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

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

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

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Fiber-reinforced polymer (FRP) systems for strengthening concrete structures are an alternative to traditional strengthening techniques such as steel plate bonding, section enlargement, and external post-tensioning. FRP strengthening systems use FRP composite mate-

rials 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 of these systems is needed. This guide provides general information on the history and use of FRP strengthening systems; a description of the material properties of FRP; and recommendations on the engineering, construction, and inspection of FRP systems used to strengthen concrete structures. This guide is based on the knowledge gained from experimental

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

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

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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 FRP U-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 440.8** provides 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, 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 20 mJ/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]) (Griffin 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 Santistevé 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 of FRP systems used as external or NSM reinforcement is presented. This information can be used to select an FRP system 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 much research 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 overall evaluation 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, past repair 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 of FRP 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 structures 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 in [ACI PRC-440.10](#).

1.2.1.3 Maximum service temperature—The physical and mechanical properties of the resin components of FRP systems 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 temperature-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 [ASTM E1640](#). Reported T_g values 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 T_g 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 T_g . 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 $T_g - 27^\circ\text{F}$ ($T_g - 15^\circ\text{C}$) ([Xian and Karbhari 2007](#)), where T_g is taken as the lowest T_g 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 industrial environments. In cases where the FRP will be exposed to a moist environment, the wet glass-transition temperature T_{gw} 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 pull-off 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'_c 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

A_{anc}	=	gross laminate area of the fiber anchor, in. ² (mm ²)
A_c	=	cross-sectional area of concrete in compression member, in. ² (mm ²)
A_{cg}	=	area of gross concrete section, neglecting reinforcement, in. ² (mm ²)
A_{cw}	=	area of concrete section of individual vertical wall, in. ² (mm ²)
A_e	=	cross-sectional area of effectively confined concrete section, in. ² (mm ²)
A_f	=	area of FRP external reinforcement, in. ² (mm ²)
$A_{fanchor}$	=	area of transverse FRP U-wrap for anchorage of flexural FRP reinforcement, in. ² (mm ²)
A_{fv}	=	area of FRP shear reinforcement with spacing s_f , in. ² (mm ²)
A_g	=	gross area of concrete section, in. ² (mm ²)
A_p	=	area of prestressed reinforcement in tension zone, in. ² (mm ²)
A_s	=	area of nonprestressed steel reinforcement, in. ² (mm ²)
A_{sc}	=	area of the longitudinal reinforcement within a distance of w_f in the compression region, in. ² (mm ²)
A_{si}	=	area of i -th layer of longitudinal steel reinforcement, in. ² (mm ²)
A_{st}	=	total area of longitudinal reinforcement, in. ² (mm ²)
A_{sw}	=	area of longitudinal reinforcement in the central area of the wall, in. ² (mm ²)
a	=	depth of the equivalent concrete compression block, in. (mm)
a_b	=	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 of prismatic cross section, in. (mm)
b_b	=	larger cross-sectional dimension for rectangular FRP bars, in. (mm)
b_w	=	web width or diameter of circular section, in. (mm)
C_E	=	environmental reduction factor
C_{sc}	=	compressive force in A_{sc} , lb (N)
c	=	distance from extreme compression fiber to the neutral axis, in. (mm)
$c_{u,frp}$	=	distance from extreme compression fiber to the neutral axis at ultimate capacity, in. (mm)
$c_{y,frp}$	=	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)	f_{ℓ}	= maximum confining pressure due to FRP jacket, psi (MPa)
d	= distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)	f_{ps}	= stress in prestressed reinforcement at nominal strength, psi (MPa)
d'	= distance from the extreme compression fiber to the center of A_{sc} , in. (mm)	$f_{ps,s}$	= stress in prestressed reinforcement at service load, psi (MPa)
d''	= distance from the extreme tension fiber to the center of A_{st} , in. (mm)	f_{pu}	= specified tensile strength of prestressing tendons, psi (MPa)
d_{bt}	= diameter of longitudinal steel in confined plastic hinge, in. (mm)	f_{py}	= specified yield strength of prestressing reinforcement, psi (MPa)
d_f	= effective depth of FRP flexural reinforcement, in. (mm)	f_s	= stress in nonprestressed steel reinforcement, psi (MPa)
d_{fv}	= effective depth of FRP shear reinforcement, in. (mm)	f_{sc}	= stress in the longitudinal reinforcement corresponding to A_{sc} , psi (MPa)
d_i	= distance from centroid of i -th layer of longitudinal steel reinforcement to geometric centroid of cross section, in. (mm)	f_{si}	= stress in the i -th layer of longitudinal steel reinforcement, psi (MPa)
d_p	= distance from extreme compression fiber to centroid of prestressed reinforcement, in. (mm)	$f_{s,s}$	= stress in nonprestressed steel reinforcement at service loads, psi (MPa)
E_2	= slope of linear portion of stress-strain model for FRP-confined concrete, psi (MPa)	f_{st}	= stress in the longitudinal reinforcement corresponding to A_{st} , psi (MPa)
E_c	= modulus of elasticity of concrete, psi (MPa)	f_{sw}	= stress in the longitudinal reinforcement corresponding to A_{sw} , psi (MPa)
E_f	= chord tensile modulus of elasticity of FRP, psi (MPa)	f_y	= specified yield strength of nonprestressed steel reinforcement, psi (MPa)
E_{ps}	= modulus of elasticity of prestressing steel, psi (MPa)	g	= clear gap between the FRP jacket and adjacent members, in. (mm)
E_s	= modulus of elasticity of steel, psi (MPa)	h	= overall thickness or height of a member, in. (mm)
e	= eccentricity of prestressing steel with respect to centroidal axis of member at support, in. (mm)		= long side cross-sectional dimension of rectangular compression member, in. (mm)
e_m	= eccentricity of prestressing steel with respect to centroidal axis of member at midspan, in. (mm)	h_{anc}	= minimum embedment depth of fiber anchor in concrete, in. (mm)
F_c	= resultant force of concrete block stress, lb (N)	h_f	= member flange thickness, in. (mm)
F_f	= resultant force of FRP system, lb (N)	h_w	= height of entire wall from base to top, or clear height of wall segment or wall pier considered, in. (mm)
F_s	= resultant force of internal reinforcing steel, lb (N)	I	= moment of inertia of section about centroidal axis, in. ⁴ (mm ⁴)
F_y	= resultant force of internal reinforcing steel assuming yield of steel, lb (N)	I_{cr}	= moment of inertia of cracked section transformed to concrete, in. ⁴ (mm ⁴)
f_c	= compressive stress in concrete, psi (MPa)	I_g	= moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement, in. ⁴ (mm ⁴)
f_c'	= specified compressive strength of concrete, psi (MPa)	I_{tr}	= moment of inertia of uncracked section transformed to concrete, in. ⁴ (mm ⁴)
f_{cc}'	= compressive strength of confined concrete, psi (MPa)	k	= ratio of depth of neutral axis to reinforcement depth measured from extreme compression fiber
f_{co}'	= compressive strength of unconfined concrete; also equal to $0.85f_c'$, psi (MPa)	k_1	= modification factor applied to κ_v to account for concrete strength
$f_{c,s}$	= compressive stress in concrete at service condition, psi (MPa)	k_2	= modification factor applied to κ_v to account for wrapping scheme
f_f	= stress in FRP reinforcement, psi (MPa)	k_f	= stiffness per unit width per ply of the FRP reinforcement, lb/in. (N/mm); $k_f = E_f t_f$
f_{fd}	= design stress of externally bonded FRP reinforcement, psi (MPa)	L_a	= total length of unbonded tendon between anchorages, in. (mm)
f_{fe}	= effective stress in the FRP; stress attained at section failure, psi (MPa)	L_e	= active bond length of FRP jacket, in. (mm)
$f_{f,s}$	= stress in FRP caused by a moment within elastic range of member, psi (MPa)	L_p	= plastic hinge length, in. (mm)
f_{fu}	= design ultimate tensile strength of FRP, psi (MPa)		
$\overline{f_{fu}}$	= mean tensile strength of a sample of at least 20 FRP test specimens		
f_{fu}^*	= ultimate tensile strength of the FRP material as reported by the manufacturer, psi (MPa)		

