organic compound that vaporizes under normal atmospheric conditions.

wet layup—manufacturing process where dry fabric fiber reinforcement is impregnated on site with a saturating resin matrix and then cured in place.

wet-out—process of coating or impregnating roving, yarn, or fabric to fill the voids between the strands and filaments with resin; it is also the condition at which this state is achieved.

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

yarn—twisted bundle of continuous filaments.

CHAPTER 3—CONSTITUENT MATERIALS AND PROPERTIES

The physical and mechanical properties of fiber-reinforced polymer (FRP) materials presented in this chapter explain the behavior and properties affecting their use in masonry structures. The effects of factors such as loading history and duration, temperature, and moisture on the properties of FRP are discussed.

FRP strengthening systems are available in a variety of forms (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 the characteristics of an FRP material. The material characteristics described in this chapter are generic and do not apply to all commercially available products. Standard test methods are available to characterize certain FRP products (refer to [Appendix B](#)). [ACI 440.8](#) provides a specification for unidirectional carbon and glass FRP materials made using the wet layup process. The licensed design professional should consult with the FRP system manufacturer to obtain the relevant characteristics for a specific product and the applicability of those characteristics.

3.1—Commercially available externally bonded FRP systems

FRP systems are available in a variety of forms, as described in Sections 3.1.1 to 3.1.4. FRP system forms can be categorized based on how they are delivered to the site and installed. The FRP system and its form should be selected based on the ease and simplicity of application and the ability to transfer structural loads. Common components of FRP system forms used for strengthening of structural members are listed in Sections 3.1.1 to 3.1.4.

3.1.1 Wet layup systems—Wet layup FRP systems consist of dry unidirectional or multidirectional fiber sheets or fabrics impregnated with a saturating resin on site. The saturating resin, along with the compatible primer and putty, bonds the FRP sheets to the masonry surface. Wet layup systems are saturated on site and cured in place. Three common types of wet layup systems are listed as follows:

(1) Dry unidirectional fiber sheets where the fibers run predominantly in one planar direction. [ACI 440.8](#) provides specifications for unidirectional carbon FRP (CFRP) and glass FRP (GFRP) wet layup systems.

(2) Dry multidirectional fiber sheets or fabrics where the fibers are oriented in at least two planar directions.

(3) Dry fiber tows that are wound or otherwise mechanically applied to the masonry surface. The dry fiber tows are impregnated with resin on site during the winding operation.

3.1.2 Prepreg systems—Prepreg FRP systems consist of partially cured unidirectional or multidirectional fiber sheets or fabrics that are pre-impregnated with a saturating resin in the manufacturer's facility. Prepreg systems are bonded to the masonry surface with or without an additional resin application, depending on specific system requirements. Prepreg systems are saturated off site and, like wet layup systems, cured in place. Prepreg systems usually require additional heat for curing. Prepreg system manufacturers should be consulted for storage and shelf-life recommendations and curing procedures. Three common types of prepreg FRP systems are:

- (1) Pre-impregnated unidirectional fiber sheets where the fibers run predominantly in one planar direction
- (2) Pre-impregnated multidirectional fiber sheets or fabrics where the fibers are oriented in at least two planar directions
- (3) Pre-impregnated fiber tows that are wound or otherwise mechanically applied to the masonry surface

3.1.3 Precured systems—Precured FRP systems consist of a wide variety of composite shapes manufactured off site. Typically, an adhesive, along with the primer and putty, is used to bond the precured shapes to the masonry surface. The system manufacturer should be consulted for recommended installation procedures. Three common types of precured systems are:

- (1) Precured unidirectional laminate sheets typically delivered to the site in the form of large flat stock or as thin ribbon strips coiled on a roll
- (2) Precured multidirectional grids, typically delivered to the site coiled on a roll
- (3) Precured shells, typically delivered to the site in the form of shell segments cut longitudinally so they can be opened and fitted around columns or other members; multiple shell layers are bonded to the masonry and to each other to provide confinement

3.1.4 Near-surface-mounted (NSM) systems—Surface-embedded NSM FRP systems consist of circular or rectangular bars installed and bonded into grooves cut into the masonry surface (typically in the mortar joints). A suitable adhesive is used to bond the FRP bar into the groove and is cured in place. The NSM system manufacturer should be consulted for recommended adhesives. Two common FRP bar types used for NSM applications are:

- (1) Round bars usually manufactured using pultrusion processes, typically delivered to the site in the form of single bars or in a roll, depending on bar diameter
- (2) Rectangular bars usually manufactured using pultrusion processes, typically delivered to the site in a roll

3.2—Constituent materials

The constituent materials used in commercially available FRP strengthening systems, including all resins, primers, putties, saturants, adhesives, and fibers, have been developed for the strengthening of masonry members based on materials and structural testing.

3.2.1 Resins—A wide range of polymeric resins, including primers, putty fillers, saturants, and adhesives, are used with FRP systems. Commonly used resin types, including epoxy, vinyl esters, and polyesters, have been formulated for use in a wide range of environmental conditions. FRP system manufacturers use resins that have:

- (a) Compatibility with and adhesion to the masonry substrate
- (b) Compatibility with and adhesion to the FRP composite system
- (c) Compatibility with and adhesion to the reinforcing fiber
- (d) Resistance to environmental effects, including but not limited to moisture, salt water, temperature extremes, and chemicals normally associated with exposed masonry
- (e) Filling ability
- (f) Workability
- (g) Pot life consistent with the application
- (h) Development of appropriate mechanical properties for the FRP composite

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

3.2.1.2 Putty fillers—Putty is a thick resin used to fill concave mortar joints and small surface voids in the masonry substrate to provide an even surface to which the FRP system can bond. Filled surface voids also prevent bubbles from forming during curing of the saturating resin.

3.2.1.3 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 also serves as the adhesive for wet layup systems, providing a shear load path between the previously primed masonry substrate and the FRP system.

3.2.1.4 Adhesives—Adhesives are used to bond precured FRP laminate and NSM systems to the masonry substrate. The adhesive provides a shear load path between the masonry substrate and the FRP reinforcing system. Adhesives are also used to bond together multiple layers of precured FRP laminates.

3.2.2 Fibers—Continuous glass, aramid, and carbon fibers are common reinforcements used in FRP systems. The fibers give the FRP system its strength and stiffness. Typical ranges of the tensile properties of fibers are given in [Appendix A](#). A more detailed description of fiber types is given in [ACI 440R](#).

3.2.3 Protective coatings—The protective coating protects the bonded FRP reinforcement from potentially damaging environmental and mechanical effects. Coatings are typically applied to the exterior surface of the FRP system after some prescribed degree of adhesive or saturating resin cure. The protection systems are available in a variety of forms. These include:

- (a) Polymer coatings that are generally epoxy or polyurethanes
- (b) Acrylic coatings that can be either straight acrylic systems or acrylic cement-based systems; acrylic systems can also come in different textures

(c) Cementitious systems that may require roughening of the FRP surface (such as broadcasting sand into wet resin) and can be installed in the same manner as they would be installed on a masonry surface

(d) Intumescent coatings that are polymer-based coatings used to provide a degree of passive fire protection and control flame spread and smoke generation per code requirements

There are several reasons why protection systems are used to protect FRP systems that have been installed on masonry surfaces. These include:

(a) **Ultraviolet light protection:** The epoxy used as part of the FRP strengthening system will be affected over time by exposure to ultraviolet light. There are numerous available methods used to protect the system from ultraviolet light. These include acrylic coatings, cementitious surfacing, aliphatic polyurethane coatings, and others. Certain types of vinyl ester resins have higher ultraviolet light durability than epoxy resins.

