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Fiber-Reinforced Polymer Composites for Construction—State-of-the-Art Review

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Abstract: A concise state-of-the-art survey of fiber-reinforced polymer (also known as fiber-reinforced plastic) composites for construction applications in civil engineering is presented. The paper is organized into separate sections on structural shapes, bridge decks, internal reinforcements, externally bonded reinforcements, and standards and codes. Each section includes a historical review, the current state of the art, and future challenges.

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Introduction

In the last 200 years, rapid advances in construction materials technology have enabled civil engineers to achieve impressive gains in the safety, economy, and functionality of structures built to serve the common needs of society. Through such gains, the health and standard of living of individuals are improved. To mark the occasion of the 150th anniversary of the American Society of Civil Engineers (ASCE), this paper reviews a class of structural materials that has been in use since the 1940s but only recently has won the attention of engineers involved in the construction of civil structures—fiber-reinforced polymer [or fiber-reinforced plastic (FRP)] composites.

The earliest FRP materials used glass fibers embedded in polymeric resins that were made available by the burgeoning petrochemical industry following World War II. The combination of high-strength, high-stiffness structural fibers with low-cost, lightweight, environmentally resistant polymers resulted in composite materials with mechanical properties and durability better than either of the constituents alone. Fiber materials with higher strength, higher stiffness, and lower density, such as boron, carbon, and aramid, were commercialized to meet the higher performance challenges of space exploration and air travel in the 1960s and 1970s. At first, composites made with these higher performing fibers were too expensive to make much impact beyond niche applications in the aerospace and defense industries. Work had already begun in the 1970s, however, to lower the cost of high-performance FRPs and promote substantial marketing opportunities in sporting goods. By the late 1980s and early 1990s, as the defense market waned, increased importance was placed by fiber and FRP manufacturers on cost reduction for the continued growth of the FRP industry. As the cost of FRP materials continues to decrease and the need for aggressive infrastructure renewal becomes increasingly evident in the developed world, pressure has mounted for the use of these new materials to meet higher public expectations in terms of infrastructure functionality. Aided by the growth in research and demonstration projects funded by industries and governments around the world during the late 1980s and throughout the 1990s, FRP materials are now finding wider acceptance in the characteristically conservative infrastructure construction industry. Hence, a brief review of the development, state of the art, and future of these promising construction materials is a timely and appropriate marker for the 150th anniversary of the ASCE.

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For the purpose of writing this paper, a learned group of writers was recruited from the ranks of the editorial board of the ASCE *Journal of Composites for Construction*. The breadth and depth of topics covered in this work are necessarily constrained by space limitations. The breakdown of topics, which roughly follows the annual summary of topics in the journal, and the respective contributing writers are as follows:

- Editor—Professor Charles E. Bakis (The Pennsylvania State Univ.),
- Structural Shapes—Professors Lawrence C. Bank (University of Wisconsin—Madison) and Edoardo Cosenza (University of Naples, Italy),
- Highway Bridge Decks—Professors John J. Lesko (Virginia Polytechnic Institute and State University) and Julio F. Davalos (West Virginia University),
- Internal FRP Reinforcements—Professors Vicki L. Brown (Widener University) and Charles E. Bakis (The Pennsylvania State University),
- Externally Bonded Reinforcements—Professor Thanasis Triantafillou (University of Patras, Greece), and
- Standards and Codes—Professors Sami H. Rizkalla (North Carolina State University) and Atsuhiko Machida (Saitama University, Japan).

The style and content of each section vary according to the different historical developments and maturities of the respective subject matters. Pultruded shapes, for example, have been in wide use in a number of industries for approximately 30 years, whereas FRP decks have been under development for only about 10 years. Hence, the discussion of FRP decks is relatively biased toward methods of analysis (structural as well as economical) and design, whereas the discussion of pultrusions involves a more historical perspective. Similarly, design guides and codes for the use of internal and external FRP reinforcements for concrete structures are only recently being finalized. Therefore, a discussion of design approaches and remaining questions in these areas is of current interest.

Structural Shapes

Introduction

Constant cross-sectioned FRP composite structural shapes, also commonly referred to as structural profiles, produced for use in the construction industry for building and bridge superstructure applications are discussed in this section. Pultruded sections for highway bridge decks are described elsewhere. Pultrusion technology used for manufacturing FRP structural shapes is briefly reviewed. This is followed by a brief discussion of the development and evolution of structural shapes from nonstructural commodity applications to current structural applications. Significant building and bridge superstructure developments are described. Recent research on pultruded FRP shapes is described and comments on the future of pultruded structural shapes are provided.

Pultrusion Process

The manufacturing method of choice, for both product consistency and economy, for structural shapes is the pultrusion process. This continuous manufacturing process, which is highly automated, consists of ‘‘pulling’’ resin impregnated reinforcing fibers and fiber fabrics through a heated curing die at speeds of up to 3 m (120 in.)/min, depending on the size and complexity of the profile shape. Both open-section and single or multicelled closed-section profiles can be produced. The common fiber reinforcement in pultruded shapes consists of fiber bundles (called rovings for glass fiber and tows for carbon fiber), continuous strand mat (also called continuous filament mat), and nonwoven surfacing veils. Typically, fiber volume fractions of 35–50% are utilized. In recent years, bidirectional and multidirectional woven, braided, and stitched fiber fabrics have been used to produce pultruded parts with enhanced mechanical properties. Filled thermosetting resins in the polyester and vinylester groups are generally used in pultrusion. Additionally, phenolic, epoxy, and thermoplastic resins have been developed for the pultrusion process. Meyer (1985) provides a thorough introduction to the pultrusion process, its early evolution, the key patents awarded, and the parameters controlling the design of a pultruded part. His book also provides an annotated bibliography of the key papers dealing with pultrusion technology from the late 1950s to the early 1980s.

Evolution of Fiber-Reinforced Polymer Structural Shapes

Large-sized pultruded FRP structural shapes [defined herein as having a cross-sectional envelope greater than 150×150 mm (6×6 in.)] for building and bridge superstructure construction applications were developed from earlier advances in pultrusion technology, which prior to the 1970s was primarily focused on developing small-sized commodity products for nonstructural building and electrical applications. A key application driver that led to significant developments and standardization of the technology was the FRP stepladder. The seminal paper by Werner (1979) describes the development of statistically reliable design property values for pultruded parts used in the pultruded ladder rail industry. B-basis allowable property values for design were developed for pultruded channels used as ladder rails following the procedures of the *U.S. military handbook 17* (*Composite* 2001). In the 1970s and early 1980s, advances in pultrusion technology led to the ability to produce larger pultruded parts capable of serving as structural members in load-bearing applications. Profile shapes were developed and first used in complete building structural systems to construct electromagnetic interference (EMI) test laboratory buildings that contained no metallic components (Smallowitz 1985). At the same time, a number of pultrusion companies in the United States began producing ‘‘standard’’ I-shaped beams for construction applications. In the pultrusion industry, then as now, the term standard does not imply anything more than the fact that the parts are produced on a regular basis by the company, are usually available off-the-shelf, have published dimensions, and meet minimum manufacturer-provided property values (Bank 1995). These standard profiles were, and still are, generally used for small structural units and parts of structural systems of nonprimary load carrying significance. Nonstandard shapes are called ‘‘custom’’ shapes. In the late 1980s and early 1990s, a customized building system of pultruded components for the construction of industrial cooling tower structures (Green et al. 1994) was developed. Cooling towers are currently constructed from either standard pultruded shapes (angles, tubes, and channel and I sections) produced by a variety of manufacturers (called ‘‘stick built’’) or customized components (called ‘‘modular’’) (i.e., www.strongwell.com or www.creativepultrusions.com). Pultruded cooling tower systems are designed according to existing building codes using property data supplied by the manufacturer and verified by the designer. In the absence of an American National Standards Institute approved design guide for pultruded structures, designers generally rely on engineering judgment, fundamental mechanics principles, experience, and manufacturer-produced "design guides" (Fiberline 1995; Creative Pultrusions 1999; Strongwell 1999). Since the early 1990s, the use of small pultruded FRP structural shapes [cross sections less than 100×100 mm (4×4 in.)] to build industrial platforms and walkways and to build relatively short single-span [9–18 m (30–60 ft)] pedestrian bridges has also increased significantly (Johansen et al. 1997).

Current Developments in Pultruded Structural Shapes

Since the 1990s, there has been a significant increase throughout the world in the use (albeit still on a demonstration project basis) of pultruded structural shapes in primary load-bearing systems for general construction. This excludes the cooling tower market, which is a well-established niche market for pultruded structural shapes. Significant bridge and building structures have been designed and constructed using pultruded profiles.

Major pedestrian bridges constructed of pultruded structural shapes include the 114-m (371-ft) long cable-stayed Aberfeldy Footbridge in Aberfeldy, Scotland, and the 40-m (130-ft) long cable-stayed Fiberline Bridge in Kolding, Denmark. The Aberfeldy Bridge, constructed in 1992, and designed by Maunsell Structural Plastics (Beckenham, U.K.), used a proprietary interlocking modular pultruded decking section produced by GEC Reinforced Plastics (now Fibreforce Composites, Runcorn, U.K.). The Kolding Bridge, constructed in 1997, and designed by the Danish firm RAMBØLL, uses standard pultruded shapes in both the cable tower and the decking system. For small highway bridge superstructure and building structural elements, Strongwell has recently developed a new standard pultruded FRP double web beam (DWB) in a 200×150 mm (8×6 in.) size. A design guide for the beam is available from Strongwell (1999). The beam has been used in a demonstration bridge (Hayes et al. 2000a). A 900×450 mm (36×18 in.) version of the beam that can be used as a highway bridge girder or a transfer girder in a building frame is also available. An eight-girder timber deck bridge [two lane, 11-m (38-ft) clear span] employing this 914-mm (36-in.) deep DWB was installed in Marion, Virginia, during the summer of 2001. Standard pultruded composites from Creative Pultrusions were recently used to design and construct a large [$7.4\times4.6\times1.5$ m ($24\times15\times5$ ft)] box-girder pultruded causeway structure (Bank et al. 2000).

Pultruded shapes, both standard and custom, have also been used in building and housing construction systems, and continue to be used in the EMI building market. A six-story 19.4-m (63-ft) high load-bearing stair-tower was recently constructed in Fort Story, Virginia, of 250×250 mm (10×10 in.) pultruded I-section shapes manufactured by Strongwell. In Avon, U.K., a two-story building was designed by Maunsell Structural Plastics using its proprietary pultruded interlocking panelized system (Raasch 1998). In Basel, Switzerland, a five-story 15 m (49 ft) high residential/office building was constructed with a primary load-bearing structural frame of FRP shapes for the 1999 Swissbau Fair. Named the "Eyecatcher Building," the building was designed using Fiberline shapes and the *Fiberline design manual* (Keller 1999). In Italy, the pultruder TopGlass S.p.A. produces a variety of structural shapes that have been used in small building constructions. In West Virginia, an experimental multicellular FRP building [$12.3\times6.5\times4.3$ m ($40\times21\times14$ ft)] was constructed for the West Virginia Department of Transportation using pultruded profiles manufactured by Creative Pultrusions. In non-building structural product markets, custom structural shapes have been developed for latticed transmission towers, light poles, and highway luminaire supports and guardrails.

