IN-LB	Inch-Pound Units
SI	International System of Units

Design and Construction of Externally Bonded Fiber-Reinforced Polymer(FRP) Systems for Strengthening Concrete Structures—Guide

Reported by ACI Committee 440

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Fiber-reinforced polymer(FRP)systems for strengthening concrete structures arean alternative to traditional strengtheningtechniques such as steel plate bonding,section enlargement,and external post-tensioning.FRP strengthening systems use FRP composite materials as supplemental externally bonded or near-surface-mounted (NSM)reinforcement.FRP systems offer advantages over traditional strengthening techniques:they are lightweight,relatively easy to install,and noncorroding.Due to the characteristics of FRP systems as well as the behavior of members strengthened with FRP,specific guidance on the use ofthese systems is needed.This guideprovides general information on the history and use ofFRP strengthening systems;a description of the material properties of FRP;and recommendations on the engineering,construction,and inspection ofFRP systems used to strengthen concrete structures. This guide is based on the knowledge gainedfrom experimental

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research,analytical work,and field applications ofFRP systems used to strengthen concrete structures.

Keywords: aramid fibers;basalt fibers;bridges;buildings;carbon fibers; corrosion;cracking;development length;carthquake resistance;fiber-reinforced polymers;glass fibers;structural design.

CONTENTS

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

The strengthening or retrofitting of existing concrete structures to resist higher design loads,correct strength loss due to deterioration,correct design or construction deficiencies, or increase ductility has traditionally been accomplished using conventional materials and construction techniques, including externally bonded steel plates,steel jackets, concrete section enlargement,and external post-tensioning.

Composite materials made of fibers in a polymeric resin, also known as fiber-reinforced polymers(FRPs),have emerged as a viable option for repair and rehabilitation.For the purposes of this guide,an FRP system is defined as the fibers and resins used to create the composite laminate,all applicable resins used to bond it to the concrete substrate, and all coatings applied to protect the constituent materials.Coatings used exclusively for aesthetic reasons are not considered part of an FRP system.

FRP materials are lightweight,noncorroding,and exhibit high tensile strength.These materials are readily available in several forms,ranging from factory-produced pultruded laminates to fabric reinforcement sheets that can be wrapped to conform to the geometry of a structure.The relatively thin profiles of cured FRP systems are often desirable in applications where aesthetics or access is a concern and FRP systems add little weight to a structure.FRP systems can also be used in areas with limited access where traditional techniques would be difficult to implement.

The basis for this document is the knowledge gained from a comprehensive review of experimental research,analytical work,and field applications of FRP strengthening systems. Areas where further research is needed are highlighted and compiled in Appendix B.

This version includes several revisions to ACI 440.2-17 as outlined herein.Basalt FRP(BFRP)is now included in the commercially available materials for FRP systems.The methodology for calculating FRP system mechanical properties has been revised in Section 4.3. Fatigue behavior of FRP systems has been updated to reflect recent research. Chapter 7 for field inspection,testing,and evaluation of FRP systems has been revised to be consistent with industry standards and specifications such as the IBC,ACI SPEC-440.12, and ACI CODE-562.The applicability of FRP systems for strengthening lightweight concrete is addressed in Section 9.1.1.In Section 9.2.1,the load combination for minimum structural fire resistance of a member for FRP strengthening has been revised to be consistent with ACI CODE-562. Sections 10.3.2 and 16.14 have been added to address FRP strengthening of members with unbonded prestressing steel. Fiber anchors for anchoring FRPU-wraps for shear strengthening are introduced in Sections 11.4.1.2 and 14.1.4.Section 13.7 for seismic strengthening of shear walls has been revised to include guidance for detailing of the FRP and for confinement of boundary elements in plastic hinge regions.

1.1.1 Use of FRP systems—This document refers to commercially available FRP systems consisting of fibers and resins combined in a specific manner and installed by a specific method.These systems have been developed through material characterization and structural testing. Untested combinations of fibers and resins could result in an unexpected range of properties as well as potential material incompatibilities and should be avoided.Any FRP system considered for use should have sufficient test data to demonstrate adequate performance of the entire system in similar applications,including its method of installation. ACI 440.8provides a specification for unidirectional carbon and glass FRP systems made using the wet layup process.

The use of FRP systems developed through material characterization and structural testing,including well-documented proprietary systems,is recommended.A comprehensive set of test standards and guides for FRP systems has been developed by several organizations, including ASTM International,ACI,the International Concrete Repair Institute(ICRI),and the International Code Council(ICC).

1.1.2 Sustainability—Sustainability of FRP materials and systems may be evaluated considering environmental, economic,and social goals.These should be considered not only throughout the construction phase,but also through the service life of the structure in terms of maintenance and preservation,and for the end-of-life phase.This represents the basis for a life-cycle approach to sustainability(Menna et al.2013).Life cycle assessment(LCA)takes into account the environmental impact of a product,starting with raw material extraction,followed by production,distribution, transportation,installation,use,and end of life.LCA for FRP composites depends on the product and market application,and results vary.FRP composite materials used to strengthen concrete elements can use both carbon fiber and glass fiber,which are derived from fossil fuels or minerals, respectively,and therefore have impacts related to raw material extraction.Although carbon and glass fibers have high embodied energies associated with production,on the order of 86,000 btu/lb and 8600 btu/lb(200 and 20mJ/kg),respectively(Howarth et al.2014),the overall weight produced and used is orders of magnitude lower than steel (having embodied energy of 5600 Btu/lb [13 mJ/kg]),concrete (430 Btu/lb [1 mJ/kg]),and reinforcing steel (3870 Btu/lb [9 mJ/kg])(Grifin and Hsu 2010).The embodied energy and potential environmental impact of resin and adhesive systems are less studied,although the volume used is also small in comparison with conventional construction materials.In distribution and transportation,FRP composites' lower weight leads to less impact from transportation,and easier material handling allows smaller equipment during installation.For installation and use,FRP composites are characterized as having a longer service life because they are more durable and require less maintenance than conventional materials.The end-of-life options for FRP composites are more complex.

Although less than 1%of FRP composites are currently recycled,composites can be recycled in many ways, including mechanical grinding,incineration,and chemical separation(Howarth et al.2014).However,separating the materials,fibers,and resins is difficult;therefore,the properties of the resulting recycled materials are generally of a lower grade than the source material.

Apart from the FRP materials and systems themselves, their use in the repair and retrofit of structures that may otherwise be decommissioned or demolished is inherently sustainable.In many cases,FRP composites permit extending the life or enhancing the safety or performance of existing infrastructure at monetary and environmental costs of only a fraction of those for replacement.Additionally,due to the high specific strength and stiffness of FRP composites,an FRP-based repair of an existing concrete structure will often represent a less energy-intensive option than a cementitious or metallic-based repair.

Within this framework of sustainability,FRP retrofit of existing structures may lead to benefits,contributing to the longevity and safety of retrofitted structures.Thus,FRP retrofit can be regarded as a viable method for sustainable design for strengthening and rehabilitation of existing structures(Maxineasa and Taranu 2018;Napolano et al.2015). The environmental advantages of FRP,as evaluated by LCA investigations,have been enumerated by Moliner Santisteve et al.(2013),Zhang et al.(2012), and Das (2011).

1.2—Scope

This document provides guidance for the selection,design, and installation of externally bonded and near-surface-mounted(NSM)FRP systems for strengthening concrete structures.Information on material properties,design,installation,quality control,and maintenance ofFRPsystems used as external or NSM reinforcement is presented.This information can be used to select an FRPsystem for increasing the strength,stiffness,or both,of reinforced concrete members or the ductility of columns.

A significant body of research serves as the basis for this guide.This research,conducted since the 1980s,includes analytical studies,experimental work,and monitored field applications of FRP strengthening systems.Based on the available research,the design procedures outlined herein are considered conservative.

The durability and long-term performance of FRP systems have been the subject of muchresearch which remains ongoing. The design guidelines in this document account for environmental degradation and long-term durability by providing reduction factors for various environments.Fatigue and creep are also addressed by stress limitations indicated in this document.As more research becomes available,these factors may be modified,and the specific environmental and loading conditions to which they apply will be better defined.Additionally,the coupling effect of environmental exposure and loading conditions requires further study.Caution is advised in applications where the FRP system is subjected simultaneously to extreme environmental and stress conditions.

Many issues regarding bond of the FRP system to the substrate remain the focus of a great deal of research.For both flexural and shear strengthening,there are different modes of debonding failure that can govern the strength of an FRP-strengthened member.While most of the debonding modes have been identified by researchers,more accurate methods of predicting debonding are still needed. Throughout the design procedures,significant limitations on the strain permitted in the FRP system (and thus,the permitted stress)are imposed to conservatively account for debonding failure modes.Future development of these design procedures should include more thorough methods of predicting debonding.

This document gives guidance on proper detailing and installation of FRP systems to prevent many types of debonding failure modes.Steps related to the surface preparation and proper termination of the FRP system are vital in achieving the levels of strength predicted by the procedures in this document.Research has been conducted on various methods of anchoring FRP strengthening systems, such as U-wraps,mechanical fasteners,fiber anchors,and U-anchors.This document contains design provisions for the use of fiber anchors for shear strengthening with FRP U-wraps.For other anchorage systems and applications, few design guidelines are currently available.The performance of any such anchorage system should be substantiated through representative physical testing that includes the specific anchorage system,installation procedure,surface preparation,and expected environmental conditions.

The design equations given in this document are the result of research primarily conducted on moderately sized and proportioned members fabricated of normalweight concrete. Caution should be given to applications involving strengthening of very large or lightweight concrete members or strengthening in disturbed regions(D-regions)of structural members such as deep beams,corbels,and dapped beam ends.When warranted,specific limitations on the size of members and the state of stress are given herein.