(b) **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. FRP 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 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 the FRP system may take place.

(c) **Vandalism:** Protective systems that are to resist vandalism should be hard and durable. There are different levels of vandalism protection, ranging from polyurethane coatings that will resist cutting and scraping to cementitious overlays that provide greater protection.

(d) **Impact, abrasion, and wear:** Protection systems for impact, abrasion, and wear are similar to those used for vandalism protection; however, abrasion and wear are different than vandalism in that they result from repeated exposure rather than a one-time event, and their protection systems are usually chosen for their hardness and durability.

(e) **Aesthetics:** Polymer and acrylic coatings, cementitious systems, and intumescent coatings or other compatible coatings may be used to conceal the FRP system.

(f) **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. Glass FRP systems may also be affected by highly alkaline environments (Porter and Barnes 1998).

(g) **Submersion in potable water:** In applications where the FRP system is to be submerged in potable water, the FRP system may leach compounds into the water supply. Protective coatings that do not leach harmful chemicals into the water may be used as a barrier between the FRP system and the potable water supply.

Table 3.3.1—Typical densities of materials, lb/ft³ (g/cm³)

Steel	Glass FRP (GFRP)	Carbon FRP (CFRP)	Aramid FRP (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 3.3.2—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.

3.3—Physical properties

3.3.1 Density—FRP materials have densities ranging from 75 to 130 lb/ft³ (1.2 to 2.1 g/cm³), which is four to six times lower than that of steel, as indicated in Table 3.3.1.

3.3.2 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 3.3.2 (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, masonry has a design coefficient of thermal expansion of approximately 4×10^{-6} in./in./°F (7.2×10^{-6} mm/mm/°C) for clay masonry and 4.5×10^{-6} in./in./°F (8.1×10^{-6} mm/mm/°C) for concrete masonry (TMS 402/602).

3.3.3 Effects of high temperature—Above the glass-transition temperature T_g , the elastic modulus of a polymer is significantly reduced due to changes in its molecular structure. The value of T_g depends on the type of resin and is normally in the range of 140 to 180°F (60 to 82°C).

The properties of the polymer at the fiber-masonry interface are essential in maintaining the bond between FRP and masonry. At a temperature close to its T_g , the mechanical properties of the polymer are significantly reduced, and the polymer begins to lose its ability to transfer stresses from the masonry to the fibers.

3.4—Mechanical properties

3.4.1 Tensile behavior—When loaded in direct tension, unidirectional FRP materials do not exhibit any plastic behavior (yielding) before rupture. The tensile behavior of FRP materials consisting of a single type of fiber material is characterized by a linear elastic stress-strain relationship until failure, which is sudden and brittle.

The tensile strength and stiffness of an FRP material is dependent on several factors. Because the fibers in an FRP material are the main load-carrying constituents, the tensile strength, fiber, the orientation of fibers, the quantity of fibers, and the

method and conditions in which the composite is produced affect the tensile properties of the FRP material. Due to the primary role of the fibers and methods of application, the properties of an FRP repair system are sometimes reported based on the net-fiber area. In other instances, such as in precured laminates, the reported properties are based on the gross-laminate area.

The gross-laminate area of an 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 an FRP system is calculated using the known area of fiber, neglecting the total width and thickness of the cured system; thus, resin is excluded. The net-fiber area is typically used for reporting properties of wet layup systems that use manufactured fiber sheets and field-installed resins. The wet layup installation process leads to controlled fiber content and variable resin content. A method similar to net-fiber area reporting is to report the tensile force or stiffness per unit width of the FRP system as required by [ASTM D7565/D7565M](#).

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 load-carrying strength ($f_{fu}A_f$) and axial stiffness (A_fE_f) of the composite remain constant. Properties reported based on the net-fiber area are not the properties of the bare fibers. When tested as a part of a cured composite, the measured tensile strength and ultimate rupture strain of the net-fiber are typically lower than those measured based on a dry fiber test. The properties of an FRP system should be characterized as a composite, recognizing not just 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 some commercially available FRP strengthening systems are given in [Appendix A](#). The tensile properties of a particular FRP system, however, should be obtained from the FRP system manufacturer or using the appropriate test method described in [ASTM D3039/D3039M](#), [D7205/D7205M](#), or [D7565/D7565M](#). 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 an ultimate rupture strain ($\epsilon_{fu}^* = \bar{\epsilon}_{fu} - 3\sigma$). This approach provides a 99.87% probability that the in-place ultimate tensile properties will exceed these statistically based design values for a standard sample distribution ([Mutsuyoshi et al. 1990](#)). The elastic modulus should be calculated in accordance with [ASTM D3039/](#)

[D3039M](#), [D7205/D7205M](#), or [D7565/D7565M](#). A minimum number of 20 replicate test specimens should be used to determine the 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.

3.4.2 Compressive behavior—Externally bonded FRP systems should not be used as compression reinforcement due to insufficient testing to validate its use in this type of application. 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. In general, compressive strengths are higher for materials with higher tensile strengths, except in the case of aramid FRP (AFRP), where the fibers exhibit nonlinear behavior in compression at a relatively low level of stress ([Wu 1990](#)). The compressive modulus of elasticity is usually smaller than the tensile modulus of elasticity of FRP materials ([Ehsani 1993](#)).

3.5—Time-dependent behavior

3.5.1 Creep rupture—FRP materials subjected to a sustained load can suddenly fail after a period referred to as the endurance time. This type of failure is known as creep rupture. As the ratio of the sustained tensile stress to the short-term strength of the FRP laminate increases, endurance time decreases. The endurance time also decreases 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 to cause creep rupture after 500,000 hours (approximately 50 years) to the short-term ultimate strength of the GFRP, AFRP, and CFRP bars were extrapolated to be approximately 0.3, 0.5, and 0.9, respectively ([Yamaguchi et al. 1997](#); [Malvar 1998](#)). Recommendations on sustained stress limits imposed to avoid creep rupture are given in [Chapter 9](#). 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.

3.5.2 Fatigue—Fatigue of the FRP system is not an issue in unreinforced masonry (URM) structures that are typically strengthened with FRP systems because the systems are intended to resist loads with low cycle counts, such as earthquake, high wind, and blast loads. Guidance on the fatigue performance for FRP composites can be found in [ACI 440.2R](#).

3.6—Durability

Many FRP systems exhibit reduced mechanical properties after exposure to certain environmental factors, including

high temperature, humidity, and chemical exposure. The exposure environment, duration of exposure, resin type and formulation, fiber type, and resin-curing method are some of the factors that influence the extent of the reduction in mechanical properties. The tensile properties reported by the manufacturer are based on testing conducted in a laboratory environment, and do not reflect the effects of environmental exposure. These properties should be adjusted in accordance with the recommendations in [Section 8.4](#) to account for the anticipated service environment to which the FRP system may be exposed during its service life.

3.7—FRP system qualification

FRP systems should be qualified for use on a project on the basis of 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 the proposed FRP system should meet all mechanical and physical design requirements, including tensile strength, durability, resistance to creep, bond to substrate, and T_g . [ACI 440.8](#) provides a specification for unidirectional carbon and glass FRP materials made using the wet layup process.