L_w	= length of the shear wall, in. (mm)	T_{gw}	= wet glass-transition temperature, °F (°C)
ℓ_{db}	= development length of near-surface-mounted FRP, in. (mm)	T_{ps}	= tensile force in prestressing steel, lb (N)
$\ell_{d,E}$	= length over which the FRP anchorage wraps are provided, in. (mm)	T_{st}	= tensile force in A_{st} , lb (N)
ℓ_{df}	= development length of FRP system, in. (mm)	T_{sw}	= tensile force in A_{sw} , lb (N)
ℓ_o	= length, measured along the member axis from the face of the joint, over which special transverse reinforcement must be provided, in. (mm)	t_f	= nominal thickness of one ply of FRP reinforcement, in. (mm)
ℓ_{prov}	= length of steel lap splice, in. (mm)	t_w	= thickness of the existing concrete shear wall, in. (mm)
M_{cr}	= cracking moment, in.-lb (N-mm)	V_c	= nominal shear strength provided by concrete, lb (N)
M_n	= nominal flexural strength at a section, in.-lb (N-mm)	V_e	= design shear force for load combinations including earthquake effects, lb (N)
M_{nf}	= contribution of FRP reinforcement to nominal flexural strength at a section, in.-lb (N-mm)	V_f	= nominal shear strength provided by FRP stirrups, lb (N)
M_{np}	= contribution of prestressing reinforcement to nominal flexural strength at a section, in.-lb (N-mm)	V_n	= nominal shear strength, lb (N)
M_{ns}	= contribution of steel reinforcement to nominal flexural strength at a section, in.-lb (N-mm)	V_n^*	= shear strength of existing member, lb (N)
M_o	= secondary moment due to prestressing at a section, in.-lb (N-mm)	V_s	= nominal shear strength provided by steel stirrups, lb (N)
M_s	= service moment at a section, in.-lb (N-mm)	V_u	= factored shear force at a section, lb (N)
M_{snet}	= service moment at a section beyond decompression, in.-lb (N-mm)	w_f	= width of FRP reinforcing plies, in. (mm)
M_u	= factored moment at a section, in.-lb (N-mm)	y_b	= distance from centroidal axis of gross section, neglecting reinforcement, to extreme bottom fiber, in./in. (mm/mm)
N	= number of plies of FRP reinforcement	y_t	= vertical coordinate within compression region measured from neutral axis position. It corresponds to transition strain ϵ_t' , in. (mm)
n_f	= modular ratio of elasticity between FRP and concrete = E_f/E_c	α	= angle of application of primary FRP reinforcement direction relative to longitudinal axis of member
n_s	= modular ratio of elasticity between steel and concrete = E_s/E_c	α_1	= multiplier on f_c' to determine intensity of an equivalent rectangular stress distribution for concrete
P_e	= effective force in prestressing reinforcement (after allowance for all prestress losses), lb (N)	α_{anc}	= angle over which fiber anchor is splayed over externally bonded FRP, degrees
P_n	= nominal axial compressive strength of a concrete section, lb (N)	α_L	= longitudinal coefficient of thermal expansion, in./in./°F (mm/mm/°C)
P_u	= factored axial load, lb (N)	α_T	= transverse coefficient of thermal expansion, in./in./°F (mm/mm/°C)
P_{fu}	= mean tensile strength per unit width per ply of FRP reinforcement, lb/in. (N/mm)	β_1	= ratio of depth of equivalent rectangular stress block to depth of the neutral axis
p_{fu}^*	= ultimate tensile strength per unit width per ply of FRP reinforcement, lb/in. (N/mm); $p_{fu}^* = f_{fu}^* t_f$	β_{anc}	= embedment angle of fiber anchors, deg
R	= nominal strength of a member subjected to elevated temperatures associated with a fire	ϵ_b	= strain in concrete substrate developed by a given bending moment (tension is positive), in./in. (mm/mm)
R_A	= ratio of area of fiber in fiber anchor to area of fiber in one leg of shear U-wrap	ϵ_{bi}	= strain in concrete substrate at time of FRP installation (tension is positive), in./in. (mm/mm)
R_n	= nominal strength of a member	ϵ_c	= strain in concrete, in./in. (mm/mm)
r	= radius of gyration of a section, in. (mm)	ϵ_c'	= compressive strain of unconfined concrete corresponding to f_c' , in./in. (mm/mm); may be taken as 0.002
r_{anc}	= length of fiber anchor splay, in. (mm)	ϵ_{ccu}	= ultimate axial compressive strain of confined concrete corresponding to $0.85f_{cc}'$ in 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
r_c	= radius of edges of a prismatic cross section confined with FRP, in. (mm)		
S_{DL}	= dead load effects		
S_{LL}	= live load effects		
S_{SL}	= snow load effects		
s_{anc}	= center-to-center spacing of fiber anchors, in. (mm)		
s_f	= center-to-center spacing of FRP strips, in. (mm)		
T_f	= tensile force in FRP, lb (N)		
T_g	= glass-transition temperature, °F (°C)		

$\epsilon_{c,s}$	= strain in concrete at service, in./in. (mm/mm)	κ_b	= efficiency factor for FRP reinforcement in determination of ϵ_{ccu} (based on geometry of cross section)
ϵ_{ct}	= concrete tensile strain at level of tensile force resultant in post-tensioned flexural members, in./in. (mm/mm)	κ_v	= bond-dependent coefficient for shear
ϵ_{cu}	= ultimate axial strain of unconfined concrete corresponding to $0.85f'_c$ or maximum usable strain of unconfined concrete, in./in. (mm/mm), which can occur at $f_c = 0.85f'_c$ or $\epsilon_c = 0.003$, depending on the obtained stress-strain curve	κ_e	= 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
ϵ_f	= strain in the FRP reinforcement, in./in. (mm/mm)	θ_p	= plastic hinge rotation demand
ϵ_{fd}	= debonding strain of externally bonded FRP reinforcement, in./in. (mm/mm)	ρ_f	= FRP reinforcement ratio
ϵ_{fe}	= effective strain in FRP reinforcement attained at failure, in./in. (mm/mm)	ρ_g	= ratio of area of longitudinal steel reinforcement to cross-sectional area of a compression member (A_s/bh)
ϵ_{fu}	= design rupture strain of FRP reinforcement, in./in. (mm/mm)	ρ_ℓ	= longitudinal reinforcement ratio
ϵ_{fu}^*	= ultimate rupture strain of FRP reinforcement, in./in. (mm/mm)	ρ_s	= ratio of nonprestressed reinforcement
ϵ_{pe}	= effective strain in prestressing steel after losses, in./in. (mm/mm)	σ	= standard deviation
ϵ_{pi}	= initial strain in prestressed steel reinforcement, in./in. (mm/mm)	τ_b	= average bond strength for near-surface-mounted FRP, psi (MPa)
ϵ_{pnet}	= 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)	τ_{max}	= bond strength for near-surface-mounted FRP, psi (MPa)
$\epsilon_{pnet,s}$	= net strain in prestressing steel beyond decompression at service, in./in. (mm/mm)	ψ_e	= factor used to modify development length based on reinforcement coating
ϵ_{ps}	= strain in prestressed reinforcement at nominal strength, in./in. (mm/mm)	ψ_f	= FRP strength reduction factor
$\epsilon_{ps,s}$	= strain in prestressing steel at service load, in./in. (mm/mm)		= 0.85 for flexure (calibrated based on design material properties)
ϵ_s	= strain in nonprestressed steel reinforcement, in./in. (mm/mm)		= 0.85 for shear (based on reliability analysis) for three-sided FRP U-wrap or two-sided strengthening schemes
ϵ_{sy}	= strain corresponding to yield strength of nonprestressed steel reinforcement, in./in. (mm/mm)		= 0.95 for shear fully wrapped sections
ϵ_t	= net tensile strain in extreme tension steel at nominal strength, in./in. (mm/mm)	ψ_s	= factor used to modify development length based on reinforcement size
ϵ_t'	= transition strain in stress-strain curve of FRP-confined concrete, in./in. (mm/mm)	ψ_t	= factor used to modify development length based on reinforcement location
η	= parameter that combines the effects of member continuity and applied load pattern for producing maximum factored moment at the critical section under consideration		
ϕ	= strength reduction factor		
ϕ_D	= design curvature for a confined concrete section		
ϕ_{ex}	= strength reduction factor used to check strength of member subject to fire or elevated temperature calculated using reduced material properties		
$\phi_{u,frp}$	= curvature of the FRP confined section at ultimate capacity, 1/in. (1/mm)		
$\phi_{y,frp}$	= curvature of the FRP confined section at steel yielding, 1/in. (1/mm)		
κ_a	= efficiency factor for FRP reinforcement in determination of f'_{cc} (based on geometry of cross section)		

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

carbon fiber-reinforced polymer—composite material comprising a polymer matrix reinforced with carbon fiber 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 of woven, 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 of fiber present in a composite, expressed as a percentage volume fraction or mass fraction of the composite.

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

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

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

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

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

glass fiber-reinforced polymer—composite material comprising a polymer matrix reinforced with glass fiber 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.

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

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

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 a percentage of total mass or total volume.

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

saturating resins (or saturants)—polymer-based resin used to impregnate the reinforcing fibers, fix them in place, and transfer load between fibers.

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.

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

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

wet layup—manufacturing process where dry fabric 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 desired 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 smokestacks, 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 first published 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 FRP system 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 multidirectional fiber sheets or fabrics impregnated with a saturating resin on site. The saturating resin, along with the compatible primer and putty, bonds the FRP sheets to the 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:



Documents

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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.