This guide applies only to FRP strengthening systems used as additional tensile reinforcement.These systems should not be used as compressive reinforcement.While FRP systems can support compressive stresses,there are numerous issues associated with the use of FRP for compression.Microbuckling of fibers can occur if any resin voids are present in the laminate.Laminates themselves can buckle if not properly adhered or anchored to the substrate,and highly unreliable compressive strengths result from misaligning fibers in the field.This document does not address the construction, quality control,and maintenance issues that would be necessary for the use of FRP systems for compressive reinforcement,nor does it address design for such applications.

This document does not specifically address masonry (concrete masonry units,brick,or clay tile)construction. Information on the strengthening of masonry structures using FRP systems can be found in ACI PRC-440.7.

1.2.1 Applications and use—FRP systems can be used to rehabilitate or restore the strength of a deteriorated structural member,retrofit or strengthen a sound structural member to resist increased loads due to changes in use of the structure, or address design or construction errors.The licensed design professional should determine if an FRP system is a suitable strengthening technique before selecting the type of FRP system.

To assess the suitability of an FRP system for a particular application,the licensed design professional should perform a condition assessment of the existing structure that includes establishing its existing load-carrying capacity,identifying deficiencies and their causes,and determining the condition of the concrete substrate.The overallevaluation should include a thorough field inspection,a review of existing design or as-built documents,and a structural analysis in accordance with ACI 364.1R. Existing construction documents for the structure should be reviewed,including the design drawings,project specifications,as-built information, field test reports,pastrepair documentation,and maintenance history documentation.The licensed design professional should conduct a thorough field investigation of the existing structure in accordance with ACI 437R,ACI CODE-562, ACI 369R,and other applicable documents.As a minimum, the field investigation should determine the following:

(a)Existing dimensions of the structural members
(b)Location,size,and cause of cracks and spalls
(c)Quantity and location of existing reinforcing steel
(d)Location and extent of corrosion of reinforcing steel
(e)Presence of active corrosion
(f)In-place compressive strength of concrete
(g)Soundness of the concrete,especially the concrete cover,in all areas where the FRP system is to be bonded to the concrete

The tensile strength of the concrete on surfaces where the FRP system may be installed should be determined by conducting a pulloff adhesion test in accordance with ICRI 210.3R or ASTM C1583/C1583M. The in-place compressive strength of concrete should be determined using cores in accordance with ACI CODE-562 requirements.The load-carrying capacity of the existing structure should be based on the information gathered in the field investigation,the review of design calculations and drawings,and as determined by analytical methods.Load tests or other methods can be incorporated into the overall evaluation process if deemed appropriate.

Fiber-reinforced polymer systems used to increase the strength of an existing member should be designed in accordance with Chapters 9 through 15,which include a comprehensive discussion of load limitations,rational load paths, effects of temperature and environment on FRP systems, loading considerations,and effects of reinforcing steel corrosion on FRP system integrity.

1.2.1.1 Strengthening limits—In general,to prevent sudden failure of the member in case the FRP system is damaged,strengthening limits are imposed such that the increase in the load-carrying capacity of a member strengthened with an FRP system is limited.The philosophy is that a loss ofFRP reinforcement should not cause member failure. Specific guidance,including load combinations for assessing member integrity after loss of the FRP system,is provided in Chapter 9.

*1.2.1.2 Fire and life safety—FRP-strengthened struc-*tures should comply with applicable building and fire codes.Smoke generation and flame spread ratings in accordance with ASTM E84 should be satisfied for the installation according to applicable building codes,depending on the classification of the building.Coatings (Apicella and Imbrogno 1999) and insulation systems(Williams et al. 2006) can be used to limit smoke and flame spread.

Because of the degradation of most FRP systems at high temperature,the strength of externally bonded FRP systems is assumed to be lost completely in a fire,unless it can be demonstrated that the FRP will remain effective for the required duration of the fire.The fire resistance of FRP-strengthened concrete members may be improved through the use of certain resins,coatings,insulation systems,or other methods of fire protection(Bisby et al. 2005b).Specific guidance,including load combinations and a rational approach to calculating structural fire resistance,is given in 9.2.1 and inACI PRC-440.10.

1.2.1.3 Maximum service temperature—The physical and mechanicalproperties ofthe resin components ofFRPsystems are influenced by temperature and degrade at temperatures close to or above their glass-transition temperature T_g(Bisby et al.2005b).The T_g for commercially available,ambient emperature-cured FRP systems typically ranges from 140 to 180°F(60 to 82°C).The T_g for a particular FRP system can be obtained from the system manufacturer or through testing by dynamic mechanical analysis(DMA)according to ASTME1640 . Reported Tgvalues should be accompanied by descriptions of the test configuration,sample preparation, sample curing conditions(time,temperature,and humidity), size,heating rate,and frequency used.The Tg defined by this method represents the extrapolated onset temperature for the sigmoidal change in the storage modulus observed in going from a hard and brittle state to a soft and rubbery state of the material under test.This transition occurs over a temperature range of approximately 54°F(30°C)centered on the Tg.This change in state will adversely affect the mechanical and bond properties of the cured laminates.In a dry environment,it is generally recommended that the anticipated service temperature of an FRP system not exceed Tg-27F (T_8-15°C)(Xian and Karbhari 2007),where Tg is taken as the lowest Tg of the components of the system comprising the load path.This recommendation is for elevated service temperatures such as those found in hot climatic regions or certain industria environments.In cases where the FRP will be exposed to a moist environment,the wet glass-transition temperature Tgw should be used (Luo and Wong 2002). Testing may be required to determine the critical service temperature for FRP in other environments.The specific case of fire is described in more detail in 9.2.1.

1.2.1.4 Minimum concrete substrate strength—FRP systems need to be bonded to a sound concrete substrate and should not be considered for applications on structural members containing corroded reinforcing steel or deteriorated concrete unless the substrate is repaired using the recommendations in 6.4. Concrete distress,deterioration,and corrosion of existing reinforcing steel should be evaluated and addressed before the application of the FRP system.Concrete deterioration concerns include,but are not limited to,alkali-silica reactions,delayed ettringite formation,carbonation,longitudinal cracking around corroded reinforcing steel,and laminar cracking at the location of the steel reinforcement.

The strength of the existing concrete substrate is an important parameter for bond-critical applications,including flexure or shear strengthening.The substrate should possess the necessary strength to develop the design stresses of the FRP system through bond.The substrate,including all bond surfaces between repaired areas and the original concrete,should have sufficient direct tensile and shear strength to transfer force to the FRP system.For bond-critical applications,the tensile strength should be at least 200 psi(1.4 MPa),determined by using a pulloff type adhesion test per ICRI 210.3R or ASTM C1583/C1583M.FRP systems should not be used when the concrete substrate has a compressive strength f!'less than 2500 psi(17 MPa). Contact-critical applications,such as column wrapping for confinement that rely only on intimate contact between the FRP system and the concrete,are not governed by these minimum values.In contact-critical applications,stresses in the FRP system are developed due to lateral expansion, also called dilation,of the concrete section,primarily under compressive stresses.

The application of FRP systems will not stop ongoing corrosion of existing reinforcing steel (El-Maaddawy et al. 2006).If steel corrosion is evident or is degrading the concrete substrate,placement of FRP reinforcement is not recommended without arresting the ongoing corrosion and repairing any degradation of the substrate.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

Aanc =gross laminate area of the fiber anchor,in.² (mm²)
Ac = cross-sectional area of concrete in compression member,in.²(mm²)
Acg = area of gross concrete section,neglecting reinforcement,in.²(mm²)
Aw = area of concrete section of individual vertical wall,in.²(mm²)
Ae = cross-sectional area of effectively confined concrete section,in.²(mm²)
A = area of FRP external reinforcement,in.²(mm²)
Afanchor = area of transverse FRP U-wrap for anchorage of flexural FRP reinforcement,in.²(mm²)
Af = area of FRP shear reinforcement with spacing s,in.²(mm²)
Ag = gross area of concrete section,in.²(mm²)
Ap = area of prestressed reinforcement in tension zone,in.²(mm²)
As = area of nonprestressed steel reinforcement,in.² (mm²)
Asc = area of the longitudinal reinforcement within a distance of w in the compression region,in.² (mm²)
Ai =area of i-th layer of longitudinal steel reinforcement,in.²(mm²)
Asr =total area oflongitudinal reinforcement,in.²(mm²)
Aw = area oflongitudinal reinforcement in the central area of the wall,in.²(mm²)
a = depth of the equivalent concrete compression block,in.(mm)
a = smaller cross-sectional dimension for rectangular FRP bars,in.(mm)
b =width of compression face of member,in.(mm)
=short side dimension of compression member ofprismatic cross section,in.(mm)
b =larger cross-sectional dimension for rectangular FRP bars,in.(mm)
bw = web width or diameter of circular section,in. (mm)
CE = environmental reduction factor
Csc = compressive force in Ac,Ib(N)
C = distance from extreme compression fiber to the neutral axis,in.(mm)
Ca,fip distance from extreme compression fiber to the neutral axis at ultimate capacity,in.(mm)
Cyfrp = distance from extreme compression fiber to the neutral axis at steel yielding,in.(mm)
D = diameter of compression member for circular cross sections or diagonal distance equal to

$\sqrt{b^2+h^2}$ for prismatic cross section (diameter of equivalent circular column), in. (mm)

d = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)

d = distance from the extreme compression fiber to the center of Ase, in. (mm)

d" = distance from the extreme tension fiber to the center of Asn, in. (mm)

dbe = diameter of longitudinal steel in confined plastic hinge, in. (mm)

d = effective depth of FRP flexural reinforcement, in. (mm)

dp = effective depth of FRP shear reinforcement, in. (mm)

dj = distance from centroid of i-th layer of longitudinal steel reinforcement to geometric centroid of cross section, in. (mm)

dp = distance from extreme compression fiber to centroid of prestressed reinforcement, in. (mm)