Recent Research

In the early 1990s, research on the use of pultruded structural shapes for civil engineering building and bridge applications increased significantly as the potential for the use of these products in nonproprietary load-bearing structural systems became evident. A search of the ASCE database (www.pubs.asce.org) reveals that archival journal papers published by the ASCE on the topic of FRP pultruded structures or materials date back only to 1990. Approximately 20 archival research papers on this topic were published since that time, and appear in the ASCE database. In 1997, the ASCE began publishing the *Journal of Composites for Construction*, which has provided an outlet for many of the research papers on the topic. In the United Kingdom, *The Structural Engineer*, published by the British Institution of Structural Engineers, has published a number of key research papers on pultruded structures for civil engineering.

Future for Pultruded Structural Shapes

The increased acceptance of pultruded structural shapes for mainstream building and bridge superstructure applications will depend on three key developments. The first is the development of an internationally accepted material specification for pultruded materials that will allow users to determine material properties of interest to designers in a rational and nonproprietary manner with well-known reliability. The second is the development of a design code for pultruded structures that is consensus based and incorporated into building and bridge codes such as the International Building Code and the American Association of State Highway and Transportation Officials (AASHTO) bridge code. The recent paper by Zureick and Steffen (2000) provides an example of what is needed to develop these two items. The third development required, as is to be expected, will be to reduce the cost of pultruded shapes, which are currently not competitive with shapes made from traditional materials for mainstream structural applications.

Highway Bridge Decks

Introduction

Within the field of highway structures, several new FRP structural systems have been proposed, designed, and experimentally implemented. These include bridge decks for rehabilitation and new construction, concrete filled FRP shells for drivable piles (Karbhari et al. 2000; Mirmiran et al. 2000), and wood FRP composite girders (Dagher et al. 1997). However, bridge decks have received the greatest amount of attention in the past few years, due to their inherent advantages in strength and stiffness per unit weight as compared to traditional steel reinforced concrete (RC) decks. Reducing the weight of replacement decks in rehabilitation projects presents the opportunity for rapid replacement and reduction in dead load, thus raising the live load rating of the structure. The New York State Department of Transportation and other organizations have successfully pursued this strategy in the rehabilitation of several short-span and through-truss bridges (Alampalli et al. 1999).

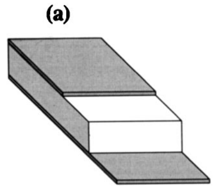

Fig. 1. Examples of two types of sandwich construction: (a) generic foam core; (b) proprietary (KSCI) corrugated core—taken from Davalos et al. (2001)

Thus, the focus of this discussion is on the efficacy of FRP bridge decks for rehabilitation and new construction. General performance and cost issues for the two major types of FRP decks currently in use—sandwich and adhesively bonded pultruded shapes—are outlined quantitatively.

Fiber-Reinforced Polymer Decks

A bridge deck in this discussion is defined as a structural element that transfers loads transversely to supports such as longitudinal running girders, cross beams, and/or stringers that bear on abutments. The connection of the deck to these underlying supports is typically made through the application of shear studs or a bolted connection in a simply supported condition that does not necessarily provide for composite action. Although decks have been designed and implemented bearing directly on abutments without underlying supports (e.g., the No-Name Creek Bridge in Russell, Kansas, and the Muddy Run Bridge on Delaware State Route 896), these types are not the focus of this discussion.

FRP decks commercially available at the present time can be classified according to two types of construction—sandwich and adhesively bonded pultruded shapes. In both cases, quality control of the product is enabled by standardized fabrication procedures within individual manufacturing facilities. The fabrication and performance of these types of decks are described next.

Sandwich Construction

Sandwich structures have been widely used for applications in the aerospace, marine, and automotive industries, where stiffness and strength requirements must be met with minimum weight, as explained in a number of textbooks on the subject (Vinson 1999). Sandwich construction implies the use of strong, stiff face sheets that carry flexural loads and a low-density, bonded core material that separates the face sheets and ensures composite action of the deck. Cellular materials are the most efficient core materials for weight-sensitive applications. Due to the ease with which face sheets and core materials can be changed in manufacturing, sandwich construction presents tremendous flexibility in designing for varied depths and deflection requirements. Face sheets of sandwich bridge decks are primarily composed of E-glass mats and/or rovings infused with a polyester or vinylester resin. Current core materials are rigid foams or thin-walled cellular FRP materials, such as those shown in Fig. 1.

Open or closed-mold composite fabrication processes whereby liquid resin is drawn through a dry fiber preform, typically with a vacuum, hold great promise for the economical manufacturing of bridge decks. In such processes, the core and face sheets can be impregnated with resin and cured at once. Changes in details related to materials, orientations, and thicknesses of the FRP face sheets or core can be determined analytically (Davalos et al. 2001) and are easily accommodated in many of these processes.

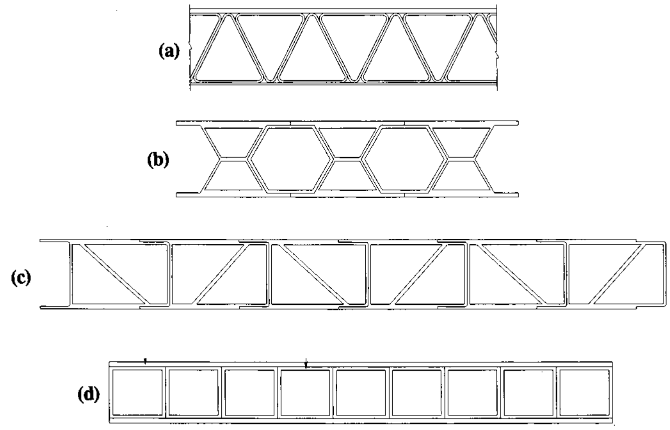

Fig. 2. FRP decks produced from adhesively bonded pultruded shapes: (a) EZSpan (Atlantic Research); (b) Superdeck (Creative Pultrusions); (c) DuraSpan (Martin Marietta Materials); (d) square tube and plate deck (Strongwell)

Individual sandwich deck panels are usually joined to each other by tongue-and-groove ends and are secured to the underlying structure using a clamp mechanism. Skew boundaries can be easily accommodated and edge panels can be delivered with preinstalled bridge railing systems. Special attention must be given to the design of connections due to the propensity of face sheets to delaminate from certain core materials in the presence of through-the-thickness tension. Connection points can be locally reinforced with thicker face sheets, a higher density core, and/or high-strength molded inserts. Thus far, the design process for sandwich decks is not in a code format. Rather, individual decks are designed on a job-by-job basis using finite-element techniques.

Adhesively Bonded Pultruded Shapes

Most currently available commercial decks are constructed using assemblies of adhesively bonded pultruded shapes. Such shapes can be economically produced in continuous lengths by numerous manufacturers using well-established processing methods (see the previous discussion of shapes in this paper). Secondary bonding operations are best done in the manufacturing plant for maximum quality control. Design flexibility in this type of deck is obtained by changing the constituents of the shapes (such as fibers and fiber orientations) and, to a lesser extent, by changing the cross section of the shapes. Due to the potentially high cost of pultrusion dies, however, variations in the cross section of shapes are feasible only if sufficiently high production warrants the tooling investment.

Closed-form, mechanics-based methods for designing section properties of a composite shape are detailed by Barbero et al. (1993). These mechanics concepts can be translated into approximate methods for estimating the equivalent orthotropic plate behavior of decks (Qiao et al. 2000). In this way, deck designs can be adjusted to derive structurally efficient and easy to manufacture pultruded sections. While systematic methods of optimizing pultruded shapes have been developed (Davalos et al. 1996), optimized deck designs are largely derived by trial and error (McGhee et al. 1991).

Several decks constructed with pultruded shapes are shown in Fig. 2. The pultruded shapes are typically aligned transverse to the traffic direction. Each deck design has advantages in terms of stiffness, strength, and field implementation. In laboratory testing,

Table 1. Summary of Deck Characteristics for Two Fabrication Methods

Deck system	Depth (mm)	kg/m² [a]	Dollars/m²	Deflection[b] (reported)	Deflection[c] (normalized)
(a) Sandwich Construction					
Hardcore composites	152–710	98–112	570–1,184	$L/785$[d]	$L/1{,}120$
KSCI	127–610	76[e]	700	$L/1{,}300$[f]	$L/1{,}300$
(b) Adhesively Bonded Pultrusions					
DuraSpan	194	90	700–807	$L/450$[g]	$L/340$
Superdeck	203	107	807	$L/530$[h]	$L/530$
EZSpan	229	98	861–1,076	$L/950$[i]	$L/950$
Strongwell	120–203	112	700[j]	$L/605$[k]	$L/325$

[a]Without wearing surface.

[b]Assumes plate action.

[c]Normalized to HS20+IM for a 2.4-m center-to-center span between supporting girders.

[d]HS20+IM loading of a 203-mm-deep section at a center-to-center span between girders of 2.7 m.

[e]For a 203-mm-deep deck targeted for RC bridge deck replacements.

[f]HS20+IM loading of a 203-mm-deep deck at a center-to-center span between girders of 2.4 m.

[g]HS20+IM loading of a 203-mm-deep deck at a center-to-center span between girders of 2.2 m.

[h]HS20+IM loading at a center-to-center span between girders of 2.4 m.

[i]HS20+IM loading at a center-to-center span between girders of 2.4 m.

[j]For a 171-mm-deep deck with a wearing surface under experimental fabrication processes.

[k]HS20+IM loading of a 171-mm-deep section at a center-to-center span between girders of 2 m.

the observed failures in such decks are generally by local punching shear and crushing or large-scale delamination of the shapes constituting the cross section. Local buckling, shearing, or delamination of internal stiffeners under concentrated wheel loads can also contribute to a loss in overall stiffness (GangaRao et al. 1999; Harik et al. 1999). Stitching and other forms of out-of-plane reinforcement are possible means of mitigating delamination.

Materials in FRP decks differ primarily in fiber architecture and resin type. Polyester resins are favored for their low cost, although vinylester resins are preferred in very moist environments (Pethrick et al. 2000). Woven and stitched fabrics are often employed (DuraSpan and Superdeck) for precise placement of multiaxial reinforcement for improved delamination resistance. EZSpan employs through-the-thickness braided preforms as the reinforcement for the triangular tubes.

