CHAPTER 45
COMPOSITES IN CONSTRUCTION

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1 INTRODUCTION

1.1 General

For the past few decades, the aerospace industry was the major user for fiber-reinforced polymer (FRP) composite materials. Recently, civil engineers and the construction industry began to realize the potential of these materials in providing remedies for many problems associated with the deterioration and corrosion of infrastructures.

Civil engineers have dealt with different types of composite materials for decades, including wood (natural composites), plywood (laminated natural composites), and concrete (particulate composites). Polymer composites are ‘‘engineered’’ materials that encompass a wide range of materials where two or more, physically distinct and mechanically separable, components are combined together to form a new material that possesses properties that are notably different from those of its individual constituents. The primary load-carrying component is the fibers, while the matrix acts as a binder, an environmental protector, and stress distribution phase of the laminate. Fibers are available in different types, grades, and shapes. Typical types of structural fibers include glass (E, S, AR grades), aramid (Kevlar), and carbon fibers with different grades. Two types of polymers are available, namely thermoplastic and thermoset polymers. In most of the structural application, thermoset resins are preferred. Examples of ther-

Handbook of Materials Selection, Edited by Myer Kutz
ISBN 0-471-35924-6

moset resins include epoxies, unsaturated polyesters, vinylesters, aminos, phenolics, and urethane resins.

1.2 Advantages

Some of the attractive and unique features of these materials are their durability and resistance to the marine environment, their toughness, particularly at low temperatures, their vibration damping capabilities, their energy absorption under earthquake loading, their electromagnetic transparency, their low value of coefficient of thermal expansion, pigmentability and decorative characteristics, and their high strength-to-weight ratio. These unique properties can be used to produce an optimum structural system with minimum life-cycle cost, fabrication and construction cost, and time.

2 CONSTRUCTION APPLICATIONS OF COMPOSITES

Applications where composite materials can show their superiority over other conventional materials are discussed below.

2.1 Aggressive Environments

- Waterfront structures
- Water and wastewater treatment plants structural elements
- Water declination plants

Fig. 1 Seismic upgrade of columns using composites. [Courtesy of Structural Composites Construction Inc. (SCCI)]

- Off-shore structures (off-shore oil rig platforms, marine risers, etc.)
- Cooling towers
- Petrochemical and nuclear power plants
- Paper and pulp mills
- Chimneys
- Pipes

2.2 Repair and Retrofit Infrastructure Systems

Due to their unique properties, composites can provide structural engineers with the answers to many structural problems. The two major applications are seismic repair and rehabilitation (Fig. 1), and corrosion repair (Fig. 2). These apply to buildings, bridges, and other infrastructure systems. Composites can also be used to upgrade the structural performance and capacity of reinforced concrete, steel, and wood and masonry structural members inland and off-shore. In this process, several laminates of composites are bonded to the finished surfaces of the structural member in the specified directions. In early 1990s, the majority of the applications focused on the ductility enhancement of concrete columns, especially in seismic areas such as California. In this particular application, the fibers

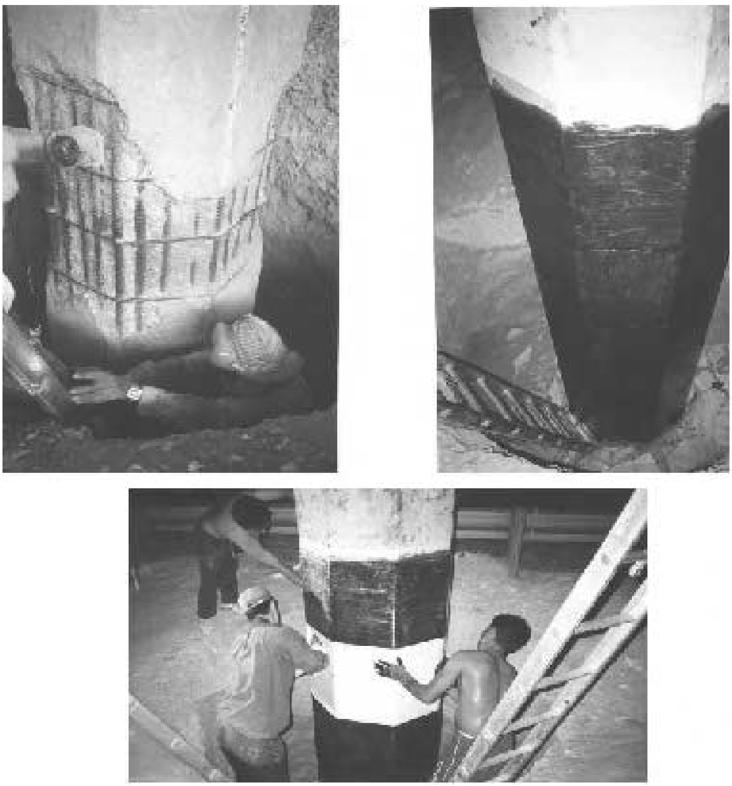
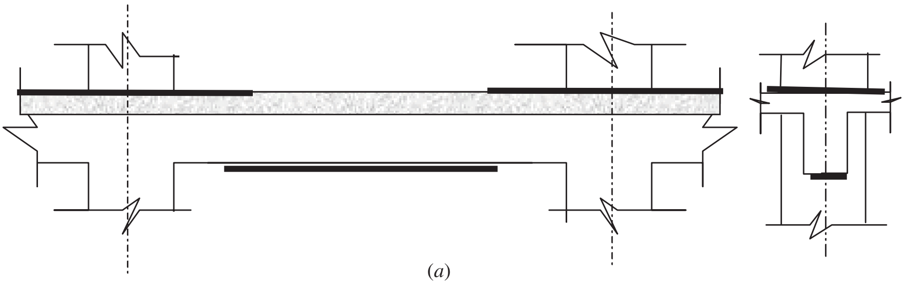


Fig. 2 Reinforced concrete corroded column repair applications using composites. (Courtesy of Sigma Composites, LLC)



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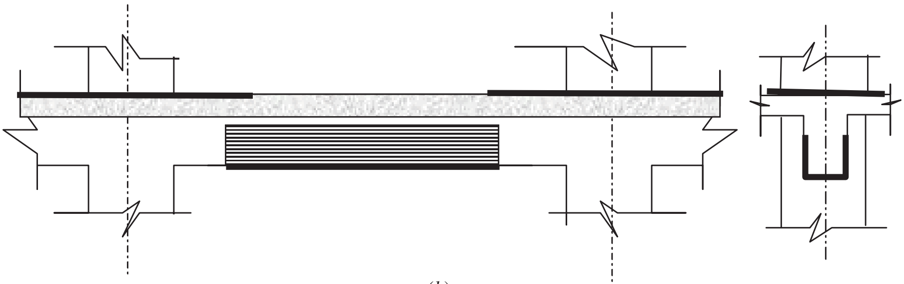

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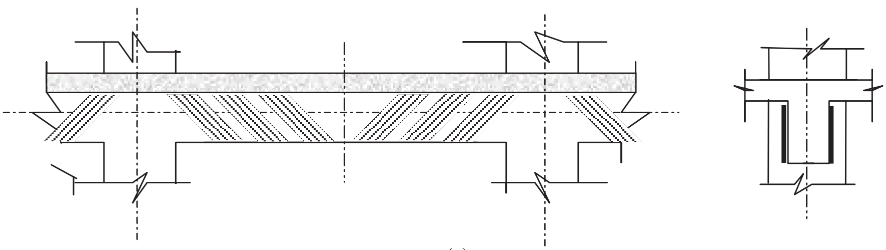

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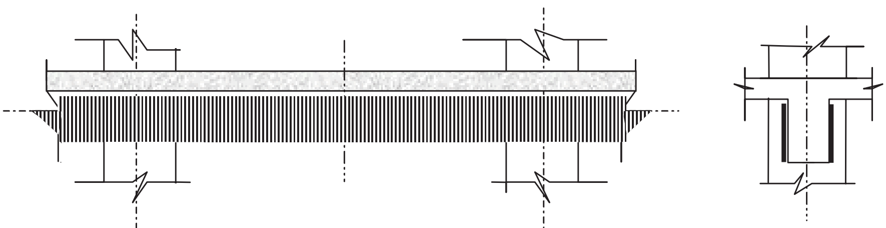

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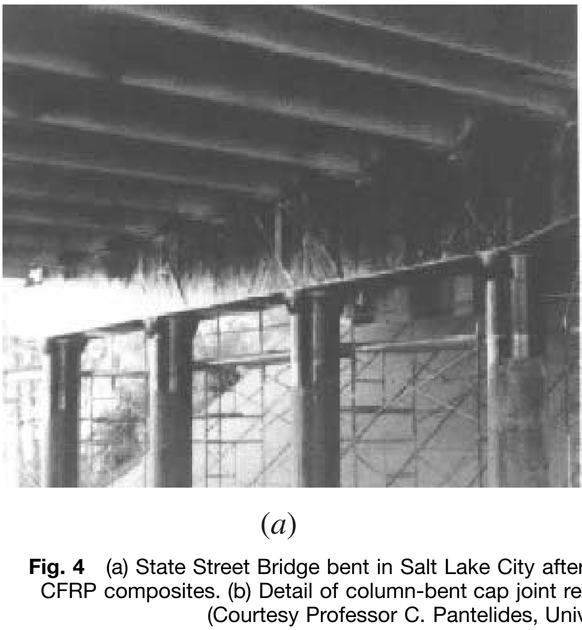
Fig. 3 Typical and the preferred FRP external flexural and shear: (*a*) Flexural reinforcement of continuous RC floor beam using flat $(0°)_n$ laminates schedule; (*b*) Flexural reinforcement of continuous RC floor beam using the preferred U-shaped $(0°)_n$ laminates schedule; (*c*) Shear reinforcement of continuous RC floor beam using inclined laminated strips; (*d*) Flexural reinforcement of continuous RC floor beam using the preferred continuous flat $(90°)_n$ laminates schedule.

are exposed to tension due to the Poisson effect, which, in turn, provide the required hoop stresses without adding to the column's stiffness (i.e., stiffness/strength decoupling). This application has been extended to cover other reinforced concrete structural members, such as beams (flexure, shear, and torsion as shown in Fig. 3), slabs, beam–column joints, and walls. Figure 4*a* shows a photograph of the U.S. Interstate 80 bridge over State Street in Salt Lake City, Utah, that was seismically retrofitted with polymer composites. The bridge consists of four reinforced concrete bents, each bent having four columns, and a bent cap supporting composite welded girders is shown in Fig. 4*b*. A seismic retrofit design was developed using carbon fiber-reinforced polymer (CFRP) composites (Pantelides et al., 2001a) to improve the displacement ductility of the bridge. The retrofit included column jacketing, as well as wrapping of the bent cap and bent cap–column joints for confinement, flexural strength, and shear strength increase. Special provisions were developed for the specifications of the CFRP composite retrofit of State Street Bridge (Pantelides et al., 2001b). The CFRP composite retrofit was implemented in the period 2000–2001.

