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Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

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Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures

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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 materials as supplemental externally-bonded or near-surface-mounted reinforcement. FRP systems offer advantages over traditional strengthening techniques: they are lightweight, relatively easy to install, and noncorroding. Due to the characteristics of FRP materials as well as the behavior of members strengthened with FRP, specific guidance on the use of these systems is needed. This guide offers 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 research, analytical work, and field applications of FRP systems used to strengthen concrete structures.

Keywords: aramid fibers; bridges; buildings; carbon fibers; corrosion; cracking; development length; earthquake resistance; fiber-reinforced polymers; 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 historically been accomplished using conventional materials and construction techniques. Externally bonded steel plates, steel or concrete jackets, and external post-tensioning are some of the many traditional techniques available.

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 applied coatings used 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 dry fiber sheets that can be wrapped to conform to the geometry of a structure before adding the polymer resin. The relatively thin profiles of cured FRP systems are often desirable in applications where aesthetics or access is a concern. 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 in this document and compiled in Appendix C.

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. 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 materials 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. The use of untested combinations of fibers and resins should be avoided. A comprehensive set of test standards and guides for FRP systems has been developed by several organizations, including ASTM, ACI, ICRI, and ICC.

1.1.2 *Sustainability*—Sustainability of FRP materials may be evaluated considering environmental, economic, and social goals. These should be considered not only throughout the construction phase, but also through the service life of the structure in terms of maintenance and preservation, and for the end-of-life phase. This represents the basis for a life-cycle approach to sustainability (Menna et al. 2013). Life cycle assessment (LCA) takes into account the environmental impact of a product, starting with raw material extraction, followed by production, distribution, transportation, installation, use, and end of life. LCA for FRP composites depends on the product and market application, and results vary. FRP composite materials used to strengthen concrete elements can use both carbon fiber and glass fiber, which are derived from fossil fuels or minerals, respectively, and therefore have impacts related to raw material extraction. Although carbon and glass fibers have high embodied energies associated with production, on the order of 86,000 Btu/lb and 8600 Btu/lb (200 and 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 percent of FRP composites are currently recycled, composites can be recycled in many ways, including mechanical grinding, incineration, and chemical separation (Howarth et al. 2014). It is difficult, however, to separate the materials, fibers, and resins without some degradation of the resulting recycled materials. The market for recycled composite materials is small, although aircraft manufacturers in particular are considering methods and programs to recycle and repurpose composite materials at the end of an aircraft's life cycle.

Apart from the FRP materials and systems, 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 a monetary and environmental cost of only a fraction of 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. The environmental advantages of FRP, as evaluated by LCA investigations, have been enumerated by Napolano et al. (2015), Moliner Santisteve et al. (2013), Zhang et al. (2012), and Das (2011).

1.2—Scope

This document provides guidance for the selection, design, and installation of FRP systems for externally strengthening concrete structures. Information on material properties, design, installation, quality control, and maintenance of FRP systems used as external reinforcement is presented. This information can be used to select an FRP system for increasing the strength, stiffness, or both, of reinforced concrete beams or the ductility of columns and other applications.

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 materials has been the subject of much research; however, this research remains ongoing. The design guidelines in this guide account for environmental degradation and long-term durability by providing reduction factors for various environments. Long-term fatigue and creep are also addressed by stress limitations indicated in this document. These factors and limitations are considered conservative. As more research becomes available, however, these factors may be modified, and the specific environmental conditions and loading conditions to which they should apply will be better defined. Additionally, the coupling effect of environmental conditions and loading conditions requires further study. Caution is advised in applications where the FRP system is subjected simultaneously to extreme environmental and stress conditions. The factors associated with the long-term durability of the FRP system may also affect the tensile modulus of elasticity of the material used for design.

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 many 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 achieved in the FRP material (and thus, the stress achieved) 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. Because no anchorage design guidelines are currently available, the performance of any 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 materials can support compressive stresses, there are numerous issues surrounding 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 involved with the use of the material for this purpose, nor does it address the design concerns surrounding such applications.

This document does not specifically address masonry (concrete masonry units, brick, or clay tile) construction, including masonry walls. Information on the repair of unreinforced masonry using FRP can be found in ACI 440.7R.