E₂ = slope of linear portion of stress-strain model for FRP-confined concrete, psi (MPa)

Ec = modulus of elasticity of concrete, psi (MPa)

Ey = chord tensile modulus of elasticity of FRP, psi (MPa)

Es = modulus of elasticity of prestressing steel, psi (MPa)

E, = modulus of elasticity of steel, psi (MPa)

e = eccentricity of prestressing steel with respect to centroidal axis of member at support, in. (mm)

em = eccentricity of prestressing steel with respect to centroidal axis of member at midspan, in. (mm)

Fe = resultant force of concrete block stress, Ib (N)

F = resultant force of FRP system, Ib (N)

F, = resultant force of internal reinforcing steel, Ib (N)

F, = resultant force of internal reinforcing steel assuming yield of steel, Ib (N)

fe = compressive stress in concrete, psi (MPa)

fe' = specified compressive strength of concrete, psi (MPa)

fc' = compressive strength of confined concrete, psi (MPa)

fc = compressive strength of unconfined concrete; also equal to 0.85f, psi (MPa)

fcs = compressive stress in concrete at service condition, psi (MPa)

f = stress in FRP reinforcement, psi (MPa)

fa = design stress of externally bonded FRP reinforcement, psi (MPa)

Jfe = effective stress in the FRP; stress attained at section failure, psi (MPa)

Jfis = stress in FRP caused by a moment within elastic range of member, psi (MPa)

Ju = design ultimate tensile strength of FRP, psi (MPa)

fa = mean tensile strength of a sample of at least 20 FRP test specimens

Jfu = ultimate tensile strength of the FRP material as reported by the manufacturer, psi (MPa)

f = maximum confining pressure due to FRP jacket, psi (MPa)

Jfps = stress in prestressed reinforcement at nominal strength, psi (MPa)

Jfpss = stress in prestressed reinforcement at service load, psi (MPa)

Jfpu = specified tensile strength of prestressing tendons, psi (MPa)

fpy = specified yield strength of prestressing reinforcement, psi (MPa)

f stress in nonprestressed steel reinforcement, psi (MPa)

fse stress in the longitudinal reinforcement corresponding to Ac, psi (MPa)

fsi = stress in the i-th layer of longitudinal steel reinforcement, psi (MPa)

JSss stress in nonprestressed steel reinforcement at service loads, psi (MPa)

fs stress in the longitudinal reinforcement corresponding to A1, psi (MPa)

fsw = stress in the longitudinal reinforcement corresponding to Asw, psi (MPa)

fy = specified yield strength of nonprestressed steel reinforcement, psi (MPa)

g = clear gap between the FRP jacket and adjacent members, in. (mm)

h overall thickness or height of a member, in. (mm)

= long side cross-sectional dimension of rectangular compression member, in. (mm)

hane = minimum embedment depth of fiber anchor in concrete, in. (mm)

h, = member flange thickness, in. (mm)

hw = height of entire wall from base to top, or clear height of wall segment or wall pier considered, in. (mm)

I = moment of inertia of section about centroidal axis, in.^{4} (mm^4)

Ic = moment of inertia of cracked section transformed to concrete, in.4 (mm^4)

Ig = moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in.4 (mm^4)

I = moment of inertia of uncracked section transformed to concrete, in.4 (mm^4)

k = ratio of depth of neutral axis to reinforcement depth measured from extreme compression fiber

k_1 = modification factor applied to k, to account for concrete strength

k_2 = modification factor applied to k, to account for wrapping scheme

ky = stiffness per unit width per ply of the FRP reinforcement, Ib/in. (N/mm); ky = Ety

La = total length of unbonded tendon between anchorages, in. (mm)

Le = active bond length of FRP laminate, in. (mm)

Lp = plastic hinge length, in. (mm)

Lw = length of the shear wall,in.(mm)
=development length of near-surface-mounted FRP,in.(mm)
laE =length over which the FRP anchorage wraps are provided,in.(mm)
Lj =development length of FRP system,in.(mm)
∘ =length,measured along the member axis from the face of the joint,over which special transverse reinforcement must be provided,in.(mm)
lprov =length of steel lap splice,in.(mm)
M =cracking moment,in.-1b(N-mm)
Mn =nominal flexural strength at a section,in.-1b (N-mm)
Mn = contribution ofFRP reinforcement to nominal flexural strength at a section,in.-1b(N-mm)
M =contribution of prestressing reinforcement to nominal flexural strength at a section,in.-1b (N-mm)
Mns = contribution of steel reinforcement to nominal flexural strength at a section,in.-1b(N-mm)
M∘ =secondary moment due to prestressing at a section,in.-1b(N-mm)
M3 = service moment at a section,in.-Ib(N-mm)
Msnet =service moment at a section beyond decompression,in.-1b(N-mm)
M = factored moment at a section,in.-1b(N-mm)
N =number of plies of FRP reinforcement
n =modular ratio of elasticity between FRP and concrete=E/E
ng =modular ratio of elasticity between steel and concrete=E/E.
Pe =effective force in prestressing reinforcement (after allowance for all prestress losses),1b(N)
P =nominal axial compressive strength of a concrete section,1b(N)
P = factored axial load,Ib(N)
Pfu =mean tensile strength per unit width per ply of FRP reinforcement,Ib/in.(N/mm)
Pfiu =ultimate tensile strength per unit width per ply of FRP reinforcement,Ib/in.(N/mm);pu= fut;
R = nominal strength of a member subjected to elevated temperatures associated with a fire
R = ratio of area of fiber in fiber anchor to area of fiber in one leg of shear U-wrap
R = nominal strength of a member
r = radius of gyration of a section,in.(mm)
Fane = length of fiber anchor splay,in.(mm)
r. = radius of edges of a prismatic cross section confined with FRP,in.(mm)
SDL = dead load effects
SL = live load effects
Ssz = snow load effects
Sane = center-to-center spacing of fiber anchors,in.(mm)
S = center-to-center spacing ofFRP strips,in.(mm)
T = tensile force in FRP,1b(N)
Tg = glass-transition temperature,F(°C)
Tgw =wet glass-transition temperature,F(°C)
Tps =tensile force in prestressing steel,1b(N)
T3 = tensile force in As,1b(N)
Tsw =tensile force in Asw,1b(N)
t = nominal thickness of one ply ofFRP reinforcement,in.(mm)
tw = thickness of the existing concrete shear wall, in.(mm)
Vc = nominal shear strength provided by concrete,Ib (N)
V =design shear force for load combinations including earthquake effects,Ib(N)
V nominal shear strength provided by FRP stirrups,Ib(N)
Vn nominal shear strength,1b(N)
V, =shear strength of existing member,Ib(N)
V = nominal shear strength provided by steel stirrups,Ib(N)
V =factored shear force at a section,Ib(N)
W =width of FRP reinforcing plies,in.(mm)
yb =distance from centroidal axis of gross section, neglecting reinforcement,to extreme bottom fiber,in./in.(mm/mm)
y =vertical coordinate within compression region measured from neutral axis position.It corresponds to transition strain ε/,in.(mm)
α angle of application of primary FRP reinforcement direction relative to longitudinal axis of member
α1 =multiplier on f'to determine intensity of an equivalent rectangular stress distribution for concrete
αanc =angle over which fiber anchor is splayed over externally bonded FRP,degrees
αL =longitudinal coefficient of thermal expansion, in./in./°F(mm/mm/°C)
αT =transverse coefficient of thermal expansion,in./in./°F(mm/mm/°C)
β1 =ratio of depth of equivalent rectangular stress block to depth of the neutral axis
Pane embedment angle of fiber anchors,deg
εb = strain in concrete substrate developed by a given bending moment(tension is positive), in./in.(mm/mm)
Ebi = strain in concrete substrate at time of FRP installation (tension is positive),in./in.(mm/mm)
εc =strain in concrete,in./in.(mm/mm)
8c' =compressive strain of unconfined concrete corresponding tof',in./in.(mm/mm);may be taken as 0.002
ccu =ultimate axial compressive strain of confined concrete corresponding to 0.85fcin a lightly confined member (member confined to restore its concrete design compressive strength),or ultimate axial compressive strain of confined concrete corresponding to failure in a heavily confined member

8c,s = strain in concrete at service,in./in.(mm/mm)

Ect = concrete tensile strain at level of tensile force resultant in post-tensioned flexural members, in./in.(mm/mm)

cu = ultimate axial strain of unconfined concrete corresponding to 0.85for maximum usable strain of unconfined concrete,in./in.(mm/mm), which can occur atfe=0.85f.'or εc=0.003, depending on the obtained stress-strain curve

8 = strain in the FRPreinforcement,in./in.(mm/mm)

Ca =debonding strain of externally bonded FRP reinforcement,in./in.(mm/mm)

je =effective strain in FRP reinforcement attained at failure,in./in.(mm/mm)

ju =design rupture strain of FRP reinforcement,in./in.(mm/mm)

Enu =ultimate rupture strain of FRP reinforcement, in./in.(mm/mm)

&pe =effective strain in prestressing steel after losses, in./in.(mm/mm)

Bpi = initial strain in prestressed steel reinforcement, in./in.(mm/mm)

Epnet = net strain in flexural prestressing steel at limit state after prestress force is discounted (excluding strains due to effective prestress force after losses),in./in.(mm/mm)

EpneLs net strain in prestressing steel beyond decompression at service,in./in.(mm/mm)

ps strain in prestressed reinforcement at nominal strength,in./in.(mm/mm)

Eps.s = strain in prestressing steel at service load,in./in.(mm/mm)

g = strain in nonprestessed steel reinforcement,in./in.(mm/mm)

Egy =strain corresponding to yield strength of nonprestressed steel reinforcement,in./in.(mm/mm)

E = net tensile strain in extreme tension steel at nominal strength,in./in.(mm/mm)

