

Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures

Reported by ACI Committee 440



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First Printing
September 2007

Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures

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ISBN 978-0-87031-259-5

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Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures

Reported by ACI Committee 440

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Applications of fiber-reinforced polymer (FRP) composites as reinforcement for concrete structures have been growing rapidly in recent years. ACI Committee 440 has published design guidelines for internal FRP reinforcement, externally bonded FRP reinforcement for strengthening, prestressed FRP reinforcement, and test methods for FRP products. Although these guidelines exist, new products and applications continue to be developed. Thus, this report summarizes the current state of knowledge on these materials and their application to concrete and masonry structures. The purpose of this report is to act as an introduction to FRP materials in areas where ACI guides exist, and to provide information on the properties and behavior of concrete structures containing FRP in areas where guides are not currently available. If an ACI guide is available, the guide document supersedes information in this report, and the guide should always be followed for design

and application purposes. ACI Committee 440 is also in the process of developing new guides and thus the current availability of guides should be checked by the reader. In addition to the material properties of the constituent materials (that is, resins and fibers) and products, current knowledge of FRP applications, such as internal reinforcement including prestressing, external strengthening of concrete and masonry structures, and structural systems, is discussed in detail. The document also addresses durability issues and the effects of extreme events, such as fire and blast. A summary of some examples of field applications is presented.

Keywords: aramid fibers; blast; bridges; buildings; carbon fibers; composite materials; corrosion; design; dowels; ductility; durability; external reinforcement; fatigue; fiber-reinforced polymer (FRP); fibers; fire; glass fiber; masonry; mechanical properties; polymer resin; prestressed concrete; seismic; stay-in-place forms; structural systems; test methods.

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

The purpose of this report is to present the current state of knowledge with regard to applications of fiber-reinforced polymer (FRP) materials in concrete. This report summarizes the fundamental behavior, the most current research, design codes, and practical applications of concrete and masonry structures containing FRP. This document is intended to complement other reports (for example, standards and design guidelines) produced by ACI Committee 440, either

by summarizing the research that supports those documents or by providing information on future developments of those documents. If an ACI guide is available, the guide document supersedes information in this report, and the guide should always be followed for design and application purposes. ACI Committee 440 is also in the process of developing new guides; thus, the current availability of guides should be checked by the reader.

FRP materials are composite materials that typically consist of strong fibers embedded in a resin matrix. The fibers provide strength and stiffness to the composite and generally carry most of the applied loads. The matrix acts to bond and protect the fibers and to provide for transfer of stress from fiber to fiber through shear stresses. The most common fibers are glass, carbon, and aramid. Matrixes are typically epoxies, polyesters, vinylesters, or phenolics.

1.2—Historical perspective of FRP composites

While the concept of composites has been in existence for several millennia (for example, bricks made from mud and straw), the incorporation of FRP composite technology into the industrial world is less than a century old. The age of plastics emerged just after 1900, with chemists and industrialists taking bold steps to have plastics (vinyl, polystyrene, and Plexiglas) mimic and outdo natural materials. Spurred on by the needs of electronics, defense, and eventually space technologies, researchers created materials with properties that seemed to defy known principles, such as bullet-stopping Kevlar. The first known FRP product was a boat hull manufactured in the mid-1930s as part of a manufacturing experiment using a fiberglass fabric and polyester resin laid in a foam mold (ACMA MDA 2006). From this modest beginning, FRP composite applications have revolutionized entire industries, including aerospace, marine, electrical, corrosion resistance, and transportation.

FRP composite materials date back to the early 1940s in the defense industry, particularly for use in aerospace and naval applications. The U.S. Air Force and Navy capitalized on FRP composites' high strength-weight ratio and inherent resistance to the corrosive effects of weather, salt air, and the sea. Soon the benefits of FRP composites, especially its corrosion resistance capabilities, were communicated to the public sector. Fiberglass pipe, for instance, was first introduced in 1948 (ACMA MDA 2006) for what has become one of its widest use areas within the corrosion market, the oil industry. FRP composites proved to be a worthy alternative to other traditional materials even in the high-pressure, large-diameter situations of chemical processing. Besides superior corrosion resistance, FRP pipe offered both durability and strength, thus eliminating the need for interior linings, exterior coatings, and cathodic protection. Since the early 1950s, FRP composites have been used extensively for equipment in the chemical processing, pulp and paper, power, waste treatment, metal refining, and other manufacturing industries (ACMA MDA 2006). Myriads of products and FRP installations help build a baseline of proven performance in the field.

The decades after the 1940s brought new, and often revolutionary, applications for FRP composites (ACMA MDA 2006). The same technology that produced the reinforced plastic hoops required for the Manhattan nuclear project in World War II spawned the development of high-performance composite materials for solid rocket motor cases and tanks in the 1960s and 1970s. In fact, fiberglass wall tanks were used on the Skylab orbiting laboratory to provide oxygen for the astronauts. In 1953, the first Chevrolet Corvette with fiberglass body panels rolled off the assembly line (ACMA MDA 2006). Now, high-performance race cars are the proving ground for technology transfer to passenger vehicles. In the 1960s, the British and U.S. Navies were simultaneously developing FRP-based minesweeper ships because FRP composites are not only superior to other materials in harsh marine environments, they are also nonmagnetic. It was also noticed at that time that one of the features of FRP is the ability of the materials to reduce the radar signature of the structure, such as a ship or an aircraft. High-performance composite materials have been demonstrated in advanced technology aircraft such as the F-117 Stealth Fighter and B-2 Bomber. Currently, FRP composites are being used for space applications and are involved in several NASA test initiatives (ACMA MDA 2006).

While the majority of the historical and durability data of FRP composite installations comes from the aerospace, marine, and corrosion-resistance industries (ACMA MDA 2006), FRP composites have been used as a construction material for several decades. FRP composite products were first demonstrated to reinforce concrete structures in the mid-1950s (ACMA MDA 2006). In the 1980s, a resurgence in interest arose when new developments were launched to apply FRP reinforcing bars in concrete that required special performance requirements such as nonmagnetic properties or in areas that were subjected to severe chemical attack.

Composites have evolved since the 1950s, starting with temporary structures and continuing with restoration of historic buildings and structural applications. Typical products developed were domes, shrouds, translucent sheet panels, and exterior building panels. A major development of FRP for civil engineering has been the application of externally bonded FRP for rehabilitation and strengthening of concrete structures.

During the late 1970s and early 1980s, many applications of composite reinforcing products were demonstrated in Europe and Asia. In 1986, the world's first highway bridge using composite reinforcing tendons was built in Germany. The first all-composite bridge deck was demonstrated in China. The first all-composite pedestrian bridge was installed in 1992 in Aberfeldy, Scotland. In the U.S., the first FRP-reinforced concrete bridge deck was built in 1996 at McKinleyville, West Virginia, followed by the first all-composite vehicular bridge deck (The No-Name Creek Bridge in 1996) in Russell, Kansas. Numerous composite pedestrian bridges have been installed in U.S. state and national parks in remote locations not accessible by heavy construction equipment, or for spanning over wetlands and railways (ACMA MDA 2006).

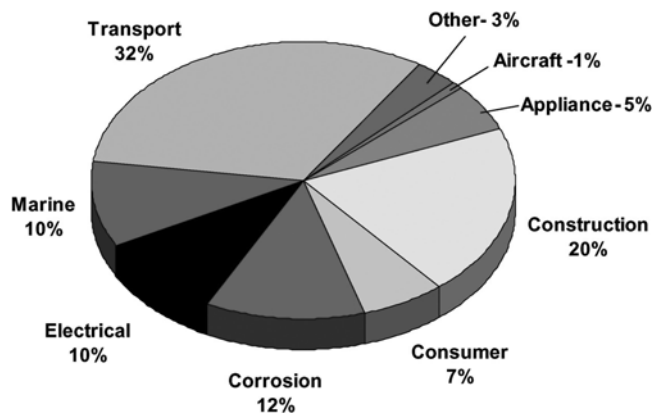


Fig. 1.1—U.S. composites shipments 2004 market share by end-use application (ACMA 2005). Total estimated volume: 1.8 billion kg (4.0 billion lb) (ACMA 2005 and PPG).

Composite fabricators and suppliers are actively developing products for the civil infrastructure, which is considered to be the largest potential market for FRP composites (ACMA MDA 2006). Concrete repair and reinforcement, bridge deck repair and new installation, composite-hybrid technology (the marriage of composites with concrete, wood, and steel), marine piling, and pier upgrade programs are just some of the areas that are currently being explored. This document describes all aspects of applications of FRP composites for concrete and masonry structures including internal reinforcement, strengthening, prestressing, and integrated stay-in-place forms.

1.2.1 Industry statistics—The composites industry associations and producers have traditionally tracked FRP market growth in several primary markets: aircraft/aerospace, appliance/business equipment, construction, consumer products, corrosion-resistant equipment, electrical, marine, transportation, and other applications. The American Composites Manufacturers Association (ACMA 2005) and PPG Industries reported that estimates of composites shipments in 2004 reached 1.8 billion kilograms (4.0 billion pounds). Figure 1.1 shows the distribution of FRP composites materials shipped in 2004. According to the *Composites News International* (ACMA 2005), the estimated size of the composites industry in North America is approximately \$9 billion. The composites industry has shown considerable growth over the past 10 years, and is projected to increase as FRP composites are accepted in new markets.

1.2.2 Product and benefits for construction applications—FRP composites provide many solutions to the needs of the owner and civil engineer. FRP products for civil infrastructure/construction applications are more resistant to corrosion than reinforcing steel, thus the service life of the structure may be increased. FRP products have high strength-to-weight ratios and strength properties greater than those of steel. In repair and rehabilitation, the light weight and ease of application of the materials can result in saving in labor costs. The main drawback of the materials is their relatively high material cost.

Currently, many FRP products are available to build or repair civil engineering structures. These products have been

extensively demonstrated and used around the world. Examples of FRP composite products include:

- FRP composite systems for repair, strengthening, and seismic retrofit for beams, columns, slabs, and walls;
- FRP reinforcing bars, grids, and tendons for concrete reinforcement;
- Bridge deck panels and pedestrian bridge systems;
- New structural shapes;
- Piling products and systems for marine waterfront structures;
- FRP dowel bars for durable long-term service in concrete highway pavements; and
- FRP tie connectors and FRP grid shear connectors for concrete sandwich wall construction.

Several examples of such applications are described in **Chapter 13** of this report.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_f	=	area of FRP reinforcement, mm ² (in. ²)
a	=	depth of equivalent rectangular stress block; length of shear span, mm (in.)
b	=	width of carbon FRP plate, mm (in.)
c	=	neutral axis depth, mm (in.)
D	=	diameter, mm (in.)
D_i	=	inner diameter of tube, mm (in.)
D_o	=	outer diameter of tube, mm (in.)
d	=	distance from extreme compression fiber to centroid of tensile reinforcement, mm (in.)
d_b	=	bar diameter, mm (in.)
E_c	=	modulus of concrete core, MPa (psi)
E_{FRP}	=	modulus of elasticity of FRP reinforcement, MPa (psi)
E_f	=	equivalent orthotropic elastic modulus of tube in hoop direction, MPa (psi)
E_s	=	elastic modulus of steel reinforcement, MPa (psi)
f'_c	=	specified concrete compressive strength, MPa (psi)
f'_{cc}	=	compressive strength of confined concrete, MPa (psi)
f_{fu}	=	ultimate strength of FRP material, MPa (psi)
f_{pi}	=	initial prestressing stress, MPa (psi)
h	=	depth of reinforced concrete beam, mm (in.)
I_{cr}	=	cracked moment of inertia of the section of a reinforced concrete beam, mm ⁴ (in. ⁴)
I_e	=	effective moment of inertia, mm ⁴ (in. ⁴)
I_{ey}	=	overall effective beam moment of inertia at yielding, mm ⁴ (in. ⁴)
L	=	length of CFFT, mm (in.)
l_d	=	development length, mm (in.)
l_t	=	transfer length for prestressing tendons, mm (in.)
M_u	=	factored moment, kNm (lb-in.)
N	=	axial load, kN (lb)
R	=	radius of FRP tube, mm (in.)
T_g	=	glass transition temperature, °C (°F)
t	=	thickness of FRP plate, mm (in.)
V_c	=	nominal shear strength provided by concrete, kN (lb)
V_{exp}	=	experimentally obtained shear force, kN (lb)
Δ	=	deflection of beam subjected to load, mm (in.)
Δf_p	=	stress range in fatigue loading, MPa (psi)

ε_{cc}	= axial strain to calculate confinement pressure in CFFT
ε_{FRP}	= strain level in FRP reinforcement
$\varepsilon_{FRP-service}$	= strain level in FRP reinforcement in service
ε_{fe}	= effective strain in FRP laminate
ε_{fu}	= design rupture strain of FRP
ε_s	= strain of steel reinforcement
ϕ	= strength-reduction factor
ϕ_u	= curvature of beam at failure, 1/mm (1/in.)
ϕ_y	= curvature of beam at yielding of internal steel, 1/mm (1/in.)
θ	= rotation of a section of a beam, radian or degree; or direction of fibers
κ_m	= coefficient to calculate effective strain in FRP laminate
μ	= ductility index
ρ	= reinforcement ratio
ρ_{FRP}	= FRP longitudinal reinforcement ratio
ρ_{fc}	= fiber composite reinforcement ratio
σ_R	= confinement pressure in circular CFFT, MPa (psi)
σ_x	= hoop tensile strength, MPa (psi)
σ_y	= axial compressive strength, MPa (psi)
τ_m	= bond strength of FRP bar, MPa (psi)
ν_c	= Poisson's ratio of concrete
ν_f	= longitudinal Poisson's ratio of tube

2.2—Definitions

AFRP—aramid fiber-reinforced polymer.

aging—the process of exposing materials to an environment for an interval of time.

aramid fiber—highly oriented organic fiber derived from polyamide incorporating aromatic ring structure.

balanced FRP reinforcement ratio—the reinforcement ratio in a flexural member that causes the ultimate strain of FRP bars and the ultimate compressive strain of concrete (assumed to be 0.003) to be simultaneously attained.

bar—a composite material formed into a long, slender structural shape suitable for the internal reinforcement of concrete and consisting of primarily longitudinal unidirectional fibers bound and shaped by a rigid polymer resin material. The bar may have a cross section of variable shape (commonly circular or rectangular), and may have a deformed or roughened surface to enhance bonding with concrete.

binder—chemical treatment applied to the random arrangement of glass fibers to give integrity to mats. Specific binders are used to promote chemical compatibility with the various laminating resins used.

BMC—bulk molding compound.

bond-critical applications—applications of FRP systems for strengthening structural members that rely on bond to the concrete substrate; flexural and shear strengthening of beams and slabs are examples of bond-critical applications.

braided string or rope—string or rope made by braiding continuous fibers or strands.

braiding—a process whereby two or more systems of yarns are wound together in the bias direction to form an integrated structure. Braided material differs from woven

and knitted fabrics in the method of yarn introduction into the fabric and the manner by which the yarns are interlaced.

b-stage—intermediate stage in the polymerization reaction of thermosets, following which material will soften with heat and is plastic and fusible. The resin of an uncured prepreg or premix is usually in b-stage.

carbon fiber—fiber produced by pyrolysis of organic precursor fibers. Used interchangeably with graphite. Types of carbon fibers include mesophase pitch carbon and pan carbon (polyacrylonitrile).

catalyst—organic peroxide used to activate the polymerization.

CET—coefficient of thermal expansion; change in linear dimension per unit length due to change in temperature.

CFFT—concrete-filled FRP tube.

CFRP—carbon fiber-reinforced polymer (includes graphite fiber-reinforced polymer).

composite—a combination of one or more materials differing in form or composition on a macroscale. Note: The constituents retain their identities; that is, they do not dissolve or merge completely into one another, although they act together. Normally, the components can be physically identified and exhibit an interface between one another.

concrete substrate—the original concrete or any cementitious repair material used to repair or replace the original concrete; the substrate can consist entirely of original concrete, entirely of repair materials, or of a combination of original concrete and repair materials; the substrate includes the surface to which the FRP system is adhered.

contact-critical applications—applications of FRP systems that rely on continuous intimate contact between the concrete substrate and the FRP system. In general, contact-critical applications consist of FRP systems that completely wrap around the perimeter of the section. For most contact-critical applications, the FRP system is bonded to the concrete to facilitate installation, but does not rely on that bond to perform as intended. Confinement of columns for seismic retrofit is an example of a contact-critical application.

continuous fiber reinforcement—any construction of resin-bound continuous fibers used to reinforce a concrete matrix. The construction may be in the shape of continuous fiber bars, tendons, or other shapes.

continuous filament—fiber that is made by spinning or drawing into one long continuous entity.

continuous filament tow—parallel filaments coated with sizing, drawn together into single or multiple strands, and wound into a cylindrical package.

continuous filament yarn—yarn that is formed by twisting two or more continuous filaments into a single continuous strand.

coupling agent—part of a surface treatment or finish that is designed to provide a bonding link between the fiber surface and the laminating resin.

cps—centipoises, unit of viscosity. The standard unit is poise. For relatively low viscosities, the units are often referred to as centipoises (cps) or 0.01 poise. The standard is 1 cps.

crimp—waviness of a fiber, a measure of the difference between the length of the unstraightened and straightened fibers.

cross-link—a chemical bond between polymer molecules. Note: An increased number of cross-links per polymer molecule increases strength and modulus at the expense of ductility.

cure of FRP systems—the process of causing the irreversible change in the properties of a thermosetting resin by chemical reaction. Cure is typically accomplished by addition of curing (cross-linking) agents or initiators, with or without heat and pressure. Full cure is the point at which a resin reaches the specified properties. Undercure is a condition where specified properties have not been reached.

curing agent—a catalytic or reactive agent that, when added to a resin, causes polymerization. Also called hardener or initiator.

deformability factor—the ratio of energy absorption (area under the moment-curvature curve) at ultimate strength of the section to the energy absorption at service level.

denier—measure of fiber diameter, taken as the weight in grams of 9000 m of the fiber.

durability—ability to resist cracking, oxidation, chemical degradation, delamination, wear, fatigue, and/or the effects of foreign object damage for a specified period of time, under the appropriate load conditions, and under specified environmental conditions.