FRP strengthening 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 FRP system. 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 formu-

lated 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, and carbon 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, lb/ft³ (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 130 lb/ft³ (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 transition temperature T_g , 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 T_g 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_g —will reduce 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 T_g , 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 of unidirectional 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, $\times 10^{-6}/^{\circ}\text{F}$ ($\times 10^{-6}/^{\circ}\text{C}$)					
	Concrete	Steel	GFRP	BFRP	CFRP	AFRP
Longitudinal, α_L	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)
Transverse, α_T	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.

material is characterized by a linear elastic stress-strain relationship until failure, which is sudden and brittle. The tensile strength and stiffness of an FRP 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 FRP repair 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 ($A_f f_{fu}$) and chord stiffness ($A_f E_f$) to be used in the design of the FRP system 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/D3039M](#). 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 ($f_{fu}^* = \bar{f}_{fu} - 3\sigma$). The chord tensile modulus (E_f) is defined as the mean chord tensile modulus of at least 20 test specimens. From these, ultimate rupture strain is determined ($\epsilon_{fu}^* = f_{fu}^*/E_f$). 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 char-

acterized 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 FRP laminate 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. (6 mm) 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 $0.52f_u$ 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 FRP materials 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 glass FRP ([Wu et 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 of FRP 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 (Mandell and 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 of basalt fibers due to their susceptibility to degradation in moisture, salt water, or acidic solutions. Hydrolyzation dominates fatigue strength degradation of BFRP 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 of tension 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 T_g . ACI 440.8 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 CFR 49.

5.2—Storage

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

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 diluents
- (d) With a sufficient concentration in air, explosion, or fire of flammable materials when exposed to heat, flames, pilot lights, sparks, static electricity, cigarettes, or other sources of ignition
- (e) Exothermic reactions of mixtures of materials causing fires or personal injury
- (f) Nuisance dust caused by grinding or handling of cured FRP systems (manufacturer's literature should be consulted for specific hazards)

The complexity of thermosetting resins and associated materials makes it essential that labels and the SDS are read and understood by those working with these products. **CFR 16 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 of resins if required by the FRP system 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 exter-

nally 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 requirements 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 preparation 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 of **ACI 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 of the 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 until 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 and putty—Where required, primer should be applied to all areas on the concrete surface where the FRP

system is to be placed. The primer should be placed uniformly on the prepared surface at the manufacturer's specified rate of coverage. The applied primer should be protected from dust, moisture, and other contaminants before applying the FRP system.

Putty should be used in an appropriate thickness and sequence with the primer as recommended by the FRP system manufacturer. The system-compatible putty, which is typically a thickened 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 operations

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 FRP ply orientation and ply stacking sequence should be specified. Small variations in angle, as little as 5 degrees, from the intended direction of fiber alignment can cause a substantial reduction in 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 of resins is a time-temperature-dependent phenomenon. Ambient-cure resins can take several days to reach full cure. Temperature extremes or fluctuations can retard or accelerate the resin curing time. The FRP system manufacturer may offer several prequalified grades of resin to accommodate these situations.

Elevated cure systems require the resin to be heated to a specific temperature for a specified 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 FRP system 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 10.10.1](#) 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 2018 IBC 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 mm²) 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 of a 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 A770/A770M** 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 and should be the same as 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 coatings 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 ([ACI 437R](#)).

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 of repair 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 FRP laminate 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 of ACI 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 ACI 318 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 reinforce-

ment combined with high ratios of FRP 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 of FRP to 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)

$$(\phi R_n)_{existing} \geq (1.1S_{DL} + 0.75S_{LL})_{new} \quad (9.2)$$

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 150 lb/ft² (730 kg/m²). 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 Structural fire resistance—The level of strengthening 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 T_g 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 adequate fire resistance. When considering the fire resis-

tance 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:

$$\phi_{ex}R \geq (0.9 \text{ or } 1.2)S_{DL} + 0.5S_{LL} + 0.2S_{SL} \quad (9.2.1)$$

where R is the nominal resistance of the member at an elevated temperature without FRP; $\phi_{ex} = 1.0$; and S_{DL} , S_{LL} , and S_{SL} 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 ACI 216.1 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 T_g of the components of the system comprising the load path.

9.2.2 Overall structural strength—While FRP systems 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 of FRP 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 of an FRP system 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 FRP system 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 $\pm 50^\circ\text{F}$ ($\pm 28^\circ\text{C}$) (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.

9.3.2 Loading considerations—Loading conditions uniquely affect different fibers of FRP systems. The licensed design professional should select an FRP system based on the known behavior of that system in the anticipated service conditions. Some important loading considerations that relate to the nature of the specific systems are given in the following. Specific information should be obtained from material manufacturers.

- (a) Impact tolerance—AFRP, GFRP, and BFRP systems demonstrate better tolerance to impact than CFRP systems.
- (b) Creep rupture and fatigue—CFRP systems are highly resistive to creep rupture under sustained loading and fatigue failure under cyclic loading. GFRP and BFRP systems are more sensitive to both loading conditions.

9.3.3 Durability considerations—Durability of FRP systems is reported in available literature (Dolan et al. 2008; Karbhari 2007). The licensed design professional should select an FRP system that has undergone durability testing consistent with the application environment. Durability testing may include hot-wet cycling, alkaline immersion, freezing-and-thawing cycling, ultraviolet exposure, dry heat, and salt water (Cromwell et al. 2011). ACI 440.9R provides guidance for assessing durability performance of external FRP reinforcement using accelerated conditioning protocols in combination with standard test methods for mechanical properties.

Any FRP system that completely encases or covers a concrete section should be investigated for the effects of a variety of environmental conditions including those of freezing and thawing, steel corrosion, alkali and silica aggregate reactions, water entrapment, vapor pressures, and moisture vapor transmission (Masoud and Soudki 2006; Soudki and Green 1997; Porter et al. 1997; Christensen et al. 1996; Toutanji 1999). Many FRP systems create a moisture-impermeable layer on the surface of the concrete. In areas where moisture vapor transmission is expected, adequate means should be provided to allow moisture to escape from the concrete structure.

9.3.4 Protective-coating selection—A coating or insulation system can be applied to the installed FRP system to protect it from exposure to certain environmental conditions (Bisby et al. 2005a; Williams et al. 2006). The thickness and type of coating should be selected based on the requirements of the composite repair; resistance to environmental effects such as moisture, salt water, temperature extremes, fire, impact, and ultraviolet exposure; resistance to site-specific effects; and resistance to vandalism. Coatings are relied upon to retard the degradation of the mechanical properties of the FRP systems. The coatings should be periodically inspected and maintained to ensure continued effectiveness.

External coatings or thickened coats of resin over fibers can protect them from damage due to impact or abrasion. In high-impact or traffic areas, additional levels of protection may be necessary. Portland cement plaster and polymer coatings are commonly used for protection where minor impact or abrasion is anticipated.

9.4—Design material properties

Unless otherwise stated, the material properties reported by manufacturers, such as the ultimate tensile strength, typically do not consider long-term exposure to environmental conditions and should be considered as initial properties. Because long-term exposure to various types of environments can reduce the tensile properties and can affect creep-rupture and fatigue endurance of FRP laminates, the material properties used in design equations should be reduced based on the environmental exposure condition.

Equations (9.4a) through (9.4c) give the tensile properties that should be used in all design equations. The design ultimate tensile strength should be determined using the environmental reduction factor given in Table 9.4 for the appropriate fiber type and exposure condition:

$$f_{fu} = C_E f_{fu}^* \tag{9.4a}$$

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

$$\epsilon_{fu} = C_E \epsilon_{fu}^* \tag{9.4b}$$

The expression for the modulus of elasticity, given in Eq. (9.4c), recognizes that the modulus is typically unaffected by environmental conditions. The modulus given in this equation will be the same as the initial value reported by the manufacturer and can be represented as:

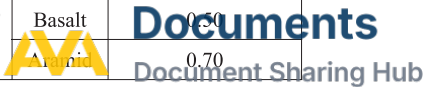
$$E_f = f_{fu} / \epsilon_{fu} = f_{fu}^* / \epsilon_{fu}^* \tag{9.4c}$$

The constituent materials, fibers, and resins of an FRP system affect its durability and resistance to environmental exposure. The environmental reduction factors given in Table 9.4 are conservative estimates based on the relative durability of each fiber type.

