ACI 440.1R-15

Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars

Reported by ACI Committee 440

American Concrete Institute
Always advancing

First Printing
March 2015
ISBN: 978-1-942727-10-1

Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars

Order information: ACI documents are available in print, by download, on CD-ROM, through electronic subscription, or reprint and may be obtained by contacting ACI.

Most ACI standards and committee reports are gathered together in the annually revised ACI Manual of Concrete Practice (MCP).

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
Phone: +1.248.848.3700
Fax: +1.248.848.3701

www.concrete.org

Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars

Reported by ACI Committee 440

Carol K. Shield, Chair
William J. Gold, Secretary
Tarek Alkhrdaji
Charles E. Bakis
Lawrence C. Bank
Abdeldjelil Belarbi
Brahim Benmokrane
Luke A. Bisby
Gregg J. Blaszak
Hakim Bouadi
Timothy E. Bradberry
Gordon L. Brown Jr.
Vicki L. Brown
John P. Busel
Raafat El-Hacha
Garth J. Fallis
Amir Z. Fam
Nabil F. Grace
Mark F. Green
Zareh B. Gregorian
Doug. D. Gremel
Shawn P. Gross*
H. R. Trey Hamilton III
Issam E. Harik
Kent A. Harries
Mark P. Henderson
Bohdan N. Horeczko
Michael W. Lee
Maria Lopez de Murphy
Ibrahim M. Mahfouz
Amir Mirmiran
John J. Myers
Antonio Nanni
Ayman M. Okeil
Carlos E. Ospina
Renato Paretti
Max L. Porter
Andrea Prota
Hayder A. Rasheed
Sami H. Rizkalla
Rajan Sen
Rudolf Seracino
Pedro F. Silva
Khaled A. Soudki
Samuel A. Steere III
Jay Thomas
Houssam A. Toutanji
J. Gustavo Tumialan
Milan Vatovec
David White
Sarah E. Witt

Consulting Members
P. N. Balaguru
Craig A. Ballinger
Harald G. F. Budelmann
C. J. Burgoyne
Elliot P. Douglas
Rami M. Elhassan
David M. Gale
Russell Gentry
Arie Gerritse
Srinivasa L. Iyer
Koichi Kishitani
Howard S. Kliger
Kyuichi Maruyama
Antoine E. Naaman
Hajime Okamura
Mark A. Postma
Ferdinand S. Rostasy
Surendra P. Shah
Mohsen Shahawy
Yasuhisa Sonobe
Minoru Sugita
Luc R. Taerwe
Ralejs Tepfers
Taketo Uomoto
Paul Zia

*Subcommittee Chair.

Fiber-reinforced polymer (FRP) materials have emerged as an alternative for producing reinforcing bars for concrete structures. Fiber-reinforced polymer reinforcing bars offer advantages over steel reinforcement because they are noncorrosive. Some FRP bars are nonconductive as well. Due to other differences in the physical and mechanical behavior of FRP materials versus steel, unique guidance on the engineering and construction of concrete structures reinforced with FRP bars is necessary. Other countries and regions, such as Japan, Canada, and Europe have established design and construction guidelines specifically for the use of FRP bars as concrete reinforcement. This guide offers general information on the history and use of FRP reinforcement, a description of the unique material properties of FRP, and guidelines for the design and construction of structural concrete members reinforced with FRP bars. This guide is based on the knowledge gained from worldwide experimental research, analytical work, and field applications of FRP reinforcement.

Keywords: anchorage (structural); aramid fiber; carbon fiber; crack control; concrete construction; concrete slabs; cover; creep rupture; deflections; design examples; durability; fiber-reinforced polymer; flexural strength; glass fiber; moments; reinforced concrete; reinforcement; serviceability; shear strength; spans; strength analysis; stresses; structural concrete; structural design.

CONTENTS

ACI 440.1R-15 supersedes ACI 440.1R-06 and was adopted and published March 2015.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Conventional concrete structures are reinforced with nonprestressed and prestressed steel. The steel is initially protected against corrosion by the alkalinity of the concrete, usually resulting in durable and serviceable construction. For many structures subjected to aggressive environments, such as marine structures, bridges, and parking garages exposed to deicing salts, combinations of moisture, temperature, and chlorides reduce the alkalinity of the concrete and result in the corrosion of reinforcing steel. The corrosion process ultimately causes concrete deterioration and loss of serviceability.