E-glass—a family of glass with a calcium alumina borosilicate composition and a maximum alkali content of 2.0%.

epoxy resin—resin formed by the chemical reaction of epoxide groups with amines, alcohols, phenols, and others.

extrusion—process by which a molten resin is forced through a die of a desired shape.

fabric—arrangement of fibers held together in two dimensions. A fabric may be woven, nonwoven, or stitched.

fabric, nonwoven—material formed from fibers or yarns without interlacing. This can be stitched, knit, or bonded.

fabric, woven—material constructed of interlaced yarns, fibers, or filaments.

fiber—general term for a filamentary material. Any material whose length is at least 100 times its diameter, typically 0.10 to 0.13 mm.

fiber content—the amount of fiber present in a composite. Note: This usually is expressed as a percentage volume fraction or weight fraction of the composite.

fiberglass—a composite material consisting of glass fibers in resin.

fiber-reinforced polymer (FRP)—composite material consisting of continuous fibers impregnated with a fiber-binding polymer then molded and hardened in the intended shape.

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

fiber weight fraction—the ratio of the weight of fibers to the weight of the composite.

filament—smallest unit of a fibrous material. A fiber made by spinning or drawing into one long continuous entity.

filament winding—process for forming FRP parts by winding continuous rovings onto a rotating mandrel. The rovings may be dry or saturated with resin.

filler—a relatively inert substance added to a resin to alter its properties or to lower cost or density. Sometimes the term is used specifically to mean particulate additives.

fire retardant—chemicals that are used to reduce the tendency of a resin to burn; these can be added to the resin or coated on the surface of the FRP.

FRC—fiber-reinforced composite.

GFRP—glass fiber-reinforced polymer.

glass fiber—fiber drawn from an inorganic product of fusion that has cooled without crystallizing. Types of glass fiber include alkali-resistant (AR-glass); general purpose (E-glass); and high-strength (S-glass).

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

graphite fiber—fiber containing more than 99% crystalline carbon made from a precursor by oxidation.

grating—a planar FRP form. Gratings may be manufactured using molding methods or by mechanically assembling pultruded FRP elements (bars, I-shapes, or rods) together in two orthogonal directions to produce sheets.

grid—a planar FRP form in which continuous fibers are aligned in two orthogonal directions and combined with resin to produce a open mesh-like structure. Grids may be made using continuous manufacturing methods and supplied on rolls, or sheets made by molding methods and supplied in sheets.

GRP—glass-reinforced plastic.

hand lay-up—an open-mold manufacturing process in which resin is applied by hand, brush, or roller on to dry fiber reinforcements and exposed to the atmosphere for cure. This process can be done in a mold or performed on an object.

hardener—substance used to cure epoxy resins.

HFRP—hybrid FRP.

hybrid—a combination of two or more different fibers, such as carbon and glass or carbon and aramid, into a structure.

impregnation—saturation of voids and interstices of a reinforcement with a resin.

initiator—a substance, usually peroxide, that speeds up the curing of a resin.

interface—the boundary or surface between two different, physically distinguishable media. On fibers, the contact area between fibers and coating/sizing.

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

isophthalic polyester resin—product of isophthalic acid, glycol, and maleic anhydride (Ashland Specialty Chemical 2006).

laminated—two or more layers of fibers, bound together in a resin matrix.

lay-up—the process of placing the FRP reinforcing material in position for molding.

LEED—Leadership in Energy and Environmental Design—a certification program for sustainable building.

mat—a fibrous material for reinforced polymer, consisting of randomly oriented chopped filaments, short fibers (with or without a carrier fabric), or long random filaments loosely held together with a binder.

matrix—in the case of FRPs, the materials that serve to bind the fibers together, transfer load to the fibers, and protect them against environmental attack and damage due to handling.

MF-FRP—mechanically fastened FRP.

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

multifilament—yarn consisting of many continuous filaments.

NDI—nondestructive inspection.

NEFMAC—new fiber composite material for advanced concrete.

NSM—near-surface-mounted.

nylon—polyamide polymer that is thermoplastic in nature.

PAN—polyacrylonitrile, a precursor fiber used to make carbon fiber.

PAN carbon fiber—carbon fiber made from polyacrylonitrile (PAN) fiber.

phenolic resin—thermoset resin produced by condensation of aromatic alcohol.

pitch—a black residue from the distillation of petroleum.

pitch carbon fiber—carbon fiber made from petroleum pitch.

plastisol—a plastisol is a liquid dispersion of polyvinyl chloride resin in a plasticizer along with materials such as stabilizers, colorants, fillers, and other additives.

ply—a single layer of fabric or mat; multiple plies, when molded together, make up the laminate.

PMC—polymer matrix composite.

polyester—one of a large group of synthetic resins, mainly produced by reaction of dibasic acids with dihydroxy alcohols; commonly prepared for application by mixing with a vinyl-group monomer and free-radical catalysts at ambient temperatures and used as binders for resin mortars and concretes, fiber laminates (mainly glass), adhesives, and the like. Commonly referred to as unsaturated polyester.

polyester resin—resin produced by the polycondensation of dihydroxy derivatives and dibasic organic acids or anhydrides yielding resins that can be compounded with styrol monomers to give highly cross-linked thermoset resins.

polymer—a high-molecular-weight organic compound, natural or synthetic, containing repeating units.

polymerization—the chemical reaction in which two or more molecules of the same substance combine to form a compound containing the same elements and in the same proportions but of higher molecular weight.

polyurethane—reaction product of an isocyanate with any of a wide variety of other compounds containing an active hydrogen group; used to formulate tough, abrasion-resistant coatings and matrixes.

postcuring, FRP—additional elevated-temperature curing that increases the level of polymer cross-linking; final properties of the laminate or polymer are enhanced.

pot life—time interval after preparation during which a liquid or plastic mixture is to be used.

precursor—the rayon, PAN, or pitch fibers from which carbon fibers are derived.

prepreg—semi-hardened fiber-matrix construction made by soaking strands or roving with resin or resin precursors.

pultrusion—process by which a molten or curable resin and continuous fibers are pulled through a die of a desired structural shape of constant cross section, usually to form a rod or tendon.

PVC—polyvinyl chloride.

reinforcement—material, ranging from short fibers through complex textile forms, that is combined with a resin to provide it with enhanced mechanical properties.

resin—polymeric material that is rigid or semi-rigid at room temperature, usually with a melting-point or glass transition temperature above room temperature.

resin content—the amount of resin in a laminate, expressed as either a percentage of total mass or total volume.

resistance factor—factor applied to a specified material property or to the resistance of a member for the limit state under considerations, which takes into account the variability of dimensions, material properties, workmanship, type of failure, and uncertainty in the prediction of resistance.

roving—a number of yarns, strands, tows, or ends of fibers collected into a parallel bundle with little or no twist.

RTM—resin transfer molding.

SCRIMP—Seemans composite reinforcement infusion molding process—a vacuum process to combine resin and reinforcement in an open mold.

SFRP—steel FRP.

shape—construction made of continuous fibers in a shape other than used to reinforce concrete monoaxially, or in the specific shape of a grid or mesh. Generally not a bar, tendon, grid, or mesh, although may be used generically to include one or more of these.

sheet, FRP—a dry, flexible ply used in wet lay-up FRP systems. Unidirectional FRP sheets consist of continuous fibers aligned in one direction and held together in-plane to create a ply of finite width and length. Fabrics are also referred to as sheets.

shelf life—the length of time packaged materials can be stored under specified conditions and remain usable.

SIP—Structurally integrated stay-in-place. Used to describe SIP form systems described in [Chapter 9](#).

sizing—surface treatment or coating applied to filaments to improve the filament-to-resin bond and to impart processing and durability attributes.

SMC—sheet molding compound.

spray-up—method of contact molding wherein resin and chopped strands of continuous filament roving are deposited on the mold directly from a chopper gun.

spun yarn—yarn made by crimping crimped staple

staple—short fibers of uniform length usually made by cutting continuous filaments. Staple may be crimped or uncrimped.

strand—bundle of filaments bonded with sizing.

synthetic fiber, types—polyacrylonitrile (PAN, acrylic); polyamide: nylon (aliphatic) and aramid (aromatic); polyvinyl alcohol; polyvinyl chloride (PVC); polyethylene (PE) (olefin).

textile—fabric, usually woven.

thermoplastic—polymer that is not cross-linked. Thermoplastic polymer generally can be remelted and recycled.

thermoset—resin that is formed by cross-linking polymer chains. A thermoset cannot be melted and recycled.

tow—bundle of fibers, usually a large number of spun yarns.

twisted string or rope—string or rope made by twisting continuous fibers or strands.

uncrimped—fibers with no crimp.

unsaturated polyester—product of a condensation reaction between dysfunctional acids and alcohols, one of which, generally the acid, contributes olefinic unsaturation.

URM—unreinforced masonry.

UV—ultraviolet.

vinylester resin—resin characterized by reactive unsaturation located primarily in terminal positions that can be compounded with styrol monomers to give highly cross-linked thermoset copolymers.

VARTM—vacuum resin transfer molding—a vacuum process to combine resin and reinforcement in an open mold.

volume fraction—the proportion from 0.0 to 1.0 of a component within the composite, measured on a volume basis, such as fiber-volume fraction.

weaving—a multidirectional arrangement of fibers. For example, polar weaves have reinforcement yarns in the circumferential, radial, and axial (longitudinal) directions; orthogonal weaves have reinforcement yarns arranged in the orthogonal (Cartesian) geometry, with all yarns intersecting at 90 degrees.

wet lay-up—a method of making a laminate product by applying the resin system as a liquid when the fabric or mat is put in place.

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

yarn—group of fibers held together to form a string or rope.

CHAPTER 3—CODES AND STANDARDS

This chapter provides an overview of available design documents addressing applications of FRP composite materials either as internal reinforcement or as an external repair material for concrete structures. For design guidance, the referenced design guidelines or codes should be consulted and take precedence over information in this report. With the exception of materials testing standards, the Canadian code documents (CSA S6 and S806), and the Egyptian code (Egyptian Ministry of Housing, Utilities, and Urban Development 2005), the available documents are intended to provide guidance for the use of FRP materials and do not carry the weight of design standards. In some cases, the issuing agency has

chosen to term the documents Bulletins (fib 2001), Interim Guidance (IStructE 1999) or, in the case of ACI, Emerging Technology Documents (ACI 440.2R and 440.4R). Nonetheless, all are consensus documents and represent the current state of the practice. ACI removed the Emerging Technology designation from ACI 440.1R.

3.1—Materials

Most major standards-writing organizations have a number of available materials testing standards appropriate for determining a variety of FRP material properties and characteristics. Materials test standards, however, are always generic and are intended to set a standard of performance based on laboratory tests; therefore, they are not necessarily well suited to determine the in-place properties of interest to the concrete designer.

ACI Committee 440 has initiated the development of test methods specifically intended for FRP products and materials used with reinforced concrete. These ACI-developed standards are aimed at generating design values useful to the concrete practitioner. Once accepted by ACI, these test methods are submitted to ASTM Committee D30.05, “Composite Materials—Structural Test Methods” to be developed as formal ASTM standards. The first collection of ACI test methods is compiled in ACI 440.3R. ASTM D30.05 is beginning the process of revising and adopting these initial standards.

Most international standards organizations issue standards for determining basic physical properties of FRP materials. Many of these have been adapted by various industry and research interests for products with applications for concrete structures. [Chapter 5](#) of this report discusses FRP materials testing more completely.

3.2—Internal FRP reinforcement

Fundamental design methodologies for FRP-reinforced concrete are similar to those of conventional steel-reinforced concrete. Cross-sectional equilibrium, strain compatibility, and constitutive material behavior form the basis of all code approaches to designing reinforced concrete, regardless of the reinforcing material. The nonductile and anisotropic natures of FRP reinforcing products, however, need to be addressed in design guidelines. In flexural design, for instance, the ultimate limit state may be defined either by FRP rupture or concrete crushing, provided that the strength and serviceability criteria are met. Because of the lack of ductility of such failure modes, a higher reserve of strength is required. Thus, strength-reduction factors or material-resistance factors are generally lower for FRP-reinforced concrete members than for steel-reinforced concrete members. In all cases, FRP design guidelines and codes are consistent with the applicable reinforced concrete design codes. No attempt is made to adjust load factors; thus, only strength-reduction factors or material-resistance factors are adjusted to reflect the use of FRP. [Chapters 6](#) and [7](#) of this document discuss, in more detail, internally FRP-reinforced and FRP-prestressed concrete members, respectively.

ACI 440.1R uses a strength design approach for FRP-reinforced concrete members that is consistent with ACI

318. In this approach, a member is designed based on its required strength and checked for fatigue and creep rupture endurance, and serviceability criteria. In many cases, these latter criteria may control the design of members, particularly where lower stiffness aramid or glass reinforcement is used. ACI 440.1R, consistent with ACI 318, provides strength-reduction factors related to the ductility of the failure mode considered. Guidance, in the form of additional reduction factors, is also provided for all durability-related criteria with the exception of fire resistance. ACI 440.4R provides similar design guidance for prestressing structures with FRP tendons.

The CSA S806 represents the first stand-alone formalized design code (rather than guide) addressing FRP-reinforced concrete. Consistent with CSA A23.3, CSA S806 prescribes partial material-resistance factors rather than strength-reduction factors. Additionally, CSA S806 does not consider FRP rupture to be a valid failure, permitting only concrete crushing. The CSA S806 does not address durability directly, but rather references CSA S478 instead. CSA S806 requires the designer to consider fire resistance, but offers no provisions or guidance in this regard. CSA S806 also provides provisions for prestressing concrete members with aramid or carbon bars.

The CSA S6 also includes formalized provisions for the application of FRP reinforcement or prestressing. Material-resistance factors and stress limits associated with serviceability, pretensioning, and post-tensioning are provided. Durability is addressed through material-resistance factors for FRP type and application, and the effects of creep and fatigue are assumed to be included in the factors and limits provided.

The ISIS *Design Manual 3—Reinforcing Concrete Structures with Fibre Reinforced Polymers* (Rizkalla and Mufti 2001) takes an approach very similar to ACI 440.1R in permitting both FRP rupture and concrete crushing failures. *Design Manual 3* provides material-resistance factors, though it does not differentiate between expected failure modes. *Design Manual 3* discusses durability, but does not provide additional factors to account for environmental exposure. Creep and fatigue are addressed in the same manner as in CSA S6. Finally, *Design Manual 3* provides listings of product-specific material properties.

In Europe, the Federation Internationale de Beton (fib) Task Group 9.3, FRP Reinforcement for Concrete Structures, is preparing a technical bulletin addressing the use of internal FRP reinforcement. As of early 2007, this document is not yet available, but several European countries have developed their own guidelines for such applications.

In Great Britain, the *Interim Guidance on the Design of Reinforced Concrete Structures using Fibre Composite Reinforcement* (IStructE 1999) takes the form of suggested changes to the British design codes BS8110, “Structural Use of Concrete, Parts 1 and 2” (British Standards Institution [BSI] 1997) and BS5400, “Part 4 Code of Practice for the Design of Concrete Bridges” (BSI 1990). The approach taken by the IStructE document is consistent with that taken by CSA S6.

The Japanese “Recommendations for the Design and Construction of Concrete Structures using Continuous Fiber

Reinforced Materials” (JSCE 1997) is intended to supplement the “JSCE Standard Specification for Concrete Structures” (JSCE 1986) with respect to the use of FRP reinforcement for structures other than buildings. The JSCE recommendations (1997) are based on limit states design with verification of the ultimate, serviceability, and fatigue limits states. Although limits associated with durability phenomena are prescribed, these are typically given in reference to the results of a standard material property test for the FRP bar or strand considered. “Design Guidelines of FRP Reinforced Concrete Building Structures” (Sonobe et al. 1997), provides similar guidelines for building structures. A third guide, “Design Methods for Prestressed FRP-Reinforced Concrete Building Structures,” is reported (Bakis et al. 2002) although it does not appear to be available in English.

The Egyptian FRP code (Egyptian Ministry of Housing, Utilities, and Urban Development 2005) represents a stand-alone formalized design code addressing FRP-reinforced concrete that includes provisions for the design and construction of concrete reinforced with FRP bars. The Egyptian document uses the limit states design approach for FRP-reinforced concrete members that is consistent with the formalized Egyptian “Code for the Design and Construction of Concrete Structures” (2001). In this approach, a member is designed based on its required strength and checked for fatigue and creep rupture endurance and serviceability criteria. The Egyptian FRP code prescribes a material-resistance factors approach related to the ductility of the failure mode considered in addition to all durability-related criteria with the exception of fire resistance.

In North America, two approaches for evaluating the resistance of members are used. In the ACI approach, the strength-reduction factor depends on the action being resisted (for example, the reduction factor is different for flexure, shear, and axial loads). The strength-reduction factor (less than 1.0) is applied to the total nominal resistance, and depends on the mode of failure. On the other hand, Canadian codes are based on a unified limit state design philosophy in which material-resistance factors, always less than 1.0, are used to reflect uncertainties in determining the nominal resistance structural components. In CSA S6, the material-resistance factor for each FRP type changes with application and was arrived at by considering both material variability and environmental factors for those specific applications.

3.3—External FRP reinforcement

Recommended design methodologies of externally bonded FRP strengthening schemes are universally consistent with concrete design methodologies. Currently, the three formalized documents addressing applications of externally bonded FRP are CSA S806, CSA S6, and the Egyptian FRP code (Egyptian Ministry of Housing, Utilities, and Urban Development 2005). All other available documents are guides. The approaches taken, in each case, are consistent with local concrete codes and related guidance for internal FRP reinforcement (Section 3.2). Similar to internal FRP reinforcement, failure modes may be associated with concrete crushing or FRP rupture or loss of bond. Additionally,

the initial strain conditions of the existing internal steel reinforcement should also be considered. Load-reduction factors and material-resistance factors are consistent with those recommended for internal FRP reinforcement. **Chapter 8** of this document discusses externally bonded FRP reinforcement used for structural repair or retrofit in more detail.

Beyond simply providing the required capacity, three significant design issues, associated with applications of external FRP for repair and strengthening, are:

1. Quality of bond (or anchorage, or both) between FRP and concrete substrate;
2. The durability and long-term performance of FRP materials; and
3. Strengthening limits.

The consensus of available design guides is that each of these issues requires special attention and additional research. Additionally, most guides for design of externally bonded composites address only reinforced concrete rectangular sections. ACI Committee 440 is currently preparing documents that address concrete members having pre- or post-tensioned steel reinforcement, irregular geometry, compression FRP reinforcement, near-surface-mounted (NSM) FRP applications, or upgrade of masonry structures.