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 562, ACI 369R, and other applicable ACI 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 pull-off adhesion test in accordance with ASTM C1583/C1583M. The in-place compressive strength of concrete should be determined using cores in accordance with ACI 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.

FRP 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 materials 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.

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; curing conditions (time, temperature, and humidity); and 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. For a dry environment, it is generally recommended that the anticipated service temperature of an FRP system not exceed T_g – 27°F (T_g – 15°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 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. Design stresses in the FRP system are developed by deformation or dilation of the concrete section in contact-critical applications.

The application of FRP systems will not stop the 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_c = cross-sectional area of concrete in compression member, 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, 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_y = distance from extreme compression fiber to the neutral axis at steel yielding, in. (mm)
D = diameter of compression member for circular cross sections or diagonal distance equal to $\sqrt{b^2+h^2}$ for prismatic cross section (diameter of equivalent circular column), in. (mm)
d = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)
d' = distance from the extreme compression fiber to the center of A_{sc}, in. (mm)
d'' = distance from the extreme tension fiber to the center of A_{st}, in. (mm)
$d_{b\ell}$ = diameter of longitudinal steel in confined plastic hinge, in. (mm)
d_f = effective depth of FRP flexural reinforcement, in. (mm)
d_{fv} = effective depth of FRP shear reinforcement, in. (mm)
d_i = distance from centroid of i-th layer of longitudinal steel reinforcement to geometric centroid of cross section, in. (mm)
d_p = distance from extreme compression fiber to centroid of prestressed reinforcement, in. (mm)
E_2 = slope of linear portion of stress-strain model for FRP-confined concrete, psi (MPa)
E_c = modulus of elasticity of concrete, psi (MPa)
E_f = tensile modulus of elasticity of FRP, psi (MPa)
E_{ps} = modulus of elasticity of prestressing steel, psi (MPa)
E_s = modulus of elasticity of steel, psi (MPa)
e_s = eccentricity of prestressing steel with respect to centroidal axis of member at support, in. (mm)
e_m = eccentricity of prestressing steel with respect to centroidal axis of member at midspan, in. (mm)
f_c = compressive stress in concrete, psi (MPa)
f_c' = specified compressive strength of concrete, psi (MPa)
f_{cc}' = compressive strength of confined concrete, psi (MPa)
f_{co}' = compressive strength of unconfined concrete; also equal to $0.85f_c'$, psi (MPa)
$f_{c,s}$ = compressive stress in concrete at service condition, psi (MPa)
f_f = stress in FRP reinforcement, psi (MPa)