The square plate tube and plate deck shown in Fig. 2 is a precommercial design composed of off-the-shelf shapes typical of many of the basic pultrusion companies (Strongwell 1999; Hayes et al. 2000b). These commonly stocked shapes are usually composed of continuous strand mat and roving, as it allows for efficient wet-out of the reinforcement and is a cost-effective means to develop a number of different shapes within a product line. Combining off-the-shelf plates and tubes of various sizes provides varied sections with performance suited to particular application requirements. A similar deck system was used by Bank et al. (2000) as the deck for a floating causeway system.

Comparison of Decks

A technical comparison of sandwich and pultruded decks is shown in Table 1. Although cost and stiffness are "system" dependent and a function of the application requirements, each manufacturer was asked *independently* to provide a representative value. Not surprisingly, there is greater flexibility with the sandwich-constructed decks to produce structures of varied depth and therefore stiffness. The mass per unit surface area is typically near 98 kg/m² (20 lb/ft²), with the exception of the KSCI (Kansas Structural Composites, Inc.) corrugated core deck system, for which the reduced weight appears to suggest extra efficiency in the use of materials.

Cost Comparison

In terms of rough cost, \$700/m² (\$65/ft²) appears to be the lower bound for current FRP decks, which corresponds to about \$7/kg (\$3/lb) of material. This cost is greater than the roughly \$322/m² (\$30/ft²) typically quoted for the construction of a new bridge or a deck replacement with conventional materials (Lopez-Anido 2001). However, the higher costs of FRP decks can be absorbed in certain conditions, particularly when a complete reconstruction is necessary in the absence of a lightweight deck alternative. It remains to be determined if the higher initial cost of FRP decks can be justified based on other economic considerations.

Comparison of Deflections

Although limited field experience and concerns over costs have slowed the introduction of FRP decks into mainstream bridge applications, the specifications for deflections have presented the greatest number of questions in the design of these systems. As indicated by the normalized deflections in Table 1 for decks of about 203-mm depth, under HS2O+IM loading (AASHTO 1998), there is no current consensus on deck deflections by the manufacturers. The discrepancy can be attributed to the way in which FRP bridge decks are currently designed—i.e., on a case-by-case basis. However, the uncertainty in defining deflection limits is also present in existing design guidelines for conventional structures, as discussed next.

In section 2 of the AASHTO load and resistance factor design (LRFD) specifications (AASHTO 1998), deflection limits for steel, aluminum, and concrete constructions under live loads are provided as *optional*. The criteria are stated as optional because, at present, there are no definitive guidelines for the limits of tolerable static deflection or dynamic motion due to vehicular traffic (Taly 1998). Under general vehicular loads, the deflection of a structural element (i.e., a bridge deck) is limited to the span length divided by 800 (span/800). The deflection of an orthotropic (steel) plate deck is limited to the span length divided by 300 (span/300). For RC bridge decks, the approach for controlling deflections is indirect. In particular, a minimum depth [$t_{\min}$ (ft)] is stated in Eq. (1), where the span is in feet

$$t_{\min}=\frac{1.2(\text{span}+10)}{30} \tag{1}$$

The commentary to the AASHTO LRFD specification states that the purpose of the above criteria is twofold—(1) to prevent excessive deflections that may cause damage to the wearing surfaces applied to bridge decks; and (2) to provide for rider comfort. At present, no criteria are given for FRP composite constructions.

For the time being, FRP bridge deck designers quantify deck performance in terms of criteria developed for conventional materials. Further experience will determine if these criteria are appropriate and sufficient for design purposes or if other criteria unique to FRP decks will be needed.

Future Challenges

A relatively large number of FRP decks are already in service (GangaRao et al. 1999; Harik et al. 1999; Temeles et al. 2000) and several others are scheduled for installation in the near future (Davalos et al. 2001). Also, there exists growing interest in the future of these structures. However, several technical needs and questions must be addressed, as follows: (1) development of design standards and guidelines; (2) efficient design and characterization of panel-to-panel joints and attachment of decks to stringers; (3) fatigue behavior of panels and connections; (4) durability characteristics under combined mechanical and environmental loads; (5) failure mechanisms and ultimate strength, including local and global buckling modes; and (6) efficiency and durability of surface overlays (e.g., polymer concrete) and application of hot-mix asphalt in relation to glass-transition temperature of the polymer. In addition, the appropriate implementation of crash-tested guardrails remains an open question when considering the variability in the deck designs. Recently, progress has been made to address these concerns for specific systems (*Product* 2000).

The situation facing the FRP bridge deck industry is not dissimilar to that faced by previous industries—such as steel and concrete—upon the introduction of new materials to a well-entrenched marketplace. When iron was first introduced as a building material, it was fashioned into shapes that resembled timber. Perhaps the FRP decks of tomorrow will evolve to take fuller advantage of the material properties and manufacturing methods of FRP materials as experience and comfort with the material grow.

Internal Reinforcements

Introduction

Non-prestressed and prestressed internal FRP reinforcements for concrete have been under development since as early as the 1960s in the United States (Dolan 1999) and the 1970s in Europe (Taerwe and Matthys 1999) and Japan (Fukuyama 1999), although the overall level of research, demonstration, and commercialization has increased markedly since the 1980s. FRP reinforcements have been used primarily in concrete structures requiring improved corrosion resistance or electromagnetic transparency. The scope of the remainder of this discussion on internal reinforcements includes products, structural behavior, applications, and future directions.

Products

The main differences between non-prestressed and prestressed FRP reinforcements are the level of stress and, correspondingly, the type of constituent FRP materials chosen for the application. Low-cost E-glass FRPs are generally chosen for non-prestressed applications, whereas high-strength carbon and aramid fiber FRPs are preferred for prestressed applications because of their capability of sustaining much higher stresses over the design life. Thermosetting resins such as vinylester and epoxy are the predominant polymers chosen for internal FRP reinforcements on account of their excellent environmental resistance, although affordable thermoplastic resins are recently gaining attention due to their potential for being heated and bent in the field.

Internal FRP reinforcements have been fabricated in a variety of one-dimensional and multidimensional shapes (Nanni 1993). To date, most commercially prefabricated multidimensional reinforcements are orthogonal, two-dimensional grids, although three-dimensional grids of various configurations have been proposed for certain precast structures. As with steel reinforcements, multidimensional FRP reinforcements can also be fabricated onsite by hand placement and tying of one-dimensional shapes.

One-dimensional FRP reinforcements are typically made by the pultrusion process or a close variant such as pull-forming. In such cases, the fibers are impregnated with resin, pulled through a forming die that compacts and hardens the material, and then coiled or cut to a prescribed length. To enhance the bond with concrete, surface deformations are applied to the bar before hardening by one or more of the following representative methods: (1) wrapping of one or more tows of fibers along the length of the bar; (2) molding of whisker reinforced ribs along the length of the bar; (3) wrapping of a textured release film along the length of the bar for the later removal and creation of a complementary impression in the bar; and (4) bonding of fine aggregate to the surface of the bar. In addition, bundles of tight-packed small-diameter FRP rods can be twisted to form a strand, as is commonly done with steel prestressing strands. Cosenza et al. (1997) review a number of one-dimensional FRP bar products. Although currently employed fibers in FRP reinforcements behave in a linear-elastic fashion to failure, developmental FRP reinforcements promise "pseudoductility," or graceful failure, by incorporating fibers of disparate ultimate strains or orientations in the reinforcement (Somboonsong et al. 1998). It is possible to incorporate an internal strain-sensing capability in pultruded FRP products as well (Benmokrane et al. 2000; Bakis et al. 2001).

Grid reinforcements have been made by winding resin-impregnated bundles of fibers into prescribed two- and three-dimensional shapes using a variety of manufacturing processes (Nanni 1993). The grids are often used as flat, two-dimensional flexural reinforcement in slabs or three-dimensional cages for combined shear and axial reinforcement in beams. Off-the-shelf pultruded shapes can also be mechanically joined with proprietary connection devices to create preformed, multidimensional grid reinforcements (Bank and Xi 1993). The joints of FRP grids dominate bond stiffness and strength, in effect providing a periodically bonded reinforcement system in cases where minimal bonding exists between the cross-over points (Matthys and Taerwe 2000).

Structural Behavior

Design Philosophy

Although analyses for flexural and shear capacities draw on many of the same assumptions used for steel reinforcement, significant differences between the material properties and mechanical behavior of FRP and steel necessitate a shift away from conventional concrete design philosophy. In particular, the linear-elastic stress-strain characteristic of most FRP composites (1–3% ultimate strain) implies that FRP-reinforced concrete design procedures must account for inherently less ductility than that exhibited by conventionally reinforced concrete.

Currently, FRP-reinforced concrete is designed using limit-states principles to ensure sufficient strength (typically based on some form of load and resistance factor design), to determine the governing failure mode, and to verify adequate bond strength. Serviceability limit states such as deflections and crack width, stress levels under fatigue or sustained loads, and relaxation losses (for prestressed concrete) are then checked. Although serviceability criteria are usually applied after strength design, relatively lower (especially for glass FRP and aramid FRP) elastic moduli mean that serviceability criteria will usually control the design.

Flexure

Flexural behavior is the best understood aspect of FRP-reinforced concrete, with basic principles applying regardless of member configuration, reinforcement geometry, or material type. Two possible flexural failure modes prevail. Sections with smaller amounts of reinforcement fail by FRP tensile rupture, while larger amounts of reinforcement result in failure by crushing of the compression-zone concrete prior to the attainment of ultimate tensile strain in the outermost layer of FRP reinforcement. The absence of plasticity in FRP materials implies that underreinforced flexural sections experience a sudden tensile rupture instead of a gradual yielding, as in the case with steel reinforcement. Thus, the concrete crushing failure mode of an overreinforced member is somewhat more desirable, due to enhanced energy absorption and greater deformability leading to a more gradual failure mode. Member recovery is essentially elastic with little or no energy dissipation resulting from large deformations.

Nominal flexural capacity is calculated from the constitutive behaviors of concrete and FRP reinforcement using strain compatibility and internal force equilibrium principles, assuming the tensile strength of the concrete is negligible, a perfect bond exists between the concrete and FRP, and strain is proportional to the distance from the neutral axis. The form of the analytical expression will depend upon the prevailing failure mode. The Whitney rectangular stress block is adequate for flexural capacity prediction when crushing of compression-zone concrete occurs in overreinforced sections, provided that strain compatibility is used to determine FRP tensile forces. If FRP tensile rupture controls failure, the Whitney stress block may not be applicable, unless compression-zone concrete is at near-ultimate conditions. An equivalent stress block that approximates the actual stress distribution in the concrete at FRP rupture can be used, or the moment capacity can be determined using an estimated tension force moment arm. Compression-zone FRP reinforcement is not considered effective for increasing moment capacity, enhancing ductility, or reducing long-term deflections.