ACI 440.2R provides strength-reduction factors based on ductility of the expected failure mode (as measured by reinforcing steel strain) consistent with ACI 318. ACI 440.2R specifically addresses environmental exposure with environmental reduction factors associated with various typical exposures. Fatigue and creep effects are addressed through prescribed FRP stress limits. Cover delamination and debonding of the FRP are mitigated through strain limits applied to the FRP. These limits are believed to reduce the shear transfer demand of the cover concrete and adhesive layers sufficiently to prevent bond failure. Finally, *de facto* strengthening limits are determined by stipulating that the ultimate capacity of the structure without the FRP reinforcement should exceed a minimum level that corresponds to the expected loads under such situations. Additional guidance is provided for fire event loading requirements. These strengthening limits are based on the premise that the FRP retrofit is rendered entirely ineffective under particular conditions, such as fire or vandalism, and the member (without FRP) should be able to carry service loads without collapse. A revision of ACI 440.2R to include NSM reinforcement and to update load factors to those adopted in the ACI 318-05 (ACI Committee 318 2005) is underway. Similarly, a separate document addressing the repair of masonry using externally bonded FRP reinforcement is in preparation.

According to ACI 440.2R, the shear strength can be improved by wrapping the FRP system around three sides of the member (U-wrap), bonding to the two sides of the member, or completely wrapping the member. The FRP system can be installed continuously along the span length of a member or placed as discrete strips. The nominal shear capacity of an FRP-strengthened concrete member can be determined by adding contributions from the reinforcing steel (stirrups, ties, or spirals) and concrete and the contribution of the FRP reinforcement based on a maximum FRP strain at

ultimate that is no greater than 0.004. FRP contribution for shear is further reduced using a reduction factor that is less than 1.0.

For compression members, ACI 440.2R allows FRP systems to be used to increase the axial compression strength of a concrete member by providing confinement with lateral (hoop) fibers. The hoop fibers provide confining effects similar to conventional spiral or tie reinforcing steel. ACI 440.2R uses a simplified approach to determine the peak confined concrete strength as a function of the FRP confining pressure. The effectiveness of FRP confinement is determined as a function of the geometry of the section of the confined member. An efficiency factor is introduced to address the shape effects. For circular sections, the efficiency factor can be taken equal to 1.0.

ACI 440.2R gives some guidelines for detailing FRP sheets or laminates to avoid bond-related failures. The details depend on the geometry of the structure, the soundness and quality of substrate, and levels of load to be sustained by the FRP sheets or laminates.

For fatigue, ACI 440.2R suggests fatigue stress limits on FRP laminates to avoid fatigue failures of the FRP. The stress limits are lowest for glass FRP (GFRP), and highest for carbon FRP (CFRP). Existing recommendations for stress range limits for reinforced concrete beams (ACI 215R) may be applied to the internal reinforcing steel, but these typically limit the service stresses in the steel and concrete to levels that may be exceeded in cases where the structure is strengthened. Indeed, exceeding these stress limits may be the reason for requiring strengthening. Finally, it should also be taken into account that by the time strengthening takes place, the structure may have been in service for a significant number of years, exhausting some of its fatigue life.

To calculate the design strength of a strengthened member, the ACI approach uses strength-reduction factors applied to the nominal resistance, while other codes use material-resistance factors applied to the strength properties of the materials themselves (including FRPs). In addition to an overall strength-reduction factor, ACI 440.2R applies an additional partial resistance factor to the portion of the strength contributed by the FRP reinforcement. To account for durability, ACI 440.2R also recommends environmental reduction factors to reduce the strength of the FRP that can be used in design. These factors depend on the type of FRP and the exposure conditions for the element to be strengthened.

The International Code Council (ICC) Evaluation Service, Inc. has acceptance criteria AC-125 and AC-178 (ICC 2003a,b). Although these criteria are not codes or standards, they are documents intended to evaluate FRP materials as alternatives to code-approved materials. They are developed in an open forum at public meetings presided by building officials.

The Canadian CSA S806 represents the first stand-alone formalized design code (rather than guide) addressing externally bonded FRP reinforcement for concrete. For strengthening applications, CSA S806 considers all possible failure modes rather than just concrete crushing (as it does for internal reinforcement). Durability is addressed through reference to CSA S478. Although a single limiting tensile strain (0.007) is provided, delamination, and

debonding are addressed by directing the designer to “currently available information appropriate to the combination of sheets and adhesive.” Strengthening limits are based on the requirement that the structure should support its nominal service load in the event that the FRP becomes ineffectual. CSA S806 addresses the repair of masonry structures.

ISIS *Design Manual 4—Strengthening Reinforced Concrete Structures with Externally-Bonded Fibre Reinforced Polymers* (Neale 2001) provides considerable guidance and a number of design examples for the use of externally bonded FRP. This document, however, is written as a state-of-the-art report, referencing the recommendations of others rather than making its own clear design recommendations. Generally, ISIS *Design Manual 4* references the recommendations of ACI 440.2R (which was in draft form when ISIS *Design Manual 4* was released).

The European Fédération Internationale de Béton (fib) *Bulletin 14* (fib 2001), produced by fib Task Group 9.3, also represents a combination guide and state-of-the-art report. Significantly, fib *Bulletin 14* recognizes the difference in expected performance, not only between FRP material types, but between preformed and wet layed-up FRP systems in the form of different material safety factors. Delamination and debonding are extensively addressed in fib *Bulletin 14* using a simplified bilinear bond model and by also addressing the effects of the loss of composite action between the FRP and concrete substrate. Durability effects are discussed, but no clear design guidance is provided. FRP-strengthened members are expected to withstand accidental loads in the case where the FRP no longer functions. In this case, reference is made to “Eurocode 1” (CEN 1994) for the loads to be considered.

In Great Britain, the Concrete Society published *Technical Report 55* (Concrete Society 2000, 2004). This document is similar to ISIS *Design Manual 4* (Neale 2001) and fib *Bulletin 14* (2001) in its approach and scope. Importantly, *Technical Report 55* has been followed by *Technical Report 57* (Concrete Society 2003). This report addresses more practical construction issues associated with externally bonded FRP materials.

The Japanese “Recommendations for the Upgrading of Concrete Structures with Use of Continuous Fiber Sheets” (JSCE 2001) adopts a performance-based approach to the design of externally bonded FRP materials. Flexure and shear capacity, column deformation capacity (jacketing applications), flexural crack width, and protection of the concrete substrate from chloride ion penetration are all considered explicitly in the JSCE recommendations. A variety of guidelines produced by various Japanese authorities are also available primarily for column and/or pier retrofit using FRP jacketing techniques (Bakis et al. 2002).

The Egyptian FRP code (Egyptian Ministry of Housing, Utilities, and Urban Development 2005) also addresses externally bonded FRP reinforcement for concrete. The approach is very similar to that of ACI 440.2R.

The Italian “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures” (CNR 2004) includes the application of externally bonded FRP materials to reinforced or prestressed concrete structures as well as to masonry structures. Delamination

failure mechanisms are explained, and a fracture mechanics approach is adopted to predict such failure modes; based on that approach, an ultimate design strength for laminate/sheet is provided. This document describes a detailed design example of strengthening a two-story building with CFRPs.

CHAPTER 4—COMPOSITE MATERIALS AND PROCESSES

4.1—Introduction

FRP composites are defined as a polymer matrix, either thermoset or thermoplastic, that is reinforced with a fiber or other reinforcing material with a sufficient aspect ratio (length-to-thickness) to provide a discernible reinforcing function in one or more directions. FRP composites are different from traditional construction materials such as steel or aluminum. FRP composites are anisotropic (properties vary with the direction), whereas steel or aluminum are isotropic (uniform properties in all directions, independent of applied load). Therefore, FRP composite properties are directional, and typically the most favorable mechanical properties are in the direction of the fiber placement.

Many terms have been used to define FRP composites. Modifiers have been used to identify a specific fiber such as glass FRP (GFRP), carbon FRP (CFRP), aramid FRP (AFRP), steel FRP (SFRP), and hybrid FRP (HFRP) for composites containing different types of fibers. In addition, other acronyms were developed over the years; their use depended on geographical location or market use. For example, fiber-reinforced composites (FRCs), glass-reinforced plastics (GRPs), and polymer matrix composites (PMCs) are found in many references.

Although these composites are defined as a polymer matrix that is reinforced with fibers, this definition should be further refined when describing composites in structural applications. In the case of structural applications such as FRP composite reinforced concrete, at least one of the constituent materials should be a continuous reinforcement phase supported by a stabilizing matrix material. For the special class of matrix materials discussed herein (that is, thermosetting polymers), the continuous fibers will usually be stiffer and stronger than the matrix.

Composite materials, in the sense that they will be discussed in this chapter, will be at the macrostructural level. This chapter will address the gross structural forms and constituents of composites, including the matrix resins and reinforcing fibers. This chapter will also briefly address additives and fillers, as well as process considerations.

The performance of any composite depends on the materials of which the composite is made, the arrangement of the primary load-bearing portion of the composite (reinforcing fibers), and the interaction between the materials (fibers and matrix).

Each of the constituent materials or ingredients plays an important role in the processing and final performance of the end product. The resin or polymer holds the fibers in place and influences the physical properties of the end product. The reinforcement provides the mechanical strength. The fillers and additives are used as process aids or to impart special properties to the end product.

The mechanical properties and composition of FRP composites can be engineered for their intended use. The type and quantity of materials selected, in addition to the manufacturing process to fabricate the product, will affect the mechanical properties and performance. Important considerations for the design of composite products include:

- Type and percentage of fiber or fiber volume;
- Orientation of fiber (0, 90, ± 45 degrees, or a combination of these);
- Type of resin;
- Cost of product;
- Volume of production (to help determine the best manufacturing method); and
- Service conditions.

4.2—Polymer matrix: resins

Resins are divided into two major groups: thermoset and thermoplastic. Thermoplastic resins become soft when heated, and may be shaped or molded while in a heated semi-fluid state. They become rigid when cooled. Thermoset resins, on the other hand, are usually liquids or low-melting-point solids in their initial form. When used to produce finished goods, these thermosetting resins are cured with a catalyst, heat, or a combination of the two. Once cured, solid thermoset resins cannot be converted back to their original liquid form. Unlike thermoplastic resins, cured thermosets will not melt and flow but will soften when heated (and lose hardness). Once formed, they cannot be reshaped. Heat distortion temperature and the glass transition temperature T_g are used to measure the softening of a cured resin. Test methods for both heat distortion temperature and T_g measure the approximate temperature where the cured resin will soften significantly to yield (bend or sag) under load.

The most common thermosetting resins used in the composites industry are unsaturated polyesters, epoxies, vinylesters, and phenolics.

4.2.1 Polyester—Unsaturated thermoset polyester resins are the workhorses of the composites industry, and they represent approximately 75% of the total resins used (ACMA MDA 2006). To avoid any confusion in terms, readers should be aware that there is an unrelated family of thermoplastic polyesters that are best known for their use as fibers for textiles and clothing. Polyesters are produced by the condensation polymerization of dicarboxylic acids and difunctional alcohols (glycols). In addition, unsaturated polyesters contain an unsaturated material, such as maleic anhydride or fumaric acid, as part of the dicarboxylic acid component. The finished polymer is dissolved in a reactive monomer such as styrene to give a low-viscosity liquid. When this resin is cured, the monomer reacts with the unsaturated sites on the polymer, converting it to a solid thermoset structure.

Polyesters are versatile because of their capacity to be modified or tailored during the building of the polymer chains. They have been found to have almost unlimited usefulness in all segments of the composites industry. The principal advantage of these resins is a balance of properties (including mechanical, chemical, and electrical), dimensional stability, cost, and ease of handling or processing.

Unsaturated polyesters are divided into classes depending upon the structure of their basic building blocks. Some common examples would be orthophthalic (ortho), isophthalic (iso), dicyclopentadiene, and bisphenol fumarate resins. In addition, polyester resins are classified according to end-use application as either general purpose or specialty polyesters.

The general-purpose polyesters define products that are relatively low in cost, offer good mechanical and electrical performance, and have a well-defined set of processing/fabricating characteristics. Almost all ortho and dicyclopentadiene resins and some iso resins fall into the general-purpose category.

Because polyesters can be chemically tailored to meet the requirements of a wide range of applications, a number of specialty polyesters that address specific performance, such as flexibility, electrical insulation, corrosion resistance, heat resistance, fire retardancy, and optical translucence, are available.

4.2.2 Epoxy—Epoxy resins have a well-established record in a wide range of composite parts, structures, and concrete repair. The structure of the resin can be engineered to yield a number of different products with varying levels of performance. A major benefit of epoxy resin over unsaturated polyester resins is its lower shrinkage. Epoxy resin can also be formulated with different materials or blended with other epoxy resins to achieve specific performance features. Cure rates can be controlled to match process requirements through the proper selection of hardeners and/or catalyst systems. Generally, epoxies are cured by addition of an anhydride or an amine hardener as a two-part system. Different hardeners, or different quantities of hardener, produce different cure profiles and give different properties to the finished composite.

Epoxies are primarily used for fabricating high-performance composites with superior mechanical properties, resistance to corrosive liquids and environments, superior electrical properties, good performance at elevated temperatures, and excellent adhesion to a substrate. Epoxy resins do not, however, have particularly good ultraviolet (UV) resistance. Because the viscosity of epoxy is much higher than that of most polyester resins, they require a post-cure (elevated heat) to obtain ultimate mechanical properties. Epoxies have little or no odor as compared with polyesters.

Epoxy resins are used with a number of fibrous reinforcing materials, including glass, carbon, and aramid. Epoxies are compatible with most composite manufacturing processes, particularly vacuum-bag molding, autoclave molding, pressure-bag molding, compression molding, filament winding, and hand lay-up. Currently, epoxy is the predominant resin used in external repair of concrete using FRP sheet and fabric products.

4.2.3 Vinylester—Vinylesters were developed to combine the advantages of epoxy resins with those of unsaturated polyester resins. These resins are produced by reacting epoxy resin with acrylic or methacrylic acid. This provides an unsaturated site, much like that produced in polyester resins when maleic anhydride is used. The resulting material is dissolved in styrene to yield a liquid that is similar to poly-

ester resin. Vinylesters are also cured with the conventional organic peroxides used with polyester resins. Vinylesters offer mechanical toughness and excellent corrosion resistance. These enhanced properties are obtained without complex processing, handling, or special shop fabricating practices that are typical with epoxy resins.

4.2.4 Phenolic—Phenolics are a class of resins commonly based on phenol (carbolic acid) and formaldehyde, and cure through a condensation reaction producing water that should be removed during processing. Phenolic composites have many desirable performance qualities, including high temperature resistance, creep resistance, excellent thermal insulation and sound-damping properties, corrosion resistance, and excellent fire/smoke/smoke toxicity properties. Phenolics are applied as adhesives or matrix binders in engineered woods (plywood), brake linings, clutch plates, and circuit boards. Phenolic composites are not currently widely available for the construction industry.

4.2.5 Structural engineered polyvinyl chloride (PVC) plastisol—Structural engineered PVC plastisol resins are, by definition, thermoplastic resins with many performance characteristics of thermosets but with many more processing-friendly attributes than traditional thermoset resins. This new resin is a single-component material with no volatiles. This resin has the potential of impacting FRP composites products; however, to date, no products have been made or tested. It features a viscosity of approximately 1.5 to 3 Pa·S (1500 to 3000 cps) with a shelf life in excess of 6 months with essentially no settling of solids. To fully fuse (or cure) this material, it is subjected to temperatures between 177 and 199 °C (350 and 390 °F) for between 10 seconds and several minutes depending on the thickness of the part and the speed of the operation. Wetout of traditional glass and carbon fibers is effective, with chemical bonding occurring between the silanes present in the sizings and the fully fused PVC plastisol.

From a processing standpoint, PVC plastisol resins are efficient in handling liquid resins and minimizing waste associated with startup and shutdown. Structural engineered PVC plastisol resins are formulated with no styrene, solvent, or volatiles. Additive packages offer additional benefits of excellent UV resistance and fire retardancy. Additionally, there is virtually no microvoiding in the finished part, which ensures much better electrical properties and significantly lower water absorption compared with traditional thermosets. The resin exhibits a T_g of approximately 63 °C (145 °F).

4.3—Reinforcing fibers

The primary function of fibers or reinforcements is to carry load along the length of the composite to provide strength and stiffness in one direction. Reinforcements can be oriented to provide tailored properties in various directions. Reinforcements can be both natural and synthetic. Most commercial reinforcements, however, are synthetic. The principal types of fibers in commercial use for civil engineering applications are glass, carbon (or graphite), and aramid.

Of these, glass fiber has by far the largest volume of reinforcement measured either in quantity consumed or in

product sales. Other composite reinforcing materials include ultra-high molecular weight polyethylene, polypropylene, polyester, and nylon.

The most common form of FRPs used in structural applications is called a laminate. Laminates are made by stacking a number of thin layers (lamina) of fibers and matrixes and consolidating them into the desired thickness. Fiber orientation in each layer, as well as the stacking sequence of the various layers, can be controlled to generate a range of physical and mechanical properties.

A unidirectional or one-dimensional fiber arrangement is transversely isotropic. This fiber orientation results in a maximum strength and modulus in the direction of the fiber axis. A planar arrangement of fibers is two-dimensional and has different strengths at all angles of fiber orientation (orthotropic). A three-dimensional array has substantially reduced strengths over the one-dimensional arrangement. Mechanical properties in any one direction are proportional to the amount of fiber by volume oriented in that direction.

Most reinforcement for either thermosetting or thermoplastic resins receives some form of surface treatment, either during fiber manufacture or as a subsequent treatment. Other materials applied to fibers as they are produced include resinous binders to hold fibers together in bundles and lubricants to protect fibers from degradation caused by process abrasion.

4.3.1 Glass fibers—Glass has been the predominant fiber for many civil engineering applications because of an economical balance of cost and specific strength properties. Glass fibers are commercially available in E-glass formulation (for electrical grade), the most widely used general-purpose form of composite reinforcement, and other formulations for high strength (S-2[®] glass), improved acid resistance (ECR glass), and alkali resistance (AR glass).

Based on an alumina-lime-borosilicate composition, E-glass fibers are considered the predominant reinforcement for polymer matrix composites because of their high electrical insulating properties, low susceptibility to moisture, and high mechanical properties.

Glass fibers used for reinforcing composites generally range in diameter from 9 to 23 microns. Fibers are drawn at high speeds through small holes in electrically heated bushings. These bushings form the individual filaments. The filaments are gathered into groups or bundles called strands or tows. The filaments are water and air cooled and then coated with a proprietary chemical binder or sizing to protect the filaments and enhance the composite laminate properties. The sizing also determines the processing characteristics of the glass fiber and the conditions at the fiber-matrix interface in the composite.

Glass is generally a good impact-resistant fiber, but is denser than carbon or aramid. Composites made from this material exhibit very good electrical and thermal insulation properties. Glass fibers are also transparent to radio frequency radiation and are used in radar antenna applications.

4.3.2 Carbon fibers—Carbon fiber is made from polyacrylonitrile (PAN), pitch, or rayon fiber products. The properties of carbon fiber are controlled by molecular structure and

degree of freedom from defects. The formation of carbon fibers requires processing temperatures above 1000 °C (1830 °F).