As Table 9.4 illustrates, if the FRP system is located in a relatively benign environment, such as indoors, the reduction factor is closer to unity. If the FRP system is located

Table 9.4—Environmental reduction factor for various FRP systems and exposure conditions

Exposure conditions	Fiber type	Environmental reduction factor C_E
Interior exposure	Carbon	0.95
	Glass	0.75
	Basalt	0.75
	Aramid	0.85
Exterior exposure (bridges, piers, and unenclosed parking garages)	Carbon	0.85
	Glass	0.65
	Basalt	0.65
	Aramid	0.75
Aggressive environment (chemical plants and wastewater treatment plants)	Carbon	0.85
	Glass	0.50
	Basalt	0.50
	Aramid	0.70



in an aggressive environment where prolonged exposure to high humidity, freezing-and-thawing cycles, salt water, or alkalinity is expected, a lower reduction factor should be used. The reduction factor can be modified to reflect the use of a protective coating if the coating has been shown through testing to lessen the effects of environmental exposure and the coating is maintained for the life of the FRP system.

CHAPTER 10—FLEXURAL STRENGTHENING

Bonding fiber-reinforced polymer (FRP) reinforcement to the tension face of a concrete flexural member with fibers oriented along the length of the member will provide an increase in flexural strength. Increases in overall flexural strength from 10 to 160% have been documented (Meier and Kaiser 1991; Ritchie et al. 1991; Sharif et al. 1994). When taking into account the strengthening limits of 9.2 and ductility and serviceability limits, however, strength increases of up to 40% are more reasonable.

This chapter does not apply to FRP systems used to enhance the flexural strength of members in the expected plastic hinge regions of ductile moment frames resisting seismic loads; these are addressed in Chapter 13.

10.1—Nominal strength

The strength design approach requires that the design flexural strength of a member exceed its required factored moment, as indicated by Eq. (10.1). The design flexural strength ϕM_n refers to the nominal strength of the member multiplied by a strength reduction factor, and the factored moment M_u refers to the moment calculated from factored loads (for example, $\alpha_{DL}M_{DL} + \alpha_{LL}M_{LL} + \dots$)

$$\phi M_n \geq M_u \quad (10.1)$$

This guide recommends that the factored moment M_u of a section be calculated by use of load factors as required by ACI 318. An additional strength reduction factor for FRP, ψ_f , should be applied to the flexural contribution of the FRP

reinforcement, M_{nf} , as described in 10.2.10. The additional strength reduction factor, ψ_f , is used to improve the reliability of strength prediction and accounts for the different failure modes observed for FRP-strengthened members (delamination of FRP reinforcement).

The nominal flexural strength of FRP-strengthened concrete members with mild steel reinforcement and with bonded prestressing steel can be determined based on strain compatibility, internal force equilibrium, and the controlling mode of failure. For members with unbonded prestressed steel, strain compatibility does not apply and the stress in the unbonded tendons at failure depends on the overall deformation of the member and is assumed to be approximately the same at all sections.

10.1.1 Failure modes—The flexural strength of a section depends on the controlling failure mode. The following flexural failure modes should be investigated for an FRP-strengthened section (GangaRao and Vijay 1998):

- (a) Crushing of the concrete in compression before yielding of the reinforcing steel
- (b) Yielding of the steel in tension followed by rupture of the FRP laminate
- (c) Yielding of the steel in tension followed by concrete crushing
- (d) Shear/tension delamination of the concrete cover (cover delamination)
- (e) Debonding of the FRP from the concrete substrate (FRP debonding)

Concrete crushing is assumed to occur if the compressive strain in the concrete reaches its maximum usable strain ($\epsilon_c = \epsilon_{cu} = 0.003$). Rupture of the externally bonded FRP is assumed to occur if the strain in the FRP reaches its design rupture strain ($\epsilon_f = \epsilon_{fu}$) before the concrete reaches its maximum usable strain.

Cover delamination or FRP debonding can occur if the force in the FRP cannot be sustained by the substrate (Fig. 10.1.1). Such behavior is generally referred to as debonding, regardless of where the failure plane propagates

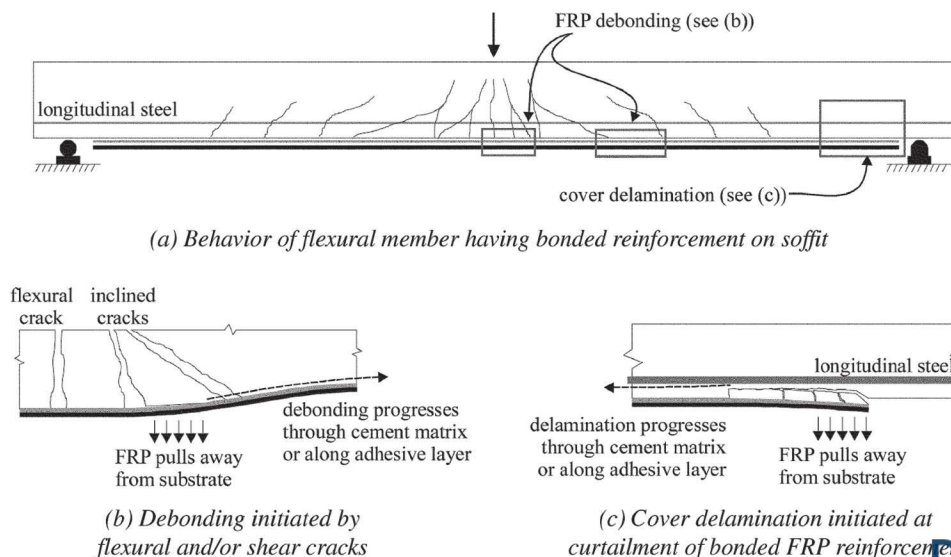


Fig. 10.1.1—Debonding and delamination of externally bonded FRP systems.

within the FRP-adhesive-substrate region. Guidance to avoid the cover delamination failure mode is given in [Chapter 14](#).

Away from the section where the externally bonded FRP terminates, a failure controlled by FRP debonding may govern (Fig. 10.1.1(b)). To prevent such an intermediate crack-induced debonding failure mode, the effective strain in FRP reinforcement should be limited to the strain at which debonding may occur, ε_{fd} , as defined in Eq. (10.1.1).

$$\begin{aligned}\varepsilon_{fd} &= 0.083 \sqrt{\frac{f'_c}{NE_f t_f}} \leq 0.9\varepsilon_{fu} \quad (\text{in.-lb}) \\ \varepsilon_{fd} &= 0.41 \sqrt{\frac{f'_c}{NE_f t_f}} \leq 0.9\varepsilon_{fu} \quad (\text{SI})\end{aligned}\quad (10.1.1)$$

Equation (10.1.1) takes a modified form of the debonding strain equation proposed by [Teng et al. \(2003, 2004\)](#) that was based on committee evaluation of a significant database for flexural beam tests exhibiting FRP debonding failure. The proposed equation was calibrated using average measured values of FRP strains at debonding for flexural tests experiencing intermediate crack-induced debonding to determine the best-fit coefficient of 0.083 (0.41 in SI). Reliability of the FRP contribution to flexural strength is addressed by incorporating an additional strength reduction factor for FRP, ψ_f , in addition to the strength reduction factor ϕ per [ACI 318](#) for structural concrete. Anchorage systems such as U-wraps and fiber anchors (examples are shown schematically in Fig. 14.1.1) have been proven to control debonding failure of the longitudinal FRP. Providing such anchorage can improve the flexural strength and deformability of the externally bonded FRP-strengthened member ([Kalfat et al. 2018](#); [Grelle and Sneed 2013](#); [Lee and Lopez 2020](#); [Smith et al. 2013](#)). Providing anchorage does not necessarily prevent local FRP debonding nor the associated brittle failure mode. However, FRP anchorage may mitigate sudden complete debonding of the FRP, allowing the FRP to continue to resist force. Experimental studies have shown that these anchorage systems can increase the effective strain in the flexural FRP to values up to tensile rupture ([Lee et al. 2010](#); [Orton et al. 2008](#)).

For near-surface-mounted (NSM) FRP applications, the value of ε_{fd} may vary from $0.6\varepsilon_{fu}$ to $0.9\varepsilon_{fu}$, depending on many factors such as member dimensions, steel and FRP reinforcement ratios, and surface roughness of the FRP bar. Based on analysis of a database of existing studies ([Bianco et al. 2014](#)), the committee recommends the use of $\varepsilon_{fd} = 0.7\varepsilon_{fu}$ for NSM bars and plates. To achieve the debonding design strain of NSM FRP bars and plates, ε_{fd} , the bonded length should be greater than the development length given in [Chapter 14](#).

10.2—Reinforced concrete members

This section presents guidance on the calculation of the flexural strengthening effect of adding longitudinal FRP reinforcement to the tension face of a reinforced concrete member. A specific illustration of the concepts in this section applied to strengthening of existing rectangular sections

reinforced in the tension zone with nonprestressed steel is given. The general concepts outlined herein can, however, be extended to nonrectangular shapes (T-sections and I-sections) and to members with steel compression reinforcement.