Composite materials made of fibers embedded in a polymeric resin, also known as fiber-reinforced polymer (FRP), are an alternative to steel reinforcement for concrete structures. Fiber-reinforced polymer reinforcing materials are made of continuous aramid fiber (AFRP), carbon fiber (CFRP), or glass fiber (GFRP) embedded in a resin matrix. Examples of FRP reinforcing bars are shown in Fig. 1.1. Because FRP materials are nonmagnetic and noncorrosive, the problems of electromagnetic interference and steel corrosion can be avoided with FRP reinforcement. Additionally, FRP materials exhibit several properties, such as high tensile strength, that make them suitable for use as structural reinforcement (ACI 440R; Benmokrane and Rahman 1998; Burgoyne 2001; Cosenza et al. 2001; Dolan et al. 1999; El-Badry 1996; Figueiras et al. 2001; Humar and Razaqpur 2000; Iyer and Sen 1991; Japan Society of Civil Engineers (JSCE) 1992, 1997a; Nanni 1993a; Nanni and Dolan 1993; Neale and Labossiere 1992; Saadatmanesh and Ehsani 1998; Taerwe 1995; Teng 2001; White 1992).

The mechanical behavior of FRP reinforcement differs from the behavior of conventional steel reinforcement. Accordingly, a change in the traditional design philosophy of concrete structures is needed for FRP reinforcement. Fiber-reinforced polymer materials are anisotropic and are characterized by high tensile strength only in the direction of the reinforcing fibers. This anisotropic behavior affects the shear strength and dowel action of FRP bars as well as the bond performance. Furthermore, FRP materials do not yield; rather, they are elastic until failure. Design procedures should account for a lack of ductility in structural concrete members reinforced with FRP bars.

This guide was first developed in 2001 as a guide for the design and construction of structural concrete with FRP bars. Other countries and regions, such as Japan (Japan Society of Civil Engineers 1997b), Canada (CAN/CSA-S6-06, CAN/CSA-S806-12), and Europe (*fib* 2007, 2010) have also established similar design-related documents. There is adequate analytical and experimental information on FRP-reinforced concrete, and significant field experience implementing this knowledge. Successful applications worldwide using FRP composite reinforcing bars during the past few decades have demonstrated that it can be used successfully and practically. Research and field implementation is ongoing and design recommendations continue to evolve. When using this technology, exercise judgment as to the appropriate application of FRP reinforcement and be aware of its limitations as discussed in this guide.

Note: Any reference to ACI 318 in this document without a year designation refers to ACI 318-11. All exceptions will have a specific year designation.

Fig. 1.1—Examples of FRP reinforcing bars.

1.2—Scope

This guide provides recommendations for the design and construction of FRP-reinforced concrete structures for nonprestressed FRP reinforcement; concrete structures prestressed with FRP tendons are covered in ACI 440.4R. The basis for this guide is knowledge gained from worldwide experimental research, analytical research work, and field applications of FRP reinforcement.

Design recommendations are based on the current knowledge and are intended to supplement existing codes and guidelines for conventionally reinforced concrete structures and to provide licensed design professionals and building officials with assistance in the design and construction of structural concrete reinforced with FRP bars.

ACI 440.3R provides a comprehensive list of test methods and material specifications to support design and construction guidelines. ACI 440.5 provides specification details for construction with FRP reinforcing bars. Material specifications for FRP bars are found in ACI 440.6.

The use of FRP reinforcement in combination with steel reinforcement for structural concrete is not addressed in this guide.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

a = depth of equivalent rectangular stress block, in. (mm)

A_f = area of fiber-reinforced polymer (FRP) reinforcement, in.^{2} (mm^2)

$A_{f,bar}$ = area of one FRP bar, in.^{2} (mm^2)

$A_{f,min}$ = minimum area of FRP reinforcement needed to prevent failure of flexural members upon cracking, in.^{2} (mm^2)

$A_{f,sh}$ = area of shrinkage and temperature FRP reinforcement per linear ft (m), in.^{2} (mm^2)

A_{fv} = amount of FRP shear reinforcement within spacing s, in.^{2} (mm^2)

$A_{fv,min}$ = minimum amount of FRP shear reinforcement within spacing s, in.^{2} (mm^2)