There are two basic types of carbon fiber: high modulus and high strength. The difference in properties between them is a result of the differences in fiber microstructure, derived from the precursor type and the processing temperature (1000 to 3000 °C [1830 to 5430 °F]).

PAN-based carbon fiber is the predominant form used in the civil engineering venue because of its very high strength (up to about 5000 MPa [720 ksi] in unidirectional form) and relatively high modulus (up to about 140 GPa [20 msi] in unicomposite form or 420 GPa [60 msi] in fiber form). Pitch-based carbon fibers have extremely high modulus values (up to 970 GPa [140 msi]) with lower strengths (up to about 690 MPa [100 ksi] in unicomposite form). They are used primarily in space and satellite applications. Carbon fiber is about five to 10 times more expensive than glass fiber; however, it has about twice the usable strength and four times the modulus of glass.

Carbon fibers are supplied in a number of different forms, from continuous filament tows to chopped fibers and mats. The highest strength and modulus are obtained from unidirectional continuous reinforcement. Carbon fiber composites have a lower strain capacity than do glass or aramid composites. Carbon fiber is highly resistant to alkali or acid attack. Nevertheless, carbon fibers can cause galvanic corrosion when in contact with metals. A barrier material, such as glass and resin, is used to prevent this occurrence. Also, carbon fibers can conduct electric current, and are thus vulnerable to strikes by lightning.

Rayon and isotropic pitch precursors are used to produce low-modulus carbon fibers (50 GPa [7000 ksi]). Both PAN and liquid crystalline pitch precursors are made into higher modulus carbon fibers by carbonizing above 800 °C (1400 °F). Fiber modulus increases with heat treatment from 1000 to 3000 °C (1830 to 5430 °F). The results vary with the precursor selected. Fiber strength appears to maximize at a lower temperature of 1500 °C (2730 °F) for PAN and some pitch precursor fibers, but increases for most mesophase (anisotropic) pitch precursor fibers.

The axial-preferred orientation of graphene layers in carbon fibers determines the modulus of the fiber. Both axial and radial textures and flaws affect the fiber strength. Orientation of graphene layers at the fiber surface affects wetting and strength of the interfacial bond to the matrix.

Carbon fibers are not easily wet by resins, particularly the higher-modulus fibers. Surface treatments that increase the number of active chemical groups (and sometimes roughen the fiber surface) have been developed for some resin matrix materials. Carbon fibers are frequently shipped with an epoxy size treatment applied to prevent fiber abrasion, improve handling, and provide an epoxy resin matrix compatible interface. Fiber and matrix interfacial bond strength approaches the strength of the resin matrix for lower-modulus carbon fibers. Higher-modulus PAN-based fibers show substantially lower interfacial bond strengths. Failure in high-modulus fiber occurs in its surface layer in much the same way as with aramids.

Carbon fibers are available as tows or bundles of parallel fibers. The range of individual filaments in the tow is normally from 1000 to 200,000 fibers. These tows can be woven or knitted into fabrics. Carbon fiber is also available as a prepreg where the fibers are preimpregnated with resin, as well as in the form of unidirectional tow sheets.

4.3.3 Aramid fibers—Aramid fiber is an aromatic polyamide organic fiber for composite reinforcement. Aramid fibers offer good mechanical properties at a low density with the added advantage of toughness or impact resistance. They are characterized as having reasonably high tensile strength, a medium modulus, and a very low density as compared with glass and carbon. The tensile strength of aramid fibers is higher than that of glass fibers, and the modulus is approximately 50% higher than that of glass. These fibers increase the impact resistance of composites and provide products with higher tensile strengths. Aramid fibers are insulators of both electricity and heat. They are resistant to organic solvents, fuels, and lubricants. Aramid composites have poor compressive strength. Dry aramid fibers are tough, have been used as cables or ropes, and are frequently used in ballistic applications.

4.3.4 Steel fibers—A new type of FRP composite strengthening system has emerged that uses high-strength steel fibers and is commonly known as SFRP. The high-strength steel fibers demonstrate a linear elastic stress-strain relationship that is similar to carbon and glass fibers. The steel fibers (also referred to as wires) have a tensile strength in the range of 2400 to 3100 MPa (350 to 450 ksi) and an elastic modulus of 200 MPa (30,000 ksi). The high-strength steel wires are twisted together to form steel cords, each containing five to 13 wires. Typical wire diameters range from 0.5 to 1.3 mm (0.02 to 0.05 in.). Because of the unwinding effects of the cords at higher tensile loads, ultimate tensile strains in the range of 0.02 to 0.05 can be achieved. The twisted steel wires have a deformed surface that allows for adequate bond to the surrounding matrix. SFRP is currently being applied for strengthening of concrete structures in a similar manner to other externally bonded FRP materials (Casadei et al. 2005a,b; Prota et al. 2006a,b).

Typical properties of glass, carbon, and aramid fibers are reported in [Table 4.1](#).

4.4—Types of reinforcement

Regardless of the material, reinforcements are available in forms to serve a wide range of processes and end-product requirements. Fibers supplied as reinforcement include (untwisted) roving; (twisted) yarns; milled fiber; chopped strands; and continuous, chopped, or thermoformable mats. Reinforcement materials can be designed with unique fiber architectures and be preformed or shaped depending on the product requirements and manufacturing process.

4.4.1 Multi-end and single-end rovings—Multi-end rovings consist of many individual strands or bundles of filaments, which are then chopped and randomly deposited into the resin matrix. They can also be woven into fabric reinforcement. Processes such as sheet molding compound (SMC) and spray-up use multi-end rovings. Single-end rovings can also be used in some filament winding and

Table 4.1—Typical material properties of fibers

Fiber	Typical diameter, microns	Density, g/cm ³ (lb/in. ³)	Tensile modulus, GPa (10 ⁶ psi)	Tensile strength, MPa (ksi)	Strain to failure, %	Coefficient of thermal expansion, 10 ⁻⁶ /°C	Poisson's ratio
Commercial composite reinforcing fibers (constructed from Mallick [1988])							
Glass							
E-glass	10	2.54 (0.092)	72.4 (10.5)	3450 (500.0)	4.8	5.0	0.2
S-glass	10	2.49 (0.090)	86.9 (12.6)	4300 (625.0)	5.0	2.9	0.22
Carbon PAN-carbon							
T-300	7	1.76 (0.064)	231 (34)	3650 (530)	1.4	−0.1 to −0.5 (longitudinal), 7 to 12 (radial)	−0.2
AS	7	1.77 (0.064)	220 (32)	3100 (450)	1.2	−0.5 to −1.2 (longitudinal), 7 to 12 (radial)	—
t-40	6	1.81 (0.065)	276 (40)	5650 (820)	2.0	—	—
HSB	7	1.85 (0.067)	345 (50)	2340 (340)	0.58	—	—
Fortafil 3™	7	1.80 (0.065)	227 (33)	3800 (550)	1.7	−0.1	—
Fortafil 5™	7	1.80 (0.065)	345 (50)	2760 (400)	0.8	—	—
Toray M40J	—	1.77 (0.064)	377 (55)	4410 (640)	1.2	—	—
Zoltek (2006)	7	1.81 (0.065)	242 (35)	3800 (550)	—	—	—
Pitch-carbon							
P-555	10	2.00 (0.072)	380 (55)	1900 (275)	0.5	−0.9 (longitudinal)	—
P-100	10	2.16 (0.078)	758 (110)	2410 (350)	0.32	−1.6 (longitudinal)	—
Aramid							
Kevlar™ 49	12	1.45 (0.052)	131 (19)	3620 (525)	2.8	−2.0 (longitudinal), +59 (radial)	0.35
Twaron™ 1055*	12	1.45 (0.052)	127 (18)	3600 (533)	2.5	−2.0 (longitudinal), +59 (radial)	0.35

*Mechanical properties: single filament at 22 °C (72 °F) per ASTM D 2101.

pultrusion applications. The single-end roving consists of many individual filaments wound into a single strand. This product is generally used in processes that use a unidirectional reinforcement such as filament winding or pultrusion. These manufacturing processes are described in [Section 4.8](#).

4.4.2 Mats—These are two-dimensional random arrays of chopped strands. The fiber strands are deposited onto a continuous conveyor and then passed through a region where thermosetting resin is dusted on them. This resin is heat set and holds the mat together. The binder resin dissolves in the polyester or vinylester matrix, thereby allowing the mat to conform to the shape of the mold.

4.4.3 Woven, stitched, and braided fabrics—Many types of fabrics can be used to reinforce resins in a composite. Multidirectional reinforcements are produced by weaving, knitting, stitching, or braiding continuous fibers into a fabric from twisted and plied yarns. Fabrics refer to all flat-sheet, rolled goods. Fabrics can be manufactured with almost any reinforcing fiber. The most common fabrics are constructed with glass, carbon, or aramid fibers. Fabrics are available in several weave constructions and thicknesses from 0.025 to 10.2 mm (0.0010 to 0.40 in.). They offer oriented strengths and high reinforcement loadings often found in high-performance applications.

Fabrics are typically supplied on rolls of 23 to 274 m (25 to 300 yd) in length and 25 to 3050 mm (1 to 120 in.) in width. The fabric should be inherently stable enough to be handled, cut, and transported to the mold, but pliable enough to conform to the mold shape and contours. Properly designed, the fabric will allow for quick wet-out and wet-through of the resin, and will stay in place once the resin is

applied. Fabrics, like rovings and chopped strands, come with specific sizings or binder systems that promote adhesion to the resin system.

Woven fabrics are fabricated on looms in a variety of weights, weaves, and widths. In a plain weave, each fill yarn or roving is alternately crossed over and under each fiber in the other direction, allowing the fabric to conform to curved surfaces. Woven fabrics are manufactured where half of the fiber strands are laid at right angles to the other half (0 to 90 degrees). Woven fabrics are commonly used in boat manufacturing.

Stitched fabrics, also known as nonwoven, noncrimped, stitched, or knitted fabrics, have optimized strength properties because of the fiber architecture. Stitched fabrics are produced by assembling successive layers of aligned fibers. Typically, the available fiber orientations include the 0-degree direction (warp), 90-degree direction (weft or fill), and ±45-degree direction (bias). The assembly of each layer is then sewn together. These fabrics have been traditionally used in boat hulls. Other applications include light poles, wind turbine blades, trucks, busses, and underground tanks. These fabrics are currently used in bridge decks and column repair systems. Multiple orientations provide a quasi-isotropic reinforcement.

Braided fabrics are engineered with a system of two or more yarns intertwined in such a way that all of the yarns are interlocked for optimum load distribution. Biaxial braids provide reinforcement in the bias direction only with fiber angles ranging from ±15 to ±95 degrees. Triaxial braids provide reinforcement in the bias direction with fiber angles ranging from ±10 to ±80 degrees and axial (0-degree) direction.

4.4.4 Unidirectional—Unidirectional reinforcements include tapes, tows, tow sheets, rovings (which are collections of fibers or strands), grids, and pultruded bars. Fibers in this form are all aligned parallel. The aligned fibers are held together with a very light crossweave or tacked in place with a thermoplastic cross yarn or other light carrier. Composites using unidirectional tapes or sheets have high strength in the direction of the fiber. Unidirectional sheets are thin, and multiple layers are required for most structural applications.

Unidirectional sheets of carbon, glass, and aramid fibers are used extensively for wrapping of concrete beams and columns, while unidirectional reinforcing bars or prestressing tendons are applied for reinforcing or prestressing concrete structures, respectively.

4.5—Additives and fillers

4.5.1 Additives and modifiers—A wide variety of additives are used in composites to modify material properties and tailor the performance of the laminate. Although these materials are generally used in relatively low quantity by weight compared with resins, reinforcements, and fillers, they perform critical functions. These include affecting shrinkage, fire resistance, emissions, viscosity, mold release, and coloration.

4.5.2 Fillers—Fillers reduce the cost of composites; they also frequently impart performance improvements that might not otherwise be achieved by the reinforcement and resin ingredients alone. Fillers can improve mechanical properties, including fire and smoke performance, by reducing organic content in composite laminates. Also, filled resins shrink less than unfilled resins, thereby improving the dimensional control of molded parts. Important properties, including water resistance, weathering, surface smoothness, stiffness, dimensional stability, and temperature resistance, can all be improved through the proper use of fillers.

Commonly used fillers include calcium carbonate, clay, alumina trihydrate, and calcium sulfate. Others include mica, feldspar, wollastonite, silica, glass microspheres, and flake glass.

When used in composite laminates, inorganic fillers can account for 40 to 65% of the composite by weight. In comparison to resins and reinforcements, fillers are the least expensive of the major ingredients.

4.6—Core materials for sandwich structures

Bonded sandwich structures have been a basic component of the composites industry for over 45 years. The concept of using relatively thin, strong face sheets bonded to thicker, lightweight core materials has allowed the industry to build strong, stiff, light, and highly durable structures that otherwise would not be practical. This technology has been demonstrated in boats, trucks, building panels, and, more recently, in bridge decks.

Face sheets can be of almost any material. In the composites industry, the most common face sheet laminates are glass and carbon. The common core materials are foam, syntactic foam, honeycomb, and balsa wood (Fig. 4.1). Some core materials can be shaped, such as a waffle pattern or corrugation, to achieve the desired mechanical properties.

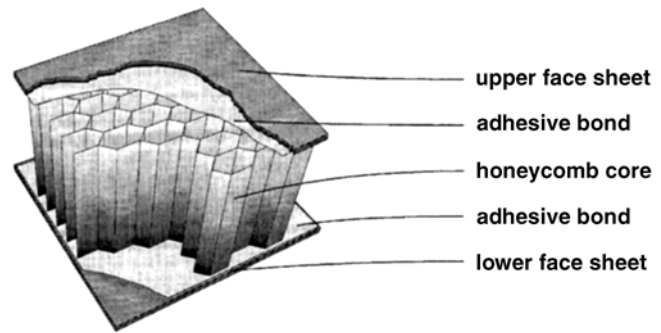


Fig. 4.1—Honeycomb sandwich construction (Hohe et al. 2001).

4.7—Adhesives

Adhesives are used to attach composites to themselves as well as to other surfaces such as concrete. Adhesive bonding is the method of choice for bonding thermoset composites. Several considerations are involved in applying adhesives effectively. The joint or interface connection should be engineered to select the proper adhesive and application method to ensure bond strength. Careful surface preparation and cure are critical to bond performance.

The most common adhesives are acrylics, epoxies, and urethanes. Epoxies provide a high-strength bond with high temperature resistance, whereas acrylics provide moderate temperature resistance with good strength and rapid curing. For applications where toughness is needed, urethane may be selected.

4.8—FRP manufacturing processes

Unique to the composites industry is the ability to create a product from many different manufacturing processes. There are a wide variety of processes available to the composites manufacturer to produce cost-efficient products. Each of the fabrication processes has characteristics that define the type of products to be produced.

4.8.1 Pultrusion—Pultrusion is a continuous molding process that combines fiber reinforcements and thermosetting resin. The pultrusion process is used in the fabrication of composite parts that have a constant cross-sectional profile. Typical examples include various rods and bar sections, bridge beams, and decks. Most pultruded laminates are formed using rovings aligned along the major axis of the part. Various continuous strand mats, fabrics (braided, woven, and knitted), and texturized or bulked rovings are used to obtain strength in the cross axis or transverse direction.

The process is normally continuous and highly automated (Fig. 4.2). Reinforcement materials, such as rovings, mats, or fabrics, are positioned in a specific location using preforming shapers or guides to form the profile. The reinforcements are drawn through a resin bath or wet-out where the material is thoroughly coated or impregnated with a liquid thermosetting resin. The resin-saturated reinforcements enter a heated metal pultrusion die. The dimensions and shape of the die will define the finished part being fabricated. Inside the metal die, heat is transferred under precise temperature control to the reinforcements and liquid resin. The heat activates the

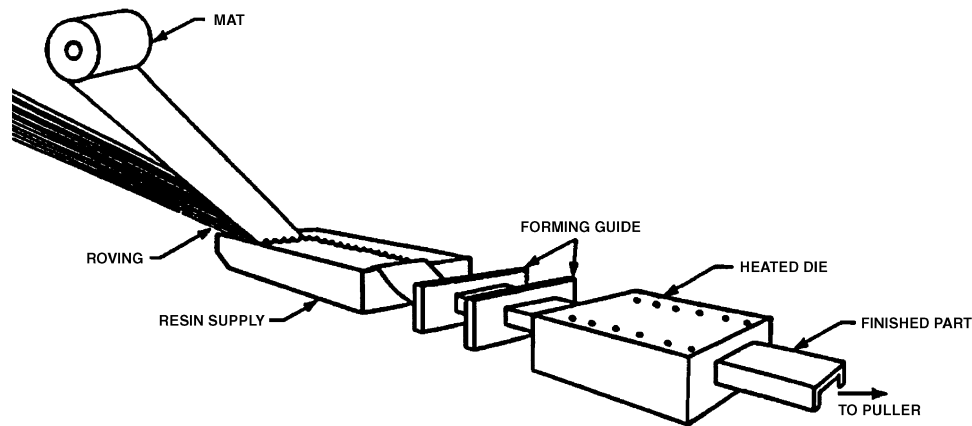


Fig. 4.2—Pultrusion process (Creative Pultrusions, Inc. 1994).

curing or polymerization of the thermoset resin, changing it from a liquid to a solid. The solid laminate emerges from the pultrusion die to the exact shape of the die cavity. The laminate solidifies when cooled, and it is continuously pulled through the pultrusion machine and cut to the desired length. The process is driven by a system of caterpillar or tandem pullers located between the die exit and the cutoff mechanism.

The process provides flexibility in the design of pultruded profiles. Currently, profiles up to 1830 mm (72 in.) wide and 530 mm (21 in.) high are possible. Pultrusion can manufacture both simple and complex profiles, eliminating the need for extensive post-production assembly of components. Because the process is continuous, length variations are limited to shipping capabilities. This process allows for optimized fiber architectures with uniform color, eliminating the need for many painting requirements.

4.8.2 Filament winding—This process takes continuous fibers in the form of parallel strands (rovings), impregnates them with matrix resin, and winds them on a rotating cylinder. The resin-impregnated rovings traverse back and forth along the length of the cylinder. The moving relationship between the rotating surface and the roving/matrix is usually controlled by a computer. A controlled thickness, wind angle, and fiber volume fraction laminate is thereby created. The material is cured on the cylinder and then removed (Fig. 4.3).

Pipes, torsion tubes, rocket cases, pressure bottles, storage tanks, and airplane fuselages are made by this process. For the construction industry, pipes are after-filled with concrete for piles and offer structural systems as described in [Chapter 9](#). Filament winding is also used for concrete column repair ([Chapter 8](#)). There can be additional add-on fiber/matrix placement systems to add chopped short-length fibers or particulate materials to increase thickness at low cost. Polyester, vinylester, and epoxy matrix materials are used.