10.2.1 Assumptions—The following assumptions are made in calculating the flexural resistance of a section strengthened with an externally applied FRP system:

- Design calculations are based on the dimensions, internal reinforcing steel arrangement, and material properties of the existing member being strengthened.
- The strains in the steel reinforcement and concrete are directly proportional to their distance from the neutral axis. That is, a plane section before loading remains plane after loading.
- There is no relative slip between external FRP reinforcement and the concrete.
- The shear deformation within the adhesive layer is neglected because the adhesive layer is very thin with only slight variations in its thickness.
- The maximum usable compressive strain in the concrete is 0.003.
- The tensile strength of concrete is neglected.
- The FRP reinforcement has a linear elastic stress-strain relationship to failure.

While some of these assumptions are necessary for the sake of computational ease, the assumptions do not accurately reflect the true fundamental behavior of FRP flexural reinforcement. For example, there will be shear deformation in the adhesive layer, causing relative slip between the FRP and the substrate. The inaccuracy of the assumptions will not, however, significantly affect the computed flexural strength of an FRP-strengthened member. An additional strength reduction factor (presented in 10.2.10) will conservatively compensate for these discrepancies.

10.2.2 Shear strength—When FRP reinforcement is being used to increase the flexural strength of a member, the member should be capable of resisting the shear forces associated with the increased flexural strength. The potential for shear failure of the section should be considered by comparing the design shear strength of the section to the required shear strength. If additional shear strength is required, FRP laminates oriented transverse to the beam longitudinal axis can be used to resist shear forces, as described in [Chapter 11](#).

10.2.3 Existing substrate strain—Unless all loads on a member, including self-weight and any prestressing forces, are removed before installation of FRP reinforcement, the substrate to which the FRP is applied will be strained. These strains should be considered to be initial strains and should be excluded from the strain in the FRP ([Arduini and Nanni 1997](#); [Nanni and Gold 1998](#)). The initial strain on the bonded substrate, ε_{bi} , can be determined from an elastic analysis of the existing member, considering all loads that will be on the member during the installation of the FRP system. The elastic analysis of the existing member should be based on cracked section properties.

10.2.4 Flexural strengthening of concave soffits—The presence of curvature in the soffit of a concrete member may lead to the development of tensile stresses normal to

the adhesive and surface to which the FRP is bonded. Such tensile stresses result when the FRP tends to straighten under load and can promote the initiation of FRP debonding or interlaminar failures that reduce the effectiveness of the FRP flexural strengthening (Aiello et al. 2001; Eshwar et al. 2003). If the extent of the curved portion of the soffit exceeds a length of 40 in. (1.0 m) with a rise of 0.2 in. (5 mm), the surface should be made flat before strengthening. Alternately, anchorage systems such as U-wraps, mechanical fasteners, fiber anchors, or NSM anchors should be installed to control delamination (Eshwar et al. 2005).

10.2.5 Strain in FRP reinforcement—It is important to determine the strain in the FRP reinforcement at the ultimate limit state. Because FRP systems are linear elastic until failure, the strain in the FRP will dictate the stress developed in the FRP. The maximum strain that can be achieved in the FRP reinforcement will be governed by either the strain developed in the FRP at the point at which concrete crushes, the point at which the FRP ruptures, or the point at which the FRP debonds from the substrate. The effective strain in the FRP reinforcement at the ultimate limit state can be found from Eq. (10.2.5)

$$\varepsilon_{fe} = \varepsilon_{cu} \left(\frac{d_f - c}{c} \right) - \varepsilon_{bi} \leq \varepsilon_{fd} \quad (10.2.5)$$

where ε_{bi} is the initial substrate strain as described in 10.2.3, and d_f is the effective depth of FRP reinforcement, as indicated in Fig. 10.2.5.

10.2.6 Stress in the FRP reinforcement—The effective stress in the FRP reinforcement is the maximum level of stress that can be developed in the FRP reinforcement before flexural failure of the section. This effective stress can be found from the strain in the FRP, assuming elastic behavior

$$f_{fe} = E_f \varepsilon_{fe} \quad (10.2.6)$$

10.2.7 Strength reduction factor—The use of externally bonded FRP reinforcement for flexural strengthening will reduce the ductility of the original member. In some cases, the loss of ductility is negligible. Sections that experience a significant loss in ductility, however, should be addressed. To maintain a sufficient degree of ductility, the strain in the steel at the ultimate limit state should be checked. For

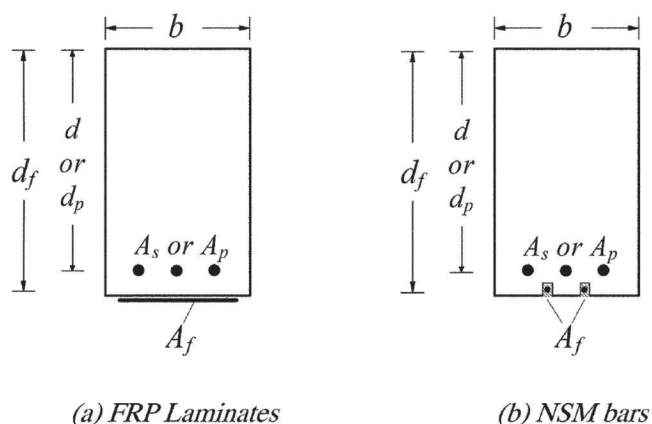


Fig. 10.2.5—Effective depth of FRP systems.

reinforced concrete members with nonprestressed steel reinforcement, adequate ductility is achieved if the strain in the steel at the point of concrete crushing or failure of the FRP, including delamination or debonding, is at least 0.005, according to the definition of a tension-controlled section, as given in ACI 318.

The approach taken by this guide follows the philosophy of ACI 318. A strength reduction factor given by Eq. (10.2.7) should be used, where ε_t is the net tensile strain in the extreme tension steel at nominal strength, as defined in ACI 318.

$$\phi = \begin{cases} 0.90 & \text{for } \varepsilon_t \geq 0.005 \\ 0.65 + \frac{0.25(\varepsilon_t - \varepsilon_{sy})}{0.005 - \varepsilon_{sy}} & \text{for } \varepsilon_{sy} < \varepsilon_t < 0.005 \\ 0.65 & \text{for } \varepsilon_t \leq \varepsilon_{sy} \end{cases} \quad (10.2.7)$$

This equation sets the reduction factor at 0.90 for ductile sections and 0.65 for brittle sections where the steel does not yield and provides a linear transition for the reduction factor between these conditions. The condition may arise in which the governing failure mode is FRP debonding; this occurs if the right term of the inequality in Eq. (10.2.5) controls. In these cases, although ε_t may be greater than 0.005, ε_c may be less than 0.003 at section capacity. This leads to section curvature less than that which defines tension-controlled behavior; that is, $\varepsilon_t + \varepsilon_{cu} < 0.008$. In these cases, anchorage of the FRP can be used to increase ε_{fd} , control a debonding failure mode, or both. The use of Eq. (10.2.7) is limited to steel having a yield strength f_y less than 80 ksi (550 MPa) (ACI 318).

10.2.8 Serviceability—The serviceability of a member (deflections and crack widths) under service loads should satisfy applicable provisions of ACI 318. The effect of the FRP external reinforcement on the serviceability can be assessed using a transformed-section analysis.

To avoid inelastic deformations of reinforced concrete members with nonprestressed steel reinforcement strengthened with external FRP reinforcement, the existing internal steel reinforcement should be prevented from yielding under service load levels, especially for members subjected to cyclic loads (El-Tawil et al. 2001). The stress in the steel reinforcement under service load should be limited to 80% of the yield strength, as shown in Eq. (10.2.8a). In addition, the compressive stress in concrete under service load should be limited to 60% of the compressive strength, as shown in Eq. (10.2.8b)

$$f_{s,s} \leq 0.80f_y \quad (10.2.8a)$$

$$f_{c,s} \leq 0.60f'_c \quad (10.2.8b)$$

10.2.9 Creep rupture and fatigue stress limits—To avoid creep rupture of the FRP reinforcement under sustained stresses or failure due to cyclic stresses and fatigue of the FRP reinforcement, the stress in the FRP reinforcement under these stress conditions should be checked. Because

this stress will be within the elastic response range of the member, the stresses can be computed by elastic analysis using cracked section properties as appropriate.

In Section 4.4, the creep rupture phenomenon and fatigue characteristics of FRP systems are described and the resistance to these effects by various types of fibers is examined. As stated in 4.4.1, research has indicated that glass, basalt, aramid, and carbon fibers can sustain approximately 0.3, 0.3, 0.5, and 0.9 times their ultimate strengths, respectively, before encountering a creep rupture problem. To avoid failure of an FRP-reinforced member due to creep rupture and fatigue of the FRP, stress limits for these conditions should be imposed on the FRP reinforcement. The stress in the FRP reinforcement can be computed using elastic analysis and an applied moment due to all sustained loads (dead loads and the sustained portion of the live load) plus the maximum moment induced in a fatigue loading cycle (Fig. 10.2.9). The sustained stress should be limited as expressed by Eq. (10.2.9) to maintain safety. Values for safe sustained plus cyclic stress are given in Table 10.2.9. These values are based approximately on the stress limits previously stated in 4.4.1 with an imposed safety factor of 1/0.6

$$f_{f,s} \leq \text{sustained plus cyclic stress limit} \quad (10.2.9)$$

10.2.10 Ultimate strength of singly reinforced rectangular section—To illustrate the concepts presented in this chapter, this section describes the application of these concepts to a nonprestressed singly-reinforced rectangular section. Figure 10.2.10 illustrates the internal strain and stress distribution for a rectangular section under flexure at the ultimate limit state.