FRP composite systems that have not been fully tested 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. Mechanical properties should be tested in general conformance with the procedures listed in [Appendix B](#). Modifications of standard testing procedures may be permitted to emulate field assemblies.

The specified material-qualification programs should require sufficient laboratory testing to measure the repeatability and reliability of critical properties. Testing of multiple 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

Fiber-reinforced polymer (FRP) system constituent materials should be packaged and shipped in a manner that conforms to all applicable federal and state packaging and shipping codes and regulations. Packaging, labeling, and shipping for thermosetting-resin materials are controlled by [CFR 49](#).

4.2—Storage

4.2.1 Storage conditions—To preserve the properties and maintain safety in the storage of FRP system constituent materials, the materials should be stored in accordance with the manufacturer's recommendations. Certain constituent materials, such as reactive curing agents, hardeners, initiators, catalysts, and cleaning solvents, have safety-related requirements, and should be stored in a manner as recom-

mended by the manufacturer and the Occupational Safety and Health Administration (OSHA). Catalysts and initiators (usually peroxides) should be stored separately.

4.2.2 Shelf life—The properties of the 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, has deteriorated, or has been contaminated should not be used. FRP materials deemed unusable should be disposed of in a manner specified by the manufacturer and acceptable to state and federal environmental control regulations.

4.3—Handling

4.3.1 Safety data sheet—Safety data sheets (SDS) for all FRP constituent materials and components should be obtained from the manufacturers and should be accessible at the construction site.

4.3.2 Information sources—Detailed information on the handling and potential hazards of FRP constituent materials can be found in company literature and guides, OSHA guidelines, and other government informational documents.

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. Some general hazards that may be encountered when handling thermosetting-resin materials are listed as follows:

- (a) Skin irritation, such as burns, rashes, and itching
- (b) Skin sensitization, which is an allergic reaction similar to that caused by poison ivy, building insulation, or other allergens
- (c) Breathing organic vapors from cleaning solvents, monomers, and diluents
- (d) 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
- (e) Exothermic reactions of mixtures of materials causing fires or personal injury
- (f) 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 the SDS are read and understood by those working with these products. [CFR 16](#) regulates the labeling of hazardous substances and includes thermosetting-resin materials. [ANSI Z400.1/Z129.1](#) provides further guidance regarding classification and precautions.

4.3.4 Personnel safe handling and clothing—Use of 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. The material manufacturer should be consulted for guidance. Some resin systems are potentially dangerous during mixing of the components. The manufacturer's literature should be consulted for proper mixing procedures, and the SDS 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 Cleanup and disposal—Cleanup can involve the use of flammable solvents, and appropriate precautions should be observed. Cleanup solvents that do not present flammability concerns are also available. All waste materials should be contained and disposed of as prescribed by the prevailing environmental authority.

CHAPTER 5—INSTALLATION

The installation of fiber-reinforced polymer (FRP) systems for strengthening of concrete and masonry elements have several common requirements and procedures. **ACI 440.2R** provides recommendations for installation of FRP systems for strengthening of concrete. This chapter provides relevant information from ACI 440.2R that is applicable to masonry strengthening, and additional information specific to masonry.

Procedures for installing FRP systems are usually developed by the system manufacturers and are often unique to the particular FRP system. In addition, installation procedures can vary within a system, depending on the type and condition of the structure or substrate. This chapter presents general guidelines for the installation of FRP systems. FRP systems should be installed by contractors trained in accordance with the installation procedures developed by the system manufacturer. Deviations from the procedures developed by the FRP system manufacturer should not be allowed without consulting with the manufacturer and the licensed design professional. FRP systems can be very sensitive to installation procedures and conditions. The use of procedures that are not approved by the manufacturer may result in the FRP system not performing as intended.

5.1—Contractor competency

The contractor installing FRP systems 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 similar work previously completed by the contractor, surface preparation, and installation of the FRP system on portions or mockups of the structure. The FRP system manufacturer or its authorized representative should train the contractor's application personnel in the installation procedures of its system.

5.2—Temperature, humidity, and moisture considerations

Temperature, relative humidity, and surface moisture at the time of installation can affect the performance of the FRP system. Conditions to be observed before and during installation include surface temperature and moisture condition of the masonry, air temperature, relative humidity, and corresponding dew point.

Primers, saturating resins, and adhesives should generally 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 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 and maintain proper temperatures during curing. The heat source should be clean and not contaminate the surface or the uncured FRP system.

Resins and adhesives should generally not be applied to damp or wet surfaces unless they have been formulated for such applications. FRP 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

Some FRP systems have unique, often system-specific, equipment designed specifically for their application. This equipment can include resin impregnators, sprayers, lifting/positioning devices, and winding machines. All equipment should be clean and in good operating condition. The contractor should have personnel trained in the operation of all equipment. Personal protective equipment, such as gloves, masks, eye guards, and coveralls, should be chosen and worn for each employee's function. All supplies and equipment should be available in sufficient quantities to allow continuity in the installation of the FRP system.

5.4—Substrate repair and surface preparation

The behavior of masonry elements strengthened or retrofitted with FRP systems is highly dependent on the adequacy of the 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 used for 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—Damage and deterioration in the existing masonry elements can compromise the integrity of the FRP system. Conditions such as spalled and cracked units, or joints with deteriorated or missing mortar should be addressed before surface preparation begins. The FRP system manufacturer should be consulted to verify the compatibility of repair materials 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 FRP system manufacturer.

5.4.2.1 Surface preparation for FRP laminates—Surface preparation may involve sandblasting or grinding to roughen the surface, grinding of excess mortar in the joints, and application of epoxy primers and putty fillers. Extra 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 with low viscosity for concrete substrates may not be appropriate for use on concrete masonry units (CMUs) due to their porous nature. Before using epoxy primers on CMUs, the FRP system manufacturer should be consulted 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 clay brick units, having less porosity, may require the use of an epoxy primer. Mortar joints should be filled and leveled with a material as recommended by the FRP system manufacturer to obtain a smooth surface flush with the masonry units.

Where fibers wrap around corners, such as in the case of strengthening of masonry columns, the corners should be rounded to a minimum 0.5 in. (13 mm) radius to reduce stress concentrations in the FRP system and voids between the FRP system and the masonry.

5.4.2.2 Surface preparation for near-surface-mounted FRP bars—Near-surface-mounted (NSM) systems are installed in grooves cut into the masonry surface. For FRP bars in the horizontal direction, the grooves are typically cut in the mortar bed joints for ease of installation. Similarly, for FRP bars in the vertical direction in stack bond masonry walls where the head joints are vertically aligned, the grooves are typically cut in the head joints. In masonry walls laid in a bond pattern other than stack bond, such as running bond, the grooves may be aligned with the head joints in alternate courses but will also extend through the masonry units. In masonry walls built with hollow units that are not grouted, the depth of the groove in the masonry units should be limited to not cut entirely through the face shell.

The masonry surface should be free of damage or deterioration 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 13.3](#).

The moisture content of the parent masonry should be evaluated and determined 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—Mixing of resins

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 FRP systems

Fumes can accompany the application of some resins. FRP systems 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 fabric. The fabric is impregnated on site with saturating resin and then

cured in place in accordance with 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—NSM systems are precured systems that consist of installing rectangular or circular FRP bars into grooves cut into the masonry surface and bonding in place using an adhesive. Grooves should be dimensioned to ensure adequate adhesive around the bars. 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 by the licensed design

professional. Small variations in angle, as little as 5 degrees, from the intended direction of fiber alignment can cause a substantial reduction in strength and performance. 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.