4.8.3 Compression molding—Compression molding is the most common method of molding thermosetting materials such as sheet molding compound (SMC) and bulk molding compound (BMC). This molding technique involves compressing materials containing a temperature-activated catalyst in a heated matched metal die using a vertical press.

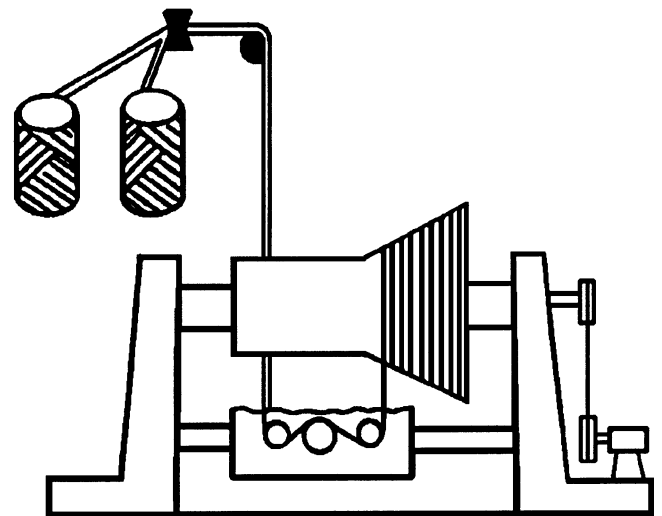


Fig. 4.3—Filament winding process (Mettes 1969).

The molding process begins with the delivery of a high-viscosity uncured composite material to the mold. Mold temperatures typically are in the range of 177 to 204 °C (350 to 400 °F). As the mold closes, composite viscosity is reduced under heat and pressure at approximately 7 MPa (1000 psi). The resin and reinforcements flow to fill the mold cavity.

While the mold remains closed, the thermoset material undergoes a chemical change or cure that permanently hardens it into the shape of the mold cavity. Mold closure times vary from 30 seconds up to several minutes depending on the design and material formulation.

When the mold opens, parts are ready for finishing operations such as deflashing, painting, bonding, and installation of inserts for fasteners. By varying the formulation of the thermoset material and the reinforcements, parts can be molded to meet applications ranging from automotive Class A exterior body panels to structural members such as automobile bumper beams.

4.8.4 Resin transfer molding—In resin transfer molding (RTM) (Fig. 4.4), a closed mold process, reinforcement material is placed between two matching mold surfaces that are then closed and clamped. A low viscosity thermoset

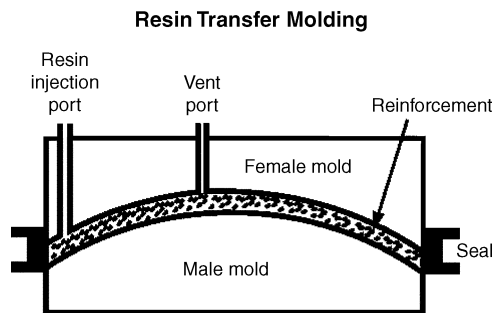


Fig. 4.4—Resin transfer molding.

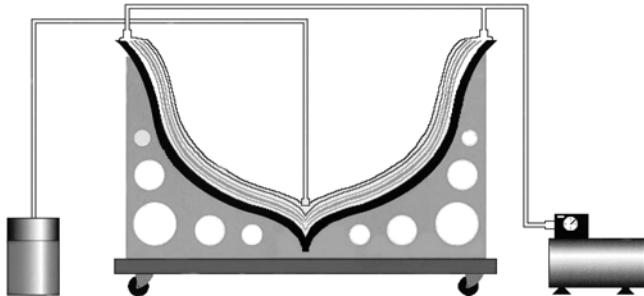


Fig. 4.5—Diagram of VARTM process.

resin is injected under moderate pressure 350 to 690 kPa (50 to 100 psi) into the mold cavity through a port or series of ports within the mold. The resin is injected to fill all voids within the mold and to penetrate all surfaces of the reinforcing materials. The reinforcements may include a variety of fiber types in various forms, such as continuous fibers or mats. The part is typically cured with heat.

RTM is compatible with a variety of resin systems including polyester, vinylester, epoxy, phenolic, modified acrylic, and hybrid resins such as polyester and urethane.

4.8.5 Vacuum-assisted resin transfer molding—Vacuum-assisted resin transfer molding (VARTM) parts are made by placing dry fiber reinforcing fabrics into a mold, applying a vacuum bag to the open surface, and pulling a vacuum, while at the same time infusing a resin to saturate the fibers until the part is fully cured (Fig. 4.5).

This process has been used in many new and large applications ranging from turbine blades to bridge decks. Unique to this process is the manufacturing method that allows the efficient processing of VARTM to produce large structural shapes that are generally void-free. This process has been used to make both thin and very thick laminates. In addition, complex shapes with unique fiber architectures allow the fabrication of large parts that have a high structural performance.

A ribbed distribution layer is placed under the vacuum bag, and the resin flow is initially along the surface of the part before being pulled by the vacuum through the dry fabrics.

4.8.6 Hand lay-up—Hand lay-up is the oldest and simplest method for producing FRP laminates. Capital investment for hand lay-up processes is relatively low. The most expensive piece of equipment is typically a spray gun for resin and gel coat application. Some fabricators pour or brush the resin

into the molds so that a spray gun is not required for this step. There is virtually no limit to the size of the part that can be made. The molds can be made of wood, sheet metal, plaster, or FRP composites.

In the hand lay-up (or wet lay-up) process, highly soluble resin is sprayed, poured, or brushed into a mold. The reinforcement is then wet-out with resin. The reinforcement is placed in the mold. Depending upon the thickness or density of the reinforcement, it may receive additional resin to improve wet-out and allow better drapeability into the mold surface. The reinforcement is then rolled, brushed, or applied using a squeegee to remove entrapped air and to compact it against the mold surface. Curing may be at room temperature or elevated temperatures using roll-in ovens or lamps.

Hand lay-up is also widely applied in the field for strengthening structures with FRP sheets.

4.8.7 Centrifugal casting—Centrifugal casting is suited to the production of hollow parts such as pipes. Fiber reinforcement in the form of fabric is placed inside a mandrel, and the resin is sprayed onto it from inside the mandrel rotating at high speed. The centrifugal force pushes the resin outwards, impregnating the reinforcement while minimizing the void ratio.

CHAPTER 5—PROPERTIES, TEST METHODS, AND NONDESTRUCTIVE EVALUATION

5.1—Introduction

This chapter lists some of the reported test methods that have been used to evaluate various properties of FRP materials used as internal or external reinforcement for reinforced and prestressed concrete. Also included are discussions of typical FRP products and properties used in applications involving concrete, as well as a brief description of nondestructive evaluation techniques for FRP systems. ACI 440.3R should be consulted for information on generally accepted test methods for various properties of FRP reinforcement or strengthening materials. A number of relevant ASTM standards also exist for the determination of physical properties of FRP materials such as specific gravity, coefficient of thermal expansion, and fiber volume fraction. These are not discussed in detail in this document.

5.2—Typical properties of currently available products

Advances in FRP technology, increased use of FRP systems in the construction industry, and steadily decreasing costs of FRP materials have led to the development of a wide range of available FRP products for a variety of specific applications. It is beyond the scope of this document to list all currently available FRP products and systems.

The properties of currently available FRP systems vary significantly depending on their specific formulation, constituents, and manufacturing method. The reader is reminded that the material properties of FRPs are highly directionally dependent, and the properties typically quoted are in the direction of the principal reinforcement. Off-axis properties are typically significantly different than those in the fiber direction. In the fiber direction, the products typically display linear elastic behavior to failure (Fig. 5.1). Common combinations, such as carbon and glass or carbon and aramid

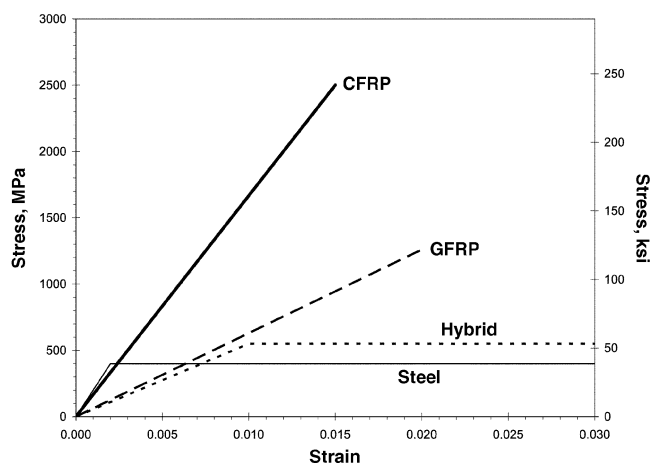


Fig. 5.1—Typical stress-strain curves for FRP products. Based on data from Teng et al. (2002), Tamužs et al. (1996), and Apinis et al. (1998).

display monotonic stress-strain behavior (Fig. 5.1) similar to that of steel (Tamužs et. al. 1996; Apinis et. al. 1998).

Tables 5.1 and 5.2 present overviews of the properties of some typical FRP products for internal reinforcement and external strengthening, respectively, of reinforced concrete structures. Included in the tables is information on FRP bars, rods, sheets, plates, and tapes. The tabulated information is that reported by the manufacturer. In Table 5.2, the material properties are reported using one of two methods specified by ACI 440.3R. Method 1 is based on composite area and uses the measured width and thickness of the specimen to determine the cross-sectional area of the specimen for calculation of the tensile strength and modulus of elasticity. Method 2 is based on equivalent fiber area and uses the equivalent thickness of a fiber layer without resin and the measured width for calculation of the tensile strength and modulus of elasticity. Specific information on the potential applications of each of these systems can be obtained by contacting the FRP manufacturers (also included in the tables). These tables should not be considered as endorsements for a particular FRP product.

TechFab LLC (2006) produces a very light carbon/epoxy grid with strengths ranging from 14 kN/m (1000 lb/ft) to over 220 kN/m (15,000 lb/ft) with grid openings from approximately 12 mm (0.5 in.) square to over 50 mm (2 in.) square. Because of the flexible nature of the textile process used to manufacture grids, grid opening sizes and strengths can be customized to suit the many various concrete product uses.

5.3—Test methods for mechanical properties

The basic mechanical properties of FRP materials can be determined by applying tensile, compressive, and shear loadings. Flexural testing is also used in some cases. Static material properties are usually of primary interest.

5.3.1 Tension test methods—Axial tension testing of high-strength unidirectional composites is often a challenge because load should be transmitted from the testing apparatus to the specimen via shear, and the shear strength of a unidirectional composite is typically much lower than its axial tensile strength. Further, shear gripping will load the

Table 5.1—Selected properties of typical currently available FRP reinforcing products as reported by the manufacturer

Reinforcement type	Designation	Diameter, mm (in.)	Area, mm ² (in. ²)	Tensile strength, MPa (ksi)	Elastic modulus, GPa (ksi)
Deformed steel	No. 3	9.5 (0.375)	71 (0.11)	420* (60)	208 (30,000)
Pultrall Inc. (2005)					
V-ROD CFRP rod	3/8	9.5 (0.375)	71 (0.11)	1596 (230)	120 (17,400)
V-ROD GFRP rod	3/8	9.5 (0.375)	71 (0.11)	852 (123)	43 (6700)
Autocon Composites Inc. (2006)					
NEFMAC GFRP rod	G10	N/A	79 (0.12)	600 (87)	30 (4400)
NEFMAC CFRP rod	C16	N/A	100 (0.16)	1200 (174)	100 (14,500)
Hughes Brothers (2005)					
Aslan 100 GFRP rod	No. 3	9.5 (0.375)	84 (0.13)	760 (110)	41 (5900)
Aslan 200 CFRP rod	No. 3	9.0 (0.360)	65 (0.10)	2068 (300)	124 (18,000)
Mitsubishi (2005)					
LEADLINE™ CFRP rod	Round	12 (0.470)	113 (0.18)	2255 (327)	147 (21,300)
Sika Corp. (2007)					
CarboDur CFRP rod	3/8	9.5 (0.375)	71 (0.11)	2800 (406)	155 (22,500)

*Specified yield strength.

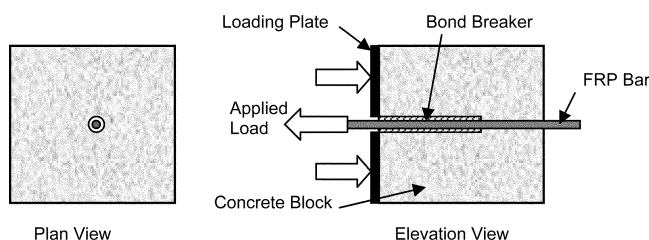
external fibers more than the internal ones causing shear lag and progressive fiber failure. To avoid these problems, end tabs are required when testing flat laminates, as described in detail in ACI 440.3R. Special anchors are required for testing of FRP rods and bars by inserting their ends into steel cylinders that are subsequently filled with either a polymer resin or a cement-based grout (also described in ACI 440.4R). For grid-type FRP reinforcements, linear test specimens can be prepared by cutting away extraneous material in such a way as not to affect the performance of the part to be tested. ASTM D 618 (Porter and Barnes 1991; ACI 440.3R) recommends leaving a minimum 2 mm (0.08 in.) projection of crossbars.

5.3.2 Compression test methods—It has been said that there is no true axial compression test for composites. The mode of failure is buckling, ranging from buckling of the entire specimen cross section or local microbuckling of individual fibers. Thus, the greater resistance to buckling the test fixture provides, the higher the compressive strength values obtained. For flat laminate FRP composites, many axial compression test methods in current use are some variation of the Celanese compression test as in ASTM D 3410. This test uses a thin, straight-sided specimen that looks very much like an axial tension specimen except that the distance between tabs is much smaller. For FRP rods, tests can be carried out according to ASTM D 695. Common problems associated with compression testing of FRPs are discussed in detail by Harper et al. (1995).

5.3.3 Shear test methods—Several ASTM methods are available for determining the shear properties of composite

Table 5.2—Selected properties of typical currently available FRP strengthening systems as reported by the manufacturer

FRP system	Fiber type	Weight, g/m ² (lb/ft ²)	Design thickness, mm (in.)	Tensile strength, MPa (ksi)	Tensile elastic modulus, GPa (ksi)	ACI 440.3R test reporting method
Fyfe Co. LLC (2005)						
Tyfo SEH51 sheet	Glass	915 (0.19)	1.3 (0.052)	575 (83.4)	26.1 (3785)	Method 1
Tyfo SCH41 sheet	Carbon	644 (0.14)	1.0 (0.040)	985 (143)	95.8 (13,900)	Method 1
Sika Corp. (2007)						
SikaWrap Hex 100G sheet	Glass	913 (0.19)	1.0 (0.040)	531 (77)	23.6 (3430)	Method 1
SikaWrap Hex 103C sheet	Carbon	618 (0.13)	1.0 (0.040)	717 (104)	65.1 (9450)	Method 1
CarboDur S plate	Carbon	1800 (0.37)	1.2 to 1.4 (0.048 to 0.055)	2800 (406)	165 (23,900)	Method 1
CarboDur M plate	Carbon	1900 (0.39)	1.2 (0.048)	2400 (348)	210 (30,500)	Method 1
CarboDur H plate	Carbon	1900 (0.39)	1.2 (0.048)	1300 (189)	300 (43,500)	Method 1
BASF (2006)						
MBrace EG 900 sheet	Glass	900 (0.19)	0.37 (0.015)	1517 (220)	72.4 (10,500)	Method 2
MBrace AK 60 sheet	Aramid	600 (0.12)	0.28 (0.011)	2000 (290)	120 (17,400)	Method 2
MBrace CF 130	Carbon	300 (0.062)	0.17 (0.007)	3800 (550)	227 (33,000)	Method 2
MBrace CF 160	Carbon	600 (0.124)	0.33 (0.013)	3800 (550)	227 (33,000)	Method 2
S&P 100/1.4	Carbon	—	1.4 (0.055)	2700 (390)	159 (23,000)	Method 1
Hughes Brothers (2005)						
Aslan 400 plate	Carbon	—	1.4 (0.055)	2400 (350)	131 (19,000)	Method 1
Aslan 500 tape	Carbon	—	2.0 (0.079)	2068 (300)	124 (18,000)	Method 1
Aslan 500 tape	Carbon	—	4.5 (0.177)	1965 (285)	124 (18,000)	Method 1

**Fig. 5.2—Pullout test specimen.**

materials. For flat FRP laminates, direct in-plane shear test methods include the V-notched beam test (ASTM D 5379/D 5379M), the two-rail and three-rail shear tests (ASTM D 4255/D 4255M), and the 45-degree laminate tensile shear test (ASTM D 3518/D 3518M). For FRP rods, shear test devices have been constructed so that a rod-shaped test specimen is sheared on two planes as in ACI 440.3R.

5.3.4 Flexural test methods—Flexural tests are relatively easy to perform; thus, they are fairly popular. The difficulty is that flexural testing does not directly provide information on basic material properties. The stress state on the loaded side of the specimen is compression, on the other side is tension, and at the neutral axis is pure shear. Usually, the shear component is minimized by making the test specimen long relative to its thickness (a ratio of approximately 32:1 is commonly used) (Adams 1992). Although flexural tests do not directly provide basic design data, their use is often justified on the basis that the material is subjected to flexural loading in service.

For testing FRP rods in flexure, ASTM D 4476 describes a standard test method for flexural properties of fiber-reinforced pultruded rods. This method has been used for FRP reinforcing bars with some modifications, as in Wang et

al. (2002). FRP laminates can also be tested in flexure in three- or four-point bending as described in Adams (1992).

5.3.5 Bond test methods for internal FRP reinforcement—Bond characteristics influence the mechanism of load transfer between FRP reinforcement and concrete, and therefore control the concrete crack spacing, crack width, required concrete cover to the reinforcement, and the reinforcement development length. The behavior of reinforced concrete structures thus depends on the integrity of the bond. Many test methods have been developed and carried out to determine the bond strength of FRP bars and rods in concrete.

5.3.5.1 Pullout tests—The concentric pullout test is a popular test method adopted by researchers for comparative bond assessment for FRP reinforcement. In this method, an FRP bar specimen is embedded in a concrete block, with the embedded length of the FRP rod typically being five times the rod diameter, and the bar is pulled in tension as shown in Fig. 5.2. The average bond stress and bond stress versus slip at the loaded end can thus be obtained. The pullout test is used for comparative tests, but is not considered a valid test to determine the development that is needed for the design embedment length for flexural beam design. Additional information and specimen fabrication details are given in ACI 440.3R.