The calculation procedure used to arrive at the ultimate strength should satisfy strain compatibility and force equilibrium, and should consider the governing mode of failure. Several calculation procedures can be derived to satisfy

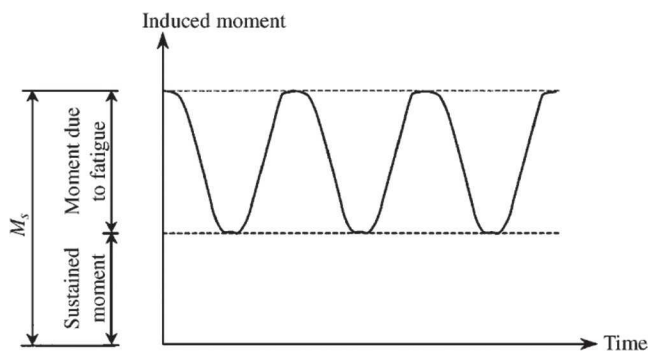


Fig. 10.2.9—Illustration of the level of applied moment to be used to check the stress limits in the FRP reinforcement.

Table 10.2.9—Sustained plus cyclic service load stress limits in FRP reinforcement

Stress type	Fiber type			
	GFRP	BFRP	AFRP	CFRP
Sustained plus cyclic stress limit	$0.20f_{fu}$	$0.20f_{fu}$	$0.30f_{fu}$	$0.55f_{fu}$

these conditions. The calculation procedure described herein illustrates an iterative method that involves selecting an assumed depth to the neutral axis, c , calculating the strain in each material using strain compatibility; calculating the associated stress in each material; and checking internal force equilibrium. If the internal force resultants do not equilibrate, the depth to the neutral axis is revised and the procedure repeated.

For any assumed depth to the neutral axis, c , the strain in the FRP reinforcement can be computed from Eq. (10.2.5). This equation considers the governing mode of failure for the assumed neutral axis depth. If the left term of the inequality controls, concrete crushing controls flexural failure of the section. If the right term of the inequality controls, FRP failure (rupture or debonding) controls flexural failure of the section.

The effective stress in the FRP reinforcement can be found from the strain in the FRP, assuming elastic behavior using Eq. (10.2.6). Based on the strain in the FRP reinforcement, the strain in the nonprestressed steel reinforcement can be found from Eq. (10.2.10a) using strain compatibility:

$$\epsilon_s = (\epsilon_{fe} + \epsilon_{bi}) \left(\frac{d - c}{d_f - c} \right) \quad (10.2.10a)$$

The stress in the steel is determined from the strain in the steel using its assumed elastic-perfectly plastic stress-strain curve:

$$f_s = E_s \epsilon_s \leq f_y \quad (10.2.10b)$$

With the stress in the FRP and steel reinforcement determined for the assumed neutral axis depth, internal force equilibrium may be checked using Eq. (10.2.10c):

$$\alpha_1 f'_c \beta_1 b c = A_s f_s + A_f f_{fe} \quad (10.2.10c)$$

The terms α_1 and β_1 in Eq. (10.2.10c) are parameters defining a rectangular stress block in the concrete equivalent to the nonlinear distribution of stress. If concrete crushing is the controlling mode of failure (before or after steel yielding), α_1 and β_1 can be taken as the values associated with the Whitney stress block (ACI 318); that is, $\alpha_1 = 0.85$ and $\beta_1 = 0.85$ for f'_c between 2500 and 4000 psi (17 and 27 MPa), and β_1 is reduced linearly at a rate of 0.05 for each 1000 psi (7 MPa) of concrete strength exceeding 4000 psi (27 MPa). Note that β_1 need not be taken less than 0.65. If FRP rupture or FRP debonding occur, the Whitney stress block will give reasonably accurate results. A nonlinear stress distribution in the concrete or a more accurate stress block appropriate for the strain level reached in the concrete at the ultimate-limit state may also be used.

The depth to the neutral axis, c , is found by simultaneously satisfying Eq. (10.2.5), (10.2.6), (10.2.10a), (10.2.10b), and (10.2.10c), thus establishing internal force equilibrium and strain compatibility. To solve for the depth of the neutral axis, c , an iterative solution procedure can be used. An initial value for c is assumed and the strains and stresses

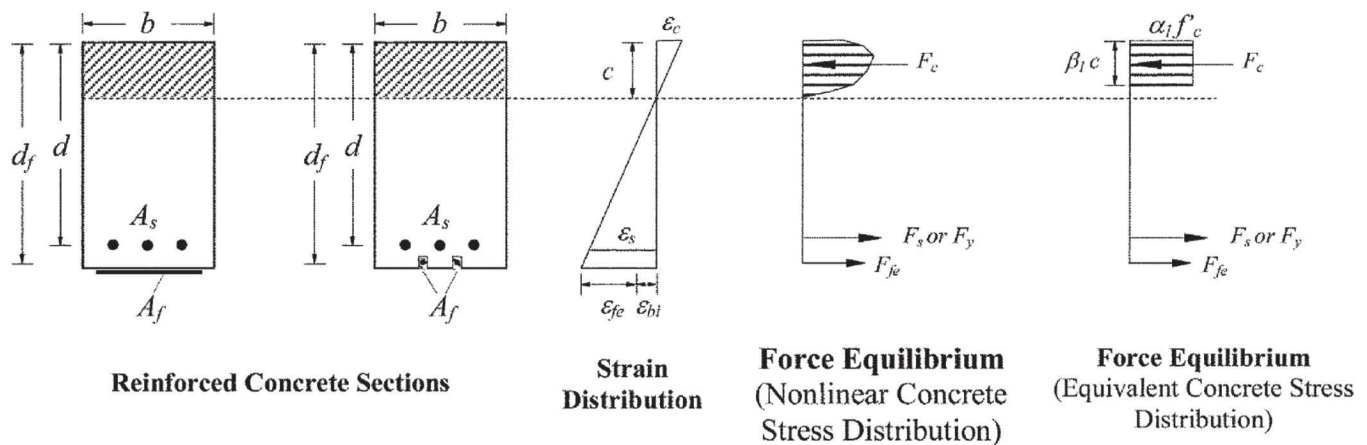


Fig. 10.2.10—Internal strain and stress distribution for a rectangular section under flexure at ultimate limit state.

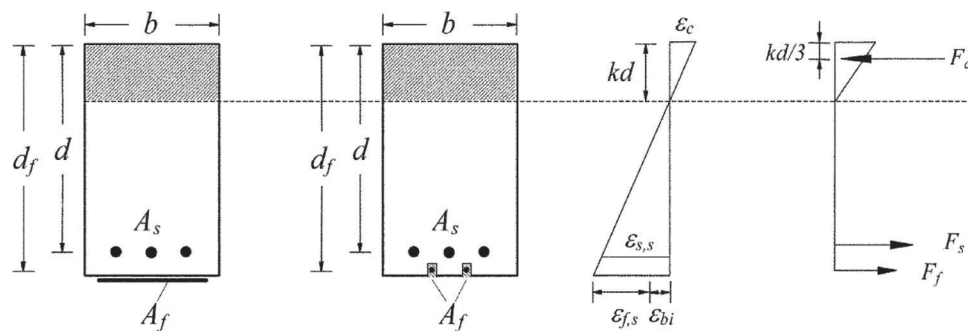


Fig. 10.2.10.1—Elastic strain and stress distribution.

are calculated using Eq. (10.2.5), (10.2.6), (10.2.10a), and (10.2.10b). A revised value for the depth of neutral axis, c , is then calculated from Eq. (10.2.10c). The calculated and assumed values of c are then compared. If they agree within an acceptable tolerance, then the correct value of c is reached. If the calculated and assumed values do not agree, another value for c is selected, and the process is repeated until convergence is attained.