5.8—Multiple plies and lap splices

Multiple plies can be used, provided that all plies are fully impregnated with the resin system, the resin shear strength is sufficient to transfer the shear load between plies, and the bond strength between the masonry and FRP system is sufficient. For long spans, multiple lengths of fiber material or precured stock can be used to continuously transfer the load by providing adequate lap splices. Lap splices should be staggered, unless noted otherwise by the licensed design professional. Lap splice details, including lap length, should be based on testing and installed in accordance with the manufacturer's recommendations. Due to the characteristics of some FRP systems, multiple plies and lap splices are not always possible.

5.9—Curing of resins

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 these situations.

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

All resins should be cured according to the manufacturer's recommendation. Field modification of resin chemistry should not be permitted. Cure of installed plies should be monitored before placing subsequent plies. Installation of successive layers should be halted if there is a curing anomaly.

5.10—Temporary protection

Adverse temperatures, direct contact by rain, dust, dirt, excessive sunlight, high humidity, or vandalism can damage an 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 bracing or shoring is required, the FRP system should be fully cured before removing the shoring and allowing the masonry 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 maintained by the fiber-reinforced polymer (FRP) system manufacturers, the installation contractors, and others associated with the project. QA is typically an owner or a licensed professional activity whereas QC is a contractor or supplier activity. The QC program should be comprehensive and cover all aspects of the strengthening project and should be detailed in the project specifications by a licensed design professional. The degree of QC and the scope of testing, inspection, and record keeping depends 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 QA 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, QA samples, cleanup, and the suggested submittals listed in [Section 14.3](#).

6.1—Inspection

FRP systems and all associated work should be inspected as required by the applicable codes. In the absence of such requirement, the licensed design professional should develop an inspection program and describe its scope in the construction documents. The frequency (that is, continuous versus periodic) of inspection and testing should be described in the construction documents. The inspection should be performed only by individuals who are knowledgeable of and trained in the installation of FRP systems. The contractor's personnel may be technically qualified to conduct some of the required inspection, testing, and documentation. However, because the applicable code may prohibit inspection services to be performed by a party employed by the contractor, the licensed design professional should consult with the authority having jurisdiction prior to finalizing details of the inspection program.

The qualified inspector should require compliance with the construction documents at all times. Inspection during the installation of the FRP system should include:

- (a) Date and time of installation
- (b) Ambient temperature, relative humidity, and general weather observations
- (c) Surface temperature of masonry
- (d) Surface preparation methods and resulting profile
- (e) Qualitative description of surface cleanliness
- (f) Type of auxiliary heat source, if applicable
- (g) Fiber or precured laminate batch number(s) and approximate location in structure
- (h) 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
- (i) Observations of progress of cure of resins
- (j) Conformance with installation procedures

(k) Pulloff test results according to [ASTM D7522/D7522M](#), indicating location, bond strength, and failure mode

(l) FRP properties from tests of field sample panels or witness panels, if required

(m) Location and size of any delaminations or air voids (refer to Section 6.2.3 for inspection methods)

(n) 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

FRP systems should be evaluated and accepted or rejected based on conformance or nonconformance with the construction documents. FRP system material properties, installation within specified placement tolerances, presence of delaminations, cure of resins, and adhesion to substrate should be included in the evaluation. Placement tolerances, including fiber orientation, cured thickness, ply orientation, width and spacing, corner radii, and lap splice lengths, should be evaluated. Witness panel and pulloff tests are also used to evaluate the installed FRP system.

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 size and complexity of the project or other factors. Evaluation of delivered FRP materials can include tests for tensile strength, T_g , and lap shear strength. These tests are usually performed on material samples sent to a laboratory according to the QC test plan. Refer to [Appendix B](#) for relevant test methods. Materials that do not meet the 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, hardness, 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 predetermined 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 in a timely manner for testing of strength and T_g . Strength and elastic modulus of FRP materials can be determined in accordance with the requirements of [ASTM D3039/D3039M](#), [D7205/D7205M](#), or [D7565/D7565](#). The properties to be evaluated by testing should be specified. The licensed design professional may waive or alter the frequency of testing.

Some FRP systems, including precured and machine-wound systems, do not lend themselves to the fabrication of small, flat, witness panels. For these cases, the licensed design professional can modify the requirements to include test panels or samples provided by the manufacturer during installation, sample cups of mixed resin should be prepared

according to a predetermined sampling plan and retained for testing to determine the degree of cure (Section 6.2.4).

6.2.2 Fiber orientations—Fiber or precured laminate orientation should be evaluated by visual inspection and by taking physical measurements. 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 and acceptance.

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 concrete. Inspection methods should be capable of detecting delaminations of 2 in.² (1300 mm²) or greater. Methods such as acoustic sounding (hammer sounding), ultrasonics, and 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:

(a) 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).

(b) Large delaminations, greater than 25 in.² (16,000 mm²) each, can 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. The overlap length should be determined by the licensed design professional or in accordance with the FRP system manufacturer's recommendations.

(c) 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 reinspected 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 using [ASTM D2240](#). 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 should be conducted using the method in [ASTM D7522/D7522M](#). Sampling frequency should be specified in the construction

documents. One test per day of installation or one test per 500 ft² (46.5 m²) of substrate contact area is recommended, whichever results in more tests being performed. In no case should the number of tests on a project be less than three. 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 licensed design professional and evaluated for acceptance.

6.2.6 Cured thickness—Small core samples, typically 0.5 in. (13 mm) in diameter, may be taken to visually ascertain the cured laminate thickness or number of plies. Cored samples required for adhesion testing can also be used for this purpose. The sampling frequency should be specified in the construction documents. 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, 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 strengthening or repair, the owner should periodically inspect and assess the performance of the fiber-reinforced polymer (FRP) system used for strengthening or repair of masonry members. These inspections should be performed 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 structure. 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 looks for changes in color, debonding, peeling, blistering, cracking, crazing, deflections, indications of reinforcing bar corrosion, and other anomalies. In addition, ultrasonic, acoustic sounding (hammer tap), or thermographic tests may indicate signs of progressive delamination.

7.2.2 Testing—Testing can include pulloff tension tests ([Section 6.2.5](#)).

7.2.3 Assessment—Test data and observations are used to assess any damage and the structural integrity of the strengthening system. The assessment can include a recommendation for repairing any deficiencies and preventing recurrence of degradation.

7.3—Repair of strengthening system

The method of repair for the strengthening system depends on causes of the damage, the type of material, the form of degradation, and the level and extent of damage. Details to

the FRP system should not be undertaken without first identifying and addressing the causes of the damage.

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. The surface coating should be replaced using a process approved by the system manufacturer.

CHAPTER 8—GENERAL DESIGN CONSIDERATIONS

This chapter presents general design recommendations for strengthening of masonry members with fiber-reinforced polymer (FRP). Common commercially available FRP systems, as described in [Section 3.1](#), can be used in conjunction with this guide. These recommendations are based on reinforced masonry (RM) design principles stated in the requirements of [TMS 402/602](#) and knowledge of the specific mechanical behavior of FRP reinforcement. FRP strengthening systems should be designed to resist tensile forces while maintaining strain compatibility between the FRP and the masonry substrate. FRP reinforcement should not be relied on to resist compressive forces. It is acceptable, however, for FRP tension reinforcement to experience compression due to moment reversals or changes in load direction. The compressive strength of the FRP reinforcement, however, should be neglected.