8' = transition strain in stress-strain curve of FRP-confined concrete,in./in.(mm/mm)

η =parameter that combines the effects of member continuity and applied load pattern for producing maximum factored moment at the critical section under consideration

ф =strength reduction factor

中D =design curvature for a confined concrete section

φex =strength reduction factor used to check strength of member subject to fire or elevated temperature calculated using reduced material properties

中 = curvature of the FRP confined section at ultimate capacity,1/in.(1/mm)

中 = curvature of the FRP confined section at steel yielding,1/in.(1/mm)

Ka = efficiency factor for FRP reinforcement in determination of fec(based on geometry of cross section)

Kb =efficiency factor for FRP reinforcement in determination of Eccu(based on geometry of cross section)

Ky = bond-dependent coefficient for shear

Kg = 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

θ, =plastic hinge rotation demand

Pr = FRP reinforcement ratio

Pg =ratio of area of longitudinal steel reinforcement to cross-sectional area of a compression member(A,/bh)

Pe longitudinal reinforcement ratio

Ps =ratio of nonprestressed reinforcement

5 = standard deviation

Tb = average bond strength for near-surface-mounted FRP,psi(MPa)

Tmax =bond strength for near-surface-mounted FRP, psi(MPa)

Ve = factor used to modify development length based on reinforcement coating

V FRP strength reduction factor

= 0.85 for flexure(calibrated based on design material properties)

= 0.85 for shear(based on reliability analysis)for three-sided FRPU-wrap or two-sided strengthening schemes

=0.95 for shear fully wrapped sections

ys =factor used to modify development length based on reinforcement size

V. =factor used to modify development length based on reinforcement location

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource,"ACI Concrete Terminology."Definitions provided herein complement that source.

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.

basalt fiber—fiber produced by heating precursor materials composed of the minerals plagioclase,pyroxene,and olivine (that is,basalt rock).

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

carbon fiber—fiber producedbyheating 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 fabric,mat,or strands.

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

contact-critical application—strengthening or repair system that relies on load transfer from the substrate to the system material achieved through contact or bearing at the interface.

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 alumina borosilicate composition and a maximum alkali content of 2.0%.

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

fabric reinforcement—reinforcing fibers in fabric form.

fiber anchor—bundle of fibers that may be either shop- or field-fabricated having a specified length and fiber content and impregnated with resin.One end of the fibers is embedded into the concrete substrate and the other end is splayed over externally bonded fabric.

fiber content—the amount offiber 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 ofa 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 fabric,mat,or strands.

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

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 fabric 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 for use as a precursor in the manufacture of some carbon fibers.

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

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

post-curing—application of elevated temperature to material containing thermosetting resin to increase the degree of polymer crosslinking and enhance the final material properties.

prepreg— sheet of fabric or mat preimpregnated 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 concrete substrate.

resin content—amount of resin in a fiber-reinforced polymer composite laminate,expressed as either apercentage 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.

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.

vinylesterresin—thermosetting reaction product ofepoxy 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 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—BACKGROUND INFORMATION

Externally bonded fiber-reinforced polymer(FRP) systems have been used to strengthen and retrofit existing concrete structures around the world since the mid-1980s. The number of projects using FRP systems worldwide has increased dramatically,from a few in the 1980s to many thousands today.Structural elements strengthened with externally bonded FRP systems include beams,slabs, columns,walls,joints/connections,chimneys and smoke-stacks,vaults,domes,tunnels,silos,pipes,and trusses. Externally bonded FRP systems have also been used to strengthen masonry,timber,steel,and cast-iron structures.

3.1—Historical development

The initial development of externally bonded FRP systems for the retrofit of concrete structures occurred in the 1980s in Europe,Japan,and the United States(Fardis and Khalili 1981;Katsumata et al.1987;Nanni 1995).In Europe,FRP systems were developed as alternates to steel plate bonding.Bonding steel plates to the tension zones of concrete members with adhesive resins was shown to be a viable technique for increasing flexural strength (Fleming and King 1967).This technique has been used to strengthen many bridges and buildings around the world.Because steel plates can corrode,leading to a deterioration of the bond between the steel and concrete,and because they are difficult to install,requiring the use of heavy equipment,researchers looked to FRP systems as an alternative to steel.Experimental work using FRP systems for retrofitting concrete structures was reported as early as 1978 in Germany(Wolf and Miessler 1989).Research in Switzerland led to the first applications of externally bonded FRP systems for flexural strengthening of reinforced concrete bridges(Meier 1987; Rostasy 1987).

In the United States,development and research into the use of these materials for retrofitting concrete structures started through the initiatives of the National Science Foundation (NSF)and the Federal Highway Administration(FHWA). The research activities led to the construction of many field projects that encompassed a wide variety of environmental conditions.Previous research and field applications for FRP rehabilitation and strengthening are described in ACI 440R and conference proceedings,including those of the Fiber Reinforced Polymers for Reinforced Concrete Structures (Aiello et al.2001;Funakawa et al.1997;Palmieri et al. 2011;Rotasy 1997; Yamaguchi et al.1997),Composites in Civil Engineering(CICE)(Avorio and Borri 2001),and Conference on Durability of Composites for Construction (CDCC)series(Green et al.1998;Malvar 1998;Carolin et al.2001).

The development of codes and standards for externally bonded FRP systems is ongoing in Europe,Japan,Canada, and the United States.The firstpublished codes and standards appeared in Japan(Japan Society of Civil Engineers 2001) and Europe(International Federation for Structural Concrete 2001).In the United States, ACI 440.8,ICC AC125,and NCHRP Report 655(Zureick et al.2010)provide criteria for evaluating FRP systems.

3.2—Commercially available externally bonded FRP systems

FRP systems come in a variety of forms,including wet layup systems and precured systems.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 acceptable transfer of structural loads and the ease of application.Common FRPsystem forms suitable for the strengthening of structural members are listed in 3.2.1 through 3.2.4.

3.2.1 Wet layup systems—Wet layup FRP systems consist of dry unidirectional or multidirectionalfiber 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 concrete surface.Wet layup systems are saturated on site and cured in place.The common types of fiber reinforcement used in wet layup systems are as follows:

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

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

Another possible system may include dry fiber tows that are impregnated during installation and wound or otherwise mechanically applied to the concrete surface.However,this system is not commonly used.

3.2.2 Prepreg systems—Prepreg FRP systems consist of partially cured unidirectional or multidirectional fiber sheets or fabrics that are preimpregnated with a saturating resin in the manufacturer's facility.Prepreg systems are bonded to the concrete 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 heating or moisture for curing.Prepreg system manufacturers should be consulted for storage and shelf-life recommendations and curing procedures.The common types of prepreg FRP systems are as follows:

1.Preimpregnated unidirectional fiber sheets where the fibers run predominantly in one planar direction.

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

Preimpregnated fiber tows that are wound or otherwise mechanically applied to the concrete surface have been developed.However,this system is not commonly used.

3.2.3 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 concrete surface. The system manufacturer should be consulted for recommended installation procedures.Three common types of precured systems are:

1.Precured unidirectional laminate sheets,typically manufactured using a pultrusion process,delivered to the site in the form of large flat stock or as thin plates 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 concrete and to each other to provide confinement

*3.2.4 Near-surface-mounted(NSM)systems—Surface-*embedded NSM FRP systems consist of circular bars or narrow rectangular plates installed and bonded into grooves made on the concrete surface.A suitable adhesive is used to bond the FRP bar or plate into the groove and is cured in place.The NSM system manufacturer should be consulted for recommended adhesives.Two common FRP types used for NSM applications are:

1.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.Plates usually manufactured using pultrusion processes, typically delivered to the site in a roll

CHAPTER 4—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 concrete structures.The effects of factors such as loading history and duration,temperature,and moisture on the properties of FRP are discussed.

FRPstrengthening systems come 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 FRPsystem.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 A).ACI 440.8 provides a specification for unidirectional carbon FRP(CFRP)and glass FRP(GFRP)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.

4.1—Constituent materials

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

4.1.1 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,polyesters,and polyurethane 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 concrete 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,the effects of moisture,salt water,temperature extremes,and chemicals normally associated with exposed concrete

(e)Filling ability

(f)Workability

(g)Pot life consistent with the application

(h)Development of appropriate mechanical properties for the FRP composite

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

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

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

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

4.1.2 Fibers—Continuous glass,basalt,aramid,andcarbon fibers are common reinforcements used in FRP systems.The fibers give the FRP system its strength and stiffness.

4.1.3 Protective coatings—Protective coatings protect 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.The 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 concrete 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

There are several reasons why protection systems are used.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 many available methods used to protect the system from ultraviolet light.These include acrylic coatings, cementitious surfacing,aliphatic polyurethane coatings,and others.Certain types of vinylester resins have higher ultraviolet light durability than epoxy resins.

(b) *Fire protection—Fire protection systems are discussed* in 1.2.1.2 and 9.2.1.

(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.Such protection systems are usually chosen for their hardness and durability.

(e) *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.

(f) *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.

Protective coatings may also serve aesthetic purposes.In such cases,these dual-purpose coatings may be designed to match the color and texture of the existing structure.

Table 4.2.1—Typical densities of FRP materials, Ib/f³ (g/cm³)

Steel	Glass FRP (GFRP)	Basalt FRP (BFRP)	Carbon FRP (CFRP)	Aramid FRP (AFRP)
490 (7.9)	75 to 130 (1.2 to 2.1)	75 to 130 (1.2 to 2.1)	90 to 100 (1.5 to 1.6)	75 to 90 (1.2 to 1.5)

4.2—Physical properties

4.2.1 Density—FRP materials have densities ranging from 75 to 1301b/t³(1.2 to 2.1 g/cm³),which is four to six times lower than that of steel(Table 4.2.1).