The ring test (Tepfers and Olsson 1992) is carried out as a pullout test, where the specimen is a concrete cylinder with the studied reinforcing bar embedded along the center axis of the cylinder. This test allows for determination of the splitting tendency of the bar in all stages of loading up to bond failure by determination of the angle between bond forces and the bar axis. The bond length corresponds to the height of the cylinder, which is chosen to be three diameters of the bar. The bond stress along the bond length becomes practically

evenly distributed. The cylinder is cast in a thin steel tube (the ring), which becomes a part of the test specimen.

5.3.5.2 Flexural bond tests—Pullout tests, while extremely useful in many circumstances, are not representative of stress field conditions in an FRP reinforced concrete beam. Flexural beam tests, such as the beam-end test, solve some of the stress field discrepancies that are present in pullout tests, and thus offer the advantages of representing the beam stress field more closely.

The beam-end test method is described in detail for steel reinforcing bars in ASTM A 944, and is specified as a test for the relative bond strength of reinforcing bars in concrete. In this method, a bar is embedded in a concrete block, and a tensile load is introduced into the bar using a special test setup as shown schematically in Fig. 5.3. This test setup has the advantages of simulating the stress field condition in a reinforced concrete member in flexure.

Various additional flexural test methods exist and have been used to study the bond behavior of FRP bars embedded in concrete. Several of these are shown schematically in Fig. 5.4, including (a) the simple beam test (Larralde et al. 1994); (b) the notched beam test (Daniali 1992); (c) the hinged beam test (Magnusson 1997); (d) the spliced beam test (Tighiouart et al. 1999); (e) the cantilever beam test (Fish 1992); and (f) the trussed beam test. If these tests are done upside down, then the effects of self-weight are practically eliminated.

5.3.5.3 Direct axial tension test—Two types of direct axial tension tests have been used with a concrete specimen having a continuous bar embedded in its center (Hasau et al. 1990). In the first type, load is directly applied to the bar protruding from the concrete ends. In the second type, load is applied to the concrete. A concrete specimen is cast with an FRP bar embedded at its center and a notch at midlength to allow for the formation of the first crack at a preset location (Fig. 5.5). Bond strength is studied indirectly through the observation of crack spacing and width in the concrete block.

5.3.6 Bond test methods for externally bonded FRP reinforcement—Flexural and shear strengthening techniques of bonding FRP plates or sheets to reinforced concrete elements is now a method of choice for structural rehabilitation. Failure of these bonded systems before achieving their FRP capacity, however, can result from a number of mechanisms collectively referred to as delamination or debonding. Teng et al. (2002) provide a thorough review of bond-related failure mechanisms and the present state of the art for modeling these. The behavior of the FRP-adhesive-concrete interface region, which should include the region of cover concrete adjacent to the interface, is collectively interpreted as bond behavior. Transfer of stresses through the cover concrete, for instance, can lead to failures through the cover concrete that are nonetheless affected by the properties of the bonding adhesive. Complicating interface region behavior is the mixed mode behavior of the debonding process and the heterogeneous material properties in this region.

Bond behavior is a critical parameter in strengthening a concrete structure with externally bonded FRP, and numerous test methods have been presented. Test methods

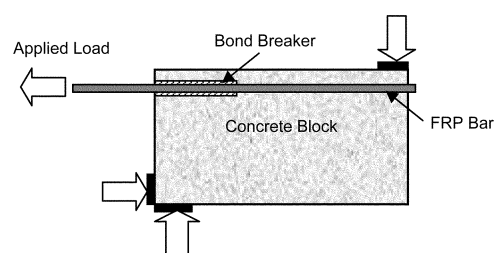


Fig. 5.3—Beam-end test method.

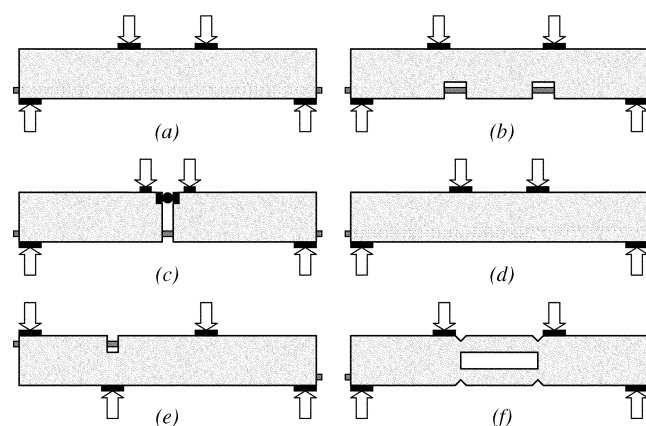


Fig. 5.4—Additional flexural bond test method configurations: (a) simple beam test; (b) notched beam test; (c) hinged beam test; (d) spliced beam test; (e) cantilever beam test; and (f) trussed beam test.

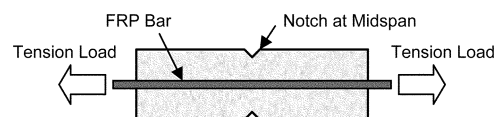


Fig. 5.5—Direct axial tension test.

can be broadly classified into three types: shear bond, tension, or mixed mode. Recent research has focused largely on mixed mode bond test methods in an effort to accurately characterize the FRP-concrete bond, which in practice experiences a combination of shear and normal stresses. A summary of bond test methods for externally-bonded FRP systems is provided by Ueda and Dai (2005).

5.3.6.1 Shear bond type tests—Because externally bonded FRP materials are most often used in configurations where stress transfer across the interface is dominated by shear (Mode II) stresses, various shear bond test methods are available in the literature. The various methods can be used to study the local interfacial shear bond behaviors by studying the bond strain distribution (Ueda and Dai 2005). Schematics showing the configurations of various types of shear bond tests are given in Fig. 5.6, including: (a) the single-lap shear bond test (Bizindavyi and Neale 1999; Chajes et al. 1996); (b) the push-apart; (c) the pull-apart double-lap shear bond test (Horiguchi and Saeki 1997; Brosens and Gemert 1997); (d) the bending-type shear bond test (Horiguchi and Saeki 1997); and (e) the tension-type shear bond test (Fukuzawa et al. 1997).

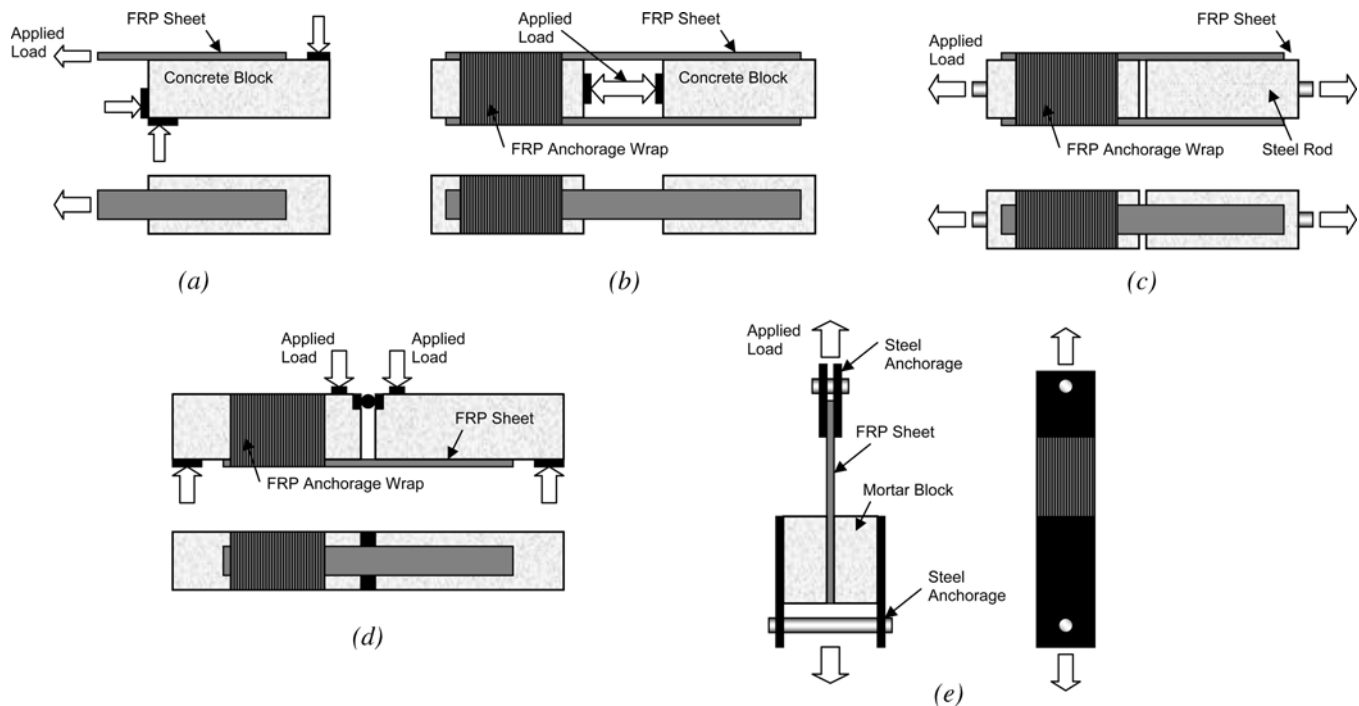


Fig. 5.6—Various shear-bond test method configurations: (a) single-lap shear bond test; (b) push-apart; (c) pull-apart double-lap shear bond test; (d) bending-type shear bond test; and (e) inserted-type shear bond test.

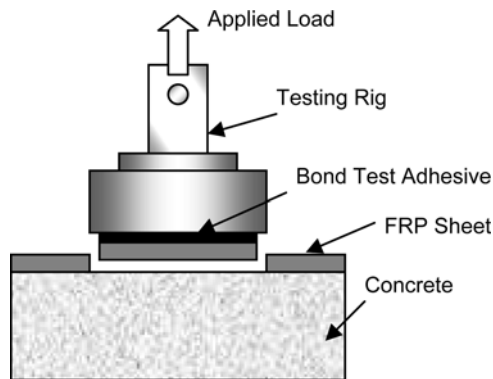


Fig. 5.7—Direct tension pulloff test method (Xu et al. 2002).

5.3.6.2 Tension-type bond tests—At least three test methods are available in the literature to evaluate the strength of the FRP-concrete bond subject to pure normal (Mode I) stresses. Figure 5.7 shows a schematic of the direct tension pulloff test method (Horiguchi and Saeki 1997), which is also presented in detail in ACI 440.3R. In this method, a special testing rig is used to pull a circular disc of bonded FRP away from the surface of the concrete in direct tension. The circular area is typically created using a core drill, and an adhesion disc is used, with an appropriate adhesive, to apply an increasing tensile load to the disc until bond failure occurs. For well-bonded FRP materials, the failure surface is in (and thus limited by) the substrate concrete. An alternate shear test arrangement uses a similar test setup, but twists the adhesion disc off of the substrate; this torsional pulloff test is not included in ACI 440.3R. Other tension-type bond test methods not discussed in detail herein, or in

ACI 440.3R, include the three-point bending pulloff test (Xu et al. 2002) and the wedge splitting test (Dai et al. 2003).

5.3.6.3 Mixed-mode bond tests—Mixed mode bond test methods are more representative of the interface bond behavior for concrete structures retrofitted with FRP sheets (Ueda and Dai 2005). Mixed-mode testing methods include the variable angle peel test (Karbhari and Engineer 1996), the beam-type and slab-type dowel tests (Ueda and Dai 2005), the single contoured cantilever beam test (Boyajian et al. 2002), the double cantilever beam test (Kim et al. 2002; Wan et al. 2002), and the modified double cantilever beam test (Wan et al. 2004). These bond test methods are considerably more complex and difficult to perform than those discussed previously, and they are typically used to study the fracture behavior of FRP-concrete interfaces. The reader is encouraged to consult the listed references for more information on mixed-mode bond testing.

Test methods are also available to study tension stiffening and secondary crack formation in applications of externally bonded FRP materials (Nanni et al. 1997).

5.3.6.4 Bond overlap tests—Test methods are available to evaluate the strength of FRP to FRP bond overlaps or splices (ACI 440.3R), and can be conducted in single-lap or double-lap configurations.

5.3.7 Concrete surface preparation for bond testing—The effects of surface preparation of the concrete on the bond between concrete and FRP are very important, and have been studied by several authors. Chajes et al. (1996) found that mechanical abrasion increased the interfacial bond strength. Shen et al. (2002) also studied the effect of surface roughness on the bond performance between FRP and concrete. Surface preparation was by rotary water jetting to

produce different roughness grades, which were classified using a laser profilometer. Specimens were subjected to flexural bond testing and direct tension and torsional pulloff tests. They concluded that moderate surface roughness was necessary for adequate bond properties to be developed and that different CFRP systems tested had different optimal surface roughnesses.

5.4—Durability testing methods

The reduction of strength and the subsequent failure of materials subjected to cyclic or sustained loading combined with environmental effects have emerged as some of the most fundamental problems of engineering materials. Because composite materials are regarded as having good long-term performance, they are used in applications where the degradation of strength and life expectancy by fatigue, creep, and environmental effects would otherwise be a concern. Thus, testing methods to evaluate the susceptibility of FRP materials to these conditions is required.

5.4.1 Tensile fatigue testing methods—Fatigue tests on FRPs can be carried out using several specimen configurations, including direct tests on rods using various kinds of gripping mechanisms (ACI 440.3R), and tests on concrete beam specimens reinforced with FRP reinforcements. In the case of performing direct tests on rods, problems are often encountered in gripping the rod, because some grips perform poorly when used for cyclic tests, and failure may occur in the anchoring zone. When performing fatigue tests on concrete beam specimens, the rod is continuously in contact with concrete, which may affect the fatigue behavior of the FRP rod through fretting or friction heating (Adimi et al. 2000).

5.4.1.1 Concrete prism tensile fatigue test method—Because of the relatively low modulus of elasticity of FRP reinforcement combined with its high strength, it is very difficult to develop high levels of stress in FRP rods used as tensile reinforcement in concrete beams. A reinforced concrete prism specimen for tensile fatigue testing has been developed (Adimi et al. 2000). Figure 5.8 shows the details of the specimen, where top and bottom blocks of concrete serve as anchors for the FRP rod while the middle block provides the concrete environment for the FRP rod at the part where the failure is expected. The middle block is separated from the end blocks by a bond breaker during casting. This specimen is loaded in tension by collars at the shoulders of the end blocks, and can be tested under any stress amplitude and with the maximum stress almost equal to the tensile strength of the FRP rod. To avoid stress concentrations near the rod and splitting of concrete end blocks during the test, a bond breaker is included, as shown, of approximately five bar diameters, and the end blocks are precompressed near the constriction with a steel compression ring (not shown in the figure).

5.4.1.2 Direct fatigue tests—Fatigue tests can also be conducted directly on FRP specimens. These specimens can be rods, flat laminates, or sections of FRP grids. A suggested test method for tensile fatigue of FRP bars is discussed in detail in ACI 440.3R.

5.4.2 Creep test methods—FRP materials may fail by creep at strengths below the maximum static strength when

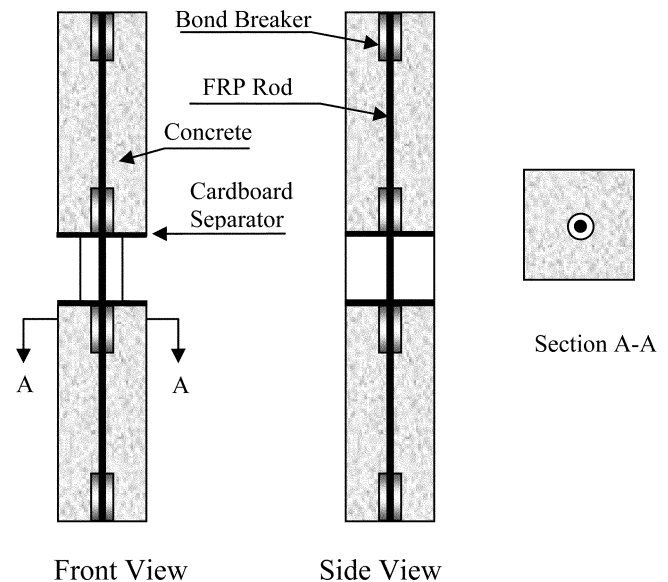


Fig. 5.8—Schematic view of test specimen (adapted from Adimi et al. 2000).

subjected to a significant sustained stress for long periods. This creep-rupture strength varies according to the type of FRP, and so the creep-rupture strength should be evaluated when determining the allowable level of sustained tension in FRP used as reinforcement. A suggested test method for creep testing of FRP bars is presented in ACI 440.3R. Traditional methods of performing creep tests, including direct gravity loading, compressed spring loading, or gravity loading using a lever arm (so called creep frame) to permit greater loads, have all been adapted for testing FRP materials.

5.5—Nondestructive inspection techniques for FRP materials

Nondestructive inspection is needed to assure the integrity of FRP materials and FRP-strengthened structures over their service life (U.S. Department of Defense 2002). Structures made of traditional materials are all susceptible to damage and environmental degradation in service. As a result, they are periodically inspected. Although decades of experience have shown composites to be reliable structural materials, they are also susceptible to damage and possible environmental degradation. Consequently, structures employing composite reinforcement should also be subjected to periodic nondestructive inspection in service. Test methods should be designed to evaluate a material system economically and quickly. This section discusses quality assurance and nondestructive testing of composites.

5.5.1 Nondestructive inspection—Nondestructive inspection (NDI) tests are used to find flaws and damage such as resin starvation, resin richness, wrinkles, ply bridging, discoloration due to overheating or lightning strike, impact damage by any cause, foreign matter, blisters, and disbanding. Some of the discrepancies are readily discernible by a visual inspection (Crane 2000; Pethrick 2000; U.S. Department of Defense 2002).

Composite NDI techniques commonly used in production of composites include visual, ultrasonic, thermography, laser

shearography, tap, and x-ray (Crane 2000; U.S. Department of Defense 2002). Advantages of thermography and shearography are that they are large area, noncontact methods that create permanent records. This is useful for monitoring possible damage growth over the life of a structure.

Despite the recognized importance of NDI to ensure reliability of composite structures, there has not been a great deal of research on NDI methods for FRP-strengthened concrete structures (Newman and Zweben 2002a). This is a significant issue considering the long service life of civil engineering structures.

5.5.1.1 Visual inspection—NDI by visual means is by far the oldest and most economical NDI method (U.S. Department of Defense 2002). Consequently, visual inspection is performed routinely as a means of quality control and damage assessment.