Some of the potential repair and retrofit applications are:

1. Strengthening of reinforced concrete columns (refer to Figs. 1 and 2, beams (Fig. 5), floor and bridge deck slabs (Fig. 6), and frame connections (Fig. 7)
2. Strengthening of concrete and steel fluid tanks (refer to Fig. 8)
3. Strengthening of stacks or chimneys (Fig. 9)
4. Reinforced concrete shear walls (Fig. 10)
5. Strengthening of slabs-on-grade (Fig. 11)
6. Strengthening of concrete, and steel pipes (Figs. 12 and 13)



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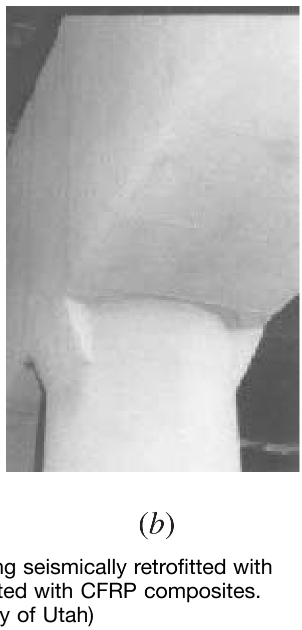

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Fig. 4 (a) State Street Bridge bent in Salt Lake City after being seismically retrofitted with CFRP composites. (b) Detail of column-bent cap joint retrofitted with CFRP composites. (Courtesy Professor C. Pantelides, University of Utah)

Fig. 5 Reinforced concrete beam strengthening applications using precured composite strips. [Courtesy of Structural Composites Construction Inc. (SCCI)]

7. Strengthening of utility wooden poles (Fig. 14)
8. Strengthening of wooden beams and columns and plywood shear walls (Fig. 15)
9. Strengthening of reinforced and unreinforced masonry walls (Fig. 16)

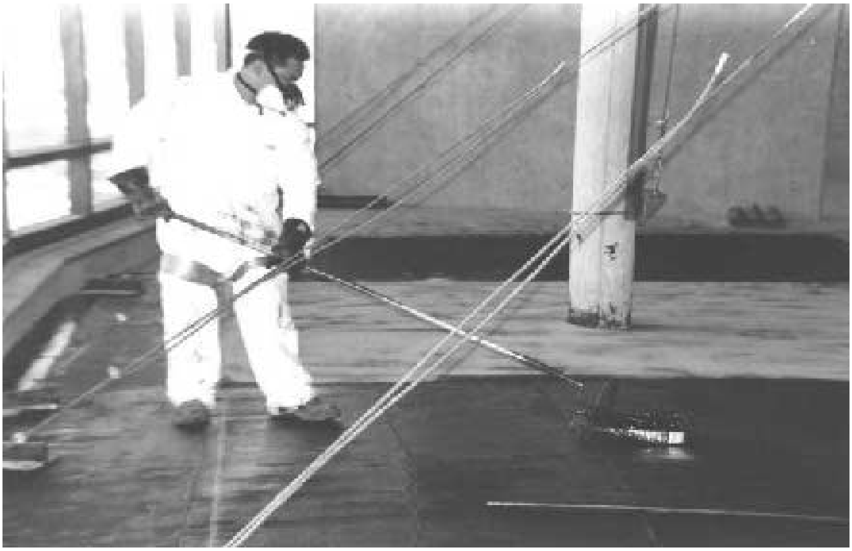

Fig. 6 Reinforced concrete floor slab strengthening applications using composites. [Courtesy of Structural Composites Construction Inc. (SCCI)]

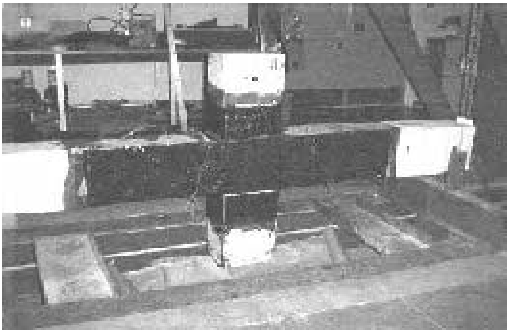

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Fig. 7 Reinforced concrete beam-column connection repair applications using composites. (a) California State University at Fullerton, and (b) McMaster University, Canada (Ghobarah and Said, 2001).

10. Strengthening of tunnels (Fig. 17)

11. Strengthening of concrete members for explosion resistance (Fig. 18)

Types of Composite Repair Systems

Currently, the composite repair methods/systems that are available, include:

Wet/Hand Lay-up. In this method, the fibers are in the form of either unidirectional or multidirectional sheets, waived, or stitched fabrics. After surface pretreatment of the structural member, and the application of a thin film of low-viscosity epoxy-based primary, the saturated fibers are applied by hand to the location indicated in the engineering drawings (Fig. 19). The preferred method of saturating the fibers is using custom-designed impregnator (or saturator) to ensure proper and complete fiber impregnation with the resin system (Fig. 20). However, some systems use brush and rollers to wet their fiber materials. The common type of matrix used in wet layup repair application is room temperature

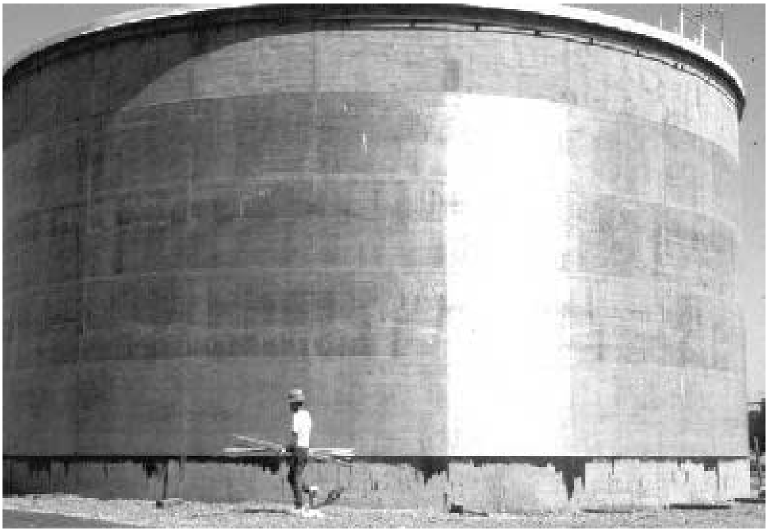

Fig. 8 Confinement of reinforced concrete tank using polymer composites. (Courtesy of Fyfe Co. LLC)

cure two-part epoxy systems. Several types of fibers are being used in this process including standard and high-modulus carbon fibers, glass fibers (including types E, S, and AR). A very limited commercial products uses aramid due to its sensitivity to wet environment that is unavoidable in construction applications. However, it should be noted that aramid-based composites can also be used in this application, provided that the fibers are completely protected from

Fig. 9 Structural strengthening of chimneys using polymer composites. (Courtesy of Fyfe Co. LLC)

Fig. 10 Applications of composites for strengthening reinforced concrete shear walls. [Courtesy of Structural Composites Construction Inc. (SCCI)]

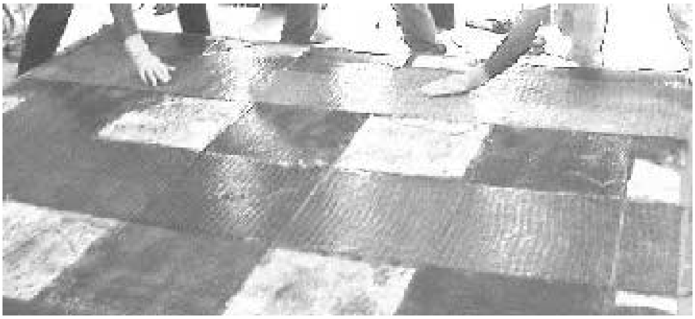

Fig. 11 Structural strengthening of unreinforced concrete slab-on-grade using polymer composites. [Courtesy of Structural Composites Construction Inc. (SCCI)]

Fig. 12 Strengthening of reinforced concrete pipes using polymer composites. [Courtesy of Structural Composites Construction Inc. (SCCI)]

Fig. 13 Seismic strengthening of steel pipe joints using polymer composites. [Courtesy of Professor O'Rourke, Cornell University (Tutuncu, 2001)]

Fig. 14 Structural strengthening of utility wooden poles using polymer composites. (Courtesy of Fyfe Co. LLC)

Fig. 15 Structural strengthening of glue-lam wooden beams using carbon/epoxy sandwich composites. (Courtesy of Sigma Composites, LLC)

the surrounding environment particularly from moisture. Other FRP composites repair systems made of hybrid materials have been used in a number of applications, especially when carbon-based composites are used around metallic parts. In this case, a thin film or a thin mat of E-glass is used to avoid the development of the corrosion process due to the galvanic action created when carbon-based composites are in direct contact with metallic parts in the presence of an electrolyte, such as water, that activates the galvanic process.

Table 1 presents average mechanical and physical values for common fibers for composites used in construction repair applications as compared to steel. The laminate properties are always lower than the dry fiber properties due to the presence of the matrix, which has negligible structural capacity. In addition, if

Fig. 16 Strengthening of unreinforced masonry walls using polymer composites. (Courtesy of Fyfe Co. LLC)

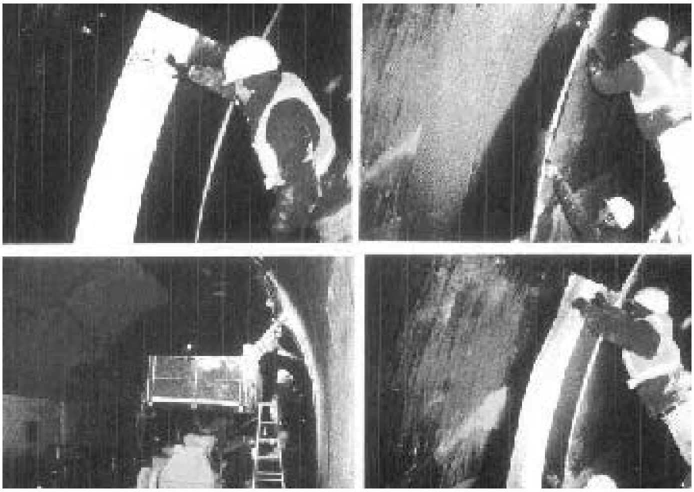

Fig. 17 Strengthening of tunnels using polymer composites. (Courtesy of TONEN Corp.)

Fig. 18 Blast-resistance enhancement of reinforced concrete structures.
[Courtesy of Structural Composites Construction Inc. (SCCI)]

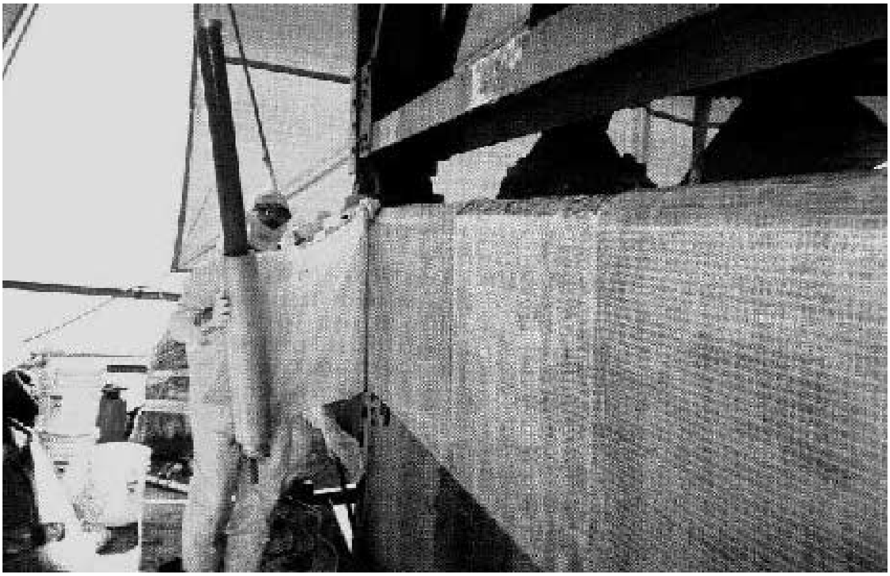

Fig. 19 Wet/hand lay-up repair process. (Courtesy of Fyfe Co. LLC)

the fibers are directed in different directions (off-axis), the uniaxial or properties parallel to the direction is expected to decrease depending upon the plies angles and the volume of fibers in each direction relative to the major fiber direction (on-axis) as shown in Fig. 21. This issue is very important and should be very clear for the civil engineer who is unfamiliar with composites. The structural engineer must distinguish between the fibers and laminate properties when designing a repair system. The most critical information that is used in the design