4.2.2 Coefficient of thermal expansion—The coefficients of thermal expansion of unidirectional FRP systems differ in the longitudinal and transverse directions,depending on the types of fiber,resin,and volume fraction of fiber.Table 4.2.2 lists the longitudinal and transverse coefficients of thermal expansion for typical unidirectional FRP systems.Note that a negative coefficient of thermal expansion indicates that the material contracts with increased temperature and expands with decreased temperature.For reference,the isotropic values of coefficient of thermal expansion for concrete and steel are also provided in Table 4.2.2.Refer to 9.3.1 for design considerations regarding thermal expansion.

*4.2.3 Effects of high temperatures—Above the glass tran-*sition temperature Tg,the elastic modulus of a polymer is significantly reduced due to changes in polymer chain mobility,causing the polymer to transition from a glassy state to a rubbery state.The value of Tg depends on the type of resin and is normally in the region of 140 to 180°F(60 to 82°C).In an FRP composite material,the fibers,which exhibit better thermal properties than the resin,can continue to support some load in the longitudinal direction until the temperature threshold of the fibers is reached.This can occur at temperatures exceeding 1800°F(1000°C)for carbon fibers,530°F(275°C)for glass fibers,1290°F(700°C)for basalt fibers,and 350°F(175°C)for aramid fibers.Due to a reduction in force transfer between fibers through bond to the resin,however,the tensile properties of the overall composite are reduced.Test results have indicated that temperatures of 480°F(250°C)—much higher than the resin T—willreduce the tensile strength of GFRP,BFRP,and CFRP materials by 20%(Kumahara et al.1993;Deák and Czigány 2009). Other properties affected by the shear transfer through the resin, such as bending strength,are reduced significantly at lower temperatures(Wang and Evans 1995).

For bond-critical applications of FRP systems,the properties of the polymer at the fiber-concrete interface are essential in maintaining the bond between FRP and concrete.At a temperature close to its Tg,the mechanical properties of the polymer are significantly reduced,and the polymer begins to lose its ability to transfer stresses from the concrete to the fibers.

4.3—Mechanical properties

4.3.1 Tensile behavior—The tensile behavior ofunidirectional FRP systems consisting of a single type of fiber mate-

Table 4.2.2—Typical coefficients of thermal expansion for concrete,steel,and FRP systems*

Direction	Coefficient of thermal expansion,×10-/0F(×10⁶C)					
	Concrete	Steel	GFRP	BFRP	CFRP	AFRP
Longitudinal,az	4.0 to 6.0 (7 to 11)	6.5 (12)	3.3 to 5.6 (6 to 10)	3.0 to 6.0 (5 to 11)	−0.6 to 0 (−1 to 0)	−3.3 to−1.1 (−6 to−2)
Tranverse, αr	4.0 to 6.0 (7 to 11)	6.5 (12)	10.4 to 12.6 (19 to 23)	8.7 to 14.3 (16 to 26)	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.

rial is characterized by a linear elastic stress-strain relationship until failure,which is sudden and brittle.The tensile strength and stiffness of an FRP system is dependent on several factors.Because the fibers in an FRP system are the main load-carrying constituents,the type of fiber,the orientation of fibers,the quantity of fibers,and method and conditions in which the composite is produced affect the tensile properties of the FRP system.Sometimes,the mechanical properties of an FRPrepair system may be reported based on the net-fiber area,which is the area of the fabric reinforcement without the resin. Section 16.1 demonstrates how the net-fiber area can be calculated.Properties reported based on the net-fiber area are typically lower than those for the individual bare fibers that are used to produce the fabric.More commonly,the properties are based on the gross laminate area of the cured FRP system,which includes the fibers and the resin.

System properties reported using the net-fiber area have lower relative thickness dimensions and higher relative strength and elastic modulus values whereas those reported using the gross laminate area have higher relative thickness dimensions and lower relative strength and elastic modulus values.Regardless of the basis for the reported values,the load-carrying strength(Afji)and chord stiffness(A_1E)to be used in the design of the FRPsystem are essentially the same (refer to 16.1).

The tensile properties of a particular FRP system should be obtained from the FRP system manufacturer or using the appropriate test method described in ASTM D7205/D7205M or ASTM D7565/D7565M.Mechanical properties determined in accordance with ASTM D7565/D7565M are reported in terms of tensile force and chord tensile modulus per unit width of material.To obtain the required strength and modulus in terms of gross laminate area,the reported tensile force and chord tensile modulus per unit width values are divided by the nominal FRP laminate thickness.ASTM D7565/D7565M prescribes tensile testing in accordance with ASTM D3039/3039M.Results from ASTM D3039/D3039M testing,which uses gross laminate area,can be reported directly.For wet layup systems, the properties should be determined in accordance with ACI 440.8.ACI 440.8 requires manufacturers to report an ultimate tensile strength,which is defined as the mean tensile strength of a sample of at least 20 test specimens minus three times the standard deviation(z*=fm-3c). The chord tensile modulus(E)is defined as the mean chord tensile modulus of at least 20 test specimens.From these, ultimate rupture strain is determined(=fu*/E).This approach provides a 99.87%probability that the actual ultimate tensile properties will exceed these statistically based design values for a normal sample distribution(Mutsuyoshi et al.1990).The manufacturer should provide a description of the method used to obtain the reported tensile properties, including the number of tests,mean values,standard deviations,and any pretreatments.

The tensile properties of the FRP system should be based on the testing of laminate samples with known fiber content. In this way,the properties of an FRP system can 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.

4.3.2 Compressive behavior—Externally bonded FRP systems should not be used as compression reinforcement due to insufficient testing to validate 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 systems(Ehsani 1993).

4.4—Time-dependent behavior

4.4.1 Creep rupture—FRP systems subjected to a sustained load can suddenly fail after a time 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 FRPlaminate increases,endurance time decreases.The endurance time also decreases under adverse environmental conditions,such as high temperature,ultraviolet-radiation exposure,high alkalinity, wet and dry cycles,or freezing-and-thawing cycles.

In general,carbon fibers are the least susceptible to creep rupture,aramid and basalt fibers are moderately susceptible,and glass fibers are most susceptible.Creep rupture tests have been conducted on 0.25 in.(6mm)diameter FRP bars reinforced with glass,aramid fibers,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).A creep rupture stress of 0.52fu was proposed for prestressed BFRP tendon(Wang et al.2014).Recommendations on sustained stress limits imposed to avoid creep rupture are given Chapter 9 through 15.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.

4.4.2 Fatigue—A substantial amount of data for fatigue behavior and life prediction of stand-alone glass and carbon FRPmaterials is available(National Research Council 1991). Most of these data were generated from materials typically used by the aerospace industry.Despite the differences in quality and consistency between aerospace and commercial-grade FRP materials,some general observations on the fatigue behavior of FRP materials can be made.More recent research studies have evaluated the tensile behavior of basalt FRP(Wuet.al.2010;Colombo et al.2012;Zhao et al.2016).

Unless specifically stated otherwise,the following cases are based on a unidirectional material with approximately 60% fiber-volume fraction subjected to tension-tension sinusoidal cyclic loading at:

(a)A frequency low enough to not cause self-heating

(b)Ambient laboratory environments

(c)A stress ratio (ratio of minimum applied stress to maximum applied stress)of 0.1

(d)A direction parallel to the principal fiber alignment

Test conditions that raise the temperature and moisture content ofFRP systems generally degrade the ambient environment fatigue behavior.

Tensile fatigue behavior of fiber-dominated FRP composites is controlled by the fatigue behavior of the fibers.Carbon (CFRP)and aramid(AFRP)composites exhibit strength degradation due to tensile fatigue on the order of 5 to 8% per decade of logarithmic cycles(Curtis 1989;Roylance and Roylance 1981).Glass(GFRP)and basalt(BFRP)composites exhibit strength degradation on the order of 10%per decade(Mandell 1982;Zhao et.al.2016;Zhao et al.2018; Wu et al.2010).As a point of comparison,steel degrades at a rate on the order of 20%per decade.Glass fibers are highly susceptible to moisture,alkalinity,and acidity,resulting in stress corrosion induced by the growth of surface flaws in the presence of even minute quantities of moisture(Mandelland Meier 1983).Thus,GFRP composite fatigue behavior can be significantly affected by environmental exposure.Similar to glass fibers,environmental factors can play an important role in the fatigue behavior ofbasalt fibers due to their susceptibility to degradation in moisture,salt water,or acidic solutions.Hydrolyzation dominates fatigue strength degradation ofBFRP in a marine environment,and higher aging temperature can lead to greater fatigue degradation of BFRP (Shi et al.2017).Similarly,AFRP fatigue degradation is accelerated by exposure to moisture and elevated temperature(Rostasy 1997).FRP composite materials do not generally exhibit a clearly defined endurance limit under conditions oftension fatigue.Thus,there is no defined fatigue life regardless of the stress level.

4.5—Durability

Many FRP systems exhibit reduced mechanical properties after exposure to certain environmental conditions, 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 of mechanical properties.These factors are discussed in more detail in 9.3. 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 9.4 to account for the anticipated service environment to which the FRP system may be exposed during its service life.

4.6—FRP systems qualification

FRP systems should be qualified for use on a project based on independent laboratory test data of the FRP-constituent materials and the laminates made with them,structural test data for the type of application being considered,and durability data representative of the anticipated environment.Test data provided by the FRP system manufacturer demonstrating the proposed FRP system should meet all mechanical and physical design requirements,including tensile strength,durability,resistance to creep,bond to substrate,and Tg.AC1440.8 provides a specification for unidirectional carbon and glass FRP systems 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 A.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 5—SHIPPING,STORAGE,AND HANDLING

5.1—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 CFR49 .

5.2—Storage

5.2.1 Storage conditions—Topreserve theproperties 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 recommended by the manufacturer and OSHA.Catalysts and initiators(usually peroxides)should be stored separately.

5.2.2 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 provides 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.