For steel-reinforced concrete, ductility can be defined as the ratio of total deformation (curvature or deflection) at failure to deformation at yielding. Members with ductility ratios of four or more exhibit significant signs of distress prior to failure. As FRP reinforcement does not yield, alternate means of quantifying the warning signs of impending failure must be used. A variety of indices to measure pseudoductility have been proposed, including deformability indices, defined as the ratio of ultimate deflection to service-load deflection or ultimate curvature to service-load curvature (or curvature at a specified concrete strain level). Deformability ratios of about eight have been reported for overreinforced beams with glass FRP bars (GangaRao and Vijay 1997). The Canadian Highway Bridge Design Code uses an overall performance factor (*J* factor), computed as the ratio of the product of moment and curvature at ultimate to moment and curvature at a concrete strain of 0.001 (corresponding to the concrete proportional limit). The Canadian code specifies minimum acceptable values for this performance index of four for rectangular sections and six for T sections (Bakht et al. 2000). Another approach considers the magnitude of the net tensile strain in the outermost layer of FRP bars as the concrete compressive strain reaches the ultimate limit state. When the net tensile strain is 0.005 or greater, the section is ‘‘tension-controlled’’ and a lower resistance factor is required to compensate for the suddenness of FRP tensile rupture (ACI Committee 440 2001).

For overreinforced members, confinement of compression-zone concrete will increase the concrete ductility and thus the member deformability. Prestressed beams with unbonded carbon FRP tendons exhibit bilinear moment-curvature behavior with considerable rotation at failure. The large rotation capacity allows moments to redistribute and energy to be stored, but as energy is not dissipated, the members are not truly ductile. Typically, sections prestressed with bonded tendons do not achieve unbonded rotation capacities, although moment capacities may be greater. Possible alternatives are partial prestressing or partially bonded tendons (Lees and Burgoyne 1999). Anchors and connectors for FRP tendons differ from those used for steel tendons due to the anisotropic strength characteristics of FRP materials with highly oriented fibers. The most successful anchors for FRP tendons minimize localized transverse and shear-stress concentrations in the tendon by the use of gripping elements with tailored stiffness and geometry (Nanni et al. 1996).

Deflections and Cracking

Deflections and crack widths are typically larger in FRP-reinforced concrete beams and slabs (especially glass FRP) than in steel-reinforced concrete beams due to FRPs’ lower elastic modulus. Limits on deflection or crack width frequently control designs and are usually satisfied by using overreinforced sections. Deflection prediction equations developed for steel-reinforced concrete typically underestimate immediate deflections, with disparities increasing as the load approaches ultimate. Such behavior correlates with observations that crack patterns at lower load levels are similar to those of steel-reinforced sections, but as loads increase beyond the service level, crack spacing decreases and crack width increases relative to steel reinforcement. Various modified expressions for the effective moment of inertia have been proposed for use with FRP (Masmoudi et al. 1998).

Creep and shrinkage behavior in FRP-reinforced members is similar to that in steel-reinforced members. American Concrete Institute (ACI) code equations for long-term deflection can be used for FRP reinforcement, with modifications to account for differences in concrete compressive stress and the particular elastic modulus and bond characteristics of the FRP reinforcement (ACI Committee 440 2001). Compression-zone FRP reinforcement does not reduce long-term deflections.

Shear

The concrete contribution to shear strength is reduced in beams with FRP longitudinal reinforcement because of smaller concrete compression zones, wider cracks, and smaller dowel forces. A reduction factor proportional to the modular ratio, $E_{\mathrm{FRP}}/E_{\mathrm{steel}}$, is typically applied to concrete shear contribution equations for conventional beams, although such an approach underestimates the shear strength in flexural members with larger amounts of FRP longitudinal reinforcement (Michaluk et al. 1998).

One-way deck slabs reinforced with glass FRP bars typically fail in diagonal tension shear, as opposed to flexure. Large deflections and crack widths provide an adequate warning of impending failure. The $E_{\mathrm{FRP}}/E_{\mathrm{steel}}$ reduction factor underestimates the shear strength of deck test panels by a factor of three (Deitz et al. 1999). In two-way test slabs, punching shear failures have been observed. The shear capacity in such cases can be predicted using a nonlinear finite-element analysis.

In beams with FRP stirrups, shear failures occur either by FRP rupture at the bend points or by shear-compression failure in the shear span of the beam. Failure from stress concentrations at stirrup bends may limit the effective capacity to as little as 35% of the strength parallel to the fibers (Shehata et al. 2000). Multidirectional FRP grids can also be used as shear reinforcement (Bank and Ozel 1999; Razaqpur and Mostofinejad 1999).

Bond and Development of Reinforcement

Differences in FRP reinforcing products make bond characteristics quite variable. In some cases, the bond strength is comparable to or greater than that in steel reinforcement, while other products exhibit less bond strength (Cosenza et al. 1997). Bond strength is largely independent of concrete strength for smooth and sand-coated rods and twisted strands, provided there is adequate cover to prevent longitudinal cracking. Bars with molded deformations and helical wraps obtain bond from mechanical interlock, and thus have relatively good bond performance and more dependency on the concrete cover. Local bond-slip relations have been applied to glass FRP reinforcements of different diameters and embedment lengths (in pullout tests), and were found to match experimental results reasonably well while providing predictive capability for bars of arbitrary diameter and embedment length (Focacci et al. 2000). Development lengths for glass FRP reinforcement bars by pullout failure are generally in the range of 26–37 times the bar diameter (ACI Committee 440 2001).

In prestressed concrete, transfer lengths of FRP tendons have been noted to be less than approximately 50 times the tendon diameter. Development length in prestressed concrete beams depends on additional factors besides the diameter, such as the difference between the stresses in the tendon initially and at failure of the beam (Lu et al. 2000).

Applications

Bridges

During the period from 1980 through 1997, there were at least 32 documented bridge projects (20 with vehicular traffic) using concrete with FRP reinforcement (*A look* 1998). Of these, six bridges were constructed in Europe (primarily in Germany), seven in North America, and 19 in Japan. Prestressed applications predominated, including 11 bridges constructed with pretensioned FRP-reinforced concrete girders and 10 with posttensioned girders. Five bridges utilized FRP for prestressed slabs, and 11 had FRP rebar in the deck slab or beams. Several bridges utilized more than one type of FRP reinforcement. In general, carbon FRP was used for prestressed reinforcement, although there were also glass and aramid FRP applications. Non-prestressed reinforcement was typically glass FRP, although carbon FRP was also used.

Reinforced Concrete

FRP reinforcing bars have been used in magnetic resonance imaging facilities, an aircraft station compass calibration pad, tunnel boring operations, chemical plants, electrical substations, highway barriers, and a variety of seafront structures. Two-dimensional glass FRP grids have been used in RC decks and tunnel linings, while a demonstration project on FRP-reinforced underground chambers is currently under way in Canada. Glass FRP dowel bars appear feasible for load transfer across highway pavement joints, provided the dowel diameter increases and/or the dowel spacing decreases relative to designs with steel bars. Performance comparable to that of epoxy-coated steel dowels has been demonstrated (Davis and Porter 1999).

Prestressed Concrete

Bridges comprise the majority of prestressed FRP applications. Piles, piers, Maglev guideway beams, and airport pavements are other examples. Deck slab systems devoid of steel reinforcement and utilizing carbon FRP prestressed tendons in the transverse direction are under investigation. The system relies on compressive membrane action to increase punching shear failure loads and to limit deflections. Also under development are precast double-T panels reinforced with glass FRP bars and prestressed internally and externally with carbon FRP strands that require no shoring or forms for installation. The double-T panels are used in a multispan prestressed concrete bridge system utilizing internal bonded tendons and continuous externally draped tendons.

Future Directions

Applications of FRP reinforcement in major and innovative concrete structures have been facilitated by the development of ''smart structure'' sensor technology, thus alleviating the lack of performance data for FRP-reinforced structures. Canada's Intelligent Sensing for Innovative Structures (ISIS) project targets the development of smart sensor technology in combination with research on FRP infrastructure applications. As long-term data become available, designers will feel more comfortable specifying internal FRP reinforcements for concrete roadways and buildings. The brisk development of design guides and codes around the world will also speed the insertion of FRP reinforcements in construction practice.

Externally Bonded Reinforcements

Background

Due to the aging of infrastructure and the need for upgrading to meet more stringent design requirements, structural repair and strengthening have received considerable emphasis over the past two decades throughout the world. At the same time, seismic retrofit has become at least equally important, especially in earthquake-prone areas. State-of-the-art strengthening and retrofit techniques increasingly utilize externally bonded FRP composites, which offer unique properties in terms of strength, lightness, chemical resistance, and ease of application. Such techniques are most attractive for their fast execution and low labor costs.

Composites for structural strengthening are available today in the form of precured strips or uncured sheets. Precured shells meant to strengthen columns are also available, but are not treated further in this discussion. Precured strips are typically 0.5–1.5 mm (0.02–0.06 in.) thick and 50–200 mm (2–8 in.) wide, and made of unidirectional fibers (carbon, glass, aramid) in an epoxy matrix. Uncured sheets typically have a nominal thickness of less than 1 mm (0.04 in.), are made of unidirectional or bidirectional fibers (often called fabrics, in the latter case) that are either preimpregnated or in situ impregnated with resin, and are highly conformable to the surface onto which they are bonded. Bonding is typically achieved with high-performance epoxy adhesives.

Historically, composites were first applied as flexural strengthening materials for RC bridges (Meier 1987; Rostasy 1987) and as confining reinforcement of RC columns (Fardis and Khalili 1981; Katsumata et al. 1987). Developments since the first research efforts in the mid-1980s have been tremendous. The range of applications has expanded to include masonry structures, timber, and even metals. The number of applications involving composites as strengthening/repair or retrofit materials worldwide has grown from just a few 10 years ago to several thousand today. Various types of structural elements have been strengthened, including beams, slabs, columns, shear walls, joints, chimneys, vaults, domes, and trusses.

Strengthening of Reinforced Concrete Structures with Fiber-Reinforced Polymer

General

Composites have gained widespread use as strengthening materials for RC structures in applications where conventional strengthening techniques may be problematic. For instance, one of the most popular techniques for upgrading RC elements has traditionally involved the use of externally epoxy-bonded steel plates. This technique is simple, cost-effective, and efficient, but it suffers from the following: deterioration of the bond at the steel-concrete interface caused by the corrosion of steel; difficulty in manipulating the heavy steel plates at the construction site; need for scaffolding; and limited delivery lengths of steel plates (in the case of flexural strengthening of long elements). As an alternative, the steel plates can be replaced by FRP strips or sheets. Another common strengthening technique involves the construction of RC, shotcrete, or steel jackets. Jacketing is quite effective as far as strength, stiffness, and ductility are concerned, but it increases the cross-sectional dimensions and dead loads of the structure, is labor intensive, obstructs occupancy, and provides RC elements with a potentially undesirable stiffness increase. Alternatively, FRP sheets may be wrapped around RC elements, resulting in considerable increases in strength and ductility without an excessive stiffness change. Furthermore, FRP wrapping may be tailored to meet specific structural requirements by adjusting the placement of fibers in various directions (ACI Committee 440 1996). An important point concerning the design of external FRP reinforcement is that, in order to maintain a sufficient safety factor in case of an accidental situation (e.g., FRP destruction due to fire), the degree of strengthening (ultimate capacity of the strengthened element divided by that of the unstrengthened element) should be limited, unless proper means of protecting the external reinforcement from loss are taken.