The nominal flexural strength of the section with FRP external reinforcement is computed from Eq. (10.2.10d). An additional reduction factor for FRP, ψ_f , is applied to the flexural-strength contribution of the FRP reinforcement. The recommended value of ψ_f is 0.85. This reduction factor for the strength contribution of FRP reinforcement is based on the reliability analysis discussed in 9.1, which was based on the experimentally calibrated statistical properties of the flexural strength (Okeil et al. 2007).

$$M_n = A_s f_s \left(d - \frac{\beta_1 c}{2} \right) + \psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2} \right) \quad (10.2.10d)$$

10.2.10.1 Stress in steel under service loads—The stress in the steel reinforcement can be calculated based on a cracked-section analysis of the FRP-strengthened reinforced concrete section, as indicated by Eq. (10.2.10.1):

$$f_{s,s} = \frac{\left[M_s + \epsilon_{bi} A_f E_f \left(d_f - \frac{kd}{3} \right) \right] (d - kd) E_s}{\left[A_s E_s \left(d - \frac{kd}{3} \right) (d - kd) + A_f E_f \left(d_f - \frac{kd}{3} \right) (d_f - kd) \right]} \quad (10.2.10.1)$$

The distribution of strain and stress in the reinforced concrete section is shown in Fig. 10.2.10.1. Similar to conventional reinforced concrete, the depth to the neutral axis at service, kd , can be computed by taking the first moment of the areas of the transformed section. The transformed area of the FRP may be obtained by multiplying the area of FRP by the modular ratio of FRP to concrete. Although this method neglects the difference in the initial strain of the FRP, the initial strain does not greatly influence the depth to the neutral axis in the elastic response range of the member.

The stress in the steel under service loads computed from Eq. (10.2.10.1) should be compared against the limits described in 10.2.8. The value of M_s from Eq. (10.2.10.1) is equal to the moment due to all sustained loads (dead loads and the sustained portion of the live load) plus the maximum moment induced in a fatigue loading cycle, as shown in Fig. 10.2.9.

10.2.10.2 Stress in FRP under service loads—The stress in the FRP reinforcement can be computed using Eq. (10.2.10.2)

with $f_{s,s}$ from Eq. (10.2.10.1). Equation (10.2.10.2) gives the stress in the FRP reinforcement under an applied moment within the elastic response range of the member:

$$f_{f,s} = f_{s,s} \left(\frac{E_f}{E_s} \right) \frac{d_f - kd}{d - kd} - \epsilon_{bi} E_f \quad (10.2.10.2)$$

The stress in the FRP under service loads computed from Eq. (10.2.10.2) should be compared against the limits described in 10.2.9.

10.3—Prestressed concrete members

This section presents guidance on the effect of adding longitudinal FRP reinforcement to the tension face of a rectangular prestressed concrete member. The general concepts outlined herein can be extended to nonrectangular shapes (T-sections and I-sections) and to members with nonprestressed steel reinforcement.

10.3.1 Members with bonded prestressing steel

10.3.1.1 Assumptions—In addition to the basic assumptions for concrete and FRP behavior for a reinforced concrete section listed in 10.2.1, the following assumptions are made in calculating the flexural resistance of a prestressed section strengthened with an externally applied FRP system:

- (a) Strain compatibility can be used to determine strain in the externally bonded FRP, strain in the nonprestressed steel reinforcement, and the strain or strain change in the prestressing steel.
- (b) A flexural failure mode controlled by prestressing steel rupture should be investigated.
- (c) For cases where the prestressing steel is draped or harped, several sections along the span of the member should be evaluated to verify strength requirements.
- (d) The initial strain of the concrete substrate, ϵ_{bi} , should be calculated and excluded from the effective strain in the FRP. The initial strain can be determined from an elastic analysis of the existing member, considering all loads that will be applied to the member at the time of FRP installation. Analysis should be based on the actual condition of the member (cracked or uncracked section) to determine the substrate initial strain.

10.3.1.2 Strain in FRP reinforcement—The maximum strain that can be achieved in the FRP reinforcement will be governed by strain limitations due to either concrete crushing, FRP rupture, FRP debonding, or prestressing steel rupture. The effective design strain for FRP reinforcement at the ultimate-limit state for failure controlled by concrete crushing can be calculated using Eq. (10.2.5)

For failure controlled by prestressing steel rupture, Eq. (10.3.1.2a) can be used. For Grade 270 and 250 ksi (1860 and 1725 MPa) strand, the value of ϵ_{pu} to be used in Eq. (10.3.1.2a) is 0.035:

$$\epsilon_{fe} = (\epsilon_{pu} - \epsilon_{pi}) \left(\frac{d_f - c}{d_p - c} \right) - \epsilon_{bi} \leq \epsilon_{fd} \quad (10.3.1.2a)$$

in which

$$\epsilon_{pi} = \frac{P_e}{A_p E_{ps}} + \frac{P_e}{A_c E_c} \left(1 + \frac{e^2}{r^2} \right) \quad (10.3.1.2b)$$

10.3.1.3 Strength reduction factor—To maintain a sufficient degree of ductility, the strain in the prestressing steel at the nominal strength should be checked. Adequate ductility is achieved if the strain in the prestressing steel at the nominal strength is at least 0.013. Where this strain cannot be achieved, the strength reduction factor is decreased to account for a less ductile failure. The strength reduction factor for a member prestressed with standard 270 and 250 ksi (1860 and 1725 MPa) prestressing steel is given by Eq. (10.3.1.3), where ϵ_{ps} is the prestressing steel strain at the nominal strength:

$$\phi = \begin{cases} 0.90 & \text{for } \epsilon_{ps} \geq 0.013 \\ 0.65 + \frac{0.25(\epsilon_{ps} - 0.010)}{0.013 - 0.010} & \text{for } 0.010 < \epsilon_{ps} < 0.013 \\ 0.65 & \text{for } \epsilon_{ps} \leq 0.010 \end{cases} \quad (10.3.1.3)$$

10.3.1.4 Serviceability—To avoid inelastic deformations of the strengthened member, the prestressing steel should be prevented from yielding under service load levels. The stress in the steel under service load should be limited per Eq. (10.3.1.4a) and (10.3.1.4b). In addition, the compressive stress in the concrete under service load should be limited to 60% of the compressive strength:

$$f_{ps,s} \leq 0.82 f_{py} \quad (10.3.1.4a)$$

$$f_{ps,s} \leq 0.74 f_{pu} \quad (10.3.1.4b)$$

When fatigue is a concern, the stress in the prestressing steel due to transient live loads should be limited to 18 ksi (125 MPa) when the radii of prestressing steel curvature exceed 29 ft (9 m), or to 10 ksi (70 MPa) when the radii of prestressing-steel curvature does not exceed 12 ft (3.6 m). A linear interpolation should be used for radii between 12 and 29 ft (3.6 and 9 m) (**AASHTO LRFD**). These limits have been verified experimentally for prestressed members with harped and straight strands strengthened with externally bonded FRP (**Rosenboom and Rizkalla 2006**).

10.3.1.5 Creep rupture and fatigue stress limits—To avoid creep rupture of the FRP reinforcement under sustained stresses or failure due to cyclic stresses and fatigue of the FRP reinforcement, the stress in the FRP reinforcement under these stress conditions should not exceed the limits provided in 10.2.9.

10.3.1.6 Nominal strength—The calculation procedure to compute nominal strength should satisfy strain compatibility and force equilibrium, and should consider the governing mode of failure. The calculation procedure described herein uses an iterative method similar to that discussed in 10.2.9.

For any assumed depth to the neutral axis, c , the effective strain and stress in the FRP reinforcement can be computed from Eq. (10.2.5) and (10.2.6), respectively. This equation considers the governing mode of failure for the assumed neutral axis depth. If the left term of the inequality in Eq. (10.2.5) controls, concrete crushing controls flexural failure of the section. If the right term of the inequality controls, FRP failure (rupture or debonding) controls flexural failure of the section.

The strain in the prestressed steel can be found from Eq. (10.3.1.6a) based on strain compatibility:

$$\varepsilon_{ps} = \varepsilon_{pe} + \frac{P_e}{A_c E_c} \left(1 + \frac{e^2}{r^2} \right) + \varepsilon_{pnet} \leq 0.035 \quad (10.3.1.6a)$$

in which ε_{pe} is the effective strain in the prestressing steel after losses, and ε_{pnet} is the net tensile strain in the prestressing steel beyond decompression, at the nominal strength. The value of ε_{pnet} will depend on the mode of failure and can be calculated using Eq. (10.3.1.6b) and (10.3.1.6c):

$$\varepsilon_{pnet} = 0.003 \left(\frac{d_p - c}{c} \right) \text{ for concrete crushing failure} \quad (10.3.1.6b)$$

$$\varepsilon_{pnet} = (\varepsilon_{fe} + \varepsilon_{bi}) \left(\frac{d_p - c}{d_f - c} \right) \quad (10.3.1.6c)$$

for FRP rupture or debonding failure modes

The stress in the prestressing steel is calculated using the material properties of the steel. For a typical seven-wire low-relaxation prestressing strand, the stress-strain curve may be approximated by the following equations (Prestressed/Precast Concrete Institute 2004).