f_{fd} = design stress of externally bonded FRP reinforcement, psi (MPa)
f_{fe} = effective stress in the FRP; stress attained at section failure, psi (MPa)
$f_{f,s}$ = stress in FRP caused by a moment within elastic range of member, psi (MPa)
f_{fu} = design ultimate tensile strength of FRP, psi (MPa)
f_{fu}^* = ultimate tensile strength of the FRP material as reported by the manufacturer, psi (MPa)
f_l = maximum confining pressure due to FRP jacket, psi (MPa)
f_{ps} = stress in prestressed reinforcement at nominal strength, psi (MPa)
$f_{ps,s}$ = stress in prestressed reinforcement at service load, psi (MPa)
f_{pu} = specified tensile strength of prestressing tendons, psi (MPa)
f_s = stress in nonprestressed steel reinforcement, psi (MPa)
f_{sc} = stress in the longitudinal reinforcement corresponding to A_{sc}, psi (MPa)
f_{si} = stress in the i-th layer of longitudinal steel reinforcement, psi (MPa)
$f_{s,s}$ = stress in nonprestressed steel reinforcement at service loads, psi (MPa)
f_{st} = stress in the longitudinal reinforcement corresponding to A_{st}, psi (MPa)
f_{sw} = stress in the longitudinal reinforcement corresponding to A_{sw}, psi (MPa)
f_y = specified yield strength of nonprestressed steel reinforcement, psi (MPa)
g = clear gap between the FRP jacket and adjacent members, in (mm)
h = overall thickness or height of a member, in. (mm)
= long side cross-sectional dimension of rectangular compression member, in. (mm)
h_f = member flange thickness, in. (mm)
h_w = height of entire wall from base to top, or clear height of wall segment or wall pier considered, in. (mm)
I_{cr} = moment of inertia of cracked section transformed to concrete, in.^{4} (mm^4)
I_{tr} = moment of inertia of uncracked section transformed to concrete, in.^{4} (mm^4)
K = ratio of depth of neutral axis to reinforcement depth measured from extreme compression fiber
k_1 = modification factor applied to κ_v to account for concrete strength
k_2 = modification factor applied to κ_v to account for wrapping scheme
k_f = stiffness per unit width per ply of the FRP reinforcement, lb/in. (N/mm); $k_f = E_f t_f$
L_e = active bond length of FRP laminate, in. (mm)
L_p = plastic hinge length, in. (mm)
L_w = length of the shear wall, in. (mm)
ℓ_{db} = development length of near-surface-mounted FRP bar, in. (mm)
$\ell_{d,E}$ = length over which the FRP anchorage wraps are provided, in. (mm)
ℓ_{df} = development length of FRP system, in. (mm)
ℓ_o = length, measured along the member axis from the face of the joint, over which special transverse reinforcement must be provided, in. (mm)
ℓ_{prov} = length of steel lap splice, in. (mm)
M_{cr} = cracking moment, in.-lb (N-mm)
M_n = nominal flexural strength, in.-lb (N-mm)
M_{nf} = contribution of FRP reinforcement to nominal flexural strength, lb-in. (N-mm)
M_{np} = contribution of prestressing reinforcement to nominal flexural strength, lb-in. (N-mm)
M_{ns} = contribution of steel reinforcement to nominal flexural strength, lb-in. (N-mm)
M_s = service moment at section, in.-lb (N-mm)
M_{snet}= service moment at section beyond decompression, in.-lb (N-mm)
M_u = factored moment at a section, in.-lb (N-mm)
N = number of plies of FRP reinforcement
n_f = modular ratio of elasticity between FRP and concrete = E_f/E_c
n_s = modular ratio of elasticity between steel and concrete = E_s/E_c
P_e = effective force in prestressing reinforcement (after allowance for all prestress losses), lb (N)
P_n = nominal axial compressive strength of a concrete section, lb (N)
P_u = factored axial load, lb (N)
$\bar{p}_{fu}$ = mean tensile strength per unit width per ply of FRP reinforcement, lb/in. (N/mm)
p_{fu}^* = ultimate tensile strength per unit width per ply of FRP reinforcement, lb/in. (N/mm); $p_{fu}^* = f_{fu}^* t_f$
R_n = nominal strength of a member
$R_{n\phi}$ = nominal strength of a member subjected to elevated temperatures associated with a fire
R = radius of gyration of a section, in. (mm)
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_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)
T_{gw} = wet glass-transition temperature, °F (°C)
T_{ps} = tensile force in prestressing steel, lb (N)
T_{st} = tensile force in A_{st}, lb (N)
T_{sw} = tensile force in A_{sw}, lb (N)
t_f = nominal thickness of one ply of FRP reinforcement, in. (mm)
t_w = thickness of the existing concrete shear wall, in. (mm)
V_c = nominal shear strength provided by concrete with steel flexural reinforcement, lb (N)
V_e = design shear force for load combinations including earthquake effects, lb (N)
V_f = nominal shear strength provided by FRP stirrups, lb (N)