This guide can be used to design an FRP strengthening system for existing individual masonry walls and columns. [Appendix A](#) includes material properties of FRP systems for strengthening of masonry following the design methodologies recommended by this guide. When strengthening an individual wall or walls that are part of the lateral-load-resisting system, the design professional should evaluate the effect of the strengthening on the entire structure, which may require performing a global analysis. In strengthening of unreinforced masonry (URM) members, the relationship between each element and the entire structure is highly relevant. 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.

Masonry members should be properly connected or tied to floor diaphragms or adjacent structural members (beams,

columns, or walls) to provide proper load paths for lateral loads, to prevent out-of-plane wall failures, or both. The design professional should evaluate the existing connections and specify remedial work if deemed necessary. Remedial work may include installation of steel angles and anchors to connect the masonry wall to adjacent structural members, steel tiebacks to tie the masonry wall to floor diaphragms, and installation of steel dowels anchored to the wall and adjacent structural members.

8.1—Design philosophy

The design recommendations are based on limit state design principles to provide acceptable safety levels. To evaluate the nominal strength of an FRP-strengthened masonry member, all possible failure modes with associated strains and stresses in each material should be assessed.

8.1.1 Design strength—FRP strengthening of masonry members should be proportioned so that the design strength equals or exceeds the required strength. Design strength is 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. The use of strength-reduction factors ϕ as specified by TMS 402/602 is recommended in this guide. If there are uncertainties regarding existing material strengths or substrate conditions, the design professional may wish to incorporate more conservative strength-reduction factors than those discussed in this guide.

8.1.2 Required strength—The required strength should be determined in accordance with the strength design load combinations of the existing building code. The existing building code refers to the code adopted by a jurisdiction that regulates existing buildings. When the existing building code does not provide factored load combinations, the FRP strengthening of masonry members should be designed to resist the combination of loads specified in [ASCE/SEI 7](#) for strength design. Members subject to compressive axial load should be designed for the factored moment accompanying the factored axial load.

8.1.3 Masonry dimensions and properties—Dimensions of the masonry elements should be obtained from the existing drawings or field measurements. 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/SEI 41](#), TMS 402/602, or historical records found in the literature.

8.2—Existing masonry strength

The existing strength of the wall should be evaluated first to determine whether FRP strengthening is required. The existing strength should be determined as required by the design basis code. Provisions of [ASCE/SEI 41](#) or TMS 402/602 can be used in the absence of specific provisions in the design basis code.

for calculation of masonry strength are applicable to masonry built with materials with similar specifications in current codes. **ASCE/SEI 41** provides lower-bound properties where materials such as type of mortar and masonry unit strength may be different to those specified in current codes. When using these values, care should be taken to consider the masonry condition because deterioration of units and mortar can negatively affect the material and engineering properties of masonry. In-place testing or laboratory testing of samples extracted from masonry elements can also be used to determine properties to calculate existing masonry strengths. **ASCE/SEI 41** provides requirements for testing of existing masonry.

8.2.1 Flexural strength—The nominal 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/SEI 41**. In the absence of test results, the flexural tensile strength of a URM wall can be estimated using **TMS 402/602** or the lower-bound flexural tensile strength values shown in Table 11-2(a) of **ASCE/SEI 41-17**. The design strength is obtained as the nominal strength multiplied by the strength-reduction factor ϕ as determined from a reliability-based calibration study. If such a detailed reliability study is not available, the use of a strength-reduction factor ϕ of 0.6 as specified in **TMS 402/602** is recommended. In the case of RM elements, the nominal flexural strength is calculated according to **TMS 402/602** provisions.

8.2.2 Shear strength—The nominal shear strength can be obtained by in-place testing following one of the test methods recommended by **ASCE/SEI 41**. In the absence of test results, the shear strength of a URM wall can be estimated using **TMS 402/602** or the lower-bound shear strength values shown in Table 11-2(a) of **ASCE/SEI 41-17**. The design strength is obtained as the nominal strength multiplied by the strength-reduction factor ϕ as determined from a reliability-based calibration study. If such a detailed reliability study is not available, the use of a strength-reduction factor ϕ of 0.8 as specified in **TMS 402/602** is recommended. In the case of RM elements, the nominal shear strength is calculated according to **TMS 402/602** provisions.

8.2.3 Axial strength—The nominal axial strength P_n should be determined in accordance with the **TMS 402/602** provisions using appropriate compressive strengths, determined by in-place testing, historical records for old masonry, or f_m' values shown in Table 11-2(a) of **ASCE/SEI 41-17**. 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. If such a detailed reliability study is not available, the use of a strength-reduction factor ϕ of 0.6 as specified in **TMS 402/602** is recommended. In the case of RM elements, the nominal axial strength is calculated according to **TMS 402/602** provisions.

8.3—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 damage or other causes (**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 strengthening, FRP systems are usually installed to increase the strength of URM or RM walls subjected to special loading events such as earthquake, high wind, 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, such as from earthquake or wind—is low; therefore, a strengthening limit for these applications is unnecessary. However, for cases of walls that are part of the primary lateral-load-resisting system, the licensed design professional should evaluate the impact of the loss of FRP strengthening in the global behavior of the structure. The evaluation should also consider that walls that are part of the lateral-load-resisting system can be subject to out-of-plane loads, in addition to in-plane loads.

There are two cases, however, in which the strengthening limits should be considered. These cases include masonry elements that are subject to sustained loads such as columns resisting gravity loads and walls resisting out-of-plane loads due to earth pressure.

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. (8.3a).

$$(\phi R_n)_{\text{existing}} \geq (0.9S_{DL} + 1.15S_H)_{\text{new}} \quad (8.3a)$$

For masonry columns, the strength of the existing column should be sufficient to meet the limitation given in Eq. (8.3b).

$$(\phi R_n)_{\text{existing}} \geq (1.1S_{DL} + 0.75S_{LL})_{\text{new}} \quad (8.3b)$$

8.4—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 initial properties. Because long-term exposure to various types of environments can reduce the tensile properties, 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 (8.4a) through (8.4c) 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 8.4 for the appropriate fiber type and exposure condition.

Table 8.4—Environmental reduction factors for various FRP systems and exposure conditions

Exposure conditions	Fiber type	Environmental reduction factor C_E
Interior exposure (structural interior walls, interior walls, and partition walls)	Carbon	0.95
	Glass	0.75
	Aramid	0.85
Exterior exposure (structural exterior walls and veneers)	Carbon	0.85
	Glass	0.65
	Aramid	0.75
Aggressive environment (below-grade walls exposed to soil* and walls in industrial facilities)	Carbon	0.85
	Glass	0.50
	Aramid	0.70

*If the FRP is exposed to alkali soils, further evaluation of the environmental reduction factor may be needed.

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

$$\epsilon_{fu} = C_E \epsilon_{fu}^* \quad (8.4b)$$

FRP 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. (8.4c).

$$E_f = f_{fu} / \epsilon_{fu} \quad (8.4c)$$

Constituent materials affect the durability and resistance to environmental exposure of an FRP system. The environmental reduction factors given in Table 8.4 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 8.4 illustrates, if the FRP system is in a relatively benign environment, such as ambient temperature and humidity, the reduction factor is closer to unity. If the FRP system is in an aggressive environment where prolonged exposure to high humidity, freezing-and-thawing cycles, high temperatures, 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 8.4 (ACI 440.2R) for the interior exposure conditions.