A_s = area of tension steel reinforcement, in.^{2} (mm^2)

b = width of rectangular cross section, in. (mm)
b_o = perimeter of critical section for slabs and footings, in. (mm)
b_w = width of the web, in. (mm)
c = distance from extreme compression fiber to the neutral axis, in. (mm)
c_b = distance from extreme compression fiber to neutral axis at balanced strain condition, in. (mm)
c_c = clear cover, in. (mm)
C = spacing or cover dimension, in. (mm)
C_E = environmental reduction factor for various fiber type and exposure conditions
d = distance from extreme compression fiber to centroid of tension reinforcement, in. (mm)
d_b = diameter of reinforcing bar, in. (mm)
d_c = thickness of concrete cover measured from extreme tension fiber to center of bar or wire location closest thereto, in. (mm)
$d_{c,side}$ = thickness of concrete cover measured from side face of member to center of longitudinal bar or wire location closest thereto, in. (mm)
E_c = modulus of elasticity of concrete, psi (MPa)
E_f = design or guaranteed modulus of elasticity of FRP defined as mean modulus of sample of test specimens ($E_f = E_{f,ave}$), psi (MPa)
$E_{f,ave}$ = average modulus of elasticity of FRP, psi (MPa)
E_s = modulus of elasticity of steel, psi (MPa)
f_c' = specified compressive strength of concrete, psi (MPa)
$\sqrt{f_c'}$ = square root of specified compressive strength of concrete, psi (MPa)
f_f = stress in FRP reinforcement in tension, psi (MPa)
f_{fb} = strength of bent portion of FRP bar, psi (MPa)
f_{fe} = bar stress that can be developed for embedment length ℓ_e, psi (MPa)
f_{fr} = required bar stress, psi (MPa)
f_{fs} = stress level induced in FRP at service loads, psi (MPa)
$f_{fs,sus}$ = stress level induced in FRP by sustained service loads, psi (MPa)
f_{fu} = design tensile strength of FRP, defined as the guaranteed tensile strength multiplied by the environmental reduction factor ($f_{fu} = C_E f_{fu}^*$), psi (MPa)
f_{fu}^* = guaranteed tensile strength of FRP bar, defined as mean tensile strength of sample of test specimens minus three times standard deviation ($f_{fu}^* = f_{fu,ave} - 3\sigma$), psi (MPa)
f_{fv} = tensile strength of FRP for shear design, taken as smallest of design tensile strength f_{fu}, strength of bent portion of FRP stirrups f_{fb}, or stress corresponding to $0.004E_f$, psi (MPa)
f_s = service stress in steel reinforcement, psi (MPa)
$f_{s,allow}$ = allowable service stress in steel reinforcement, psi (MPa)
$f_{u,ave}$ = mean tensile strength of sample of test specimens, psi (MPa)
f_y = specified yield stress of nonprestressed steel reinforcement, psi (MPa)
h = overall height of flexural member, in. (mm)
I = moment of inertia, in.^{4} (mm^4)
I_{cr} = moment of inertia of transformed cracked section, in.^{4} (mm^4)
I_e = effective moment of inertia, in.^{4} (mm^4)
I_{e+} = effective moment of inertia at location of maximum positive moment, in.^{4} (mm^4)
I_{e1-} = effective moment of inertia at location of maximum negative moment at near end of span, in.^{4} (mm^4)
I_{e2-} = effective moment of inertia at location of maximum negative moment at far end of span, in.^{4} (mm^4)
I_g = gross moment of inertia, in.^{4} (mm^4)
k = ratio of depth of neutral axis to reinforcement depth
k_b = bond-dependent coefficient
K_1 = parameter accounting for boundary conditions
K_4 = coefficient used in computing development length of bent bar
ℓ = span length of member, ft (m)
ℓ_a = additional embedment length at support or at point of inflection, in. (mm)
ℓ_{bhf} = basic development length of FRP standard hook in tension, in. (mm)
ℓ_d = development length, in. (mm)
ℓ_e = embedded length of reinforcing bar, in. (mm)
ℓ_{thf} = length of tail beyond hook in FRP bar, in. (mm)
L = distance between joints in slab-on-grade, ft (m)
M_a = maximum service load moment in member, lb-in. (N-mm)
M_{cr} = cracking moment, lb-in. (N-mm)
M_n = nominal moment capacity, lb-in. (N-mm)
$M_{s,sus}$ = moment due to sustained service loads, lb-in. (N-mm)
M_{serv} = service level moment
M_u = factored moment at section, lb-in. (N-mm)
n_f = ratio of modulus of elasticity of FRP bars to modulus of elasticity of concrete
r_b = internal radius of bend in FRP reinforcement, in. (mm)
s = stirrup spacing or pitch of continuous spirals, in. (mm)
s_{max} = maximum permissible center-to-center bar spacing for flexural crack control, in. (mm)
T_g = glass transition temperature, °F (°C)
u = average bond stress acting on the surface of FRP bar, psi (MPa)
V_c = nominal shear strength provided by concrete, lb (N)
V_f = shear resistance provided by FRP stirrups, lb (N)
V_n = nominal shear strength at section, lb (N)
V_s = shear resistance provided by steel stirrups, lb (N)
V_u = factored shear force at section, lb (N)
w = maximum allowable crack width, in. (mm)
w_{slab} = dead weight of slab, lb/ft^2 (N/m^2)