V_n = nominal shear strength, lb (N)
V_n^* = shear strength of existing member, lb (N)
V_s = nominal shear strength provided by steel stirrups, lb (N)
w_f = width of FRP reinforcing plies, in. (mm)
y_b = distance from centroidal axis of gross section, neglecting reinforcement, to extreme bottom fiber, in./in. (mm/mm)
y_t = vertical coordinate within compression region measured from neutral axis position. It corresponds to transition strain ε_t', in. (mm)
α = angle of application of primary FRP reinforcement direction relative to longitudinal axis of member
α_1 = multiplier on f_c' to determine intensity of an equivalent rectangular stress distribution for concrete
α_L = longitudinal coefficient of thermal expansion, in./in./°F (mm/mm/°C)
α_T = transverse coefficient of thermal expansion, in./in./°F (mm/mm/°C)
β_1 = ratio of depth of equivalent rectangular stress block to depth of the neutral axis
ε_b = strain in concrete substrate developed by a given bending moment (tension is positive), in./in. (mm/mm)
ε_{bi} = strain in concrete substrate at time of FRP installation (tension is positive), in./in. (mm/mm)
ε_c = strain in concrete, in./in. (mm/mm)
ε_c' = compressive strain of unconfined concrete corresponding to f_c', in./in. (mm/mm); may be taken as 0.002
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
$\varepsilon_{c,s}$ = strain in concrete at service, in./in. (mm/mm)
ε_{ct} = concrete tensile strain at level of tensile force resultant in post-tensioned flexural members, in./in. (mm/mm)
ε_{cu} = ultimate axial strain of unconfined concrete corresponding to $0.85f_{co}'$ or maximum usable strain of unconfined concrete, in./in. (mm/mm), which can occur at $f_c = 0.85f_c'$ or $\varepsilon_c = 0.003$, depending on the obtained stress-strain curve
ε_f = strain in the FRP reinforcement, in./in. (mm/mm)
ε_{fd} = debonding strain of externally bonded FRP reinforcement, in./in. (mm/mm)
ε_{fe} = effective strain in FRP reinforcement attained at failure, in./in. (mm/mm)
ε_{fu} = design rupture strain of FRP reinforcement, in./in. (mm/mm)
$\overline{\varepsilon}_{fu}$ = mean rupture strain of FRP reinforcement based on a population of 20 or more tensile tests per ASTM D3039/D3039M, in./in. (mm/mm)
ε_{fu}^* = ultimate rupture strain of FRP reinforcement, in./in. (mm/mm)
ε_{pe} = effective strain in prestressing steel after losses, in./in. (mm/mm)
ε_{pi} = initial strain in prestressed steel reinforcement, in./in. (mm/mm)
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)
$\varepsilon_{pnet,s}$ = net strain in prestressing steel beyond decompression at service, in./in. (mm/mm)
ε_{ps} = strain in prestressed reinforcement at nominal strength, in./in. (mm/mm)
$\varepsilon_{ps,s}$ = strain in prestressing steel at service load, in./in. (mm/mm)
ε_s = strain in nonprestessed steel reinforcement, in./in. (mm/mm)
ε_{sy} = strain corresponding to yield strength of nonprestressed steel reinforcement, in./in. (mm/mm)
ε_t = net tensile strain in extreme tension steel at nominal strength, in./in. (mm/mm)
ε_t' = transition strain in stress-strain curve of FRP-confined concrete, in./in. (mm/mm)
ϕ = strength reduction factor
ϕ_D = design curvature for a confined concrete section
$\phi_{y,frp}$ = curvature of the FRP confined section at steel yielding
κ_a = efficiency factor for FRP reinforcement in determination of f_{cc}' (based on geometry of cross section)
κ_b = efficiency factor for FRP reinforcement in determination of ε_{ccu} (based on geometry of cross section)
κ_v = bond-dependent coefficient for shear
κ_ε = efficiency factor equal to 0.55 for FRP strain to account for the difference between observed rupture strain in confinement and rupture strain determined from tensile tests
θ_p = plastic hinge rotation demand
ρ_f = FRP reinforcement ratio
ρ_g = ratio of area of longitudinal steel reinforcement to cross-sectional area of a compression member (A_s/bh)
ρ_l = longitudinal reinforcement ratio
ρ_s = ratio of nonprestressed reinforcement
σ = standard deviation
τ_b = average bond strength for near-surface-mounted FRP bars, psi (MPa)
ψ_e = factor used to modify development length based on reinforcement coating
ψ_f = FRP strength reduction factor
= 0.85 for flexure (calibrated based on design material properties)
= 0.85 for shear (based on reliability analysis) for three-sided FRP U-wrap or two sided strengthening schemes
= 0.95 for shear fully wrapped sections
ψ_s = factor used to modify development length based on reinforcement size
ψ_t = factor used to modify development length based on reinforcement location

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," https://www.concrete.org/store/productdetail.aspx?ItemID=CT13. 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.

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

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

catalyst—substance that accelerates a chemical reaction and enables it to proceed under conditions 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 percent.

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

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

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

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

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

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

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

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

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 fiber reinforcement.

laminate—multiple plies or lamina molded together.

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

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

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

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

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

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

postcuring—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 meth-