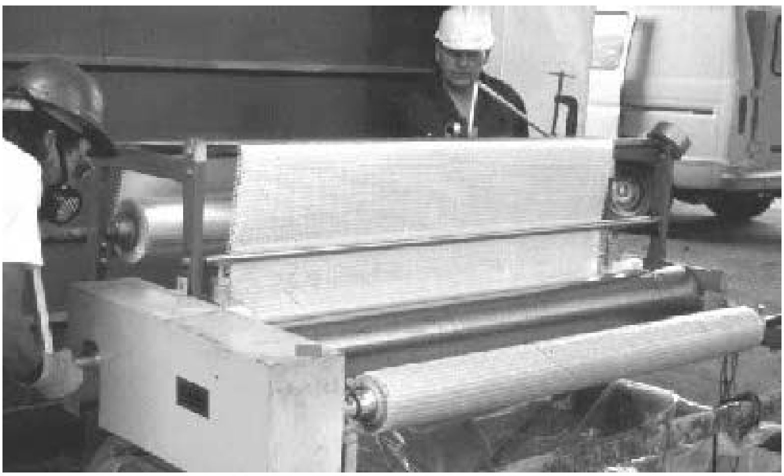

Fig. 20 Use of automated saturators is the preferred method for wet lay-up repair process. (Courtesy of Fyfe Co. LLC)

Table 1 Average Mechanical and Physical Values for Common Fibers for Composites Used in Construction Repair Applications as Compared to Steel

	Average Tensile Strength		Average Tensile Modulus		Density	Average Elongation
Fiber Type	MPa	ksi	GPa	Msi	g/cm^2 ($lb/in.^3$)	(%)
E-glass	3450	500	72.50	10.50	2.54 (0.092)	>4.7
S-glass	4480	650	85.60	12.40	2.49 (0.09)	>5.2
Carbon	4825	700	228	33	1.80 (0.065)	>1.3
Aramid	3800	550	131	19	1.45 (0.052)	>2.5
Steel (AISI 1025)	394	57	207	30	7.80 (0.282)	0.12[a]

[a] Yield strain.

is the "laminate" rather than "fibers" properties. Fibers and matrix properties can also be used to predict some laminate mechanical properties, and these results can be used to confirm the uniaxial FRP composite laminates properties supplied by the manufacturer. In this case the civil engineer should have the following information:

- E_{1f} = longitudinal fiber modulus
- E_m = Longitudinal matrix modulus
- ν_{12f} = Longitudinal Poisson ratio of the fibers
- ν_{12m} = Longitudinal Poisson ratio of the matrix
- V_f = fiber volume ratio
- V_m = matrix volume ratio

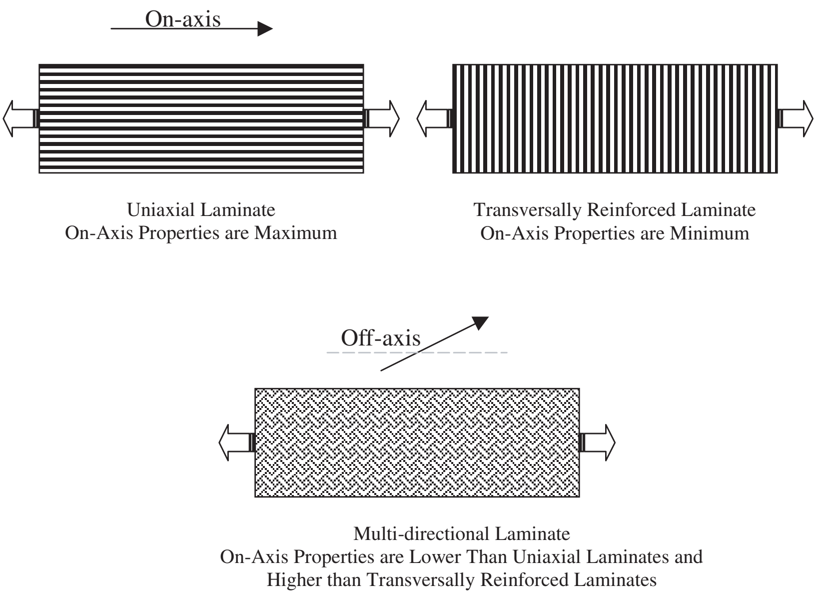

Fig. 21 On-axis and off-axis mechanical properties of composite laminates.

The fiber and matrix volume fractions or ratios, V_f and V_m, can expressed as:

$$V_f = \frac{\text{Volume of fibers}}{\text{Volume of composite}} \tag{1}$$

$$V_m = \frac{\text{Volume of matrix}}{\text{Volume of composite}} \tag{2}$$

Knowing the ratios, V_f and V_m, the void volume ratio can be calculated as:

$$V_\nu = 1 - V_m - V_f = \frac{\text{Volume of voids}}{\text{Volume of composite}} \tag{3}$$

The FRP laminate longitudinal and transversal mechanical properties can be predicted using the following simple expressions (commonly called "rule of mixtures"):

$$E_1 = V_f E_{1f} + V_m E_m \tag{4}$$

$$\nu_{12} = V_f \nu_{12f} + V_m \nu_m \tag{5}$$

$$E_2 = \frac{E_{2f} E_m}{V_f E_m + V_m E_{2f}} \tag{6}$$

where E_1 = laminate longitudinal (major) modulus
E_2 = laminate transverse modulus
ν_{12} = laminate longitudinal (major) Poisson ratio

For simple unidirectional laminate tensile strength predictions, two cases should be considered:

1. If ultimate tensile fiber strain (ε_f^u) is lower than ultimate tensile matrix strain (ε_m^u), i.e.,

$$\varepsilon_f^u < \varepsilon_m^u \tag{7}$$

Accordingly, the laminate failure will occur when the composite laminate strain reaches the tensile fiber strain. In this scenario, the laminate tensile strength can be expressed by the following simple formula:

$$\sigma_t^u = \sigma_{tf}^u V_f + E_m \varepsilon_f^u V_m \tag{8}$$

Assuming a composite laminate with relatively stiff fibers as compared to the matrix, i.e., when $E_f >>> E_m$, Eq. 8 can be simplified further as:

$$\sigma_t^u \cong \sigma_{tf}^u V_f \tag{9}$$

where σ_t^u = laminate longitudinal tensile strength
σ_{tf}^u = fibers longitudinal tensile strength

2. If ultimate tensile matrix strain (ε_m^u) is lower than ultimate tensile fiber strain (ε_f^u), i.e.,

$$\varepsilon_m^u < \varepsilon_f^u \tag{10}$$

In this case, the laminate failure will occur when the composite laminate strain reaches the tensile matrix strain. The laminate tensile strength can approximately be calculated using the following simple formula, which does not account for the statistical distribution of fiber and matrix strengths:

$$\sigma_t^u \cong \sigma_{tm}^u(V_f \xi + V_m) \tag{11}$$

where σ_{tm}^u = matrix 1 tensile strength
ξ = fiber/matrix stiffness ratio (modular ratio) given by:

$$\xi = \frac{Ef}{E_m} \tag{12}$$

Table 2 presents some average mechanical values for typical FRP composites repair systems. It should be noted that these values are based on 50% volume fraction. In reality, and especially for wet lay-up field applications, the typical expected volume fraction ranges from 35 to 45%. For this reason, the values presented in Table 2 may be reduced accordingly using Eqs. 4–12. It is strongly recommended that the civil engineer require random sampling and American Society for Testing and Materials (ASTM) tensile coupon tests from different patches mixed at the site in order to verify the design-based mechanical properties and to allow for design modifications based on actual field properties of the FRP composite system. A comprehensive document describing these procedures, called AC178 (ICBO, 2001a), has recently been approved and published by the International Conference of Building Officials (ICBO). The engineer is

Table 2 Average Unidirectional Composite Laminate Room Temperature Mechanical Values for Typical Composite Repair Systems Used in Construction Applications

Laminate Composition	Typical Laminate Longitudinal Tensile Strength, σ_{11}		Typical Laminate Longitudinal Tensile Modulus, E_{11}		Typical Laminate Transversal Tensile Modulus, E_{22}		Average Laminate Elongation (Rupture Strain)
	MPa	ksi	GPa	Msi	GPa	Msi	%
E-glass/epoxy	950	138	34.0	5.0	8.3	1.2	2.7
S-glass/epoxy	1100	160	41.3	6.0	8.9	1.3	2.7
Carbon/epoxy	1400	200	138.0	20	10.3	1.5	1.20
Aramid/Epoxy	1300	189	65.0	9.5	5.5	0.8	2.0

Note: Based on 50% Volume Fraction; *Fiber:Resin Volumetric Ratio 1:1* advised to review this important document during the design process as well as during the construction phase for quality control and quality assurance of the composite repair system.

Preimpregnated (Prepreg) Composite Systems. Preimpregnated laminates (prepreg system) are also available commercially for construction repair applications. In this case, dry fabrics are preimpregnated with resin at the controlled shop conditions. Unlike the wet lay-up system, where the composite laminates are fabricated and cured at the site, the prepegs are fabricated at the shop and cured at the construction site. Prepreg composite repair system requires heat blankets for curing the prepreg laminates, which is one of the disadvantages of this system, especially at remote areas and for complex geometry of the structural members to be repaired. In addition, the useful life of such systems is limited and dependant on the storage environmental conditions.

Prefabricated Composite Laminates or Shells. In this method, the fibers are in the form of either unidirectional strips, shells, or sandwich panels. In the case of flat members such as beams and slabs, prefabricated unidirectional composite strips are bonded to the specified locations using epoxy after surface treatment. The common manufacturing process for the prefabricated composite flat strips is called "pultrusion," which is a continuous process that will be explained later in this chapter. However, several other manufacturing processes are also available for fabricating these strips including press molding, resin transfer molding, and others. In all cases, the average fiber volume fraction for commercially available composite strips is about 65%. The procured unidirectional composite laminates are commonly delivered to the construction site in the form of large flat stock or coiled on a roll for thin laminates. A peel ply is preferred when the surfaces are pretreated to ensure clean bond surface at the time of application.

In applying the prefabricated strips, sanding or removal of the outmost matrix-rich layer is performed to ensure sufficient bondline strength between the composites and the concrete surface. To verify the bondline strength, a pullout field test is often required by the engineer of record (refer to Fig. 22).

For columns repair, prefabricated shells with majority of fibers in the hoop direction are used. After surface preparation, a thin coat of epoxy is applied, and the shell is placed at the required location per the engineering drawings. Straps are used to squeeze out any excess resin (Fig. 23). It is critical that the split lines be staggered with a phase angle of 90°.

Automated Machine Lamination. In this method, the fibers are either dry or preimpregnated. Thermal blanket or mobile curing oven is usually used to achieve the complete cure of the composite laminate (Fig. 24). Following the initial curing process, textured urethane-based paint is hand applied over the cured laminates, which provides ultraviolet (UV) protection of the composites.