y_t = distance from centroidal axis of gross section, neglecting reinforcement, to tension face, in. (mm)
α = top bar modification factor
α_L = longitudinal coefficient of thermal expansion, 1/°F (1/°C)
α_T = transverse coefficient of thermal expansion, 1/°F (1/°C)
α_1 = ratio of average stress of equivalent rectangular stress block to f_c'
β = ratio of distance from neutral axis to extreme tension fiber to distance from neutral axis to center of tensile reinforcement
β_1 = factor taken as 0.85 for concrete strength f_c' up to and including 4000 psi (28 MPa). For strength above 4000 psi (28 MPa), this factor is reduced continuously at a rate of 0.05 per each 1000 psi (7 MPa) of strength in excess of 4000 psi (28 MPa), but is not taken less than 0.65
$\Delta_{(cp+sh)}$ = additional deflection due to creep and shrinkage under sustained loads, in. (mm)
$(\Delta_i)_{sus}$ = immediate deflection due to sustained loads, in. (mm)
$(\Delta/\ell)_{max}$ = limiting deflection-span ratio
ε_c = strain in concrete
ε_{cu} = ultimate strain in concrete
ε_f = strain in FRP reinforcement
$\varepsilon_{f,ave}$ = mean tensile strain at rupture of sample of test specimens
ε_{fs} = strain level induced in FRP at service loads
ε_{fu} = design rupture strain of FRP reinforcement, defined as the guaranteed tensile rupture strain multiplied by the environmental reduction factor ($\varepsilon_{fu} = C_E\varepsilon_{fu}*$)
$\varepsilon_{fu}*$ = guaranteed rupture strain of FRP reinforcement defined as the mean tensile strain at failure of sample of test specimens minus three times standard deviation ($\varepsilon_{fu}* = \varepsilon_{f,ave} - 3\sigma$), in./in. (mm/mm)
ϕ = strength reduction factor
γ = parameter to account for the variation in stiffness along the length of the member
η = ratio of distance from extreme compression fiber to centroid of tension reinforcement (d) to overall height of flexural member (h)
λ = modification factor reflecting the reduced mechanical properties of lightweight concrete
λ_Δ = multiplier for additional long-term deflection
μ = coefficient of subgrade friction for calculation of shrinkage and temperature reinforcement
θ = angle of inclination of stirrups or spirals
ρ' = ratio of steel compression reinforcement; $\rho' = A_s'/bd$
ρ_b = steel reinforcement ratio producing balanced strain conditions
ρ_f = fiber-reinforced polymer reinforcement ratio
ρ_f' = ratio of FRP compression reinforcement
$\rho_{f,ts}$ = reinforcement ratio for temperature and shrinkage FRP reinforcement
ρ_{fb} = fiber-reinforced polymer reinforcement ratio producing balanced strain conditions
ρ_{fv} = ratio of FRP shear reinforcement
ρ_{min} = minimum reinforcement ratio for steel
σ = standard deviation
ξ = time-dependent factor for sustained load

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://www.concrete.org/tools/concreteterminology.aspx. Definitions provided herein compliment that source.

alkalinity—the condition of having or containing hydroxyl (OH^-) ions; containing alkaline substances.

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

balanced fiber-reinforced polymer reinforcement ratio—an amount and distribution of reinforcement in a flexural member such that in strength design, the tensile fiber-reinforced polymer (FRP) reinforcement reaches its ultimate design strain simultaneously with the concrete in compression reaching its assumed ultimate strain of 0.003.

braiding—a process whereby two or more systems of yarns are intertwined 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.