Flexural Strengthening

Flexural strengthening of RC elements using composites may be provided by epoxy bonding the materials to portions of the elements in tension, with fibers parallel to the principal stress direction. Well-established strengthening procedures for RC structures may be followed, provided that special attention is paid to issues related to the linear-elastic nature of FRP materials and the bond between the concrete and FRP.

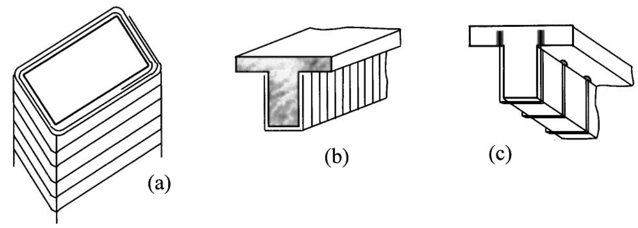

Fig. 3. Shear strengthening: (a) closed jacket applied to column; (b) open jacket applied to beam; (c) strips with end anchorage

Central to the analysis and design of FRP-strengthened RC elements is the identification of all of the possible failure modes. These include the following modes: (1) steel yielding followed by FRP fracture; (2) steel yielding followed by concrete compressive crushing (while the FRP is intact); (3) concrete compressive crushing; (4) FRP peel-off at the termination or cutoff point, due to shear failure of the concrete; (5) FRP peel-off initiating far from the ends, due to inclined shear cracks in the concrete; (6) FRP peel-off at the termination point or at a flexural crack due to high tensile stresses in the adhesive; and (7) debonding at the FRP-concrete interface in areas of concrete surface unevenness or due to faulty bonding. Of the above, mode (2) is the most desirable. Modes (4) and (5) will be activated when the element's shear strength is approached; hence, they may be prevented by providing shear strengthening. Mode (6) can be suppressed by limiting the tensile strain in the FRP to a value of roughly 0.008. Finally, mode (7) may be avoided by proper quality control. Slip at the concrete-FRP interface may be ignored in design.

Shear Strengthening

Shear strengthening of RC elements may be provided by epoxy-bonding FRP materials with fibers as parallel as practically possible to the principal tensile stresses. Depending on accessibility, strengthening can be provided either by partial or by full wrapping of the elements, as illustrated in Fig. 3.

The effectiveness of the external FRP reinforcement and its contribution to the shear capacity of RC elements depend on the mode of failure, which may occur either by peeling-off through the concrete (near the concrete-FRP interface) or by FRP tensile fracture at a stress that may be lower than the FRP tensile strength (e.g., because of stress concentrations at rounded corners or at debonded areas). Whether peeling-off or fracture will occur first depends on the bond conditions, the available anchorage length and/or the type of attachment at the FRP termination point (full wrapping versus partial wrapping, with or without mechanical anchors), the axial rigidity of the FRP, and the strength of the concrete. In many cases, the actual mechanism is a combination of peeling-off at certain areas and fracture at others. In light of the above, the load carried by FRP at the ultimate limit state in shear of the RC element is extremely difficult to quantify based on rigorous analysis.

According to a simplified method of calculation of shear force in external FRP reinforcement, the FRP material is assumed to carry only normal stresses in the principal FRP material direction. It is also assumed that, in the ultimate limit state in shear, the FRP develops an *effective strain* (in the principal material direction),

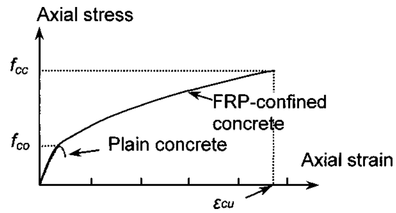

Fig. 4. Axial stress-strain response of FRP-confined concrete versus plain concrete

$\varepsilon_{f,e}$, which is generally less than the tensile failure strain. For RC elements with a rectangular cross section, the aforementioned effective strain decreases as the axial rigidity of the FRP (that is, the product of the FRP shear reinforcement ratio times its elastic modulus in the principal material direction) increases and as the concrete tensile strength decreases (Triantafillou and Antonopoulos 2000). Moreover, keeping in mind that large values of $\varepsilon_{f,e}$ correspond to considerable opening of diagonal cracks, to the extent that the contribution of concrete shear-resisting mechanisms is reduced by degraded aggregate interlock, $\varepsilon_{f,e}$ should be limited to a value on the order of 0.004–0.005 for the case of fibers perpendicular to the longitudinal axis of the RC element.

In the case of elements with a circular cross section (e.g., wrapped circular columns), experimental and analytical studies have demonstrated that FRP jackets with fibers in the circumferential direction significantly increase both the strength and the ductility in the presence of monotonic or cyclic lateral loads. The contribution of FRP to shear resistance in such cases may be estimated by taking $\varepsilon_{f,e}$ approximately equal to 0.004 (Priestley and Seible 1995).

Confinement

The enhancement of confinement in structurally deficient RC columns in seismically active regions of the world has proven to be one of the most significant early applications of FRP materials in infrastructure applications. Proper confinement increases the rotational capacity (and hence the ductility) in plastic hinge regions and prevents debonding of the internal reinforcement in lap splices. Confinement may be beneficial in nonseismic zones too, where, for instance, survivability of explosive attacks is required (Crawford et al. 1997) or the axial load capacity of a column must be increased due to higher vertical loads (e.g., increased traffic on a bridge). In any case, confinement may be provided by wrapping RC columns with FRP materials (prefabricated jackets or in situ cured sheets), in which the principal fiber direction is circumferential.

In *circular* columns, an FRP wrap effectively curtails the lateral expansion of concrete shortly after the unconfined strength is reached. It then reverses the direction of the volumetric response, and the concrete responds through large and stable volume contraction (this is not the case with steel confinement jackets, where yielding is associated with unstable volumetric expansion). As a result, the stress-strain response of FRP-confined concrete is characterized by a distinct bilinear response with a sharp softening at a stress level near the strength of unconfined concrete, f_{co} (Fig. 4). After this softening point, the tangent stiffness stabilizes at a nearly constant value. The ultimate state (f_{cc}, ε_{cu} in Fig. 4) is characterized by tensile failure of the wrap. At failure, the tensile stress in the FRP wrap is generally less than the uniaxial tensile strength of the FRP material due to triaxial stresses and variations in the quality of installation that could lead to unequal load sharing among fibers, misalignment, and damaged fibers at sharp corners and local protrusions.

From the arguments discussed above, it is realized that reliable models for FRP-confined concrete must account for a number of parameters, including: (1) the circumferential stiffness of the FRP; (2) the continuous effect of the restraint provided by the FRP on the dilation tendency of the concrete; and (3) the composite action of the FRP-concrete column and the FRP-concrete interaction, based on micromechanics. As a simplified approach, one may assume a maximum compressive axial strain in the concrete at the ultimate limit state of approximately 0.01 and a fixed Poisson's ratio of approximately 0.5 to determine the confinement effect.

Confinement of RC columns is less effective if the cross section is rectangular. In this case, the confining stress is transmitted to the concrete at the four corners of the cross section and increases with the corner radius. The confinement model in this case must account for a reduced volume of fully confined concrete (Mirmiran et al. 1998).

Masonry

Recent years have seen proposals and practical applications that use composites as alternative strengthening materials for masonry structures, including those of considerable historical importance. The general approach is to epoxy-bond FRP strips to the surface of masonry in locations and directions dictated by the principal tensile stress field (Schwegler 1994).

In terms of design, masonry strengthened with FRP strips or sheets may be treated in the same manner as RC, following the procedures of modern design codes (Triantafillou 1998). The analysis of simple cases has led to the following conclusions: (1) When out-of-plane bending dominates (e.g., as in the case of upper levels of masonry buildings), horizontally applied FRP may offer a considerable strength increase; (2) in the (rather rare) case of in-plane bending, the amount and distribution of reinforcement are of high importance; high reinforcing ratios placed near the highly stressed zones give a significant strength increase; (3) the achievement of full in-plane flexural strength depends on the proper anchorage of the strips at their ends, in the sense that short anchorage lengths and/or the absence of clamping at the strips' curtailment positions may result in premature failures through peeling-off beneath the adhesive (as in the case of RC); and (4) the in-plane shear capacity of masonry walls strengthened with FRP may be quite high, too, especially in the case of low axial loads.

FRP composites can also be applied as confinement reinforcement to masonry using unbonded strips that are color-matched with the underlying masonry structure, and can be removed if necessary at a later time (Triantafillou and Fardis 1993). Recent applications include strengthening of vaults in old masonry buildings either from below, using transparent glass FRP fabrics, or from above, using epoxy-bonded FRP sheets in a gridlike pattern (Borri et al. 2000).

Timber and Metals

The high potential of FRP strips or sheets to increase the strength (flexural or shear), stiffness, and ductility of *timber* beams and/or columns has been demonstrated in various research studies and quite a few field applications (Plevris and Triantafillou 1992). Moreover, FRP wrapping has been used as an effective means of enhancing the durability of timber elements (Qiao et al. 1998).

Research and development related to FRP combined with *metals* used in construction (e.g., steel, cast iron, and wrought iron) have started relatively recently (Karbhari and Shulley 1995). High-stiffness sheets (such as carbon) may enhance the mechanical properties of metallic elements while offering certain other advantages, such as the low weight of bonded material, the easy applicability, and the ability to effectively cover areas with high bolt or rivet congestion.

Special Strengthening Techniques

A number of special techniques related to the application of composites as externally bonded reinforcement need to be mentioned, although space limitations prevent detailed descriptions.

- *Prestressed strips*. Prestressing of composite strips prior to the bonding procedure results in a more economical use of materials (Triantafillou et al. 1992), but requires special clamping devices.
- *Automated wrapping and curing*. Wrapping of columns (or other vertical elements, such as chimneys) with flexible FRP sheets is possible today by using automated machinery. The machinery can also apply heat and vacuum to assist curing.
- *Fusion-bonded pin-loaded straps*. A number of nonlaminated thermoplastic FRP layers that may move relative to each other when loaded are applied in a single, continuous, thin tape that is fusion-bonded (welded) to itself for anchorage (Winistoerfer and Mottram 1997).
- *Placement inside slits*. FRP strips or even rods may be bonded into slits, which are cut into the concrete or into masonry mortar joints (Blaschko and Zilch 1999; Tinazzi et al. 2000).
- *Prefabricated shapes*. Prefabricated angles or shells may be externally bonded to structures.
- *Mechanically fastened FRP strips*. Specially designed, precured FRP strips can be rapidly attached to concrete beams for flexural strengthening using powder-actuated fasteners (Lamanna et al. 2001).