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

9.1—General

This chapter applies to fiber-reinforced polymer (FRP) systems used to enhance the flexural strength of unreinforced and reinforced masonry walls for out-of-plane loads. The

design methodologies are applicable to masonry walls with slenderness h/t (or ℓ_w/t) ratios less than or equal to 20 and behave as simply supported elements. The design methodologies are not applicable to masonry walls that can develop an arching mechanism such as walls constructed between rigid supports with slenderness h/t (or ℓ_w/t) ratios less than or equal to 12.

Masonry walls subject to out-of-plane loads caused by earthquake, wind pressure, or earth pressure are typically isolated elements spanning vertically between floors or spanning horizontally between columns or pilasters. FRP reinforcement bonded to the tension face of masonry walls can significantly increase the flexural strength of existing unreinforced masonry (URM) and reinforced masonry (RM) walls (Al-Jaberi et al. 2018; Hamilton and Dolan 2001; Hrynyk and Myers 2008; Galati et al. 2006; Lunn and Rizkalla 2014; Tumialan et al. 2003a). FRP reinforcement is often applied on both wall faces because of the reversed stresses caused by out-of-plane loads due to wind pressures (windward and leeward) and earthquake excitations. Depending on the direction of the stresses, the fibers can be oriented in the vertical direction (along the wall height) if the wall spans between beams or slabs or can be oriented in the horizontal direction (along the wall length) if the wall spans between columns or pilasters.

FRP reinforcement is very effective for strengthening of masonry walls that behave as simply supported elements, or very nearly so, such as slender walls. FRP reinforcement can also be effective for strengthening stocky walls (walls with slenderness h/t less than 12), provided that these walls are not built between rigid supports (reinforced concrete or steel beams), and that the floor or roof structure bearing on the wall is not rigid and can be assumed to provide simply supported boundary conditions (for example, steel or wood framing). When externally bonded FRP systems are used to increase the flexural strength of a masonry wall, the wall should be checked to verify that it has adequate shear strength to resist the design shear forces. In the case of walls subject to out-of-plane forces, if the shear strength of the existing masonry is inadequate, supplementary methods for shear strengthening should be implemented to increase

the shear strength. These methods can involve grouting of hollow units near the supports, and lateral bracing.

URM walls with low slenderness h/t (or ℓ_w/t) ratios, typically less than 12, and built between rigid supports can develop arching action when subject to out-of-plane loads, mainly due to restraint of the wall ends against rotation as a wall bends due to the out-of-plane loads. This action induces in-plane compressive forces, which, depending on the stiffness of the supports, can significantly increase the wall resistance to out-of-plane loads (Galati 2002). Walls that are able to develop arching do not typically require strengthening and, therefore, are not addressed by these guidelines. URM walls having h/t less than 12 and having surrounding floor, roof, column, or pilaster elements having sufficient stiffness and strength to resist thrusts from arching do not need to be analyzed for out-of-plane loads and, therefore, do not require strengthening for such load cases.

This guideline does not recommend the use of FRP to strengthen URM walls with slenderness h/t (or ℓ_w/t) ratios larger than 20, which are calculated using nominal dimensions. This recommendation is based on the geometry of test specimens in the database used to develop the flexural design methodology, where the majority of the test specimens did not exceed this value. This recommendation is also based on typical values for lateral wall support used in the industry for empirical masonry design with the purpose to limit flexural tensile stresses due to out-of-plane loads (TMS 402/602). In general, behavior of walls with large slenderness h/t ratios and subject to out-of-plane loads should be carefully evaluated before specifying FRP strengthening. Slender URM walls strengthened with FRP can exhibit large out-of-plane deflections, which can cause secondary moments due to the wall self-weight or other axial load acting on the wall, and lead to instability of the wall.

9.2—Nominal flexural strength of FRP-strengthened masonry walls subjected to out-of-plane loads

The strength design method requires that the design flexural strength of the FRP-strengthened wall exceeds the factored moment, as indicated by Eq. (9.2a).

$$\phi M_n \geq M_u \quad (9.2a)$$

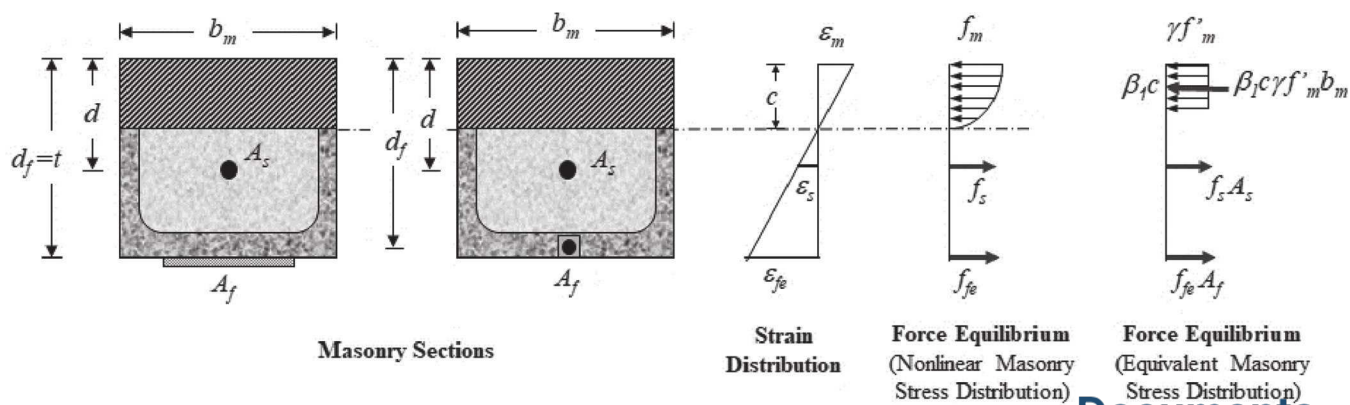


Fig. 9.2—Internal stress and strain distribution for a masonry wall section under flexure at the ultimate limit state

This guide recommends the use of a strength-reduction factor of $\phi = 0.6$ for URM walls and $\phi = 0.9$ for RM walls as required by TMS 402/602 for elements subjected to flexural load, axial load, or a combination thereof.

The nominal flexural strength M_n of the FRP-strengthened masonry wall can be determined from Eq. (9.2b) using strain compatibility, internal force equilibrium, and the controlling mode of failure. Figure 9.2 illustrates the internal stress and strain distribution for a masonry wall section under flexure at the ultimate limit state.

$$M_n = A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2} \right) + A_s f_s \left(\frac{d}{2} - \frac{\beta_1 c}{2} \right) + \frac{P_u}{\phi} \left(\frac{t}{2} - \frac{\beta_1 c}{2} \right) \quad (9.2b)$$

where f_{fe} represents the effective stress to be calculated according to Eq. (9.2.4b) with the strain level ϵ_{fe} defined in Eq. (9.2.4a). A_s and f_s are the area of existing steel reinforcement and steel stress, respectively, for the case of strengthening of RM walls. This equation considers the effect of compressive vertical loads increasing the flexural strength of the masonry section. Conservatively, the effect of the vertical loads can be neglected.