Design Considerations for FRP Composite Repair

One of the major issues that the structural engineer should clearly identify is the state of the existing underdesigned or diffident member. This includes the existing and expected future loads, as well as the extent of damage and/or

Fig. 22 Prefabricated composite laminate R/C slab applications and on-site bondline strength test. [Courtesy of Structural Composites Construction Inc. (SCCI)]

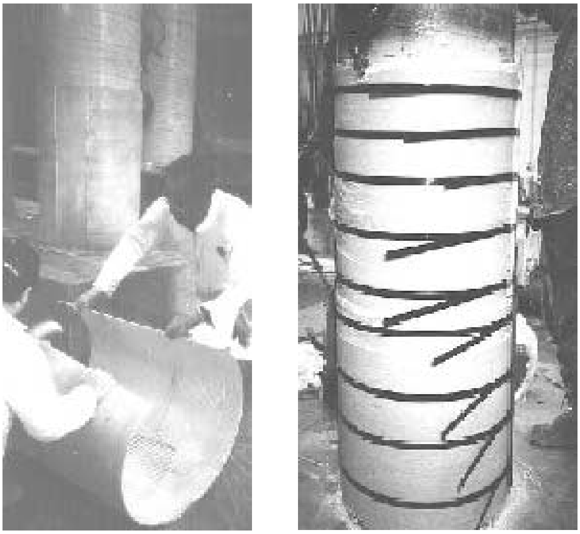

Fig. 23 Hard shell precured composite retrofit system. (Courtesy of Professor M. Haroun, University of California, Irvine)

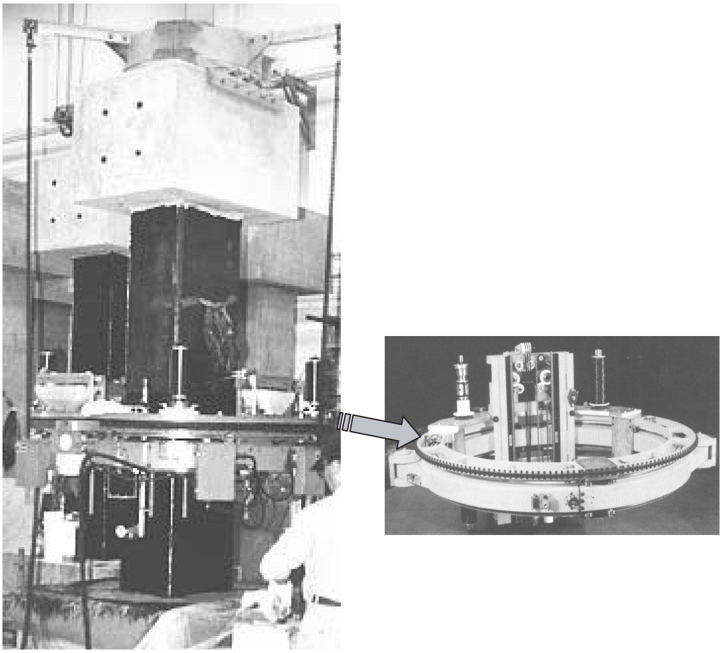

Fig. 24 Automated machine lay-up for bridge column retrofit applications. (Courtesy of Professor M. Haroun, University of California, Irvine)

structural deficiency of the structural members. This includes the residual strength of the concrete that can be determined by testing random core samples from the member to be repaired to instigate the feasibly of using the composites, as well as to determine the type and required specifications for the resin (for wet lay-up systems) or the adhesive (for prefabricated systems) and the type and viscosity of the primer to be used prior to the application of the composite laminates. The next step is the identification of the environmental exposure of the structure. This step is very critical in the selection process for fibers, resin system, required additives (e.g., the requirements of adding UV inhibitors for outdoor applications and fire-retardant additives for indoor applications), as well as the preferred fabrication process of the composites. The structural engineer should identify the locations of damages, for example, in a reinforced concrete member, the locations and quantity of the damaged steel reinforcements should be defined in order to calculate the structural demands for different types of stresses using the appropriate FRP composite repair system. Also, the engineer should quantify the limit state for her/his design in order to specify the efficient composite repair system.

For example, if the main concern were the loss of stiffness, the carbon-based composites would be the preferred choice in this case. On the other hand, if the ductility enhancement for seismic applications is the design objective, glass-based FRP composites would be appropriate to the inherent lower longitudinal stiffness modulus of the materials. Of course, both materials can be used, but the question is the efficiency and the reliability of the system, which is the sole responsibility of the engineer of record. Another issue that should be analyzed beforehand is the creep rupture effects of the FRP composite repair system, particularly for both glass-based and aramid-based composite systems. In this case, a knockdown factor, relatively higher than that for carbon-based composites, should be used to avoid any potential failure due to the exposure to sustained loading conditions. In determining these knockdown factors, several parameters should be considered, including the stiffness and strength degradation due to the exposure to aggressive environments, as well as the strain rate and the type of application. For example, composite jackets used for ductility enhancement, often called "contact-critical" application, will undergo a light strain level until the application of the seismic forces. In this case, a lower creep rupture (or static fatigue) knockdown factor may be used. On the other hand, a composite system applied at the bottom surface of a reinforced concrete beam, often called "bond-critical" application, especially if the a cumber has been introduced to the beam before complete cure of the composites, will be exposed to a relatively higher state of strains. In this case, a relatively higher creep rupture knockdown factor should consider. In this particular example, the carbon-based composite system is the preferred choice.

Design Philosophy of FRP Composite Repair of Reinforced Concrete and Masonry Structures

Flexural Capacity Upgrade of Concrete Members. As mentioned earlier, one of the major tasks in designing with FRP composites is the strength assessment of both concrete and steel reinforcements as well as the present stress conditions. The major design criterion for FRP repair of reinforced concrete structures is based upon the strain compatibility principles. FRP composites have different thermomechanical properties as compared to concrete. Upon loading, the strain developed in the concrete, steel, and composites are assumed to follow a linear pattern (refer to Fig. 25).

Following the ACI318 ultimate strength code procedure, the factored moment should be larger than or equal to the ultimate bending moment of the section, i.e.,

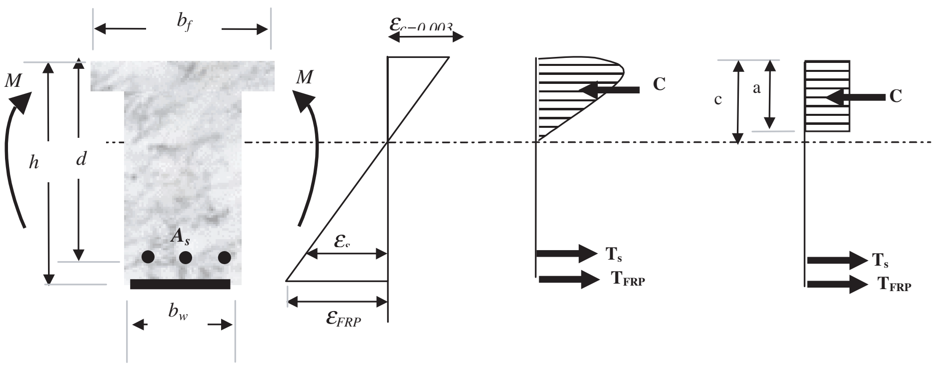

Fig. 25 Distribution of flexural strain and stresses at ultimate for concrete beam reinforced internally with tension steel and externally with FRP composite laminate(s).

$$\phi M_n \geq M_u \tag{13}$$

where ϕ = strength reduction factor, which depends on ductility of ultimate mode of failure and type of stresses (if failure is ductile, i.e., internal steel yielded at time of failure of FRP composites, typical value of 0.9 can be used, otherwise value should be reduced to account for brittleness of ultimate failure)
M_n = nominal or predicted moment
M_u = ultimate moment capacity of the section

The strain compatibility condition can be derived using the linear strain distribution in Fig. 25, and assuming

- the ultimate strain of concrete in compression is 0.003,
- the tensile strength of concrete in tension is ignored, and
- strain distribution along the depth of the beam is linear,

then

$$\varepsilon_{\mathrm{FRP}} = 0.003\left(\frac{h - c}{c}\right) \leq \omega\varepsilon_{\mathrm{FRP}}^{\mathrm{ult}} \qquad (\omega < 1) \tag{14}$$

Here:

- The reduction factor ω is used to prevent delamination of bondline failure. For design purposes, this factor should be taken less than unity and the upper bound depends on the type of the FRP system.
- The strain developed in the laminate at ultimate, $\varepsilon_{\mathrm{FRP}}$, may be reduced if the existing member is exposed to existing service loads, which generates another existing strain component $\varepsilon_{\mathrm{ext}}$ (refer to Fig. 26). In this case,

$$\varepsilon_{\mathrm{FRP}} = 0.003\left(\frac{h - c}{c}\right) - \varepsilon_{\mathrm{ext}} \leq \omega\varepsilon_{\mathrm{FRP}}^{\mathrm{ult}} \tag{15}$$

- The term $\varepsilon_{\mathrm{FRB}}^{\mathrm{ult}}$ is the ultimate or rupture strain of the FRP composites.

Based on the strain compatibility condition and the ACI318-99 procedure (ACI, 1999), the ultimate moment capacity of the strengthened section is given by

$$M_n = A_s f_x(d - 0.5a) + A_{\mathrm{FRP}} f_{\mathrm{FRP}}(h - 0.5a) \tag{16}$$

where A_s = area of tension steel
f_s = stress in steel at ultimate
f_{FRP} = stress in the FRP laminates

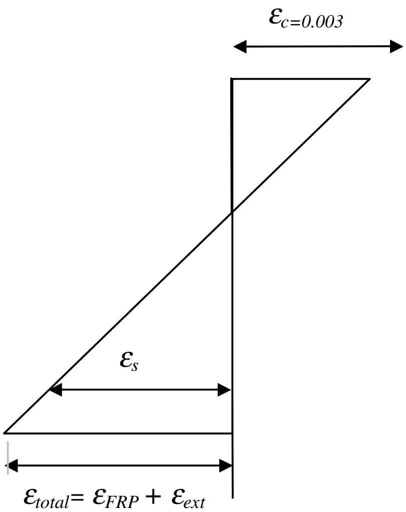

Fig. 26 Total tensile flexural strain when FRP repair applied while the member is loaded.

$a = \beta_1 c$

β_1 = ratio of the average concrete compressive stress to the maximum stress. For concrete compressive stresses f'_c, the factor β_1 shall be taken as

$$\beta_1 = 0.85 \quad \text{for} \leq 4000 \text{ psi} \tag{17}$$

$$\beta_1 = 1.05 - 0.05 \frac{f'_c}{1{,}000} \quad \text{for 4000–8000 psi} \tag{18}$$

$$\beta_1 = 0.65 \quad \text{for} > 8000 \text{ psi} \tag{19}$$

Similar procedure for predicting the flexural strength of FRP externally reinforced concrete and masonry members is described in the ICBO AC125 (2001) document. According to ICBO AC125 (ICBO, 2001), the flexural strength gain (the component T_{FRP} in Fig. 22, which is referred to ΔF in the Eq. 20) can be calculated using the following equation:

$$\Delta F = \frac{t_f \cos^2\theta f_{jf}}{\text{unit} - \text{width}} \tag{20}$$

where t_f = thickness of the FRP laminates
θ = angle of fiber direction to member axis
f_{jf} = confining strength of FRP composites calculated by following equation:

$$f_{jf} = E_f \varepsilon_f \cos^2 \theta \leq \lambda f_{uj} \tag{21}$$

where E_f = tensile modulus of elasticity of FRP composites
ε_f = composite material strain at designated strength
λ = strength reduction factor dependent on type of composites.

This factor is taken as 0.75 for all composites in the original ICBO AC125 [ICBO, 2001b, equation (1), section 7.3.2.1]; however, it is strongly recommended to have different values for different composite repair materials to avoid creep rupture in the polymeric composite laminate(s). Table 3 presents the recommended values of λ for different FRP composite systems.