Concluding Remarks

The use of advanced composites as external reinforcement of concrete and other structures has progressed well in the past decade in selective applications where their cost disadvantage is outweighed by a number of benefits. There are clear indications that the FRP strengthening technique will increasingly continue to be the preferred choice for many repair and rehabilitation projects involving buildings, bridges, historic monuments, and other structures.

Codes and Standards

Introduction

Due to the importance of controlling risk in matters of public safety, standards and codes for FRP materials used in civil structures have been in development since the 1980s. FRP materials warrant separate treatment in standards and codes on account of their lower modulus and ductility in comparison with conventional materials such as metals. Without standards and codes, it is unlikely that FRP materials could make inroads beyond limited research and demonstration projects. Standardized test methods and material identification schemes minimize uncertainty in the performance and specification of FRP materials. Codes allow structures containing FRP materials to be designed, built, and operated with safety and confidence. This section describes the standard and code development activities in Japan, Canada, the United States, and Europe. The main accomplishments of these activities, to date, pertain to the use of FRP materials for the reinforcement of new structures and for the repair and retrofit of existing structures.

Japan

Efforts to prescribe specifications for the design and construction of concrete structures with FRP reinforcements started in Japan in the 1980s. Examples of specifications for internal reinforcements completed by the middle of the 1990s are as follows:

1. Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials.
2. Guideline for Structural Design of FRP-Reinforced Concrete Buildings in Japan.
3. Design Methods for Prestressed FRP-Reinforced Concrete Building Structures.

Item 1, referred to here as the recommendation, was published by the Japan Society of Civil Engineers (JSCE) in 1997, and is intended for concrete structures other than buildings (Machida 1997b). The recommendation includes quality specifications and test methods for FRP materials, as well as recommendations for design and construction with FRP materials. The quality specifications for FRP reinforcements define the required characteristics and properties of the reinforcements, and serve to guide the development of new reinforcements for practical applications. Reinforcement characteristics addressed include fiber type and reinforcement configuration. Specified properties include the volume ratio of axial fibers, reinforcement cross-sectional area, guaranteed tensile strength, tensile modulus, elongation, creep rupture strength, relaxation rate, and durability, among others. Most of the specified properties are determined based on tests described in the recommendation. Further details are also given by Uomoto et al. (1997).

The design and construction recommendations in item 1 above are based on the JSCE Standard Specification for Design and Construction of Concrete Structures, which is for concrete structures in general (JSCE 1986a,b). The recommendations for construction in item 1 deal with issues such as FRP constituent materials, FRP storage and handling, assembly and placement of FRP reinforcements, precautions in concrete placing and tendon jacking, and quality control. Some details covered in the recommendation have also been presented elsewhere in the literature (Machida et al. 1995; Machida 1997a; Tsuji et al. 1997).

Items 2 and 3 listed above are intended for building structures. These specifications were developed in 1993 as the final output of the research and development project, ''Effective Utilization of Advanced Composite on Construction,'' sponsored by the Ministry of Construction of the Japanese government. Item 2 adopts a limit state–based design method with specific provisions somewhat different from those of item 1. Details can be found in the English-language publications by Sonobe et al. (1995, 1997).

After the Hyogoken-Nanbu earthquake in 1995, the use of externally bonded carbon fiber sheets for seismic retrofitting of RC piers and columns greatly increased in Japan. Prior to this time, the use had been mainly for repair. Aramid fiber sheets for retrofit and repair were also developed at this time.

Design guidelines for the application of FRP sheets to highway bridge piers or railway viaduct columns are as follows:

1. Proposed Design and Construction Guidelines for Retrofitting of Reinforced Concrete Piers Using Carbon (Aramid) Fiber Sheets by the Japan Road Association and
2. Design and Construction Guidelines for Seismic Retrofitting of Railway Viaduct Columns Using Carbon (Aramid) Fiber Sheets by the Railway Technical Research Institute (1996a,b).

These guidelines include equations for evaluating the effects of FRP sheets on shear capacity and ductility. Similar guidelines have also been prescribed for building columns and center pillars of subway tunnels and bridge decks.

Standard test methods have been developed for FRP sheets by the Japan Concrete Institute (1998). The methods include a test for tensile properties of FRP sheets and a test for bond strength.

Canada

The use of FRP for civil engineering applications in Canada began in earnest in the late 1980s when the Canadian Society for Civil Engineers created a Technical Committee on the Use of Advanced Composite Materials in Bridges and Structures. Efforts of the committee were supported by the Canadian federal government, and led to the establishment of the Network on Advanced Composite Materials in Bridges and Structures in 1992. The network sponsored several missions in Japan, Europe, and the United States, and documented the findings in state-of-the-art reports in this field (Mufti et al. 1991a,b). In 1995, the Canadian federal government established the Network of Centers of Excellence on Intelligent Sensing for Innovative Structures. One area of focus of ISIS is the use of FRP materials for new structures and the rehabilitation of existing structures. ISIS published several design guidelines on externally bonded and internal FRP reinforcements, participated in several Code and Standards committees, and sponsored several national and international conferences.

In the year 2000, Canadian Highway Bridge Design Code section 16, ''Fiber Reinforced Concrete,'' was completed (CSA 2000). The French translation is expected to be published in early 2001 (Bakht et al. 2000). The Canadian Standards Association also approved the code, ''Design and Construction of Building Components with FRP in 2002'' (CSA 2002).

United States

The United States has had a long and continuous interest in fiber-based reinforcement for concrete structures. Accelerated development and research activities on the use of these materials started in the 1980s through the initiatives and vision of the National Science Foundation and the Federal Highway Administration, who supported research at different universities and research institutions. In 1991, the ACI established Committee 440, ''FRP Reinforcement.'' The committee published a state-of-the-art report on FRP reinforcement for concrete structures in 1996 (ACI Committee 440 1996). Committee 440 recently produced two documents approved by the Technical Activities Committee for publication in the year 2001. The documents are (1) ''Guide for the design and construction of concrete reinforced with FRP bars'' (ACI Committee 440 2001); and (2) ''Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures.'' The committee is currently working on the following documents: (1) ''Stay-in place structural FRP forms;'' (2) ''Durability of FRP for concrete structures;'' and (3) ''Guide for the design and construction of concrete members prestressed with FRP,'' which are expected to be completed in 2002 and 2003.

Europe

Research on the use of FRP began in Europe in the 1960s. A Pan-European collaborative research program (EUROCRETE) was established in 1993 and ended in 1997. The program was aimed at developing FRP reinforcement for concrete, and included partners from the United Kingdom, Switzerland, France, Norway, and The Netherlands. The International Federation for Structural Concrete [Fédération Internationale du Béton (FIB) 2001] Task Group 9.3, ''FRP Reinforcement for Concrete Structures,'' was convened in 1993 with an aim to establish design guidelines following the format of the Comité Euro-International du Béton–Fédération International de la Précontrainte Model Code and Eurocode 2 (http://allserv.rug.ac.be/~smatthys/fibTG9.3/). Task Group 9.3 is divided into subgroups on material testing and characterization, RC, prestressed concrete, externally bonded reinforcement, and marketing and applications. The task group consists of members representing most European universities, research institutes, and companies involved with FRP reinforcements for concrete. Membership includes representatives from Canada, Japan, and the United States. The task group has completed the development of an FIB bulletin on design guidelines for externally bonded FRP reinforcement for reinforced-concrete structures (FIB 2001). Supporting the work of Task Group 9.3 is a European Union Training and Mobility of Researchers (TMR) Network, ''ConFibreCrete.'' More information about the TMR ConFibreCrete Network can be found at http://www.shef.ac.uk/~tmrnet.

In the United Kingdom, the Institution of Structural Engineers has published an interim guide on the design of RC structures with FRP reinforcement (Institution 1999). Prestressing and externally bonded reinforcements are not addressed in the guide. The guide is closely based on and refers to related British design codes (British 1985, 1990, 1997). The approaches adopted are similar to those under development in Japan, Canada, and the United States.

Future Work on Standards and Codes

From a technical standpoint, the need for specialized standards and codes for FRP materials arises from their substantially different mechanical and physical properties in comparison with conventional construction materials. As the preceding discussion points out, the development of standards and codes for the use of FRP reinforcement with concrete structures is ongoing and is expected to continue in the next several years. Much of this activity is motivated by immediate, obvious needs for improved, economical materials for the repair and retrofit of structures that are obsolete, degraded, or located in seismic zones. In other cases such as new construction, where the need for new materials is not always clear from a short-term economic standpoint, standards and codes will facilitate the use of FRP materials so that additional long-term experience can be accrued. This experience may eventually lead to the realization of promised life-cycle cost benefits of FRP materials by designers and owners of structures. Of the applications covered in this review paper, FRP shapes and bridge decks suffer from the least amount of development of standards and codes. Future research efforts on standards and codes should therefore be increasingly concentrated in these areas.

Conclusion

This paper attests to the many potential applications of FRP composite materials in construction, although the need for brevity prevents all topics from being fully addressed. It can be said that the amount of experience with various forms of FRP construction materials varies in accordance with the perceived near-term economic and safety benefits of the materials. In the case of externally bonded reinforcements, for example, the immediate cost and safety benefits are clear, and adoption of the material by industry is widespread. In other cases where FRP materials are considered to be primary load-bearing components of structures, field applications still maintain a research flavor while long-term experience with the material accumulates. A number of careful monitoring programs of structures with primary FRP reinforcement have been set up around the world and should provide this experience base in the coming years.

Standards and codes for FRP materials and their use in construction are either published or currently being written in Japan, Canada, the United States, and Europe. These official documents are typically similar in format to conventional standards and codes, which should ease their adoption by governing agencies and organizations. The most significant mechanical differences between FRP materials and conventional metallic materials are the higher strength, lower stiffness, and linear-elastic behavior to failure of the former. Other differences such as the thermal expansion coefficient, moisture absorption, and heat and fire resistance need to be considered as well.

The education and training of engineers, construction workers, inspectors, and owners of structures on the various relevant aspects of FRP technology and practice will be crucial in the successful application of FRP materials in construction. However, it should be emphasized that even with anticipated moderate decreases in the price of FRP materials, their use will be mainly restricted to those applications where their unique properties are crucially needed.

References

ACI Committee 440. (1996). ''State-of-the-art report on fiber reinforced plastic (FRP) reinforcement for concrete structures.'' *ACI 440 R-96*, American Concrete Institute, Farmington Hills, Mich.

ACI Committee 440. (2001). ''Guide for the design and construction of concrete reinforced with FRP bars.'' *ACI 440.1 R-01*, American Concrete Institute, Farmington Hills, Mich.