Once detected, the affected area becomes a candidate for closer inspection. Flashlights, magnifying glasses, mirrors, and borescopes are employed as aids in the visual inspection of composites. Visual inspection cannot find internal flaws in the composite, such as delaminations, disbonds, or matrix crazing. In addition, impact damage is frequently not visible to the naked eye, and tight surface cracks and edge delaminations may not be detected visually. Therefore, visual inspection techniques need to be supplemented by other methods of nondestructive testing.

5.5.1.2 Tap testing—Sometimes referred to as audio, sonic, or coin tap, this technique makes use of frequencies in the audible range (10 to 20 Hz) to detect damage (U.S. Department of Defense 2002). Although it can be an accurate method in the hands of skilled and experienced personnel, tap testing is highly subjective, time consuming, and does not create a permanent test record. Despite these limitations, tap testing is a common technique used for the detection of delamination or debonding. The method is performed by tapping the inspection area with a solid round disk or lightweight hammer and listening to the audible response of the structure. A clear, sharp, ringing sound is indicative of a well-bonded solid structure, while a dull sound indicates a damaged area.

5.5.1.3 Ultrasonics—Ultrasonic inspection has proven to be a useful tool for the detection of internal delaminations, voids, or inconsistencies in composite components not otherwise discernible using visual or tap testing (Tittmann and Crane 2000; U.S. Department of Defense 2002).

A high-frequency sound wave is introduced into the structure, and may be directed to travel normally to its surface, along the surface, or at some predefined angle to the surface. Different directions are often used because flaws may not be noticeable from only one direction.

When an ultrasonic wave strikes an interrupting object, part of the wave or energy is transmitted through the object, and the rest of the energy is reflected back to the surface. The disrupted or diminished sonic energy is then picked up by a receiving transducer and converted into a display on an oscilloscope or a chart recorder. The display allows the operator to comparatively evaluate the discrepant indications against those areas known to be good.

5.5.1.4 Radiography—Radiography, or x-ray as it is often referred to, allows a view into the interior of the part (Crane 2000; U.S. Department of Defense 2002) by passing x-rays through the part while recording the absorption of the rays onto an x-ray sensitive film. Because the method records changes in total density through its thickness, it is not a preferred method for detecting defects, such as delaminations, that are in a plane normal to the ray direction.

Although radiography may be useful in a factory environment, it is expensive and not practical for field application. Furthermore, most composites are nearly transparent to x-rays, so low-energy rays should be used. Opaque penetrant can be used to enhance the visibility of surface breaking defects, although this is generally not available for in-service inspections.

Operators should be protected by sufficient lead shields because the possibility of exposure exists either from the x-ray tube or from scattered radiation. Maintaining a distance from the x-ray source is essential.

5.5.1.5 Shearography—Shearography is an optical NDI technique that detects defects by measuring variations in reflected light (speckle pattern) from the surface of the object when stressed (Krishnaswamy 2000; U.S. Department of Defense 2002; Newman and Zweben 2002a,b). Using a laser light source, an original image of the illuminated surface is recorded via a video image. The part is subsequently stressed by heating, mechanical loading, changes in pressure, or acoustic vibrations during which a second video image is made. Changes in the surface contour caused by debonding or delaminations become visible on the video display. Shearography is being used in production environments for rapid inspection of bonded composite structures.

5.5.1.6 Thermography—Thermal inspection includes all methods in which heat-sensing devices are used to measure temperature variations (Thomas 2000; U.S. Department of Defense 2002; Newman and Zweben 2002a,b). The basic principle of thermal inspection consists of measuring or mapping surface temperatures when heat flows from, to, or through a test object.

All thermographic techniques rely on differentials in thermal conductivity between normal, defect-free areas and those having a defect. Normally, a heat source is used to elevate the temperature of the specimen being examined while the surface heating effects are observed. Because defect-free areas conduct heat more efficiently than areas with defects, the amount of heat that is absorbed or reflected indicates the quality of the bond. The type of defects that affect the thermal properties include debonding, cracks, impact damage, panel thinning, and water ingress. Thermal methods are most effective for thin laminates or for defects near the surface.

CHAPTER 6—PERFORMANCE OF CONCRETE MEMBERS WITH INTERNAL FRP REINFORCEMENT

This chapter summarizes research findings regarding the performance of FRP as the main structural reinforcement for non-prestressed concrete members. FRP internal reinforcement is widely used in commercial applications and the development of design guidelines for internal FRP reinforcement.

ment dates back to the pioneering work of Nanni (1993). Additional work by others facilitated and contributed to the design guidelines in their current format (Jaeger et al. 1997; GangaRao and Vijay 1997; Theriault and Benmokrane 1998). The widespread implementation of FRP as reinforcement for concrete structural members requires: 1) a comprehensive understanding of how these two materials behave together as a structural system; and 2) analytical techniques that reliably predict the composite behavior. In this regard, three important physical characteristics of FRP materials should be considered: 1) high tensile strength; 2) low modulus of elasticity; and 3) linear-elastic brittle behavior to failure. Substitution of FRP for steel on an equal area basis typically results in significantly higher deflections with wider crack widths and greater flexural strength. As a consequence, serviceability criteria are often governing parameters in design considerations.

6.1—Strength

Flexural failure of concrete members reinforced with currently available FRP materials is governed by either concrete crushing or FRP tensile rupture. Such failure modes are brittle and differ from the behavior of concrete beams under-reinforced with steel. In addition, the shear capacity of concrete beams is reduced as a result of increased crack width and reduced size of compressive stress blocks.

6.1.1 Flexural strength—Nawy and Neuwerth (1971) monotonically tested 20 simply supported rectangular beams reinforced with GFRP and steel reinforcing bars. The beams failed by compression of the concrete; hence, they did not develop the full capacity of the FRP bars. The authors suggested that because the modulus of FRP bars was only slightly higher than that of concrete, limited tensile stresses could be transmitted from the concrete to the FRP reinforcement. In a second study, Nawy and Neuwerth (1977) found that the behavior of the beams with respect to cracking, ultimate load, and deflection could be predicted with the same degree of accuracy as for steel reinforced concrete beams. Satoh et al. (1991) reached similar conclusions.

Faza and GangaRao (1992) investigated the flexural performance of simply supported rectangular concrete beams reinforced with GFRP reinforcing bars. They concluded that, to take advantage of the high FRP reinforcing bar ultimate strength, use of high-strength concrete instead of normal-strength concrete (69 versus 27.6 MPa [10 versus 4 ksi]) is essential. The ultimate moment capacity of high-strength concrete beams increased by 90% when an equal area of FRP reinforcing bars of ultimate tensile strength of 896 MPa (130 ksi) was used instead of mild steel reinforcing bars. Sand-coated FRP reinforcing bars, in addition to high-strength concrete, were found to increase the cracking moment of the beams and to reduce the crack widths in addition to eliminating the sudden propagation of cracks toward the compression zone.

Bank and Xi (1992) tested nine simply supported slabs having shear-span-to-effective-depth ratios of approximately three and reinforced with a variety of molded and pultruded GFRP gratings. Following initial cracking, flexural cracks developed in the constant moment region at regular

spacing of approximately 76 mm (3 in.). With increasing load, diagonal tension shear cracking developed in the shear span. Flexural compression failure occurred in three of the first six slabs, and the remaining slabs failed in shear. The slabs that failed in compression had the lowest concrete strength. In several of the shear failures, the concrete below the reinforcement in the shear span was completely separated from the slab. In all slabs, the experimental shear force V_{exp} was significantly larger than V_c as predicted by ACI 318.

Nanni et al. (1992) tested five concrete beams reinforced with hybrid reinforcing bars, steel deformed bars, and FRP reinforcing bars. Load-deflection behavior for the different reinforcing bar types was characterized as follows: 1) for steel reinforcing bars, a typical three-stage behavior of an under-reinforced concrete beam consisting of uncracked-section, cracked-section linear elastic to yield, and post-yield of reinforcement; 2) for FRP reinforcing bars, a two-stage behavior consisting of uncracked section behavior followed by cracked-section linear-elastic behavior to failure; and 3) for hybrid reinforcing bars, a three-stage behavior typical of under-reinforced steel beam characterized by an uncracked section and linear-elastic response followed by steel core yielding before ultimate failure. Test results showed that, relative to ultimate flexural capacity, coating the FRP and hybrid reinforcing bars with sand increased flexural capacity by approximately 25%. Smaller crack widths and higher postcrack flexural rigidity were also reported for the sand-coated reinforcing bars as compared with the corresponding uncoated reinforcing bars.

Matthys and Taerwe (2000) carried out four-point bending tests on eight reinforced concrete slabs. The materials used to reinforce the slabs were steel, carbon, and hybrid carbon-glass NEFMAC grids and CFRP bars. The authors found that the design of concrete structures with FRP reinforcement was mainly governed by serviceability criteria. In general, crack control was less restrictive than deflection control. A deformability index was defined as the ratio of the deflection at ultimate load to deflection at service load. For the FRP-reinforced slabs of this study, the deformability index was between 10 and 110% higher than the deformability index obtained for steel-reinforced slabs. The margin between the ultimate load and the service load of the FRP-reinforced slabs was on the order of 2.5 to 4.5 times higher than for steel-reinforced structures.

Nanni and Faza (2002) outlined design and construction using FRP bars with an objective to provide a meaningful overview of the design protocol for FRP-reinforced concrete members. Thiagarajan (2003) presented an analytical and experimental study on the flexural behavior of concrete beams reinforced with sand-coated CFRP rods and found that the analytical capacities, predicted using equilibrium equations; strain compatibility condition; and finding the concrete compressive forces by integrating Hognestad's equations, were within 8% of the experimental capacities.

6.1.2 Beam shear—Larralde (1992) tested a series of eight FRP-grating/concrete composite slabs. The shear span-depth ratio and concrete thickness was varied in

an attempt to force different types of failures. Test results showed that, for samples with a shear span-depth ratio of 7.7 or greater, failure occurred by crushing of the concrete. For these samples, the calculated flexural capacity was very close to the test results. For shear span-depth ratios of 5 or less, failure occurred as a result of diagonal tension cracking.

Shehata (1999) investigated the effect of bend radius, the crack angle, the stirrup anchorage, the stirrup spacing, and the material type of flexural reinforcement in tests on 52 panel specimens. The following limitations were proposed for detailing FRP stirrups to achieve a capacity of at least 50% of the guaranteed strength parallel to the fibers: 1) the bend radius should not be less than 50 mm (2 in.) or four times the effective bar diameter, whichever is greater; and 2) the tail length should not be less than 70 mm (2.75 in.), or six times the effective bar diameter, whichever is greater. Beams reinforced with CFRP strands for flexure showed less concrete contribution to shear strength than did beams reinforced with steel strands. This observation was attributed to the wide cracks, the small depth of the compression zone, and poor dowel action associated with the use of FRP as longitudinal reinforcement. Beams with GFRP stirrups showed better performance than those with CFRP stirrups.

Razaqpur and Mostofinejad (1999) tested four continuous beams that were reinforced with FRP grids as shear reinforcement. The beams did not collapse, and retained nearly 80% of their strength when they reached their load capacity in the negative moment regions. CFRP stirrups experienced strains of 4000 $\mu\epsilon$ without rupture, which was well above the limit of 2000 $\mu\epsilon$ set by the CSA S6. The authors observed the same tendency in the behavior of beams reinforced with CFRP stirrups and beams reinforced with steel stirrups. The use of CFRP for longitudinal reinforcement reduced the shear strength of the beams due to a lower contribution of aggregate interlock to shear resistance. The bars in dowel action carried low shear force due to the relatively poor strength and stiffness of FRP bars in the transverse direction. After failure, the concrete was removed from some of the beams to inspect the CFRP grid stirrups. Researchers noticed that, even in the most distressed parts of the beam, no CFRP stirrup had ruptured.

Deitz et al. (1999) tested 12 concrete deck panels reinforced with three reinforcing schemes. One scheme used GFRP reinforcement at the top and bottom of the deck. Another scheme used all epoxy-coated steel reinforcement, and the third scheme used GFRP bars at the top and steel at the bottom. Two modes of failure were observed: the specimens reinforced with steel failed in flexure, while the specimens with the other two reinforcement schemes failed in diagonal tension. The slabs with GFRP failed in diagonal tension because the lower modulus of the GFRP reinforcement compared with steel allowed wider diagonal cracks leading to shear failure before flexural failure. The diagonal tension modes provided adequate warning of failure because large crack widths and displacements developed.

In 2006, ACI 440.1R adopted the beam shear model of Tureyen and Frosch (2003) in which the concrete shear capacity V_c of flexural members using FRP bars as main reinforcement is based on the depth of the elastic cracked

section neutral axis. The formulation is independent of reinforcing bar material properties but accounts for the axial stiffness of the FRP reinforcement indirectly through the elastic neutral axis depth. This method has shown good agreement with test data from a variety of bar stiffnesses and concrete strengths (Tureyen and Frosch 2003). Additional testing by El-Sayed et al. (2005, 2006) found that the method proposed by Tureyen and Frosch (2003) gave reasonably conservative results.

6.1.3 Punching shear—El-Ghandour et al. (1999) carried out tests on flat slabs reinforced with FRP bars. The authors found problems of bond slip and crack localization over the main flexural bars. As a result, the slabs failed at loads lower than their expected flexural and punching shear capacities. According to the authors' observations, the ACI 318-95 (ACI Committee 318 1995) equation for punching shear capacity ignored the influence of tension flexural reinforcement when calculating the concrete shear resistance, which was heavily dependent on the concrete strength. The authors estimated that the ACI equation for punching shear was not conservative, and proposed an alternative equation.

Matthys and Taerwe (2000) conducted tests on 17 FRP circular reinforced concrete simply supported slabs reinforced with FRP grids. The authors found that most slabs had a punching shear failure mode. The slabs with FRP reinforcement with a similar strength as the reference steel reinforced slabs required a lower load to produce cracking and had lower postcracking stiffness than the reference slabs. Evaluation of their test results showed that the punching shear design provisions in the European, Japanese, and ACI 318 codes need to be modified to accurately predict the punching capacity of slabs with FRP reinforcement. The computed punching failure load was lower than the measured failure load for slabs reinforced with FRP bars with a low modulus. The authors proposed to modify the value in the punching shear capacity code equations that account for the reinforcement ratio effect with the factor E_{frp}/E_s .

Ospina et al. (2003) tested four interior column two-way slab specimens subjected to uniform gravity loading, two of which were reinforced with GFRP bars and one with a GFRP grid. Results show that the axial stiffness of the FRP reinforcement, as well as the concrete strength f'_c , significantly affect the concentric punching shear response of FRP-reinforced slabs. Punching shear failure in slabs reinforced with FRP bars was sudden and brittle; however, two-way slabs reinforced with FRP grids exhibited a much more ductile failure (Bank and Xi 1992; Jacobson et al. 2006; Ospina et al. 2003). El-Gamal et al. (2005) tested six full-scale bridge deck slabs reinforced with GFRP, CFRP, or steel bars. They found little to no correlation between reinforcement ratio and punching shear capacity for the GFRP and CFRP reinforced slabs.

Ospina (2005) performed a statistical evaluation of available punching shear test results from slabs with either FRP reinforcement or steel and concluded that the one-way shear design model of Tureyen and Frosch (2003) can be modified to predict the punching capacity of two-way slabs with FRP reinforcement. This modified equation forms the basis of the punching shear equation adopted by ACI 440.1R.

6.2—Serviceability

Serviceability of FRP-reinforced flexural members is described in terms of deflection and crack width limitations.

6.2.1 Deflection considerations—Nawy and Neuwerth (1971) determined that deflection of FRP-beams at ultimate load was approximately three times greater than that of the corresponding steel-reinforced beams. Larralde et al. (1988) found that theoretical deflection predictions as used for steel-reinforced concrete beams underestimated test results for loads above 50% of ultimate; deflection values were fairly well predicted at load levels up to approximately 30% of ultimate. The study suggested a procedure in which values of curvature calculated at different sections of the beam should be used to obtain a better estimate of deflection values.

Faza and GangaRao (1992) found predicted deflections of FRP-reinforced beams to be underestimated using the effective moment of inertia I_e as prescribed by ACI 318-89 (ACI Committee 318 1989). The authors introduced a new method of calculating the effective moment of inertia of concrete beams reinforced with FRP reinforcement. The new expression was based on the assumption that the concrete section between the point loads was fully cracked, while the end sections were assumed to be partially cracked.

Benmokrane et al. (1994) compared the flexural behavior of concrete beams reinforced with GFRP bars to conventionally reinforced ones. At 25% of M_u , the crack pattern and spacing in FRP-reinforced beams were similar to those in conventional steel-reinforced beams. At service (50% of M_u) and ultimate (90% of M_u) loads, there were more and wider cracks in the FRP-reinforced beams than in the steel-reinforced beams. At service and ultimate loads, FRP-reinforced beams experienced maximum deflections three times higher than steel-reinforced beams. Thus, predicted deflections using the Branson expression for effective moment of inertia I_e , as prescribed in ACI 318-89 (ACI Committee 318 1989), resulted in underestimated deflections. This was attributed to the width, depth, and spacing of the cracks.

A study by Engel et al. (1999) proposed modified ACI 318 equations to compute the deflection of concrete beams reinforced with FRP grids. The researchers tested beams with different grid configurations. Grids with fibers that crossed the grid intersections and grids with fibers turned at a right angle to the grid intersections were tested. For all grid joint designs, the modified ACI code design predictions were in good agreement with the measured deflection response for the midpoint deflection of FRP grid-reinforced concrete beams. The stiffness of the grids can be calculated from a grid section in a stand-alone tension test.

Joh et al. (1999) tested 17 beams reinforced with nine types of FRP bars. The beams were reinforced with GFRP, AFRP, CFRP, and steel. The average ratio of long-term deflection, measured at 9.5 months, to short-term deflection was 0.34 for beams with GFRP bars, 0.65 for beams with AFRP bars, and 0.56 for beams with CFRP bars. The ratio for the steel-reinforced control beam was 0.60. Although the AFRP and CFRP reinforced beams had ratios similar to the control beam, the GFRP-reinforced beams' ratio averaged only 56% of the control beam ratio. This finding is in agreement

with Brown (1997), who performed a parametric study of GFRP-reinforced rectangular beams and concluded that the ratio of long-term deflection to short-term deflection was, on average, 55% of the same ratio for steel-reinforced beams.

Toutanji and Saafi (1999) tested concrete beams reinforced with GFRP bars. The authors found that the deflections predicted using the ACI 318 equation were lower than the measured deflections.

A method for determining deflections of FRP-reinforced concrete beams was proposed by Razaqpur et al. (2000), assuming that the moment-curvature relation of FRP sections was linear in the precracked and postcracked stages, and that the tension-stiffening effect could be ignored. The predicted deflections agreed within 5%, with deflections obtained in a number of flexure tests on reinforced concrete beams and slabs measured at service load (50 to 60% of ultimate). The method presented did not account for shear deformations.