5.3—Handling

5.3.1 Safety data sheet—Safety data sheets(SDSs)for all FRP-constituent materials and components should be obtained from the manufacturers and should be accessible at the jobsite.

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

5.3.3 General handling hazards—Thermosetting resins describe a generic family of products that includes unsaturated polyesters,vinyl esters,epoxy,and polyurethane resins.The materials used with them are generally described as hardeners,curing agents,peroxide initiators,isocyanates, fillers,and flexibilizers.There are precautions that should be observed when handling thermosetting resins and their component materials.Some general hazards that may be encountered when handling thermosetting resins 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 dilutents

(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 cured FRP systems (manufacturer's literature should be consulted for specific hazards)

The complexity of thermosetting resins and associated materials makes it essenial that labels and the SDS are read and understood by those working with these products. CFR 16 Part 1500 regulates the labeling of hazardous substances and includes thermosetting-resin materials. ANSI Z400.1/Z129.1 provides further guidance regarding classification and precautions.

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

5.3.5 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.

5.3.6 Cleanup and disposal—Cleanup can involve use of flammable solvents,and appropriate precautions should be observed.Cleanup solvents are available that do not present flammability concerns.All waste materials should be contained and disposed of as prescribed by the prevailing environmental authority.

CHAPTER 6—INSTALLATION

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

6.1—Contractor competency

The FRP system installation contractor should demonstrate competency for surface preparation and application of the FRP system to be installed.Contractor competency can be demonstrated by providing evidence of training and documentation of related work previously completed by the contractor or by actual surface preparation and installation of the FRP system on portions of the structure.The FRP system manufacturer or its authorized agent should train the contractor's application personnel in the installation procedures of its system and ensure they are competent to install the system.

6.2—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 concrete,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 temperature of the concrete 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 concrete surfaces that are subject to moisture vapor transmission.The transmission of moisture vapor from a concrete surface through the uncured resin materials typically appears as surface bubbles and can compromise the bond between the FRP system and the substrate.

6.3—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 project and quality assurance.

6.4—Substrate repair and surface preparation

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

6.4.1 Substrate repair—All problems associated with the condition of the original concrete and the concrete substrate that can compromise the integrity of the FRP system should be addressed before surface preparation begins. ACI 546R and ICRI 310.2R detail methods for the repair and surface preparation of concrete.All concrete repairs should meet the requirements of the design drawings and project specifications.The FRP system manufacturer should be consulted on the compatibility of the FRP system with materials used for repairing the substrate.

6.4.1.1 Corrosion-related deterioration—Externally bonded FRP systems should not be applied to concrete substrates suspected of containing actively corroding reinforcing steel.The expansive forces associated with the corrosion process are difficult to determine and could compromise the structural integrity of the externally applied FRP system. The cause(s)of the corrosion should be addressed,and the corrosion-related deterioration should be repaired before the application of any externally bonded FRP system.

***6.4.1.2** Injection of cracks—Cracks that are 0.010 in.* (0.3 mm)and wider can affect the performance of the externally bonded FRP systems.Consequently,cracks wider than 0.010 in.(0.3 mm)should be pressure-injected with epoxy before FRP installation in accordance with ACI 224.1R. Smaller cracks exposed to aggressive environments may require resin injection or sealing to prevent corrosion of existing steel reinforcement.Crack-width criteria for various exposure conditions are given in ACI 224.1R.

*6.4.2 Surface preparation—Surface preparation require-*ments should be based on the intended application of the FRP system.Applications can be categorized as being bond-critical or contact-critical.Bond-critical applications,such as flexural or shear strengthening of beams,slabs,columns,or walls,require an adhesive bond between the FRP system and the concrete.Contact-critical applications,such as confinement of columns,only require intimate contact between the FRP system and the concrete.Contact-critical applications do not require an adhesive bond between the FRP system and the concrete substrate,although one is typically provided to facilitate installation.

*6.4.2.1 Bond-critical applications—Surface prepara-*tion for bond-critical applications should be in accordance with recommendations of ACI 546R and ICRI 310.2R.The concrete or repaired surfaces to which the FRP system is to be applied should be freshly exposed and free of loose or unsound materials.Where fibers wrap around corners,the corners should be rounded to a minimum 0.5 in.(13 mm) radius(or greater if specified by FRP system manufacturer) to reduce stress concentrations in the FRP system and voids between the FRP system and the concrete.Roughened corners should be smoothed with putty.Obstructions and embedded objects may need to be removed before installing the FRP system.Inside corners and concave surfaces may require special detailing to ensure that the bond of the FRP system to the substrate is maintained.Surface preparation can be accomplished using abrasive or water-blasting techniques.All laitance,dust,dirt,oil,curing compound, existing coatings,and any other matter that could interfere with the bond of the FRP system to the concrete should be removed.Bug holes and other small surface voids should be completely exposed during surface profiling.After the profiling operations are complete,the surface should be cleaned and protected before FRP installation so that no materials that can interfere with bond are redeposited on the surface.

The concrete surface should be prepared to a surface profile not less than CSP 3,as defined by ICRI 310.2R or to the tolerances recommended by the FRP system manufacturer.Localized out-of-plane variations,including form lines,should not exceed 1/32 in.(1 mm)or the tolerances recommended by the FRP system manufacturer.Localized out-of-plane variations can be removed by grinding,before abrasive or water blasting,or can be smoothed over by using resin-based putty if the variations are very small.Bug holes and voids should be filled with resin-based putty.

All surfaces to receive the strengthening system should be as dry as recommended by the FRP system manufacturer. Water in the pores can inhibit resin penetration and reduce mechanical interlock.Moisture content should be evaluated in accordance with the requirements ofACI 503.4.

6.4.2.2 Contact-critical applications—In applications involving confinement of structural concrete members, surface preparation should promote continuous intimate contact between the concrete surface and the FRP system. Surfaces to be wrapped should,at a minimum,be flat or convex to promote proper loading of the FRP system.Large voids in the surface should be patched with a repair material compatible with the existing concrete.Materials with low compressive strength and elastic modulus,such as plaster, can reduce the effectiveness of the FRP system and should be removed.Corners should be prepared in the same manner as for bond-critical applications.

6.4.3 Near-surface-mounted (NSM)systems—NSM systems are typically installed in grooves cut onto the concrete surface.The existing steel reinforcement should not be damaged while cutting the groove.The soundness of the concrete surface should be checked before installing the bar. The inside faces ofthe groove should be cleaned to ensure adequate bond between adhesive and concrete.The resulting groove should be free of laitance or other compounds that may interfere with bond.The moisture content of the concrete should be controlled to suit the bonding properties of the adhesive.The grooves should be completely filled with the adhesive.The adhesive should be specified by the NSM system manufacturer.

6.5—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 the proper temperature and mixed in the correct ratio untl there is a uniform and complete mixing of 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.Resin mixing should be in quantities sufficiently small 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.The resin should not be diluted or otherwise modified except as permitted by the FRP system manufacturer.

6.6—Application of FRP systems

Fumes can accompany the application of some FRP resins. FRP systems should be selected with consideration for their impact on the environment,including emission of volatile organic compounds and toxicology.

***6.6.1** Primer andputty—Where required,primer should* be applied to all areas on the concrete surface where the FRP system is to be placed.The primer shouldbe 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 resin-based 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 partially cure as specified by the FRP system manufacturer.If the putty and primer are fully cured,additional surface preparation may be required before the application of the saturating resin or adhesive. Surface preparation requirements should be obtained from the FRP system manufacturer.

6.6.2 Wet layup systems—Dry fiber reinforcement is impregnated on site with a saturating resin and then cured in place.A saturation machine may be used to impregnate the fibers.In this process,the dry fabric is passed through a bath created by placing resin between two rollers,which are gapped so that the specified fiber-to-resin ratio is achieved. As the fabric passes through the bath and between the rollers the fibers are impregnated with the resin.The fabric may also be impregnated manually using rollers.The resin is applied to both sides of the fiber at a rate or fiber-to-resin weight ratio as specified by the FRP system manufacturer.Once saturated,the wet fiber fabrics are placed onto the prepared surface.Successive layers of saturated fiber should be placed before the complete cure of the previous layer provided additional layers do not lead to sliding of previously placed layers.If previous layers are cured,interlayer surface preparation,such as mechanical abrading and solvent wiping,as recommended by the system manufacturer,may be required.

6.6.3 Machine-applied systems—Machine-applied systems can use resin-preimpregnated tows or dry-fiber tows.Prepreg tows are impregnated with saturating resin off site and delivered to the jobsite as spools of prepreg tow material.Dry fibers are impregnated at the jobsite during the winding process.

Wrapping machines are primarily used for the automated wrapping of concrete columns.The tows can be wound either horizontally or at a specified angle.The wrapping machine is placed around the column and automatically wraps the tow material around the perimeter of the column while moving up and down the column.

After wrapping,prepreg systems should be cured at an elevated temperature.Usually,a heat source is placed around the column for a predetermined temperature and time schedule in accordance with the manufacturer's recommendations.Temperatures are controlled to ensure consistent quality.The resulting FRP jackets do not have any seams or laps because the tows are continuous.In all the previous application steps,the FRP system manufacturer's recommendations should be followed.

6.6.4 Precured systems—Precured systems include shells, plates,and open grid forms that are typically installed with an adhesive.Adhesives should be uniformly applied to the prepared surfaces where precured systems are to be placed, except in certain contact-critical applications where adhesion of the FRP system to the concrete substrate may not be required.

Precured laminate surfaces to be bonded should be clean and prepared in accordance with the manufacturer's recommendation.The precured plates or curved shells should be placed on or into the wet adhesive in a manner recommended by the FRP system manufacturer.Entrapped air between layers should be released or rolled out before the adhesive sets.The adhesive should be applied at a rate recommended by the FRP system manufacturer.