Detailed information on design procedures can be found in Nanni and Gold (1998), Mosallam et al. (2000), and ICBO AC125 (ICBO, 2001b). Analytical modeling of special applications of concrete slabs retrofit with composites is reported by Mosalam and Mosallam (2001).

Minimum Bond Strength Requirements. For repair applications where the structural performance of the composite system depends largely on the bondline strength of the composites to the concrete or masonry (often called bond-critical applications such as beams, slabs, and walls), the ICBO AC125 (ICBO, 2001b) requires that under ultimate flexural strength conditions, the bond stress developed between the composites and concrete or masonry rate of change shall not exceed:

$$u_u = \frac{d(t_f f_j)}{dx} \leq 0.75 f_t \tag{22}$$

where u_u = bond stress between FRP composite laminates and concrete or masonry
t_f = composite laminate thickness
f_j = laminate stress
x = direction parallel to the fibers

The term $d(t_f f_j)/dx$ describes the rate of change of the fibers net force $(t_f f_j)$ with respect to the distance (x) parallel to the major fiber direction. Equation 22 should be evaluated at sections where this rate is maximum, which is normally at the ends where maximum shear stresses exist. For comprehensive coverage

Table 3 Recommended Values of λ (in Eq. 21) for Different FRP Composite Systems[a]

FRP Composite System	Recommended Reduction Factor, λ
Carbon/epoxy	0.50
E-glass/epoxy	0.30
Aramid/epoxy	0.35

[a] These values are based on room temperature environment. For higher service temperatures and/or severe environments, these values shall be reduced.

of this subject, the reader is referred to two design textbooks, one by Hollaway and Head (2001) and one by Hollaway and Leeming (1999).

Shear and Torsional Strengths Upgrade. As mentioned earlier, the shear strength of reinforced and unreinforced concrete and masonry members can be upgraded using external FRP composite laminates. The previous procedures dealing with flexural strength upgrade assumed that the engineer has checked the shear capacity of the member, and if the member is deficient in shear, additional FRP laminates should be applied. Studies on the torsion straightening of reinforced concrete beams are scarce. The first pilot study on confirming the validity of upgrading the torsional capacity of reinforced concrete rectangular beams using FRP laminates was reported recently by Ghobarah et al. (2001).

Comprehensive studies on the use of FRP laminates to increase the shear capacity of reinforced concrete columns and beams are reported by Haroun et al. (1999) and Kachlakev et al. (2000), respectively.

Circular Sections. According to ICBO AC125 (ICBO, 2001b), the nominal shear strength gain for circular reinforced concrete members of diameter D is given by

$$V_{sj} = 2.25 t_f f_j D \sin^2\theta \tag{23}$$

where V_{sj} = shear strength enhancement provided by FRP composite laminates, lb (N)
t_f = composite laminate thickness
f_j = allowable laminate stress = $0.004E_j \leq \lambda f_{uj}$
λ = reduction factor (refer to Table 3)
E_j = composite laminate tensile modulus
f_{uj} = ultimate tensile strength of the composite laminate
θ = angle of fiber orientation relative to the member axis

Rectangular Concrete Beams or Columns Sections. According to ICBO AC125 (ICBO, 2001b), the estimated shear strength gain for rectangular concrete cross sections or a depth H, parallel to the direction of the applied shear load is given by

$$V_{sj} = 2.86 t_f\, f_j\, h \sin^2\theta \qquad \theta \geq 75° \tag{24}$$

where V_{sj} = shear strength enhancement provided by FRP composite laminates, lb (N)
t_f = composite laminate thickness
f_j = allowable laminate stress = $0.004E_j \leq \lambda f_{uj}$
λ = reduction factor (refer to Table 3)
E_j = composite laminate tensile modulus
f_{uj} = ultimate tensile strength of the composite laminate
H = cross-sectional dimension parallel to the applied shear force
θ = angle of fiber orientation relative to the member axis

For the composites to perform effectively, the corner of rectangular or square concrete section must be rounded using mechanical grinders or other appropriate techniques to a minimum radius of 0.75 in. (20 mm) before the application of the FRP laminate to the pretreated concrete surfaces (Fig. 27).

Rectangular Masonry Wall Sections. According to section 7 of the ICBO AC125 (ICBO, 2001b), the nominal shear strength gain for rectangular masonry wall sections of depth H parallel to the applied shear load is given by

$$V_{sj} = 2t_f\, f_j\, H \sin^2 \theta \tag{25}$$

for composites applied at two sides

$$V_{sj} = 0.75t_f\, f_j\, H \sin^2 \theta \tag{26}$$

for composites applied at one side only with $\theta \geq 75°$. Equations 25 and 26 assume that adequate anchorage is provided by bonding to the wall ends. In addition, it is recommended to use a special anchoring system between the composites and the wall and foundation using metallic or composite connectors to ensure effective shear transfer. It is also recommended to introduce appropriate shear strength gain reduction factors.

Axial Load Capacity Upgrade. The axial (in-plane) capacity of the concrete or masonry member can be upgraded by applying FRP composites in the direction of the applied force. For concrete members, no data is available to confirm this application. However, for masonry walls, numerous large-scale test results indicated that an appreciable gain in the in-plane capacity of the wall members could be achieved by adding fibers in the directions of the applied in-plane loads.

The common method of increasing the axial capacity of concrete members such as columns is by applying the fibers in the transverse (hoop) direction. In this case the composite laminates are subjected to tensile stresses due to the Poisson effect. A large number of research studies were conducted on the behavior of reinforced concrete columns with FRP composite jackets. An early

Fig. 27 Minimum radius of 0.75 in. (20 mm) for noncircular columns is required before the application of FRP composites. (Courtesy of Professor M. Haroun, University of California, Irvine)

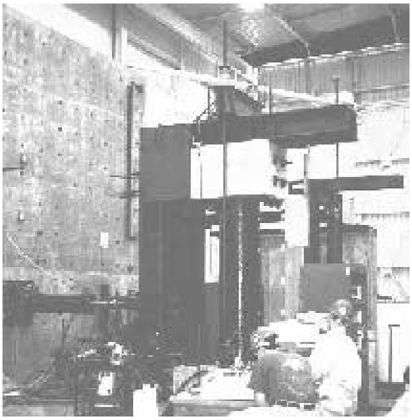

Fig. 28 Caltrans large-scale testing of highway bridge column with FRP jackets. (Courtesy of Professor M. Haroun, University of California, Irvine)

study was reported by Priestley et al. (1992) on the use of E-glass/epoxy composite jackets for seismic retrofit reinforced concrete columns. Another study was conducted by Xiao et al. (1995) on large-scale columns retrofitted with precured shell composite laminates. A comprehensive report prepared for the California Department of Transportation (Caltrans) on retrofitting reinforced concrete bridge columns using different composite systems was presented by Haroun et al. (1999). In this report, both circular and rectangular large-scale columns were evaluated for different retrofit applications including lap-splice enhancement, shear enhancement, and flexural enhancement (Figs. 28 and 29). Currently, a comprehensive experimental and theoretical program is conducted as a joint research project between the University of California at Irvine and California State University at Fullerton. In this program a total of 110 large-

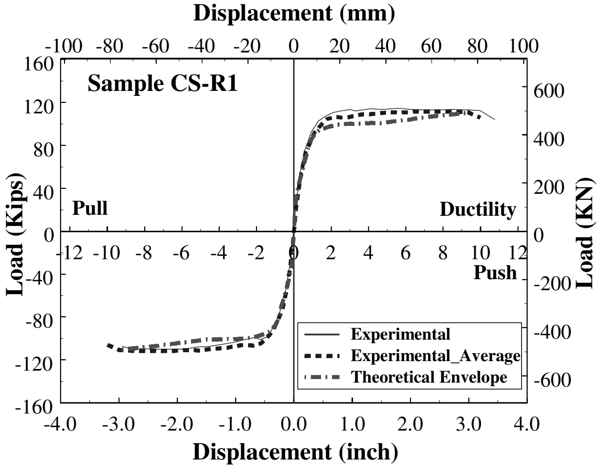

Fig. 29 Theoretical and experimental load–displacement envelope for a large-scale reinforced column with composite jacket (Elsanadedy, 2001).

scale reinforced and reinforced concrete column specimens with different cross-sectional areas including rectangular, square, circular, hexagonal, and octagonal have been tested (Fig. 30). A sample of the experimental stress–strain relations for confined and unconfined columns is shown in Fig. 31. Tables 4 and 5 present summaries for full-scale test results of rectangular, hexagonal, and octagonal column specimens tested in this program. A description of the testing program is presented by Haroun et al. (2000).

Design Procedures. The ICBO AC125 (ICBO, 2001b) has established analytical procedures to predict the strength gain of concrete members transversally reinforced with FRP composite jackets. For circular columns, an equation based on the Mander model (Mander et al., 1988) is adopted. The equation requires that the aspect ratio of the repaired column cross section does not exceed 1.5, otherwise a special analysis is required. According to section 7 of the ICBO AC125 (ICBO, 2001b), the concrete confined compressive strength, f'_{cc}, of a *circular column* jacketed with composites in the hoop direction is given by

Fig. 30 Samples of reinforced and unreinforced column specimens (Youssef, 2001).

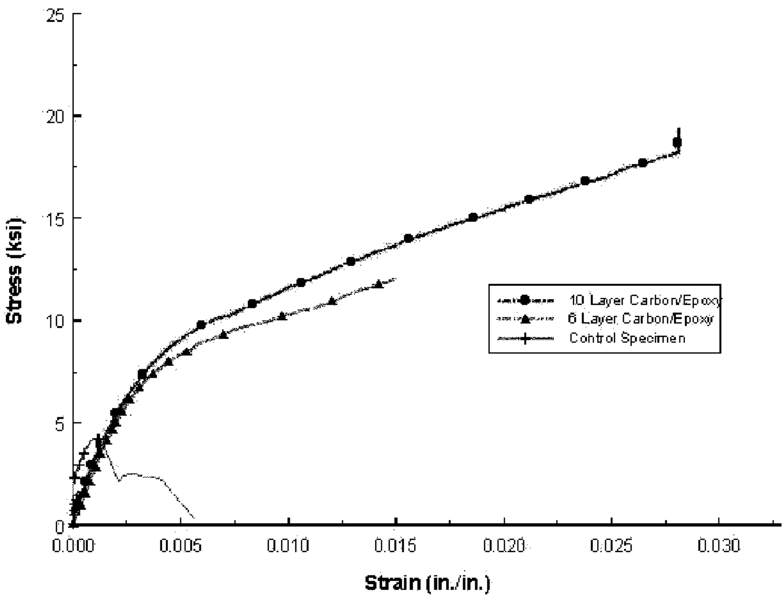

Fig. 31 Experimental stress–strain curves for confined with FRP and unconfined circular columns (Youssef, 2001).

$$f'_{cc} = f'_{co} \left[2.25 \sqrt{1 + 7.9 \frac{f'_l}{f'_c}} - 2 \frac{f'_l}{f'_c} - 1.25 \right] \tag{27}$$

where f'_{co} = unconfined compressive strength of the column

f'_{cc} = confined compressive strength of the column

$$f_l = \text{lateral confining stress} = 0.26 \rho_{sj} f_{uj} \sin^2 \theta \tag{28}$$

$$\rho_{sj} = \frac{4t_f}{D} \tag{29}$$

Table 4 Rectangular Specimens Summary Test Results

No. of (0) Plies	Unconfined Stress (ksi)	Unconfined Capacity (kips)	Confined Stress (ksi)	Confined Capacity (kips)	Percent Increase in Capacity
		E-Glass/Epoxy Confined Specimens			
3	*4.23*	*634.32*	*5.02*	*753.00*	*18.71*
4	*4.23*	*634.32*	*5.47*	*820.50*	*29.35*
7	*4.23*	*634.32*	*6.24*	*936.00*	*47.56*
11	*4.23*	*634.32*	*7.10*	*1,064.55*	*67.83*
		Carbon/Epoxy Confined Specimens			
2	4.23	634.32	4.81	721.34	13.72
3	4.23	634.32	5.75	862.50	35.97
5	4.23	634.32	6.09	913.50	44.01
8	4.23	634.32	6.30	945.00	48.98

Table 5 Test Results of Hexagonal and Octagonal Column Specimens Confined with FRP Composites

Specimen Shape	No. of (0°) Plies	Unconfined Stress (ksi)	Unconfined Capacity (kips)	Confined Stress (ksi)	Confined Capacity (kips)	Percent Increase in Capacity
			E-Glass/Epoxy Confined Specimens			
Hexagonal	6	3.23	472.73	9.53	1392.61	194.59
Octagonal	6	3.05	485.16	9.85	1566.64	322.91
			Carbon/Epoxy Confined Specimens			
Hexagonal	4	3.23	472.73	8.76	1280.73	170.92
Octagonal	4	3.05	485.16	9.53	1516.92	312.66

f_{uj} = ultimate tensile strength of the composite laminates
t_f = thickness of the composite jacket
D = column's diameter
θ = angle of fiber orientation relative to the member axis $\geq 75°$ (the maximum efficiency for this application is achieved at $\theta = 90°$).