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

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

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

degradation—deleterious change in the chemical structure, physical properties, or appearance of a FRP composite.

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

endurance limit—the number of cycles of deformation or load that causes a material, test specimen, or structural member to fail.

fiber-reinforced polymer (FRP) bar—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.

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.

glass fiber—fiber drawn from an inorganic product of fusion that has cooled without crystallizing.

grid—a two-dimensional (planar) or three-dimensional (spatial) rigid array of interconnected FRP bars that form a contiguous lattice that can be used to reinforce concrete.

precursor—for carbon or graphite fiber, the rayon, PAN, or pitch fibers from which carbon and graphite fibers are derived.

pultrusion—continuous process for manufacturing composites that have a uniform cross-sectional shape; process consists of pulling a fiber-reinforcing material through a resin impregnation bath then through a shaping die where the resin is subsequently cured.

vinyl esters—class of thermosetting resins containing ester of acrylic, methacrylic acids, or both, many of which have been made from epoxy resin.

CHAPTER 3—BACKGROUND

3.1—Historical development

The development of fiber-reinforced polymer (FRP) reinforcement can be traced to the expanded use of composites after World War II in the 1940s. The aerospace industry had long recognized the advantages of the high strength and light weight of composite materials and, during the Cold War, advancements in the aerospace and defense industry caused an increase in their use. Furthermore, the rapidly expanding economy of the United States demanded inexpensive materials to meet consumer demands. Pultrusion offered a fast and economical method of forming constant profile parts, and pultruded composites were being used to make golf clubs and fishing poles. It was not until the 1960s, however, that these materials were seriously considered for use as reinforcement in concrete.

Expansion of the national highway systems in the 1950s increased the need to provide year-round maintenance. It became common to apply deicing salts on highway bridges and, as a result, reinforcing steel in these structures and those subject to marine salt experienced extensive corrosion, becoming a major concern and leading to high maintenance cost. Various solutions were investigated, including galvanized coatings, electro-static-spray fusion-bonded (powder resin) coatings, polymer-impregnated concrete, epoxy coatings, alloyed steel bars, and glass FRP reinforcing bars (ACI 440R). Of these options, epoxy-coated steel reinforcement appeared to be the best solution and was therefore implemented in aggressive corrosion environments. Fiber-reinforced polymer reinforcing bar was not considered a viable solution and not commercially available until the late 1970s.

Initially, GFRP bars were considered a viable alternative to steel as reinforcement for polymer concrete because their use eliminated the need to address the incompatibility of thermal expansion characteristics between polymer concrete and steel. The 1980s market demanded nonmetallic reinforcement for specific advanced technology. The largest demand for electrically nonconductive reinforcement was in facilities for MRI medical equipment. FRP reinforcement became the standard in this type of construction. Other uses developed as the advantages of FRP reinforcement became better known and desired, specifically in seawall construction, substation reactor bases, airport runways, and electronics laboratories (Brown and Bartholomew 1996).

Concern for the deterioration of bridges due to chloride-ion-induced corrosion dates back to the 1970s, and its effects on aging bridges in the United States has become apparent (Boyle and Karbhari 1994). Additionally, detection of corrosion in the commonly used epoxy-coated reinforcing bars increased interest in alternative methods of avoiding corrosion. Once again, FRP reinforcement began to be considered as a general solution to address problems of corrosion in bridge decks and other structures (Benmokrane et al. 1996).

3.2—History of use

Up to the mid-1990s, the Japanese had the most FRP reinforcement applications, with more than 100 demonstration or commercial projects. Fiber-reinforced polymer design provisions were included in the design and construction recommendations of the Japanese Society of Civil Engineering (1997b). In the 2000s, China became the largest user of composite reinforcement for new construction in applications that span from bridge decks to underground works (Ye et al. 2003).

The use of FRP reinforcement in Europe began in Germany with the construction of a prestressed FRP highway bridge in 1986 (Meier 1992). Since the construction of this bridge, programs have been implemented to increase the research and use of FRP reinforcement in Europe (Taerwe 1997).