For Grade 250 ksi (1725 MPa) steel:

$$f_{ps} = \begin{cases} 28,500\varepsilon_{ps} & \text{for } \varepsilon_{ps} \leq 0.0076 \\ 250 - \frac{0.04}{\varepsilon_{ps} - 0.0064} & \text{for } \varepsilon_{ps} > 0.0076 \end{cases} \quad (\text{in.-lb})$$

$$f_{ps} = \begin{cases} 196,500\varepsilon_{ps} & \text{for } \varepsilon_{ps} \leq 0.0076 \\ 1720 - \frac{0.276}{\varepsilon_{ps} - 0.0064} & \text{for } \varepsilon_{ps} > 0.0076 \end{cases} \quad (\text{SI}) \quad (10.3.1.6d)$$

For Grade 270 ksi (1860 MPa) steel:

$$f_{ps} = \begin{cases} 28,500\varepsilon_{ps} & \text{for } \varepsilon_{ps} \leq 0.0086 \\ 270 - \frac{0.04}{\varepsilon_{ps} - 0.007} & \text{for } \varepsilon_{ps} > 0.0086 \end{cases} \quad (\text{in.-lb})$$

$$f_{ps} = \begin{cases} 196,500\varepsilon_{ps} & \text{for } \varepsilon_{ps} \leq 0.0086 \\ 1860 - \frac{0.276}{\varepsilon_{ps} - 0.007} & \text{for } \varepsilon_{ps} > 0.0086 \end{cases} \quad (\text{SI}) \quad (10.3.1.6e)$$

With the strain and stress in the FRP and prestressing steel determined for the assumed neutral axis depth, internal force equilibrium may be checked using Eq. (10.3.1.6f):

$$\alpha_1 f_c' \beta_1 b c = A_p f_p + A_f f_{fe} \quad (10.3.1.6f)$$

For the concrete crushing mode of failure, the equivalent compressive stress block factor α_1 can be taken as 0.85, and β_1 can be estimated as described in 10.2.10. If FRP rupture or FRP debonding failure occurs, the use of equivalent rectangular concrete stress block factors is appropriate. Methods considering a nonlinear stress distribution in the concrete can also be used.

The depth to the neutral axis, c , is found by simultaneously satisfying Eq. (10.2.5), (10.2.6), and (10.3.1.6a) to (10.3.1.6f), thus establishing internal force equilibrium and strain compatibility. To solve for the depth of the neutral axis, c , an iterative solution procedure can be used. An initial value for c is assumed, and the strains and stresses are calculated using Eq. (10.2.5), (10.2.6), and (10.3.1.6a) to (10.3.1.6e). A revised value for the depth of neutral axis, c , is then calculated from Eq. (10.3.1.6f). The calculated and assumed values for c are then compared. If they agree, then the correct value of c is reached. If the calculated and assumed values do not agree, another value for c is selected, and the process is repeated until convergence is attained.

The nominal flexural strength of the section with FRP external reinforcement can be computed using Eq. (10.3.1.6g). The additional reduction factor $\psi_f = 0.85$ is applied to the flexural-strength contribution of the FRP reinforcement:

$$M_n = A_p f_{ps} \left(d_p - \frac{\beta_1 c}{2} \right) + \psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2} \right) \quad (10.3.1.6g)$$

10.3.1.7 Stress in prestressing steel under service loads—

The stress in the prestressing steel can be calculated based on the actual condition (cracked or uncracked section) of the strengthened reinforced concrete section. The strain in prestressing steel at service, $\varepsilon_{ps,s}$, can be calculated as:

$$\varepsilon_{ps,s} = \varepsilon_{pe} + \frac{P_e}{A_c E_c} \left(1 + \frac{e^2}{r^2} \right) + \varepsilon_{pnet,s} \quad (10.3.1.7a)$$

in which ε_{pe} is the effective prestressing strain, and $\varepsilon_{pnet,s}$ is the net tensile strain in the prestressing steel beyond decompression at service. The value of $\varepsilon_{pnet,s}$ depends on the effective section properties at service, and can be calculated using Eq. (10.3.1.7b) and (10.3.1.7c):

$$\varepsilon_{pnet,s} = \frac{M_{snet} e}{E_c I_g} \text{ for uncracked section at service} \quad (10.3.1.7b)$$

$$\varepsilon_{pnet,s} = \frac{M_{snet} e}{E_c I_{cr}} \text{ for cracked section at service} \quad (10.3.1.7c)$$

where M_{snet} is the net service moment beyond decompression. The stress in the prestressing steel under service loads can then be computed from Eq. (10.3.1.6d) and (10.3.1.6e) and compared against the limits described in 10.3.1.4.

10.3.1.8 Stress in FRP under service loads—Equation (10.3.1.8) gives the stress in the FRP reinforcement under an applied moment within the elastic response range of the member. The calculation procedure for the initial strain ε_{bi} at the time of FRP installation will depend on the state of the concrete section at the time of FRP installation and at service condition. Prestressed sections can be uncracked at both installation and service, uncracked at installation and cracked at service, or cracked at both installation and service. The initial strain on the bonded substrate, ε_{bi} , can be determined from an elastic analysis of the existing member, considering all loads that will be on the member during the installation of the FRP system. The elastic analysis of the existing member should be based on cracked or uncracked section properties, depending on existing conditions. In most cases, the initial strain before cracking is relatively small, and may conservatively be ignored:

$$f_{f,s} = \left(\frac{E_f}{E_c} \right) \frac{M_s y_b}{I} - \varepsilon_{bi} E_f \quad (10.3.1.8)$$

Depending on the actual condition at service (cracked or uncracked), the moment of inertia, I , can be taken as the moment of inertia of the uncracked section transformed to concrete, I_{tr} , or the moment of inertia of the cracked section transformed to concrete, I_{cr} . The variable y_b is the distance from the centroidal axis of the gross section, neglecting reinforcement, to the extreme bottom fiber. The computed stress in the FRP under service loads should not exceed the limits provided in 10.2.9.

10.3.2 Members with unbonded prestressing steel—The design procedure of FRP strengthening for members having unbonded prestressing (post-tensioning) reinforcement is similar to that for those having bonded prestressing reinforcement. In sections having unbonded prestressed reinforcement, the unbonded steel slips relative to the surrounding concrete resulting in the calculation of steel strain or stress becoming a function of overall member deformation rather than just section curvature. The same equilibrium approach

applied to a flexural section with bonded prestressing may be used to determine the nominal strength of the FRP-strengthened member provided an appropriate method is used to calculate the strains or stresses in the unbonded tendons at the ultimate flexural strength (El Meski and Harajli 2014). Although many expressions have been presented in the technical literature for evaluating the stress f_{ps} in prestressing steel at nominal flexural strength, a simplified expression may be adopted for FRP-strengthened simply supported and continuous members as is described herein.

10.3.2.1 Assumptions—In addition to the assumptions listed in Sections 10.2.1 and 10.3.1, the effect of concrete precompression strain on the tendon stress at nominal flexural capacity is assumed to be minor and may be neglected in unbonded members when calculating the flexural resistance of an unbonded prestressed section strengthened with an externally applied FRP system (Harajli 2012).

10.3.2.2 Nominal strength—The calculation procedure to compute nominal strength at a critical section follows the same trial-and-error calculation procedure described in Section 10.3.1.

At a critical section under consideration, and for any assumed depth to the neutral axis, c , the effective strain and stress in the FRP reinforcement can be computed from Eq. (10.2.5) and (10.2.6), respectively. This equation considers the governing mode of failure for the assumed neutral axis depth. If the left term of the inequality in Eq. (10.2.5) controls, concrete crushing controls flexural failure of the section and the value of ε_c in Eq. (10.3.2.2b) is equal to ε_{cu} . If the right term of the inequality controls, FRP failure (rupture or debonding) controls flexural failure of the section and the value of ε_c in Eq. (10.3.2.2b) is found from Eq (10.3.2.2a):

$$\varepsilon_c = (\varepsilon_{fd} + \varepsilon_{bi}) \left(\frac{c}{d_f - c} \right) \quad (10.3.2.2a)$$

The strain level in the unbonded prestressed steel at the corresponding critical section can be found from Eq. (10.3.2.2b) (Harajli 2012; El Meski and Harajli 2014):

$$\varepsilon_{ps} = \varepsilon_{pe} + \eta \varepsilon_c \left(\frac{d_p - c}{L_a} \right) \quad (10.3.2.2b)$$

in which ε_{pe} is the effective strain in the prestressing steel after losses, and L_a is the total length of tendon between anchorages. H is a parameter that combines the effects of member continuity and applied load pattern for producing maximum factored moment at the critical section under consideration and may be taken as follows (Harajli 2012; El Meski and Harajli 2014):

Positive moment:

simply supported spans $\eta = 14.0$
 exterior spans $\eta = 19.0$
 interior spans $\eta = 24.5$

Negative moment at first interior support:

two-span members $\eta = 38.5$