Rasheed et al. (2004) developed closed-form expressions for deflection calculation by exactly integrating the bilinear moment-curvature response along the beam span. The results were in excellent agreement with experiments. A modified version of ACI 318 was proposed.

Kassem et al. (2002) tested 12 full-scale concrete beams reinforced with carbon FRP bars. The test parameters included the type of the CFRP bars (mechanical properties and surface finishing) and the reinforcement ratio. They concluded that the deflection predictions based on beams reinforced with GFRP bars may underestimate the experimental deflection values for CFRP-reinforced beams, especially at load levels less than twice the cracking moment.

Because of the variable stiffness, brittle-elastic nature, and particular bond features of FRP reinforcement, deflections of FRP-reinforced concrete members are more sensitive to the variables affecting deflection than steel-reinforced members of identical size and reinforcement layout (Ospina et al. 2001). Deflections in members with FRP reinforcement tend to be greater in magnitude because of the lower stiffness of most commercially available FRP reinforcements. An indirect deflection-control procedure in which deflections in beams and one-way slabs with FRP reinforcement are controlled by the selection of a minimum member thickness for preliminary design (Ospina and Gross 2006) is presented in ACI 440.1R.

6.2.2 Crack width and patterns—As with steel reinforcement, the maximum crack width at the tension face of a reinforced concrete member is heavily influenced by the strain level in the reinforcement, the concrete cover, the bar spacing, and the mechanical properties of the reinforcement (Frosch 1999). ACI 440.1R includes a variation of Frosch's (1999) crack control equation found in ACI 318, with a recommendation to limit the predicted crack widths to 0.5 and 0.7 mm (0.020 to 0.028 in.) for exterior and interior exposure conditions, respectively. These values, adopted from CSA S806, are larger than the crack width limits traditionally accepted in steel-reinforced concrete design due to the superior corrosion resistance of FRP.

Nawy and Neuwerth (1971) found that beams reinforced with steel had fewer cracks than corresponding FRP-reinforced

beams. The large number of well-distributed cracks in the FRP-reinforced beams indicated that good mechanical bond was developed between the FRP bar and surrounding concrete.

Faza and GangaRao (1992) determined that concrete beams reinforced with spirally deformed FRP reinforcing bars using normal-strength concrete (27.6 MPa [4000 psi]) exhibited crack formation that was sudden and propagated toward the compression zone soon after the concrete stress reached its tensile strength. Crack spacing was very close to the stirrup spacing, and cracks formed at or near the stirrups. This sudden propagation of cracks and wider crack widths decreased when higher-strength concrete 51.7 to 69 MPa (7.5 to 10 ksi) and sand-coated FRP reinforcing bars were employed. Based on the assumption that maximum crack width can be approximated by an average strain in FRP reinforcing bar multiplied by expected crack spacing, an expression for maximum crack spacing governed by the following parameters was developed: 1) bond strength of the FRP reinforcing bar; 2) splitting tensile strength of the concrete; 3) area of the concrete cross section in tension; 4) number of reinforcing bars in tension; 5) size of reinforcing bar; and 6) working stress of the FRP reinforcing bar.

In a study by Toutanji and Saafi (2000), the authors suggest that crack width depends primarily on average crack spacing and on average reinforcement stress, which are related to the mechanical properties of the concrete, the reinforcement, and the bond between them. They proposed an equation for crack width prediction.

6.3—Bond and development of reinforcement

The evaluation of bond characteristics of FRP reinforcement is of prime importance in the design of FRP-reinforced concrete members. Bond characteristics are influenced by factors such as: 1) size and type of reinforcement (wires or strands); 2) surface conditions (smooth, deformed, and sand-coated); 3) Poisson's ratio; 4) concrete strength; 5) concrete confinement (helix or stirrups); 6) type of loading (static, cyclic, and impact); 7) time-dependent effects; 8) amount of concrete cover; and 9) type and volume of fiber and matrix.

A study on bond of GFRP reinforcing bars was conducted by Tao (1994) on 102 straight and 90-degree hook specimens. New limits for allowable slip were suggested as 0.064 mm (0.0025 in.) at the free end, or 0.38 mm (0.015 in.) at the loaded end. According to this study, the basic development length of straight and hooked GFRP reinforcing bars could be computed knowing the bar size, ultimate strength of the reinforcement, and concrete strength.

Shield et al. (1999) tested 72 inverted half-beam specimens. The tests did not use stirrups in the beams to simulate the lack of confinement present in bars of bridge decks. GFRP rods of 19.1 mm (0.75 in.) diameter and No. 5 bars were tested, and the development length was determined to be between $42d_b$ and $63d_b$. Nonuniformly spaced cracks perpendicular to the bar developed.

Katz et al. (1999) studied the bond behavior of five reinforcing bar types at room and high temperatures. One bar had lugs on the surface to provide the desired bond to concrete. Three other bar types had an extra layer of resin on the surface and

a coat of sand. Also, a steel bar was included in the study for comparison purposes. The bars were tested at temperatures of 20, 130, and at 250 °C (68, 266, and 482 °F). Two main bond failure mechanisms were observed. At room temperature, portions of the concrete surface in contact with the FRP bars pulled out in some specimens. At high temperatures, however, all the slip took place at the surface of the FRP bar because the shear properties of the resin on the surface of the FRP bar deteriorated. At 250 °C (482 °F), all FRP bars lost 80% or more of their room temperature bond strength, while the steel bars lost only 40% of their room temperature bond strength. The bond strength of all FRP bars decreased with increases in temperature, and it appeared to level off at a temperature of approximately 200 °C (392 °F). The authors agreed with a model proposed by Greszczuk (1969) that assumed the controlling parameters for bond strength were the shear modulus and the thickness of the outer layer of resin on the FRP reinforcing bar. The bond stiffness (initial slope of the bond-slip curve at the loaded end) decreased with increasing temperature. FRP bars with helical fiber wrapping and sand coating tended to exhibit better bond behavior than was seen in bars that relied on lugs of polymer for bond strength. The FRP bars with lugs of resin showed abrupt drops in the bond-slip curves after the peak load was reached.

Several weaknesses in the use of pullout tests (cylinders or pullout specimens) have been identified in discussions in ACI Committees 408 and 440 because such tests do not sufficiently account for all types of mechanical behavior, such as the flexural curvature and the combinations of shear and flexure. Many attempts have been made to find a better standard test method.

Malvar (1995) conducted tension and pullout bond tests on four types of reinforcing bars and studied the effects of confining pressure on bond. All bars had a diameter of 19 mm (3/4 in.) and were composed of E-glass fibers with a fiber volume fraction of 45%, embedded in a vinylester or polyester resin.

Five different confining pressure levels were studied: 3.45, 10.3, 17.2, 24.1, and 31 MPa (500, 1500, 2500, 3500, and 4500 psi). The measured adhesion (bond stress at zero average slip) was between 0.69 and 2.1 MPa (100 and 300 psi). Beyond this adhesion, the slope of the bond-slip curve appeared to increase with higher confinement. For an identical amount of confinement, the bond strength for a steel bar was, on average, 1.2 to 1.5 times higher than that for an FRP bar. Large variations in indentation depths of the bars resulted in a large variation of bond strength. Bond strength can be increased threefold by increasing confining pressure by a factor of 7.

Cosenza et al. (1997) reviewed the current knowledge of bond performance of FRP bars embedded in concrete. They found that the longitudinal shear modulus of the FRP bar was an important parameter. Coating the surface of bars with sand enhanced the bond strength and bond stiffness, but led to more brittle bond behavior. Bars with a surface coated with sand had excellent bond strength ($\tau_m > 10$ MPa [1.45 ksi]), even higher than steel bars. The bond strength of smooth FRP bars was poor ($\tau_m < 2.37$ MPa [0.34 ksi]). The bond

strength of spirally glued bars had values slightly higher than those of smooth bars ($\tau_m = 4.50$ MPa [0.65 ksi]).

Wambeke and Shield (2004) consolidated a database of 269 beam bond tests. The database was limited to beam-end tests, notch-beam tests, and splice tests. Two equations for development length were developed; one based on a splitting mode of failure, and the other on a pullout mode of failure. These equations form the basis for the design recommendations in ACI 440.1R.

Research on spliced FRP bars conducted by Aly (2005), Aly and Benmokrane (2005), and Aly et al. (2005, 2006) found that the development length of FRP bars was dependent on the square root of the longitudinal modulus of the bars.

6.4—Fatigue performance

Benmokrane et al. (1999) tested concrete slabs 3200 mm (126 in.) long, 1000 mm (39.3 in.) wide, and 260 mm (10.2 in.) thick, reinforced with CFRP gratings. The beams were subjected to 4 million cycles of loading, with load amplitude of 10 to 100 kN (2.25 to 22.5 kips). The first 2 million cycles were applied at a frequency of 2 Hz, and the remaining cycles at 3 Hz. After 4 million cycles, the maximum deflection was 12 mm (0.47 in.) (span/250). The same slab had a deflection of 8 mm (0.34 in.) under a 100 kN (22.5 kips) load applied statically before the fatigue test.

Rahman et al. (2000) conducted a 4 million cycle fatigue test on a full-scale model of a bridge deck slab. The slab was a composite structure supported by steel I-beams. The deck was reinforced using CFRP grating size C10 bars with 46 mm² (0.071 in.²) cross-sectional area and 100 mm (4 in.) grid spacing. The FRP reinforcement ratio was 0.3%. The researchers found that the deflection after 4 million cycles increased by 26% when compared with the deflection under static 100 kN (22.5 kip) loading. A deflection increase of 32% was observed for the 125 kN (28.1 kip) loading. Crack widths increased 42% after 4 million cycles under the 100 kN (22.5 kip) load. Stresses in the reinforcement were also increased by the fatigue loading by approximately 10%. The failure modes of the slab were punching shear in five loading cases and flexure in one loading case. The minimum capacity of the slab was over five times the design service load.

Kumar and GangaRao (1998) found that the rate of fatigue degradation in bridge decks reinforced with GFRP bars was similar to that of bridge decks reinforced with steel for a range of stringer stiffnesses and amount of composite action.

El-Ragaby et al. (2006) tested four full-size concrete deck slabs reinforced with GFRP bars to failure under a concentric fatigue loading. They concluded that the GFRP reinforced concrete bridge decks had better fatigue performance and longer fatigue life than equivalent steel reinforced decks.

6.5—Members reinforced with FRP grating systems

Bank et al. (1991) tested seven full-size concrete bridge deck slabs, six of which were reinforced with pultruded GFRP gratings, and one with steel reinforcing bars. The slabs were designed for a live load moment designated by AASHTO (1989) using a nominal HS-25 loading with a live load impact factor of 30%. Failure was the result of concrete

crushing followed immediately by propagation of a flexural-shear crack in a diagonal path towards the outer support. This crack was intercepted by the top surface of the FRP grating and redirected horizontally along the top surface of the grating to the free end. No failure of the FRP grating was observed. The steel-reinforced slab failed by yielding of the reinforcing bars and subsequent crushing of the concrete. The service load midspan deflections for all FRP-reinforced slabs were close to the allowable limit of 4.9 mm (0.192 in.). Deflection was found to stabilize after a limited number of cycles. All slabs failed at loads in excess of three times the service load.

Bank and Xi (1992) tested the performance of four full-scale two-span continuous concrete slabs, doubly reinforced (top and bottom) with 51 mm (2 in.) deep, commercially produced, pultruded FRP gratings having longitudinal bar spacings of 76 and 51 mm (3 and 2 in.) on center, respectively. Slabs were loaded as follows: first, under a monotonically increasing load to 115 kN (26 kips), then subjected to 10 loading/unloading cycles of 0 to 115 kN (0 to 26 kips), and finally loaded monotonically to failure. Flexural cracking developed early in both the positive and negative moment regions and were in line with the transverse bar locations. All slabs experienced shear failure in the short shear span between the middle support and the load point. The ratios of failure to service load for FRP-reinforced slabs were 4.26, 3.89, 4.17, and 4.16. For the steel-reinforced slab, this ratio was 3.34. No evidence of shear cracking was observed before failure. The local radius of curvature in the positive moment region generally satisfied AASHTO serviceability specifications. In the negative moment region, however, this criterion was violated. Service load deflections were well below the $L/500$ limit, where L is the length of the beam.

6.6—Members reinforced with FRP grids

Since 2004, carbon fiber/epoxy resin grids have been used to reinforce a wide variety of precast concrete structures including insulated wall panels, architectural cladding panels, double tees, and residential members. In addition to being used as a secondary reinforcement for crack control, the grids have also been used as primary reinforcement.

Most grids being used as internal reinforcement for concrete parts are constructed using continuous carbon fibers impregnated with thermoset epoxy resins. Glass and basalt fibers may also be used. Grids can be produced by a number of manufacturing processes. Grids can be woven and then impregnated with a thermoset or thermoplastic resin.

Grids further enhance the potential for more effective reinforcement of concrete structures using composite materials because they can be used near either surface of the concrete structure (but embedded within the concrete) to control cracking, reduce the thickness of the concrete structure, and to provide tension reinforcement. Grids may be used as the only reinforcement material or in combination with traditional reinforcement such as reinforcing bars and welded wire fabric. Because of differences in the physical and mechanical behavior of FRP materials versus steel, it is important to note the fact that grids offer the unique opportunity to position a

noncorrosive structural reinforcement very close to the surface, unique guidance on the engineering and construction of concrete structures reinforced with FRP grids is needed and is being developed as an activity of ACI Committee 440.

6.7—Pavement applications

FRP dowel bars have been extensively investigated by Davis and Porter (1999) and others. These dowel bars have been used primarily in highway concrete pavement construction. The results of this research have shown that GFRP dowels are able to carry the shear transfer across the pavement joint. For example, 44 mm (1.75 in.) diameter GFRP dowels spaced at 200 and 300 mm (8 and 12 in.) were shown to give favorable results compared with the typical 38 mm (1.5 in.) diameter steel dowel for up to 10 million cycles of repeated loading simulating 40 kN (9 kip) wheel loads on each side of the joint for full-scale pavement slabs.

Choi and Chen (2003, 2005) studied the concrete stresses induced in a GFRP-reinforced concrete slab due to concrete shrinkage and temperature variations. The results showed that the stress level in concrete was reduced with GFRP reinforcing bars because of the low Young's modulus of GFRP. The stress distribution and crack width in the GFRP-reinforced continuously reinforced concrete pavement section were predicted under various design considerations, such as the coefficient of thermal expansion (CTE) of concrete, the friction from the subbase of the pavement, and the bond-slip between concrete and reinforcement. The stress levels in the GFRP reinforcement, the crack widths, and the crack spacing of the proposed pavements were shown to be within the allowable AASHTO pavement design requirements. Other work on FRP-reinforced concrete pavements has been conducted by Walton and Bradberry (2005).

CHAPTER 7—PRESTRESSED CONCRETE MEMBERS

Much of the available research has concentrated on the short-term static behavior of bonded FRP prestressed beams. Both pretensioned and post-tensioned systems have been considered. ACI 440.4R provides details of prestressing systems for FRP and guidelines for the design of FRP prestressed concrete structures.

7.1—FRP tendons

This section examines commercially available tendons and anchorage systems. For more detailed information, the reader is referred to ACI 440.4R. Properties and characteristics of selected available tendon/anchorage systems are summarized in [Table 7.1](#) and are based on the manufacturer's published data. The trade names of the products are used for clarity. The properties of the tendons may change as the manufacturers modify their products. More details about the manufacturers are provided in ACI 440.4R. Variations in the properties of the tendons (for example, modulus and ultimate stress) are generally due to differences in the fiber volume fraction or to the orientation of the fibers in the tendon. For example, Arapree tendons have a volume fraction of 0.45, whereas Parafil rope has no polymer at all. Thus, the strength

and modulus values for Parafil are higher. Also, the CFCC tendons are twisted seven-wire strands; thus, not all the fibers are aligned along the longitudinal axis. Therefore, the modulus and strength properties are lower than the Leadline tendons that have all the fibers oriented longitudinally.

7.2—Anchorages

Conventional anchorage systems for steel prestressing reinforcement have hardened teeth that bite into the reinforcement to enhance transfer of stress. With FRP reinforcement, these teeth cause premature failure of the reinforcement at the grip location. Different anchorage systems have been used with FRP tendons, such as clamp, plug and cone, resin sleeve, resin potted, metal overlay, and split wedge anchorages, as shown in [Fig. 7.1](#). These anchorages and their gripping mechanisms are briefly described herein and in more detail in ACI 440.4R.

7.2.1 Clamp anchorage—A clamp anchorage ([Fig. 7.1\(a\)](#)) consists of two or four grooved steel plates sandwiching the FRP tendon and held together by pretensioned bolts and springs. The force is transferred by a shear-friction mechanism (Malvar and Bish 1995).

7.2.2 Plug and cone anchorage—The plug and cone (or barrel and spike) anchorage ([Fig. 7.1\(b\)](#)) is made of a socket housing and a conical spike (Burgoyne 1992). Such a system is suited to anchor Parafil ropes where the fibers are not encased in resin media but are held only by an outer protection sheath.

7.2.3 Resin sleeve anchorage—In this anchorage system, the FRP tendon is embedded in resin filling a metallic housing such as a steel or copper tube ([Fig. 7.1\(c\)](#)). The resin used ranges from nonshrink cement with or without sand to epoxy-based material. The load transfer mechanism depends completely on the bonding and interlocking between the anchorage components. This type of anchorage has been used for both round and flat tendons.

7.2.4 Resin potted anchorage—The potted anchorage ([Fig. 7.1\(d\)](#)) varies depending on the internal configuration of the socket: straight, linearly tapered, or parabolically tapered. The load transfer mechanism from the tendon to the sleeve is by interfacial shear stress that is a function of bonding and normal stress produced by the variation of the resin profile (Kim and Meier 1991). The practical drawbacks include precutting the tendons to length and the curing time for the resin or grout.

7.2.5 Metal overlaying—The die-cast wedge system ([Fig. 7.1\(e\)](#)) for the carbon fiber composite cable (CFCC) requires that the tendon length be predefined so that metal can be cast onto the tendon during fabrication with the result that adjustment on site is not possible. The tendon and the metal material are compressed by a typical wedge anchorage similar to those used on steel tendons. The load transfer of this anchorage is achieved by shear friction, which is a function of compressive stress and friction at the contact surfaces.

7.2.6 Split wedge anchorage—Split wedge anchorages ([Fig. 7.1\(f\)](#)) are generally preferred because of their compactness, ease of assembly, reusability, and reliability. The wedge system is widely used in anchoring steel tendons. The anchorages are modified for use with FRP tendons by