For *a rectangular column,* a similar expression is used as follow:

$$f'_{cc} = f'_c(1 + 1.5\rho_{sj}\cos^2\theta) \tag{30}$$

where

$$\rho_{sj} = 2t_f\frac{B + H}{BH} \tag{31}$$

and B, H are the cross-sectional dimensions of the column.

It should be noted that the above equations are based on a confinement model for concrete with steel jackets, which behaves differently than FRP composites. For this reason, several models were proposed to account for the unique properties of composite jackets. One of the early models was proposed by Almusallam and Alsayed (1995). The model proved to be effective in predicting the behavior of concrete axial members confines with FRP composites. We recommend reviewing the development of the current model to account for the linear nature of FRP composites. In 1997, Mirmiran followed the same path and developed a simple model based on small and medium unreinforced circular column specimens. At the present, the use of the Mirmiran model is highly recommended for predicting the strength of ''circular'' concrete axial members with external composite jackets. This model was developed only for circular concrete columns in which the axial response is bilinear with no descending branch. According to this model, the confined compressive strength of a circular axial member with composite jacket applied in the hoop direction is given by the following equation:

$$f'_{cc} = f'_{co} + 4.269 f_l^{(0\ 587)} \tag{32}$$

Figure 32 shows the effectiveness of the Mirmiran model (1997) in predicting the experimental stress–strain curve of a circular standard concrete cylinder 6 in. × 12 in. (152 mm × 304.8 mm).

Additional design information on predicting the ductility enhancement of circular and rectangular columns, and the lap splice confinement gain is described in the ICBO AC125 (ICBO, 2001b) document. The structural engineer is also referred to a useful design textbook by Priestley et al. (1995). As mentioned earlier, the Mirmiran model is only proven to be effective for columns with circular cross sections, and for columns with other geometries, special models are under development at the University of California at Irvine and will be available in the near future.

Durability and Long-Term Performance of Composite Repair Systems

One of the major issues facing the civil engineer when deciding the use of polymer composites in construction applications is durability and long-term performance. For that reason, active programs addressing this subject were initiated by different state and federal agencies, as well as professional organizations such as the U.S. Federal Highway Administration (FHWA), the California Department of Transportation (Caltrans), the International Conference of Building Officials (ICBO), and many other organizations.

Pioneering efforts regarding the durability of FRP composites for infrastructure applications were initiated by Caltrans as a joint project with the Aerospace

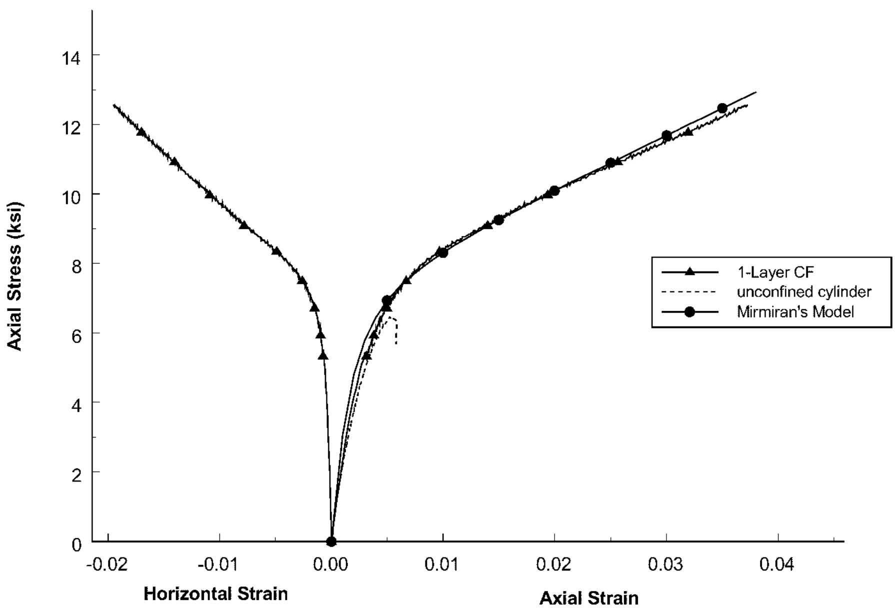

Fig. 32 Successful prediction of the stress–strain behavior of FRP-jacketed unreinforced concrete cylinder using Mirmiran model (Eq. 32).

Corporation (Sultan et al., 1998; Steckel et al., 1999) for composite repair for highway bridge columns. For general building applications, a similar program was developed by the ICBO-ES and is described in details in Tables 1 and 20 of the ICBO AC125 (ICBO, 2001b).

2.3 Internal Reinforcement of Concrete Members Using FRP Composites

FRP composites can also be used as an internal reinforcement for concrete and masonry members. Currently, FRP internal reinforcements are produced in several forms, such as (1) FRP rebars and grid and (2) FRP prestressing cables. There are several applications where composites are the preferred choice as internal reinforcement to concrete and masonry, including:

1. Corrosion environments [e.g., waterfront and marine structures, desalination plants, parking garages and bridges exposed to deicing salts (Fig. 33), and others]
2. Structural members of magnetic resonance imaging (MRI) in hospitals, due to the electromagnetic transparency of composites
3. Electrical applications of E-glass composites internal reinforcement due to its nonconductivity properties that contributes in avoiding electrical-

Fig. 33 FRP composite reinforced bridge deck. (Courtesy of Hughes Brothers Company)

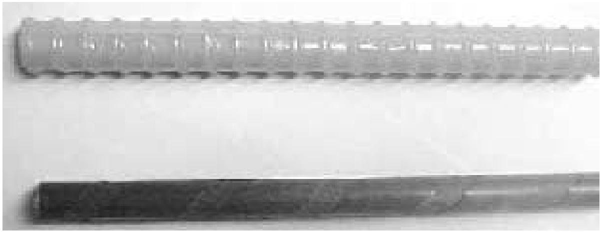

Fig. 34 GFRP and CFRP reinforcing rebars.

related hazards and interference at high-voltage environments (e.g., reinforced concrete power poles, foundations of structural systems in power stations, etc.)

The common form of composite internal reinforcement is FRP rebars made from E-glass (GFRP) and carbon-based composites (CFRP) (Fig. 34). FRP composite rebars are available in standard lengths and diameter grids. According to ACI440 (2001), the tensile strength of commercially produced FRP rebars varies from 70 to 230 ksi (483 to 1600 MPa) for GFRP and from 87 to 535 ksi (600 to 3690 MPa) for CFRP. The longitudinal modulus of elasticity ranges from 5.1 to 7.4 ksi (35 to 51 GPa) for GFRP and from 15.9 to 84 $\times$ 10^3 ksi (120 to 580 GPa). The ranges for rupture strain for GFRP and CFRP rebars are 1.2–3.1%, and 0.5–1.7%, respectively. Figure 35 presents a comparison between the mechanical properties of two types of FRP internal reinforcement as compared to conventional steel reinforcing bars.

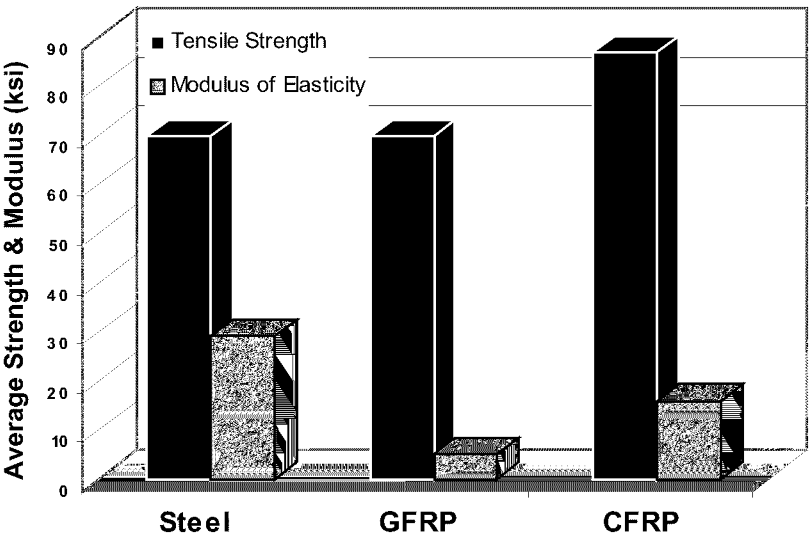

Fig. 35 Comparison between steel and FRP composite rebars mechanical properties (lower bound).

An early study on the use of FRP composites internal reinforcement was initiated by Bank et al. (1991). In this work, a pilot experimental study on the use of FRP grids and gratings as internal reinforcements of one-way concrete slabs was conducted.

The use of GFRP rebars as internal reinforcement for concrete slabs and beams was first initiated in United States at West Virginia University (Faza, 1991). Over the past few years, a number of studies on the durability and long-term performance of FRP internal reinforcement were reported (e.g., GangaRao and Vijay, 1997; Sen et al., 1998; Porter et al., 1995, Alsayed et al., 2001). The majority of the durability studies concluded the sensitivity of GFRP reinforcing materials to alkaline environment found in fresh concrete. The strength degradation of GFRP rebars can reach values up to 75%, while the stiffness degradation, in many cases, can reach to a value up to 20% (ACI440, 2001).

For this reason, it is the author's recommendation to limit the use of GFRP as primary reinforcement in a high pH alkaline environment to low stress level exposure to minimize the possibility of the development of microcracks in the matrix, which opens the doors for alkaline attack of the E-glass. Another alternative is using alkaline-resistant (AR) glass fibers, although the cost may be higher relative to E-glass fibers. For heavier stress environments, carbon-based composite reinforcements are highly recommended. Again the cost may be the issue, but the reliability in this particular environment is higher.

For a comprehensive coverage of the construction and design aspects of FRP composite internal reinforcement of concrete members, the reader is referred to a recent document published by the American Concrete Institute (ACI440.1R-01, 2001).