Canadian civil engineers have developed provisions for FRP reinforcement in the Canadian Highway Bridge Design Code (CAN/CSA-S6-06) and have constructed a number of FRP-reinforced concrete structures. The Headingley Bridge in Manitoba included both CFRP and GFRP reinforcement (Rizkalla 1997). The Floodway Bridge over the Red River in Winnipeg, MB, Canada, was completed in 2006. The bridge comprises 16 spans, each approximately 50 x 143 ft (15.3 x 43.5 m). All concrete elements above the girders are reinforced with GFRP bars. The project consumed 310,000 lb (140,000 kg) of GFRP reinforcing bar, making it the largest nonmetallic-reinforced concrete bridge in the world. Moreover, several bridges have been built in Quebec using GFRP bars in the decks, such as the Wotton Bridge in Wotton, the Magog Bridge on Highway 55 North, the Cookshire-Eaton Bridge on Route 108, and the Val-Alain Bridge on Highway 20 East (El-Salakawy and Benmokrane 2003; El-Salakawy et al. 2003, 2005; Benmokrane et al. 2004, 2007). Some of these bridges have been in service for more than 10 years without any signs of deterioration of the GFRP reinforcement (Mufti et al. 2007, 2011). Consequently, there is a remarkable increase in the use of GFRP bars in Canada where more than 200 bridge structures have been successfully constructed. Straight and bent FRP bars were used for the deck slab, for the concrete barriers and girders of the bridges, or both (Drouin et al. 2011). In addition, GFRP bars have been used in Canada in other concrete structures such as parking garages (Benmokrane et al. 2012), highway concrete pavement (Benmokrane et al. 2007), water tanks (Benmokrane and Mohamed 2014), and incinerators (Beaulieu-Michaud et al. 2013). In the United States, typical uses

Fig. 3.2a—FRP-reinforced deck constructed in Lima, OH (Pierce Street Bridge), in 1999.

Fig. 3.2b—GFRP bars used in the redecking of Dayton, OH, Salem Avenue Bridge in 1999.

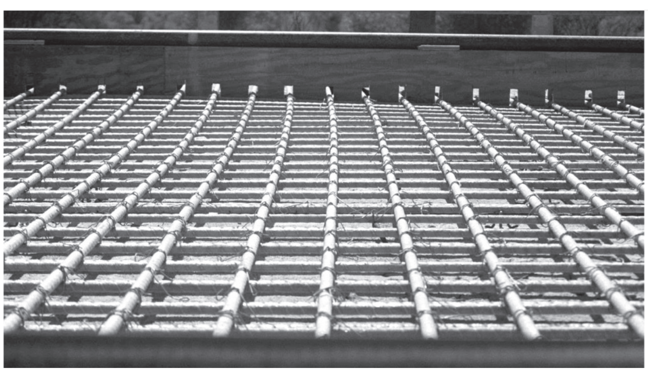

Fig. 3.2c—Transverse view of GFRP bars in Sierrita de la Cruz Creek Bridge deck near Amarillo, TX, in 2000.

of FRP reinforcement have been previously reported (ACI 440R). Figures 3.2a, 3.2b, and 3.2c show applications in bridge deck construction. The use of GFRP bars in MRI hospital room additions is becoming commonplace. Other applications, such as waterfront construction, top mat reinforcing for bridge decks, various precast applications, and ornamental and architectural concrete, are also becoming more frequent. Some of the largest projects include the Gonda Building at the Mayo Clinic in Rochester, MN; the

Fig. 3.2d—Emma Park Bridge deck panel with GFRP reinforcing bars, top and bottom mat.

Fig. 3.2e—GFRP bars used in rail plinths.

National Institute of Health in Bethesda, MD, for MRI applications; the bridge on RM 1061 at Sierrita de la Cruz Creek in Potter County, TX, and the bridge at 53rd Avenue in Bettendorf, IA, for deck reinforcement applications (Nanni 2001). Glass FRP bars are making great strides to support accelerated bridge construction with application in precast concrete deck panels. One example is the Emma Park Bridge in Utah constructed in 2009. Glass FRP bars were used in the top and bottom mat, as shown in Fig. 3.2d. In 2011 in Miami, FL, 2.4 miles (3.9 km) of GFRP bar were used in the rail plinths (Fig. 3.2e) for AirportLink, which connects the existing Earlington Heights Station to the new Miami Intermodal Center (MIC). Glass FRP bars were selected, as they provided electrical insolation in the rail bed. Designed by the Florida Department of Transportation, the MIC is a major transportation hub that serves as a central transfer point to different modes of transportation, including Metrorail,