Alampalli, S., O'Connor, J., Yannotti, A. P., and Luu, K. T. (1999). ''Fiber-reinforced plastics for bridge construction and rehabilitation in New York.'' *Materials and Construction: Exploring the connection, Proc., 5th Materials Engineering Congress*, L. C. Bank, ed., ASCE, Reston, Va., 344–350.

American Association of State Highway and Transportation Officials (AASHTO). (1998). *Load and resistance factor design (LRFD) bridge design specifications*, 2nd Ed., Washington, D.C.

Bakht, G. A., et al. (2000). ''Canadian bridge design code provisions for fiber-reinforced structures.'' *J. Compos. Constr.*, 4(1), 3–15.

Bakis, C. E., Nanni, A., Terosky, J. A., and Koehler, S. W. (2001). ''Self-monitoring, pseudo-ductile, hybrid FRP reinforcement rods for concrete applications.'' *Compos. Sci. Technol.*, 61(6), 815–823.

Bank, L. C. (1995). ''How standards will develop markets in building construction.'' *Proc., 50th Annual SPI Con.*, Composites Institute, Society for the Plastics Industry, Cincinnati, 14.1–14.4.

Bank, L. C., et al. (2000). ''Construction of a pultruded composite structure: Case study.'' *J. Compos. Constr.*, 4(3), 112–119.

Bank, L. C., and Ozel, M. (1999). ''Shear failure of concrete beams reinforced with 3-D fiber reinforced plastic grids.'' *Proc., 4th Int. Symposium, Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, C. W. Dolan, S. H. Rizkalla, and A. Nanni, eds., *SP-188*, American Concrete Institute, Farmington Hills, Mich., 145–156.

Bank, L. C., and Xi, Z. (1993). ''Pultruded FRP grating reinforced concrete slabs.'' *Fiber-Reinforced Plastic for Concrete Structures—Int. Symposium*, A. Nanni and C. W. Dolan, eds., *SP-138*, American Concrete Institute, Farmington Hills, Mich., 561–583.

Barbero, E. J., Lopez-Anido, R., and Davalos, J. F. (1993). ''On the mechanics of thin-walled laminated composite beams.'' *J. Compos. Mater.*, 27(8), 806–829.

Benmokrane, B., et al. (2000). ''Use of fibre reinforced polymer reinforcement integrated with fibre optic sensors for concrete bridge deck slab construction.'' *Can. J. Civ. Eng.*, 27(5), 928–940.

Blaschko, M., and Zilch, K. (1999). ''Rehabilitation of concrete structures with CFRP strips glued into slits.'' *Proc., 12th Int. Conf. on Composite Materials*, T. Mussard, ed., International Committee on Composite Materials.

Borri, A., Avorio, A., and Bottardi, M. (2000). ''Theoretical analysis and a case study of historical masonry vaults strengthened by using advanced FRP.'' *Proc., 3rd Int. Conf. on Advanced Composite Materials in Bridges and Structures*, J. L. Humar and A. G. Razaqpur, eds., *ACMBS-3*, Canadian Society for Civil Engineering, Montréal, Québec, 577–584.

British Standards Institute (BSI). (1985). ''Structural use of concrete. Code of practice for special circumstances.'' *BS 8110-2*, London.

British Standards Institute (BSI). (1990). ''Steel, concrete and composite bridges. Code of practice for design of concrete bridges.'' *BS 5400-4*, London.

British Standards Institute (BSI). (1997). ''Structural use of concrete. Code of practice for design and construction.'' BS 8110-1, London.

Canadian Standards Association International (CSA). (2000). ''Canadian Highway bridge design code.'' *CSA-S6-00*, Toronto.

Canadian Standards Association International (CSA). (2002). ''Design and construction of building components with fibre reinforced polymers.'' *CSA-S8-06*, Toronto.

Composite materials handbook (*MIL-HDBK-17*). (2001). ⟨http://www.mil17.org⟩ (August 2001).

Cosenza, E., Manfredi, G., and Realfonzo, R. (1997). ''Behavior and modeling of bond of FRP rebars to concrete.'' *J. Compos. Constr.*, 1(2), 40–51.

Crawford, J. E., Malvar, L. J., Wesevich, J. W., Valancius, J. R., and Aaron, D. (1997). ''Retrofit of reinforced concrete structures to resist blast effects.'' *ACI Struct. J.*, 94(4), 371–377.

Creative Pultrusions. (1999). *Pultex design manual*, ⟨www.creativepultrusions.com⟩ (August 2001).

Dagher, H. J., Schmidt, A. L., Abdel-Magid, B., and Iyer, S. (1997). ''FRP post-tensioning of laminated timber bridges.'' *Evolving Technologies for the Competitive Edge, Proc., 42nd Int. SAMPE Symposium*, Vol. 2, Society for the Advancement of Material and Process Engineering, Covina, Calif., 933–938.

Davalos, J. F., Qiao, P., and Barbero, E. J. (1996). ''Multiobjective material architecture optimization of pultruded FRP I beams.'' *Compos. Struct.*, 35(3), 271–281.

Davalos, J. F., Qiao, P. Z., Xu, X. F., Robinson, J., and Barth, K. E. (2001). ''Modeling and characterization of fiber-reinforced plastic honeycomb sandwich panels for highway bridge applications.'' *J. Compos. Constr.*, 52(3-4), 441–452.

Davis, D., and Porter, M. L. (1999). ''Glass fiber reinforced polymer dowel bars for transverse pavement joints.'' *Proc., 4th Int. Symposium, Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, C. W. Dolan, S. H. Rizkalla, and A. Nanni, eds., *SP-188*, American Concrete Institute, Farmington Hills, Mich., 297–304.

Deitz, D. H., Harik, I. E., and Gesund, H. (1999). ''One-way slabs reinforced with glass fiber reinforced polymer reinforcing bars.'' *Proc., 4th Int. Symposium, Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, C. W. Dolan, S. H. Rizkalla, and A.

Nanni, eds., *SP-188*, American Concrete Institute, Farmington Hills, Mich., 279–286.

Dolan, C. W. (1999). ''FRP prestressing in the USA.'' *Concr. Int.*, 21(10), 21–24.

Fardis, M. N., and Khalili, H. (1981). ''Concrete encased in fiberglass reinforced plastic.'' *ACI J.*, 78(6), 440–446.

Fédération Internationale du Béton (FIB). (2001). ''Externally bonded FRP reinforcement for RC structures.'' *Bulletin 14*, Lausanne, Switzerland.

Fiberline. (1995). *Fiberline design manual*, ⟨www.fiberline.de⟩.

Focacci, F., Nanni, A., and Bakis, C. E. (2000). ''Local bond-slip relationship for FRP reinforcement in concrete.'' *J. Compos. Constr.*, 4(1), 24–31.

Fukuyama, H. (1999). ''FRP composites in Japan.'' *Concr. Int.*, 21(10), 29–32.

GangaRao, H. V. S., Thippeswamy, H. K., Shekar, V., and Craigo, C. (1999). ''Development of glass fiber reinforced polymer composite bridge deck.'' *SAMPE J.*, 35(4), 12–24.

GangaRao, H. V. S., and Vijay, P. V. (1997). ''Design of concrete members reinforced with GFRP bars.'' *Proc., 3rd Int. Symposium, Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, Vol. 1, Japan Concrete Institute, Tokyo, 143–150.

Green, A., Bisarnsin, T., and Love, E. A. (1994). ''Pultruded reinforced plastics for civil engineering structural applications.'' *J. Reinf. Plast. Compos.*, 13(10), 942–951.

Harik, I., et al. (1999). ''Static testing on FRP bridge deck panels.'' *Proc., 44th Int. SAMPE Symposium and Exhibition*, Vol. 2, Society for the Advancement of Material and Process Engineering, Covina, Calif., 1643–1654.

Hayes, M. D., Lesko, J. J., Haramis, J., Cousins, T. E., Gomez, J., and Massarelli, P. (2000a). ''Laboratory and field testing of composite bridge superstructure.'' *J. Compos. Constr.*, 4(3), 120–128.

Hayes, M. D., Ohanehi, D., Lesko, J. J., Cousins, T. E., and Witcher, D. (2000b). ''Performance of tube and plate fiberglass composite bridge deck.'' *J. Compos. Constr.*, 4(2), 48–55.

Institution of Structural Engineers (ISE). (1999). ''Interim guidance on the design of reinforced concrete structures using fiber composite reinforcement.'' *Reference No. 319*, London.

Japan Concrete Institute (JCI). (1998). ''Technical report on continuous fiber reinforced concrete.'' *TC 952*, Committee on Continuous Fiber Reinforced Concrete, Tokyo.

Japan Society of Civil Engineers (JSCE). (1986a). ''Standard specification for design and construction of concrete structures. Part 1 (design).'' *SP1*, Tokyo.

Japan Society of Civil Engineers (JSCE). (1986b). ''Standard specification for design and construction of concrete structures. Part 2 (construction).'' *SP2*, Tokyo.

Johansen, G. E., Wilson, R. J., Roll, F., and Gaudini, G. (1997). ''Design and construction of long span FRP pedestrian bridges.'' *Building to last, Proc., Structures Congress XV*, L. Kempner and C. B. Brown, eds., ASCE, New York, 46–50.

Karbhari, V. M., Seible, F., Burgueno, R., Davol, A., Wernli, M., and Zhao, L. (2000). ''Structural characterization of fiber-reinforced composite short and medium-span bridge systems.'' *Appl. Compos. Mater.*, 7(2), 151–182.

Karbhari, V. M., and Shulley, S. B. (1995). ''Use of composites for rehabilitation of steel structures—Determination of bond durability.'' *J. Mater. Civ. Eng.*, 7(4), 239–245.

Katsumata, H., Kobatake, Y., and Takeda, T. (1987). ''A study on the strengthening with carbon fiber for earthquake-resistant capacity of existing reinforced concrete columns.'' *Proc., Workshop on Repair and Retrofit of Existing Structures*, U.S.-Japan Panel on Wind and Seismic Effects, U.S.-Japan Cooperative Program in Natural Resources, Tsukuba, Japan, 1816–1823.

Keller, T. (1999). ''Towards structural forms for composite fibre materials.'' *Struct. Eng. Int. (IABSE, Zurich, Switzerland)*, 9(4), 297–300.

Lamanna, A. J., Bank, L. C., and Scott, D. W. (2001). ''Flexural strengthening of reinforced concrete beams using fasteners and fiber reinforced polymer strips.'' *ACI Struct. J.*, 98(3), 368–376.

Lees, J. M., and Burgoyne, C. J. (1999). ''Design guidelines for concrete beams prestressed with partially-bonded fiber reinforced plastic tendons.'' *Proc., 4th Int. Symposium, Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, C. W. Dolan, S. H. Rizkalla, and A. Nanni, eds., *SP-188*, American Concrete Institute, Farmington Hills, Mich., 807–816.