2.4 All-Composites Structural Applications

In addition to the repair and reinforcement application of composites in construction, composite materials are being used to build the entire structure such as warehouses, buildings, highway bridge decks, and other civil engineering structures. One of the popular types of composites in construction applications is pultruded composites. For decades, pultruded fiber-reinforced polymeric (PFRP) composites have been used as secondary structural members in several construction applications such as petrochemical plants plate forms, cooling tower structures, and in water and wastewater treatment plants applications. The pultrusion process is a continuous manufacturing process where the saturated fibers are pulled through heated die using continuous pulling equipment. The hardening or gelation of the resin is initiated by the heat from the die producing a cured rigid pultruded profile that is cut to length by an automated saw (refer to Fig. 36). Pultrusion is considered to be the only closed-mold process that allows for combining a variety of reinforcement types and hybrids in the same section. Most of the commercially produced PFRP structural shapes are composed of multilayers of surfacing veil or Nexus, continuous fibers (roving), and continuous strand mat. The typical volume fraction of fibers for "off-the-shelf" sections is in the range of 40–45%. A variety of structural profiles (open and closed web) are now available similar to steel sections (H, I, C, L, . . .). The major reinforcements of these sections are concentrated in the longitudinal direction of the section with minimum reinforcement in the transverse direction. The most

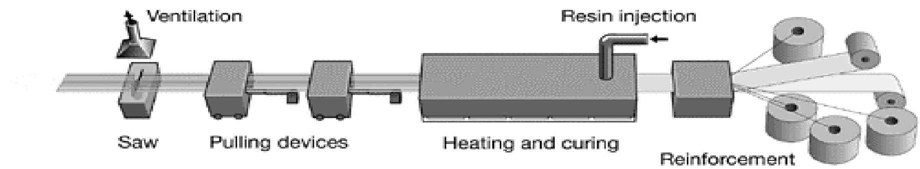

Fig. 36 Pultrusion process. (Courtesy of Fiberline Composites A/S)

common fiber type is the E-glass in the form of rovings and strand mats. However, recently, carbon/E-glass composite profiles have been produced in limited bridge applications.

As shown in Fig. 37, with few exceptions, the majority of the off-the-shelf pultruded profiles is similar, in geometry, to steel profiles and are commercially available in different sizes and grades [Fiberline (2000), Bedford (1999), Creative Pultrusions (1985), Strongwell (1990)].

Although the use of unidirectional reinforcement schedule may be satisfactory for lightweight or secondary structural members, it indeed is not sufficient for primary structural carrying members such as bridge decks, girders, and columns. Other disadvantages of using thin-walled unidirectional "steel-like" PFRP profiles include the insufficient lateral and buckling resistance of the section. In addition, in the majority of commercially produced unidirectional open web (e.g., H-profile, channels, angles, etc.) and closed-web (e.g. rectangular and box profiles) there is a lack of fiber continuity between the web(s) and flanges. For this reason a premature failure at the web–flange junction is the common mode of failure of such profiles. A comprehensive discussion on this issue is reported by Mosallam (1993, 1996).

Research and Development of PFRP Composite Structures

In the late 1980s, several major research projects were initiated to study the structural performance of pultruded composite structures. In 1990, Mosallam conducted a comprehensive study on the behavior of PFRP portal frame. The

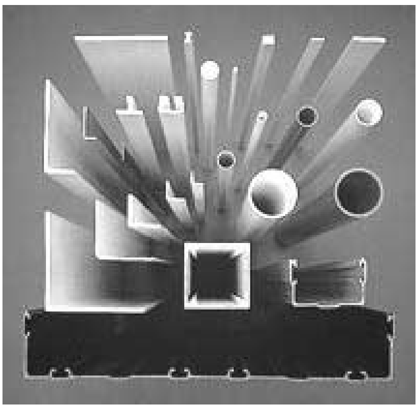

Fig. 37 Sample of pultruded composites profiles. (Courtesy of Fiberline Composites A/S)

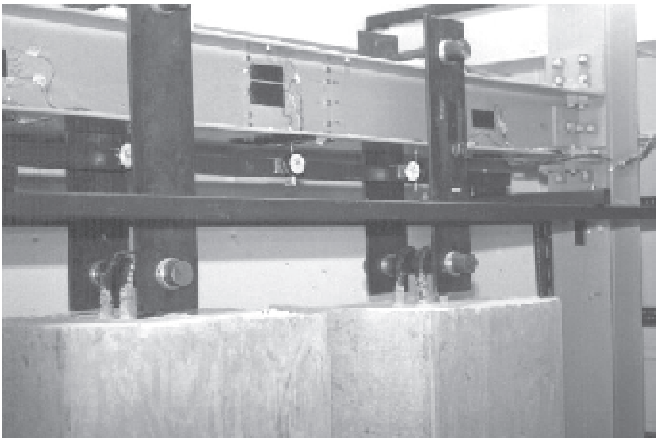

Fig. 38 10,000-h full-scale creep test of a PFRP composite portal frame (Mosallam, 1990).

study included both full-scale experimental testing and theoretical modeling. The experimental part focused at the creep behavior (Fig. 38), service and ultimate behavior, framing connections, and buckling and postbuckling performance of PFRP frames. Simple expressions for the viscoelastic moduli (axial and shear) of the PFRP composites were developed. The ultimate mode of failure and the effect of the nonlinearity of the framing joints on the stiffness and buckling behavior of the pultruded thin-walled sections were also performed (Bank and Mosallam, 1992). Based on the test results (Mosallam, 1990), a premature local failure of open-web unidirectional PFRP sections occurred due to the inadequacy of reinforcement continuity at the web–flange junction (Fig. 39). This premature failure caused by the separation of the web and the flanges of the open-web PFRP elements at the stress concentration locations (usually at the connections and the girder midspan) affects the general behavior of the structure. For ex-

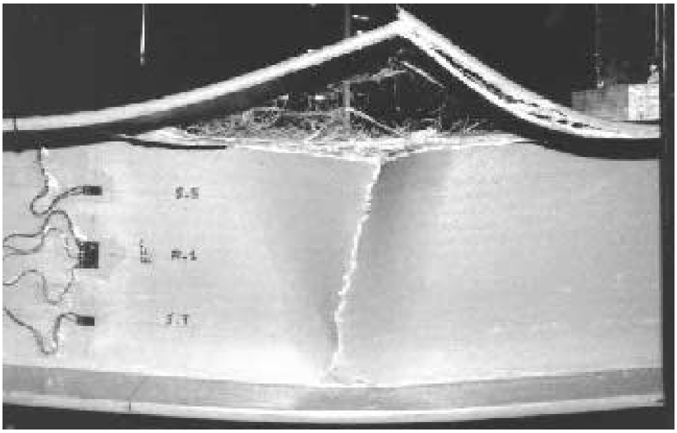

Fig. 39 Failure of web/flange junction of PFRP open-web profiles (Mosallam, 1990).

ample, results of experimental and theoretical research work (Mosallam, 1993; Mosallam et al., 1993) showed the direct effect of this premature failure of the column section of frame structures in the rotational stiffness PFRP frame connections during the crack growth up to the failure. The loss of the flexural stiffness results in a decrease of the connection rotational capacity, and consequently an increase in the flexural stresses at the girder midspan of a PFRP frame structure. Simple reinforcement techniques for overcoming this pre-mature failure were reported by Mosallam (1996).

Unlike aerospace-type joints where the majority of applications is concerned with lap splice joints, the majority of composite joints used in construction applications involve frame connections.

For any frame structure, connections are considered to be of the most critical structural elements, which play a major role in controlling both the serviceability and ultimate strength of the PFRP frame structures. Careful design of the connecting elements will ensure both the safety and the efficient use of the material. Previous studies on PFRP frame structures (Mosallam, 1990; Bank et al., 1990) showed that a premature failure of pultruded shapes would occur if a wrong connection details were used (refer to Fig. 40). Based on this fact, Bank et al. (1992) have extended this work by introducing different connection details to overcome the premature failure of the pultruded shapes at the web–flange junction of PFRP H-beams. The connection details presented in their study considered the anisotropic properties of the PFRP structures. Their results showed that maximum strength and maximum stiffness could be achieved by using a connection with both mechanical and adhesive elements.

All PFRP connections developed and tested in all previous studies (e.g., Bank et al., 1992) have utilized PFRP connecting elements, which were commercially produced and were not intended specifically for connecting purposes. This was an appropriate approach to demonstrate the deficiency of the existing connection details, as well as to provide strengthening details for reinforcing the existing PFRP connections. To overcome this problem, a different approach for connecting PFRP structural elements to ensure the prosperity and the efficient and

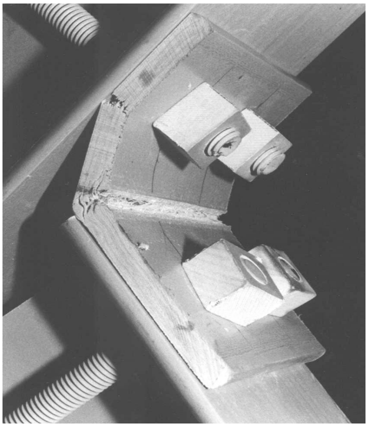

Fig. 40 Premature failure of steellike connection details (Mosallam, 1993).

safe use of this material should be used. This approach is to develop a special connecting element or system using a mixture of past experience, available research and design data, and knowledge of the anisotropic behavior of the composite materials. The design criteria of the connecting elements include proper fiber orientation, ease of erection and duplication, geometrical flexibility of the use for different structural connections, and maximizing both the overall connection stiffness and ultimate capacity. Based on these criteria, a custom-made FRP prototype connector was developed and was fabricated [using resin transfer molding (RTM)] from E-glass/vinylester composition. This FRP-connecting element [designated, herein, as the universal connector (UC)] was developed by Mosallam (1993). The UC element can be used for the majority of PFRP connection details for joining different structural shapes, e.g., exterior and interior beam-to-column connection, column–base connections, continuous beam connections, beam-to-girder connections, and others (Fig. 41). An extensive theoretical and experimental program on the development and characterization of PFRP connections is in progress.

The dynamic response of both PFRP materials and structures was investigated by Mosallam et al. (1993). In this study, results of experimental dynamic tests of FRP pultruded structural elements and framed structures were presented. The thin-walled elements used in this study were standard "off-the-shelf" pultruded 4 in. (101.6 mm) × 4 in. (101.6 mm) × $\frac{1}{4}$ in. (6.35 mm) H-beam and 2 in. (50.8 mm) × 2 in. (50.8 mm) × $\frac{1}{4}$ in. (6.35 mm) square tube made of E-glass–polyester composition. All the connectors and connection elements were made of PFRP threaded rods, nuts, and high-strength epoxy adhesive. The test specimens in this study were excited dynamically using both impact loading and shaking loads. Experimental modal analysis was used to extract the natural frequencies, modal damping, and mode shapes of the test specimens. Comparison between two types of frame connections was also performed to determine the effect of using high-strength adhesives. The study further showed the validity of using both the material properties and the lay-up of the coupons in modeling PFRP beams and frame structures.

A pilot study on evaluating the structural cyclic performance of composite frame connections for pultruded structural systems was conducted by Mosallam (1999). In this study, several full-scale cyclic tests were conducted on several

Fig. 41 FRP composite continuous universal connectors for PFRP framing joints. (Courtesy of Sigma Composites, LLC)

pultruded framing elements (Fig. 42). This included box and H-beam profiles with different sizes. The emphasis of this study was on interior framing connections with both flange and web attachments. In addition to high-strength adhesives, both FRP and steel mechanical fasteners were studied. Bolted-only, adhesively bonded only, and combined joint details were evaluated using both metallic and nonmetallic bolts. Strain, deflection, and load information were collected using a computerized data acquisition system. Hysteresis curves M/θ and P/δ were developed and analyzed (Fig. 43). For FRP mechanical fasteners bolted-only connections, a common mode of failure was observed for all specimens. This was a combination of bolt thread shaving and flexural fatigue-type failure of pultruded threaded rods. Other local failures to the pultruded thin-walled beam sections were observed at the ultimate moment. Delamination cohesive failures were also observed for adhesively bonded connection details.