9.2.1 Design assumptions—The following assumptions are considered in the analysis of masonry walls strengthened in flexure with FRP:

- There is strain compatibility between the FRP reinforcement, existing steel reinforcement in RM, and masonry.
- The nominal strength of the FRP-strengthened masonry cross sections for combined flexure and axial load is based on applicable conditions of equilibrium.
- Strains in the FRP reinforcement, existing steel reinforcement in RM, and masonry are directly proportional to their distance from the neutral axis.
- The maximum usable compressive strain ϵ_{mu} is 0.0025 for concrete masonry, and 0.0035 for clay or natural stone masonry.
- The tensile behavior of the FRP reinforcement is linear elastic to failure.
- The contributions of both masonry in tension and FRP reinforcement in compression are neglected.
- There is no relative slip between external FRP reinforcement and masonry until debonding failure occurs.

(h) The wall behaves as a simply supported element, or very nearly so, and the influence of wall arching mechanisms can be neglected.

9.2.2 Failure modes—The following failure modes typically control the out-of-plane behavior of masonry walls strengthened with externally bonded FRP systems (Tumialan et al. 2003a; Galati et al. 2006):

(a) Crushing of the masonry in compression

(b) 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. FRP debonding is the most common failure mode in masonry walls strengthened with FRP systems (Tumialan et al. 2003a; 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 is typically a cohesive failure within a shallow depth in the substrate, as the tensile strength of masonry is lower than that of the epoxy used to bond the FRP system. Debonding typically starts from flexural cracks at the maximum bending moment region and propagates toward the supports. To prevent debonding, the design protocol introduces a bond reduction coefficient κ_m to limit the strain level in the FRP reinforcement according to the provisions given in Section 9.2.3.

9.2.3 Design strain for flexure-controlled failure modes—The design strain ϵ_{fd} and design stress f_{fd} used for the design of FRP flexural strengthening of masonry walls can be computed according to Eq. (9.2.3a) and (9.2.3b), respectively.

$$\epsilon_{fd} = \kappa_m \epsilon_{fu}^* \leq 0.9 C_E \epsilon_{fu}^* \quad (9.2.3a)$$

$$f_{fd} = E_f \epsilon_{fd} \quad (9.2.3b)$$

where κ_m is a bond reduction coefficient calibrated using available experimental data (Tumialan et al. 2010), defined as in Eq. (9.2.3c).

$$\kappa_m = \begin{cases} 0.45 & \text{for surface-mounted FRP systems} \\ 0.35 & \text{for NSM FRP systems} \end{cases} \quad (9.2.3c)$$

Typically, the κ_m values control over the C_E values. The κ_m values, however, have been set as a lower bound from experimental data on URM specimens.

Based on current knowledge and experimental data, Eq. (9.2.3c) is applicable only when the total force per unit width (per bar for near-surface-mounted [NSM] systems) p_{fm} that the FRP system transfers to the masonry substrate satisfies the limitation given in Eq. (9.2.3d). This equation is intended to limit the maximum force transferable from FRP to masonry.

$$p_{fm} = \begin{cases} nt_f f_{fe} \leq 2200 \text{ lb/in. width of surface-mounted FRP systems} \\ A_{f, \text{bar}} f_{fe} \leq 10,000 \text{ lb/bar of NSM FRP systems} \end{cases} \quad (\text{in.-lb})$$

$$p_{fm} = \begin{cases} nt_f f_{fe} \leq 385 \text{ N/mm width of surface-mounted FRP systems} \\ A_{f, \text{bar}} f_{fe} \leq 44,500 \text{ N/bar of NSM FRP systems} \end{cases} \quad (\text{SI}) \quad (9.2.3d)$$

If experimental data for a particular masonry strengthening application is available and shows larger κ_m and p_{fm} values than the values indicated in Eq. (9.2.3c) and (9.2.3d), respectively, the designer may use these values. For instance, some experimental data have shown that larger κ_m values may be appropriate for the case of reinforced concrete masonry units (CMU) walls strengthened with FRP (Al-Jaberi et al. 2018).

9.2.4 Effective strain and stress in 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 can be found based on the assumption that plane sections remain plane and can be calculated as

$$\epsilon_{fe} = \epsilon_{mu} \left(\frac{d_f - c}{c} \right) \leq \epsilon_{fd} \quad (9.2.4a)$$

The effective stress can be calculated from the strain level in the FRP system, assuming perfectly elastic behavior, as given in Eq. (9.2.4b).

$$f_{fe} = E_f \epsilon_{fe} \quad (9.2.4b)$$

9.2.5 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. (9.2.4a). 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.

When FRP debonding is the governing failure mode, the effective stress in the FRP reinforcement can be computed from Eq. (9.2.3b) 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 specified in TMS 402/602. 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 elaborate methods such as Todeschini's method appropriately modified for 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. 2003a).

9.3—Serviceability

The serviceability of a masonry member, for example, deflections, under service loads, should satisfy applicable

provisions of **TMS 402/602**. FRP systems can be moderately effective in reducing deflections. 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 requirements.

Evaluation of the stress level in the FRP reinforcement at service is recommended for masonry walls that resist sustained loads, such as retaining walls. For this case, calculations should include any sustained lateral loads due to earth and hydrostatic pressure that are applied after the FRP system is installed. Depending on the service condition, a fraction or all lateral loads due to surcharge may also need to be included. The effect of FRP reinforcement on the in-service performance of a masonry wall can be evaluated using an elastic analysis for a cracked transformed section. The strain level in the FRP reinforcement at service conditions should be compared with the limitations described in Section 9.4 for the case of sustained or cyclic load conditions. For the case of RM, the stress in the existing steel reinforcement should be limited to 80% of the yield strength.

For URM walls strengthened with FRP, the in-service stress in the FRP reinforcement can be estimated using an elastic section analysis described in Eq. (9.3a), where M_s represents the moment due to all sustained loads, applied after the FRP is installed.

$$f_{f,s} = M_s \frac{\left(\frac{E_f}{E_m}\right) d_f (1-k)}{\frac{b_m d_f^3}{3} k^3 + \left(\frac{E_f}{E_m}\right) A_f d_f^2 (1-k)^2} \quad (9.3a)$$

For RM walls strengthened with FRP, the in-service stress, due to all sustained loads, in the steel and FRP reinforcement can be estimated using an elastic section analysis described in Eq. (9.3b) and (9.3c), respectively.

$$f_{s,s} = \frac{\left[M_s + \epsilon_{bi} A_f E_f \left(d_f - \frac{kd}{3} \right) \right] (d - kd) E_s}{A_s E_s \left(d_f - \frac{kd}{3} \right) (d - kd) + A_f E_f \left(d_f - \frac{kd}{3} \right) (d_f - kd)} \quad (9.3b)$$

$$f_{f,s} = f_{s,s} \left(\frac{E_f}{E_s} \right) \frac{d_f - kd}{d - kd} \quad (9.3c)$$

E_m in the previous equations is the modulus of elasticity of masonry in compression, which can be calculated as specified by TMS 402/602. Equation (9.3d) calculates the coefficient k for depth to the neutral axis at service.

$$k = \sqrt{2 \left(\rho_s \frac{E_s}{E_m} + \rho_f \frac{E_f}{E_m} \left(\frac{d_f}{d} \right) \right) + \left(\rho_s \frac{E_s}{E_m} + \rho_f \frac{E_f}{E_m} \right)^2} - \left(\rho_s \frac{E_s}{E_m} + \rho_f \frac{E_f}{E_m} \right) \quad (9.3d)$$

Table 9.4—Sustained plus cyclic service load stress limits in FRP reinforcement

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

9.4—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 in basements. To avoid creep rupture of the FRP systems under sustained loads, the in-service stress calculated from Eq. (9.3a) should not exceed the values shown in Table 9.4. 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—General

This chapter applies to fiber-reinforced polymer (FRP) systems used to enhance the shear and flexural strengths of unreinforced masonry (URM) walls subject to in-plane loads. This chapter does not provide recommendations for FRP strengthening of reinforced masonry (RM) walls.