6.6.5 Near-surface-mounted (NSM)systems—NSM systems consist of installing FRP bars or narrow plates into grooves cut onto the concrete surface and bonding these in place using an adhesive.Grooves should be dimensioned to ensure adequate adhesive around the bars or plates.Typical groove dimensions for NSM FRP bars and plates are found in Section 14.3.NSM systems can be used on the topside of structural members and for overhead applications.Adhesive type and installation method should be specified by the NSM system manufacturer.

6.6.6 Protective coatings—Coatings should be compatible with the FRP strengthening 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 for FRP surface preparation before the application of protective coatings.The coatings should be periodically inspected and maintenance should be provided to ensure the effectiveness of the coatings.

6.7—Alignment of FRP systems

The FRPply orientation and ply stacking sequence should be specified.Small variations in angle,as little as 5 degrees, from the intended direction of fiber alignment can cause a substantial reduction in strength and modulus.Deviations in ply orientation should not exceed 5 degrees unless approved by the licensed design professional.

Sheet and fabric materials should be handled in a manner to maintain the fiber straightness and orientation.Fabric kinks,folds,or other forms of waviness should be reported to the licensed design professional.

6.8—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 shearing load between plies,and the bond strength between the concrete 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.Specific guidelines on lap splices are given in Chapter 14. Specific guidance on tolerances for wet layup installation are given in ACI SPEC-440.12.

6.9—Curing of resins

Curing ofresins 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 time.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.

6.10—Temporary protection

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

CHAPTER 7—FIELD INSPECTION,TESTING, AND EVALUATION

7.1—General

Field inspection and evaluation of installed FRP systems should be performed as required by the governing building code and as specified in the construction documents. Chapter 7 covers only quality assurance activities conducted during installation.Quality control activities performed prior to installation generally consist of requiring the manufacturer and contractor to submit product information and evidence of qualifications to the licensed design professional responsible for the construction documents for review,as discussed in Section 15.3.

In jurisdictions where the International Building Code (IBC) is the governing code,Section 1705.1 of the 2018 edition should apply for FRP systems because such systems are considered as an alternate to IBC-prescribed materials and systems.In addition,the IBC 2018 Section 1704.3 requires a statement of special inspections prepared by the licensed design professional in responsible charge. ACI CODE-562 also contains requirements for inspection and related quality assurance measures that may be applicable.

The field inspection and evaluation program defined by the construction documents should specify the test or evaluation method,frequency of inspection and testing,personnel qualifications,and acceptance criteria.In general,the licensed design professional should bear the primary responsibility for developing the scope of inspection and evaluation.Sections 1703.1 and 1704.3 of the 2018IBC designate the Licensed Design Professional for the project as the party responsible for identifying the scope of inspections.

For the purposes of this document,the term inspector refers to the individual tasked with observing,testing,or otherwise evaluating field installations of FRP systems for compliance with the construction documents.The IBC 2018 Section 1704.2 requires that the inspector be retained by the owner as opposed to the contractor(or a contractor-retained entity,such as a specialty engineer that designed the FRP system).The inspector's experience,training,and knowledge of FRP systems should be commensurate with the type, size,and complexity of the FRP system to be evaluated.If the licensed design professional possesses the necessary expertise,the IBC 2018 Section 1704.2.1 permits that individual to perform some or all of the inspections.

Inspections performed by the inspector pursuant to building code or construction document requirements should not supplant or relieve the contractor from conducting its own quality assurance tasks.Examples of such tasks include daily reports documenting environmental conditions,fiber lot numbers associated with use in the structure,production of witness panels,and any instances of substrate repair.

7.2—Field inspection

Compliance with the design drawings,project specifications,and approved shop drawings should be checked. Because FRP installations vary significantly with respect to scope,type,structural demands,application criteria,regional practice,and other factors,this document can only provide general guidance regarding common inspection requirements.The construction documents prepared by the licensed design professional should contain job-specific and building code compliant descriptions of required inspections,tests, evaluations,and acceptance criteria.The licensed design professional should consider reviewing the IBC,ACI SPEC-440. 12, ACI CODE-562, ICRI 330.2,and ICC-ES AC178 for additional guidance.

7.2.1 Scope—The following items are commonly included in a field inspection program:

(a)Materials—Verification that the specified FRP system is being installed.

(b)Surface preparation—Inspection of preparation method and resulting profile.

(c)Concrete substrate—Inspection of general condition, including moisture condition,treatment of corners, protrusions,cracks,deteriorated concrete,corrosion of internal steel reinforcement,interfering embedments, and surface contaminants.

(d)Recording of environment at the time of installation and during the cure of the FRP system—Air and surface temperature,humidity,concrete moisture,and dew point.

(e)Inspection of resin—For wet lay-up systems,resin mixing and application to fiber.For precured laminates,adhesive mixing and application to substrate or laminate.

(f)Inspection of fiber placement—Fiber layout,dimensions,spacing,number of layers,splices,and fiber direction and alignment.

(g)Verification of relative resin cure

(h)Verification of pulloff strength in accordance with ASTM D7522/D7522M.

(i)Inspection of witness panels—Refer to 7.3 for details.

(j)Inspection of delaminations—Acoustic sounding, infrared thermography,or other diagnostic measures capable of detecting delaminations 2 in.^{2}(1290 mm^2) or smaller in cured FRP system.

(k)Inspection of remedial measures 2 in.^{2}Inspection of epoxy injection of delaminations,reinstallation of unacceptably installed fibers,or other remedial measures deemed necessary by the licensed design professional.

7.2.2 Extent and frequency—The extent and frequency of inspections should be determined by the licensed design professional based on job-specific parameters.If the authority having jurisdiction approved the use of the FRP system on the basis of a representation that the installation would be in accordance with an ICC-ES or equivalent evaluation service report,then inspection criteria set forth in that document should also be followed.

7.2.3 Reporting—Written reports should be prepared by the inspector and submitted to appropriate parties.Reports should document results of field observations and bond strength test results.The reports should also document the date and time of the inspection,installation location on structure,batch numbers,resin/adhesive mixture ratios and mixing times,and other general information.Inclusion of annotated plans showing the location of inspected work and photographs to illustrate special conditions will clarify the report narrative.All deviations from the drawings,specifications,or manufacturer's instruction should be clearly identified and promptly communicated to appropriate parties.

7.3—Material testing

FRP materials should be evaluated during installation for compliance with properties reported by the manufacturer. Testing to determine tensile properties ofa wet layup system should be performed by fabricating and testing witness panels in accordance with ASTM D7565/D7565M.

For precured systems,in place of witness panels,the licensed design professional should require the manufacturer to submit test results of FRP bars using ASTM D7205/D7205M and precured plates using ASTM D7565/D7565M.

Prepreg systems should be tested as required by the licensed design professional.

In addition to witness panel testing,evaluation of resins should be performed using sample cups to check adequacy of mixing and degree of cure.The frequency of sampling should be specified by the licensed design professional but should be sufficient to evaluate each batch of mixed resin used.Similar to the witness panels,the sample cups should be stored at the jobsite under temperature,moisture,and curing conditions similar to conditions expected during installation.

7.4—Evaluation and acceptance criteria

The construction documents should set forth evaluation and acceptance criteria so that material properties,quality, and workmanship expectations are clearly communicated to the contractor.

7.4.1 Installation tolerances—The effect of deviations from installation tolerances on the structural performance of the FRP system should be reviewed by the licensed design professional.

7.4.2 Delaminations—The effect of delaminations on the structural performance and durability of the FRP system should be reviewed by the licensed design professional based on the size,location,quantity,and other factors.

For precured FRP systems,delaminations should be evaluated and repaired in accordance with direction from the licensed design professional.

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

7.4.4 Bond strength—Bond (that is,pulloff or adhesion) strengths for bond-critical applications of wet layup or precured systems should be evaluated using ASTM D7522/D7522M .For NSM systems,sample cores may be extracted to visually assess the degree of consolidation of the resin adhesive around the FRP bar.

The location of ASTM D7522/D7522M test cores for wet layup systems and visually-examined cores for NSM systems should be approved by the licensed design professional.The cored holes can be filled and smoothed with a repair mortar or the FRP system putty.If required,an overlapping FRP patch of equivalent plies may be applied over the filled and smoothed core hole in accordance with the manufacturer's installation procedures and other criteria by the licensed design professional.

7.4.5 Cured thickness—Small core samples(typically approximately 0.5 in.[13 mm]diameter)may be taken to allow direct measurement of the cured laminate thickness or number of plies present.Cored samples for bond strength testing also can be used for this purpose(7.4.3).The core locations should be approved by the licensed design professional andshould be the sameas described in 7.4.4.

7.5—Evaluation of coatings

7.5.1 Coatings (other than for thermal protection)— Protective coatings do not contribute directly to the strength of FRP systems,and by definition given in this document, are not considered to be part of the FRP system.Coatings serve many functions including UV protection,aesthetics, and flame spread and smoke generation mitigation.Compliance with the coating manufacturer's application instructions is essential for proper durability and performance. Thus,all specified coatings should be evaluated for adhesion to substrate,uniformity of application,thickness,and other criteria.

*7.5.2 Coatings (thermal protection)—Protective coat-*ings intended for thermal protection should be inspected as required by the construction documents,IBC requirements for special inspection,and product-specific evaluation service report.For spray-and trowel-applied systems,items to be inspected should include adhesion to substrate,extent of coverage,thickness,and density.

CHAPTER 8—MAINTENANCE AND REPAIR

8.1—General

As with any strengthening or retrofit repair,the owner should periodically inspect and assess the performance of the fiber-reinforced polymer(FRP)system used for strengthening or retrofit repair of concrete members.

8.2—Inspection and assessment

8.2.1 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 delamination.

8.2.2 Testing—Testing can include pulloff tension tests (7.4.4)or structural loading tests(ACI437R).

8.2.3 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.