A look at the world's FRP composite bridges. (1998). Market Development Alliance, Society of Plastics Engineers Composites Institute, New York.

Lopez-Anido, R. (2001). ''Life-cycle cost survey of concrete decks—A benchmark for FRP bridge deck replacement.'' (CD-Rom), *Proc., 80th Transportation Research Board Meeting*.

Lu, Z., Boothby, T. E., Bakis, C. E., and Nanni, A. (2000). ''Transfer and development length of FRP prestressing tendons.,'' *Precast Concrete Institute J.*, 45(2), 84–95.

Machida, A. (1997a). ''Issues in developing design code for concrete structures with FRP.'' *Proc., 3rd Int. Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Vol. 1, Japan Concrete Institute, Tokyo, 129–140.

Machida, A., ed. (1997b). ''Recommendation for design and construction of concrete structures using continuous fiber reinforcing materials.'' *Concrete Engineering Series 23*, Japan Society of Civil Engineers, Tokyo.

Machida, A., Kakuta, Y., Tsuji, Y., and Seki, H. (1995). ''Initiatives in developing the specifications for design and construction of concrete structures using FRP in Japan.'' *Proc. 2nd Int. RILEM Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, L. Taerwe, ed., E & FN Spon, London, 627–635.

Masmoudi, R., Thèriault, M., and Benmokrane, B. (1998). ''Flexural behavior of concrete beams reinforced with deformed fiber reinforced plastic reinforcing rods.'' *ACI Struct. J.*, 95(6), 665–676.

Matthys, S., and Taerwe, L. R. (2000). ''Concrete slabs reinforced with FRP grids. I: One-way bending.'' *J. Compos. Constr.*, 4(3), 145–153.

McGhee, K. K., Barton, F. W., and McKeel, W. T. (1991). ''Optimum design of composite bridge deck panels.'' *Advanced Composite Materials in Civil Engineering Structures, Proc., Specialty Conf.*, S. I. Iyer and R. Sen, eds., ASCE, New York, 360–370.

Meier, U. (1987). ''Bridge repair with high performance composite materials.'' *Mater. Tech. (Duebendorf, Switz.)*, 4, 125–128 (in German).

Meyer, R. W. (1985). *Handbook of pultrusion technology*, Chapman & Hall, London.

Michaluk, C. R., Rizkalla, S., Tadros, G., and Benmokrane, B. (1998). ''Flexural behavior of one-way concrete slabs reinforced by fiber reinforced plastic reinforcements.'' *ACI Struct. J.*, 95(3), 353–364.

Mirmiran, A., Naguib, W., and Shahawy, M. (2000). ''Principles and analysis of concrete-filled composite tubes.'' *J. Adv. Mater.*, 32(4), 16–23.

Mirmiran, A., Shahawy, M., Samaan, M., El Echary, H., Mastrapa, J. C., and Pico, O. (1998). ''Effect of column parameters on FRP-confined concrete.'' *J. Compos. Constr.*, 2(4), 175–185.

Mufti, A. A., Erki, M. A., and Jaeger, L. G., eds. (1991a). *Advanced composite materials in bridges and structures in Japan*, Canadian Society for Civil Engineering, Montréal, August.

Mufti, A. A., Erki, M. A., and Jaeger, L. G., eds. (1991b). *Advanced composite materials with application to bridges*, Canadian Society for Civil Engineering, Montréal, May.

Nanni, A., ed. (1993). *Fiber-reinforced-plastic for concrete structures: Properties and applications*, Elsevier Science, Amsterdam.

Nanni, A., Bakis, C. E., O'Neil, E. F., and Dixon, T. O. (1996). ''Performance of FRP tendon-anchor systems for prestressed concrete structures.'' *PCI J.*, 41, 34–44.

Pethrick, R. A., Boinard, E., Dalzel-Job, J., and MacFarlane, C. J. (2000). ''Influence of resin chemistry on water uptake and environmental aging in glass fibre reinforced composites—Polyester and vinyl ester laminates.'' *J. Mater. Sci.*, 35(8), 1931–1937.

Plevris, N., and Triantafillou, T. C. (1992). ''FRP-reinforced wood as structural material.'' *J. Mater. Civ. Eng.*, 4(3), 300–317.

Priestley, M. J. N., and Seible, F. (1995). "Design of seismic retrofit measures for concrete and masonry structures." *Constr. Build. Mater.,* 9(6), 365–377.

Product selection guide: FRP composite products for bridge applications. (2000). 1st Ed., J. P. Busel and J. D. Lockwood, eds., Market Development Alliance, Harrison, N.Y.

Qiao, P., Davalos, J. F., and Brown, B. (2000). "A systematic approach for analysis and design of single-span FRP deck/stringer bridges." *Composites, Part B,* 31(6-7), 593–610.

Qiao, P., Davalos, J. F., and Zipfel, M. G. (1998). "Modeling and optimal design of composite-reinforced wood railroad crosstie." *Compos. Struct.,* 41(1), 87–96.

Raasch, J. E. (1998). "All-composite construction system provides flexible low-cost shelter." *Compos. Technol.,* 4(3), 56–58.

Railway Technical Research Institute (RTRI). (1996a). "Design and construction guidelines for seismic retrofitting of railway viaduct columns using aramid fiber sheets." Tokyo (in Japanese).

Railway Technical Research Institute (RTRI). (1996b). "Design and construction guidelines for seismic retrofitting of railway viaduct columns using carbon fiber sheets." Tokyo (in Japanese).

Razaqpur, A. G., and Mostofinejad, D. (1999). "Experimental study of shear behavior of continuous beams reinforced with carbon fiber reinforced polymer." *Proc., 4th Int. Symposium, Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, C. W. Dolan, S. H. Rizkalla, and A. Nanni, eds., *SP-188*, American Concrete Institute, Farmington Hills, Mich. 169–178.

Rostasy, F. S. (1987). "Bonding of steel and GFRP plates in the area of coupling joints. Talbrucke Kattenbusch." *Research Report No. 3126/1429*, Federal Institute for Materials Testing, Braunschweig, Germany (in German).

Schwegler, G. (1994). "Masonry construction strengthened with fiber composites in seismically endangered zones." *Proc., 10th European Conf. on Earthquake Engineering*, Vol. 3, G. Duma, ed., Balkema, Rotterdam, The Netherlands, 2299–2304.

Shehata, E., Morphy, R., and Rizkalla, S. (2000). "Fiber reinforced polymer shear reinforcement for concrete members: Behavior and design guidelines." *Can. J. Civ. Eng.,* 27(5), 859–872.

Smallowitz, H. (1985). "Reshaping the future of plastic buildings." *Civ. Eng. (N.Y.),* 55(5), 38–41.

Somboonsong, W., Ko, F. K., and Harris, H. G. (1998). "Ductile hybrid fiber reinforced plastic reinforcing bar for concrete structures: Design methodology." *ACI Mater. J.,* 95(6), 655–666.

Sonobe, Y., et al. (1997). "Design guidelines of FRP reinforced concrete building structures." *J. Compos. Constr.,* 1(3), 90–115.

Sonobe, Y., Mochizuki, S., Matsuzaki, Y., Shimizu, A., Masuda, Y., and Fukuyama, H. (1995). "Guidelines for structural design of FRP reinforced concrete buildings in Japan." *Proc., 2nd Int. RILEM Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, L. Taerwe, ed., E&FN Spon, London, 636–645.

Strongwell. (1999). *EXTREN fiberglass structural shapes—Design manual*, Bristol, Va., ⟨www.strongwell.com⟩ (August).

Taerwe, L. R., and Matthys, S. (1999). "FRP for concrete construction." *Concrete Int.,* 21(10), 33–36.

Taly, N. (1998). *Design of modern highway bridges*, McGraw-Hill, New York.

Temeles, A. B., Cousins, T. E., and Lesko, J. J. (2000). "Composite plate and tube bridge deck design: Evaluation in the Troutville, Virginia weigh station test bed." *Proc., 3rd Int. Conf. on Advanced Composite Materials in Bridges and Structures, ACMBS-3*, J. L. Humar and A. G. Razaqpur, eds., Canadian Society for Civil Engineering, Montréal, 801–808.

Tinazzi, D., Arduini, M., Modena, C., and Nanni, A. (2000). "FRP-structural repointing of masonry assemblages." *Proc., 3rd Int. Conf. on Advanced Composite Materials in Bridges and Structures, ACMBS-3*, J. L. Humar and A. G. Razaqpur, eds., Canadian Society for Civil Engineering, Montréal, 585–592.

Triantafillou, T. C. (1998). "Strengthening of masonry structures using epoxy-bonded FRP laminates." *J. Compos. Constr.,* 2(2), 96–104.

Triantafillou, T. C., and Antonopoulos, C. P. (2000). "Design of concrete flexural members strengthened in shear with FRP." *J. Compos. Constr.,* 4(4), 198–205.

Triantafillou, T. C., Deskovic, N., and Deuring, M. (1992). "Strengthening of concrete structures with prestressed FRP sheets." *ACI Struct. J.,* 89(3), 235–244.

Triantafillou, T. C., and Fardis, M. N. (1993). "Advanced composites for strengthening historic structures." *Proc., Symposium on Structural Preservation of the Architectural Heritage*, International Association for Bridge and Structural Engineering, Zurich, Switzerland, 541–548.

Tsuji, Y., Umehara, H., Hattori, A., Uomoto, T., and Machida, A. (1997). "Japanese recommendation for design and construction of continuous fiber reinforced concrete in public works— Part 2: Construction." *Proc., 3rd Int. Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Vol. 1, Japan Concrete Institute, Tokyo, 183–190.

Uomoto, T., Hattori, A., Maruyama, K., and Machida, A. (1997). "Notes on the proposed quality standards for continuous fiber reinforcing materials (*JSCE-E131-1995*)." *Proc., 3rd Int. Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures*, Vol. 1, Japan Concrete Institute, Tokyo, 167–173.

Vinson, J. R. (1999). *The behavior of sandwich structures of isotropic and composite materials*, Technomic, Lancaster, Pa.

Werner, R. I. (1979). "Properties of pultruded sections of interest to designers." *Proc., 34th Annual Technical Conf.*, Reinforced Plastics/Composites Institute, Society of the Plastics Industry, Inc., Washington, D.C., 1–7.

Winistoerfer, A., and Mottram, T. (1997). "The future of pin-loaded straps in civil engineering applications." *Recent Advances in Bridge Engineering, Proc., U.S.-Canada-Europe Workshop on Bridge Engineering*, U. Meier and R. Betti, eds., EMPA, Duebendorf, Switzerland, 115–120.

Zureick, A., and Steffen, R. (2000). "Behavior and design of concentrically loaded pultruded angle struts." *J. Struct. Eng.,* 126(3), 406–416.