FRP systems are effective in increasing the shear and flexural strength of URM walls subjected to in-plane loads (ElGawady et al. 2005; Marcari et al. 2007; Marshall and Sweeney 2002; Moon et al. 2003, 2007; Santa-Maria and Alcaino 2011; Tumialan et al. 2001).

The structural behavior of URM walls subject to in-plane loads can be controlled by shear or flexural failures. The behavior of the walls depends on several parameters, including geometry such as dimensions and thickness; construction type such as bond pattern, and type and strength of masonry units and mortar; axial loading; and boundary conditions. Whether a wall is dominated by shear behavior or flexural behavior is largely dependent on the aspect ratio and the vertical axial compressive forces. For walls with an aspect ratio L/h less than 1.0 with relatively light axial stress, behavior is usually dominated by flexure and limiting mechanism of either rocking or toe crushing. For walls with an aspect ratio L/h greater than 1.5 with moderate to heavy axial stress, shear usually dominates behavior and leads to failure through bed-joint sliding or diagonal tension (Magenes and Calvi 1997).

Walls under in-plane loads can have the following four modes of failure: diagonal tension; bed-joint sliding; toe crushing; and rocking. According to ASCE/SEI 41, diagonal tension and toe crushing are force-controlled failures, whereas bed-joint sliding and rocking are deformation-controlled failures (Fig. 10.1). Deformation-controlled failures are more ductile than force-controlled failures. A URM wall failing due to bed-joint sliding or rocking (deformation-controlled failures) has the ability to absorb more energy after initial cracking than URM walls failing due to force-controlled failures. Thus, an approach for strengthening of

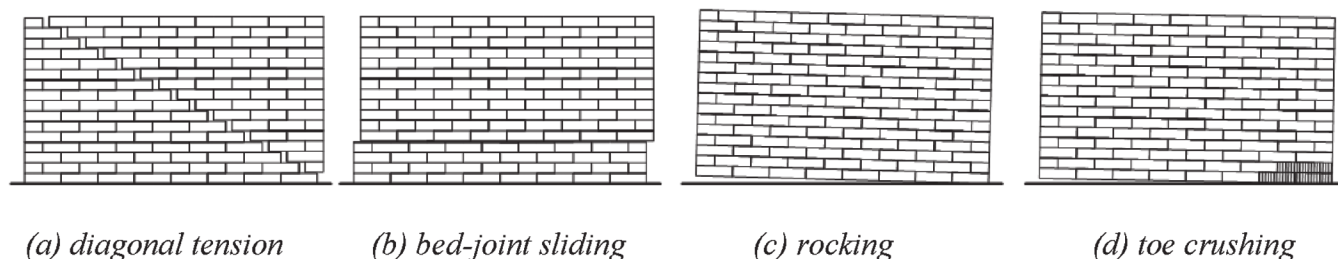


Fig. 10.1—Failure modes.

URM walls should be aimed at precluding the occurrence of force-controlled failures. In particular, FRP systems have been shown to increase the shear strength of existing URM walls subjected to in-plane loads by placing FRP reinforcement on one or two sides of the walls (Casareto et al. 2002; Grando et al. 2003; Tumialan et al. 2001). FRP systems are effective in increasing the shear strength of URM walls prone to crack in the diagonal direction.

There is limited research on infill walls (walls built within reinforced concrete or steel frames) strengthened with FRP and, therefore, this guide does not provide recommendation for shear strengthening of infill walls. In general, the in-plane behavior of infill walls is dependent on the relative stiffness ratio between the masonry and the surrounding frame, aspect ratio of the wall, and occurrence of premature failures such as crushing of corners in contact with the frame. Available research on infill walls strengthened with FRP (El-Dakhkhni et al. 2004; Tumialan et al. 2003b) shows marginal increases in the lateral carrying capacity but a significant improvement in the wall ability to reach larger lateral drifts without losing lateral carrying capacity.

10.2—Nominal shear strength of FRP-strengthened masonry walls subjected to in-plane loads

The strength design method requires that the design shear strength of the FRP-strengthened wall exceeds the factored shear demand as indicated by Eq. (10.2a).

$$\phi V_n \geq V_u \quad (10.2a)$$

The design strength is obtained as the nominal strength multiplied by the strength-reduction factor ϕ equal to 0.8 as required by TMS 402/602 for URM walls subject to in-plane shear loads.

A typical FRP strengthening scheme performed either with wet layup or near-surface-mounted (NSM) systems is indicated in Fig. 10.2(a) and (b), respectively. This guide discusses the most commonly used 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).

For walls subjected to in-plane loads only, extending the FRP systems a distance equal to the development length ℓ_{df} (refer to Chapter 13) beyond the wall, as shown in Fig. 10.2, is a good detailing practice but it is not required by the design methodology. This is because the design method is based on the assumption that FRP debonding governs the behavior of the FRP-strengthened wall. In several situations, however,

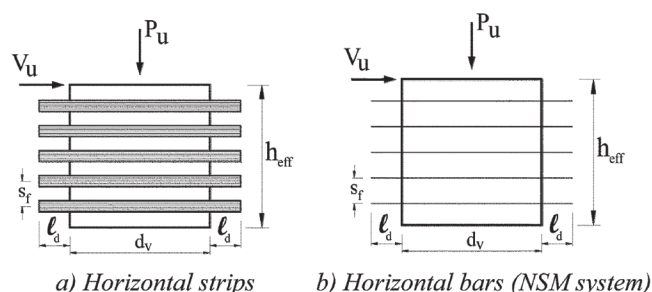


Fig. 10.2—FRP strengthening of shear-controlled walls.

extension 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. Bonding the FRP into boundary elements such as beams or columns to reduce the risk of wall overturning due to out-of-plane loads is not recommended. In such cases, other methods such as anchorage with steel elements should be considered.

Extending the FRP into the adjacent structural elements is not recommended for walls that will be simultaneously subjected to in-plane and out-of-plane loads. This is the case of seismic loads where the load reversal due to out-of-plane loads can cause localized damage and progressive debonding of the FRP at the wall boundaries with the adjacent elements. FRP mechanical anchors can be used to control localized debonding; however, the effectiveness of such mechanical anchorages should be substantiated through representative physical testing before specifying their use.

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 single-wythe or ungrouted URM walls (Grando et al. 2003; Tumialan et al. 2001). 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. For the case of multi-wythe brick walls, test results indicated that the contribution of FRP can be marginal (Casareto et al. 2002). In the absence of project-specific experimental evidence, this guide recommends FRP strengthening layouts based on the masonry construction as shown in Table 10.2, where the wall thicknesses are given in nominal dimensions. Further evaluation by the licensed design professional is required for cases that are not included in Table 10.2.