8.3—Repair of strengthening system

The method ofrepair for the strengthening system depends on the causes of the damage,the type of material,the form of degradation,and the level of damage.Repairs to the fiber-reinforced polymer(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 or ply orientation,as the original laminate and extend a distance past the damaged area as specified by the manufacturer.The FRP patches should be installed in accordance with the material manufacturer's recommendation.Minor delaminations can be repaired by resin injection.Major damage,including peeling and debonding of large areas,may require removal of the affected area, reconditioning of the cover concrete,and replacement of the FRP laminate.

8.4—Repair of surface coating

In the event that the surface-protective coating should be replaced,the FRPlaminate should be inspected for structural damage or deterioration.The surface coating may be replaced using a process approved by the system manufacturer.

CHAPTER 9—GENERAL DESIGN CONSIDERATIONS

General design recommendations are presented in this chapter.The recommendations presented are based on the traditional reinforced concrete design principles stated in the requirements ofACI 318 and knowledge of the specific mechanical behavior of fiber-reinforced polymer(FRP)reinforcement.Where applicable,requirements of ACI CODE-562,such as strengthening limits,are referenced herein.

FRP strengthening systems should be designed to resist tensile forces while maintaining strain compatibility between the FRP and the concrete 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 pattern.The compressive strength of the FRP reinforcement,however,should be neglected.

9.1—Design philosophy

These design recommendations are based on limit states design principles.This approach sets acceptable levels of safety for the occurrence of both serviceability limit states (excessive deflections and cracking)and ultimate limit states (failure,stress rupture,and fatigue).In assessing the nominal strength of a member,the possible failure modes and subsequent strains and stresses in each material should be assessed.For evaluating the serviceability of a member, engineering principles,such as transformed section calculations using modular ratios,can be used.

FRP strengthening systems should be designed in accordance with ACI318 strength and serviceability requirements using the strength and load factors stated in ACI 318.Additional reduction factors applied to the contribution of the FRP reinforcement are recommended by this guide to reflect uncertainties inherent in FRP systems different from steel-reinforced and prestressed concrete.These reduction factors were determined based on statistical evaluation of variability in mechanical properties,predicted versus full-scale test results,and field applications.FRP-related reduction factors were calibrated to produce reliability indexes typically above 3.5.Reliability indexes between 3.0 and 3.5 can be encountered in cases where relatively low ratios of steel reinforcement combined with high ratios ofFRP reinforcement are used.Such cases are less likely to be encountered in design because they violate the recommended strengthening limits of 9.2.Reliability indexes for FRP-strengthened members are determined based on the approach used for reinforced concrete buildings(Nowak and Szerszen 2003;Szerszen and Nowak 2003).In general,lower reliability is expected in retrofitted and repaired structures than in new structures.

9.1.1 Lightweight concrete—Limited data are available for the application ofFRPto lightweight concrete substrates. If such substrates are considered,the lower tensile and shear strength of lightweight concrete should be accounted for (Al-Allaf et al.2016).The effective design strain of FRP, shear strength and shear design limits,and development length requirements may not be equivalent to normalweight concrete of the same compressive strength and should be verified by testing.

9.2—Strengthening limits

Strengthening limits are imposed to guard against collapse of the structure should bond or other failure of the FRP system occur due to damage,vandalism,or other causes. The unstrengthened structural member,without FRP reinforcement,should have sufficient strength to satisfy Eq.(9.2)

$$(\varphi Rm)erisiang \geq (1.1SDL+0.75SLLnew \tag{9. 2}$$

A dead load factor of 1.1 is used because a relatively accurate assessment of the dead loads of the structure can be determined.A live load factor of 0.75 is used to exceed the statistical mean of the yearly maximum live load factor of 0.5,given in ASCE/SEI 7. The strengthening limit resulting from compliance with Eq.(9.2)will allow the strengthened member to maintain sufficient structural capacity until the damaged FRP is repaired.

In cases where the design live load acting on the member to be strengthened has a high likelihood of being present for a sustained period of time,a live load factor of 1.0 should be used instead of 0.75 in Eq.(9.2).Examples include library stack areas,heavy storage areas,warehouses,and other occupancies with a live load exceeding 1501b/ft^2(730 kg/m^2).Additional limits for structures requiring a fire resistance rating are given in 9.2.1.The application of the limits given by Eq.(9.2)and in Section 9.2.1 are not intended for retrofits required solely for seismic actions;these are addressed in Chapter 13.

9.2.1 Structuralfire resistance—The level ofstrengthening that can be achieved through the use of externally bonded FRP reinforcement can be limited by the code-required fire-resistance rating of a structure.The polymer resins typically used in wet layup and prepreg FRP systems and the polymer adhesives used in precured FRP systems suffer deterioration of mechanical and bond properties at temperatures close to or exceeding the Tg of the polymer,as described in 1.2.1.3.

Although the FRP system itself is significantly affected by exposure to elevated temperatures,a combination of the FRP system with an existing concrete structure may still have an adequate fire resistance.When considering the fire resistance of an FRP-strengthened concrete element,it is important to recognize that the strength of a reinforced concrete element is reduced during fire exposure due to heating of both the reinforcing steel and the concrete.Performance in fire of the existing concrete member can be enhanced by installing an insulation system,which will provide thermal protection to existing concrete and internal reinforcing steel, thus improving the overall fire rating,although the FRP system contribution may be reduced (Bisby et al.2005a; Williams et al.2006;Palmieri et al.2011;Firmo et al.2012; ACI PRC-440.10).

An evaluation should be performed to ensure an FRP-strengthened structure will not collapse in a fire event.The required member resistance of an FRP-strengthened structural element can be determined using the load combination for a fire event specified in ACI CODE-562 as follows:

$$中eR\geq(0.9 \quad or \quad 1.2)SpL+0.5S+0.2Ss \qquad (9.2.1)$$

where R is the nominal resistance of the member at an elevated temperature without FRP;φer=1.0;and SpL,Su, and Ssz are the specified dead,live,and snow loads,respectively,calculated for the strengthened structure.The dead load factor of 0.9 is applied when the dead load effect mitigates the total load effect;otherwise,the dead load factor of 1.2 is used.For cases where the design live load has a high likelihood of being present for a sustained period of time, a live load factor of 1.0 should be used in place of 0.5 in Eq.(9.2.1).

If the FRP system is meant to allow greater load-carrying capacity,such as an increase in live load,the load effects should be computed using these greater loads.If the FRP system is meant to address a loss in strength,such as deterioration,the resistance should reflect this loss.

The nominal resistance of the member at an elevated temperature R may be determined using the procedure outlined in ACI216.1 or through testing.The nominal resistance R should be calculated based on the reduced material properties of the existing member(ACI PRC-440.10).The resistance should be computed for the time required by the member's fire-resistance rating—for example,a 2-hour fire rating—and should not account for the contribution of the FRP system unless the continued effectiveness of the adhesive resin during fire exposure can be proven through testing. More research is needed to accurately identify temperatures at which effectiveness is lost for different types of FRP.Until better information on the properties of FRP at high temperature is available,the critical temperature at which the FRP is considered ineffective during a fire event can be taken as the lowest Tg of the components of the system comprising the load path.

9.2.2 Overall structural strength—While FRPsystems are effective in strengthening members for flexure and shear and providing additional confinement,other modes of failure, such as punching shear and bearing capacity of footings, may be only marginally affected by FRP systems(Sharaf et al.2006).All members of a structure should be capable of withstanding the anticipated increase in loads associated with the strengthened members.

Additionally,analysis should be performed on the member strengthened by the FRP system to check that,under overload conditions,the strengthened member will fail in a flexural mode rather than in a shear mode.

9.2.3 Seismic applications—Requirements for seismic strengthening using FRP are addressed in **Chapter 13.**

9.3—Selection ofFRP systems

9.3.1 Environmental considerations—Environmental conditions uniquely affect resins and fibers of various FRP systems.The mechanical properties(for example,tensile strength,ultimate tensile strain,and elastic modulus)of some FRP systems degrade under exposure to certain environments such as alkalinity,salt water,chemicals,ultraviolet light,high temperatures,high humidity,and freezing-and-thawing cycles.The material properties used in design should account for this degradation in accordance with 9.4.

The licensed design professional should select an FRP system based on the known behavior of that system in the anticipated service conditions.Some important environmental considerations that relate to the nature of specific systems are given as follows.Specific information can be obtained from the FRP system manufacturer.

(a)Alkalinity/acidity—The performance ofan FRPsystem over time in an alkaline or acidic environment depends on the matrix material and the reinforcing fiber.Dry, unsaturated bare,or unprotected carbon fiber is resistant to both alkaline and acidic environments whereas bare glass fiber can degrade over time in these environments.A properly selected and applied resin matrix, however,should isolate and protect the fiber from an alkaline/acidic environment and resist deterioration.

(b)Thermal expansion—FRP systems may have thermal expansion properties that are different from those of concrete.In addition,the thermal expansion properties of the fiber and polymer constituents of an FRPsystem can vary.Carbon fibers have a coefficient of thermal expansion near zero whereas glass fibers have a coefficient of thermal expansion similar to concrete.The polymers used in FRP strengthening systems typically have coefficients of thermal expansion approximately five times that of concrete.Calculation of thermally induced strain differentials are complicated by variations in fiber orientation,fiber volume fraction,and thickness of adhesive layers.Experience indicates, however,that thermal expansion differences do not affect bond for small ranges of temperature change, such as±50°F(±28°C)(Motavalli et al.1997;Soudki and Green 1997;Green et al.1998).

(c)Electrical conductivity—Glass FRP(GFRP),basalt FRP(BFRP),and aramid FRP(AFRP)are effective electrical insulators,whereas carbon FRP(CFRP)is conductive.To avoid potential galvanic corrosion of steel elements,carbon-based FRP systems should not be placed in direct contact with steel.