Currently, a pilot experimental program has been initiated by the author on the seismic behavior of PFRP three-dimensional frame structures (Fig. 44). In this program, both one- and two-story three-dimensional frames made entirely from PFRP composites and gratings are evaluated under ground motion. The tests focus on evaluating the effect of different connection details on the dynamic response of the PFRP frame structure.

Construction Applications of PFRP Composites

Buildings Applications. Several projects have been constructed entirely using pultruded fiber-reinforced polymer (PFRP) composite sections as the main structural elements. One of the early applications is the construction of four PFRP turret towers on top of the Sun Bank Building, Orlando, Florida. Figure 45 shows the framing of one of the three-story high towers, which was built entirely from PFRP shapes (H, angles, threaded rods, and nuts). All columns and girders were constructed using open-web H sections, which were connected together using FRP bolts and nuts. The use of PFRP composites was the preferred choice because of the electromagnetic transparency and radio wave reflection properties of composites. Due to the nonmagnetic properties of PFRP

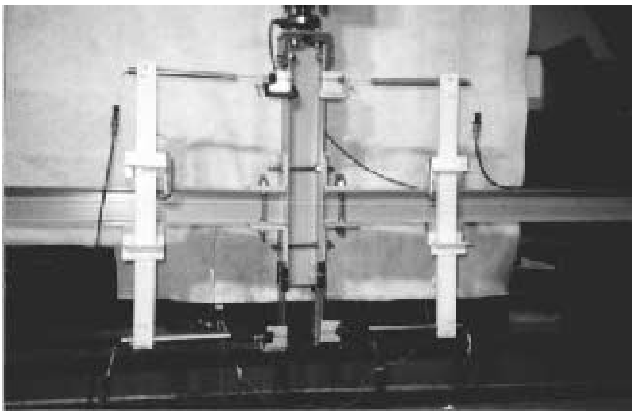

Fig. 42 Cyclic behavior of PFRP composite frame joints (Mosallam, 1999).

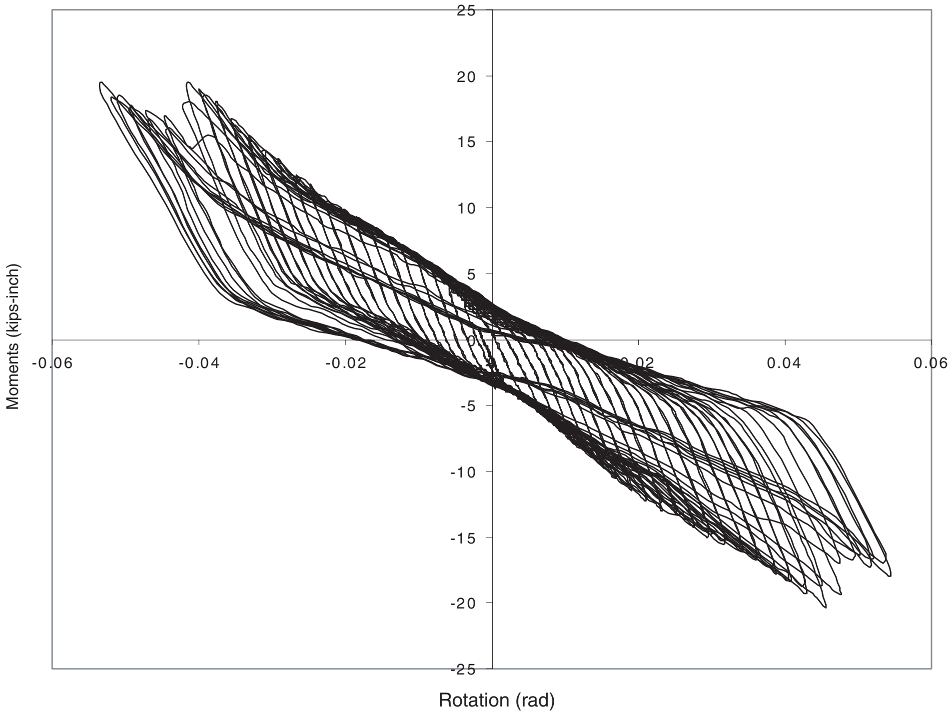

Fig. 43 Typical M/Θ hysteresis of PFRP composite frame joint (Mosallam, 1999).

Fig. 44 Seismic evaluation of three-dimensional PFRP frame structure with PFRP gratings.

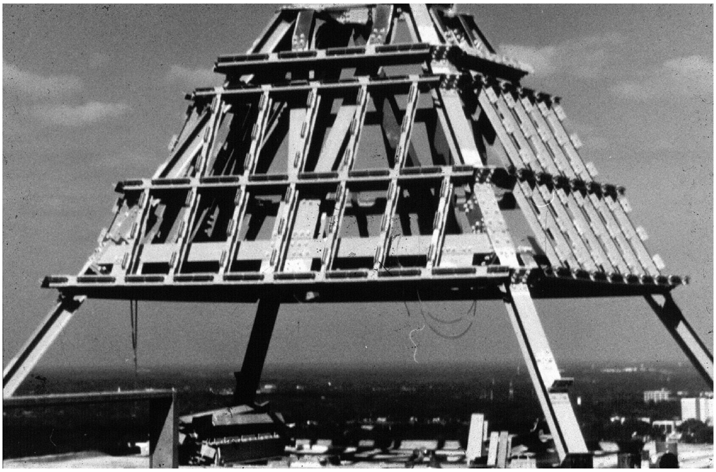

Fig. 45 Three-story high towers framing of the Sun Bank Building, Orlando, Florida. (Courtesy of Strongwell Company)

composites, it is commonly used for facilities with delicate instrumentation. Figures 42 and 44 show a complete frame structure, which was constructed using PFRP materials. The ease of fabrication, transportation, and erection resulted in shorter construction time.

The first residential/office building with PFRP structural profiles was presented as the *Eyecatcher Project* at the Swissbau'99 Fair in Basel, Switzerland. After the exhibition, the construction was disassembled and brought to its new location at Münchensteinerstrasse 210, Basel, where it now serves as a permanent office building. The Eyecatcher all-composite building is open to the public on agreement. The height of the all-composite 5-story building is 15 m (49.21 ft) (with a ground-floor area of 10 × 12 m (30.48 × 39.37 ft). The inclined and vertical columns were fabricated as a buildup section made of one H-profile and two U-profiles. The horizontal frame girders were also built-up sections made of two U-profiles and four flat pultruded plates. In all builtup sections, the pultruded composite profiles were bonded using high-strength epoxy and were subsequently bolted together with steel bolts. Figure 46 shows the skeletons during construction and the finished office building. Other examples of composite framing structures are shown in Figs. 47 and 48.

Bridge Applications. In the United States, there are over 90,000 weight-restricted bridges. In most cases, there are no funds allocated to solve the problem by replacing these decks. These bridges are frequently replaced with a modern multigirder design to restore the route to traffic without weight restrictions. To replace the bridge would have cost $2.4 million. In the past few years, FRP composite decks have proven to be an ideal solution to this problem, with a cost reduction of up to 30% as well as the tremendous saving in construction time and traffic interruption.

In the past few years, the U.S. Department to Transportation (DOT) has utilized composite decks to replace corroded and underrated bridge decks. For ex-

Fig. 46 All-composite ″Eyecatcher″ building in Switzerland: (a) pultruded frame skeletons and (b) the completed structure. (Courtesy of Fiberline Composites A/S)

Fig. 47 Pultruded composites frame structure. (Courtesy of Strongwell Company)

Fig. 48 All-composites skeleton. (Courtesy of Strongwell Company)

ample, the New York DOT has selected the composite deck solution to replace the old deck of the Chemung County Bridge. This steel truss bridge was originally built in 1940, with a span length of 140 ft (42.7 m) and a width 24 ft (7.32 m). The average daily traffic on this bridge (AADT) is 3250 and 7% of this volume is trucks. There were several factors contributing to the posting problem of this bridge, which is typical of the majority of old steel bridges, including:

- Over the past 60 years, little more than a new course of asphalt every few years was added to smooth the wearing surface. This resulted in an increase of dead load.
- In addition, some steel sections were rusted.
- In the original design, the bridge was never intended to carry the heavy loads on the road today.

The engineers in New York DOT Region 6 decided to adopt the FRP composite lightweight solution (refer to Fig. (49), in addition to repairing and painting the steel truss members. After the addition of the FRP bridge deck, the load rating of the bridge raises from the original *inventory* of HS12 (22 tons) with *operating* capacity of HS18 (33 tons) to an inventory of HS23 (42 tons) with operating capacity of HS34 (61 tons). Figures 50 and 51 show the FRP bridge deck during fabrication and installation, respectively.

Another major highway bridge project that utilized FRP composite decks is the Salem Avenue Bridge located just west of downtown Dayton, Ohio. Four different FRP composite decks were used.

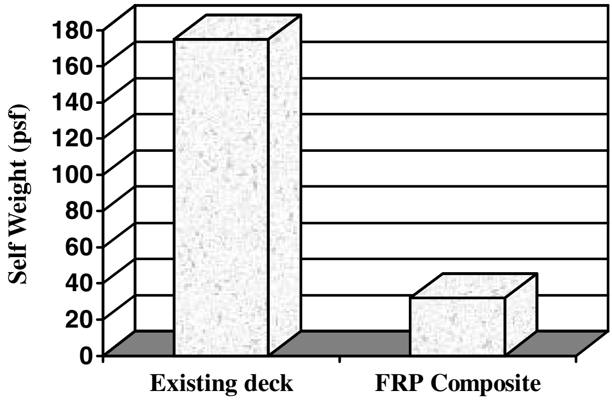

Fig. 49 Self-weight comparison between existing and new FRP composite deck of the Bentley Creek, Chemung County, New York.

1. *CDS Deck.* Consists of FRP stay-in-place forms that act as bottom reinforcement for the composite/FRP hybrid deck. The top layer of reinforcement consists of GFRP rebars. The composite forms were filled with high-strength concrete.

2. *CPI Deck.* Consists of pultruded interlocking profiles that run transverse to the bridge centerline and are adhesively bonded at the shop to form 8-ft-wide (2.43-m) composite panels (refer to Fig. 52). The panels were attached to the existing steel girders using Nelson shear studs that were welded to the top of the steel girders.

3. *HCI Deck.* Coinsists of a sandwich panel with high-density foam core that were manufactured using Seemman Composite Resin Infusion Molding Process (SCRIMP). The composite panels were connected to the steel girders using Nelson studs.

4. *ICI Deck.* Consists of deep sandwich panels with prefabricated corrugated and straight E-glass composite shells bonded together. Same connectors were used.

Fig. 50 Fabrication of the FRP composite bridge deck of NY 367 over Bentley Creek, Chemung County, New York. (Courtesy of New York DOT, Region 6, Hornell, NY)

Fig. 51 Installation of all-composite bridge deck of NY 367 over Bentley Creek, Chemung County, New York (2000). (Courtesy of New York DOT, Region 6, Hornell, NY)

The latest application of all-composite deck for a highway steel bridge has been initiated by Caltrans. A hybrid (carbon/E-glass) sandwich composite deck developed by Martin Marietta (Fig. 53) is planned to be installed at the Schuyler Heim steel lift bridge in Long Beach, California. The 1212 ft (370 m) long, four-lane bridge provides vehicles access to Terminal Island in the Port of Long Beach. The middle lift portion of this bridge uses a 224-ft, (68.3-m) lightweight open-grated steel deck. Due to the high volume of heavy trucks crossing the bridge in the recent year, the welded steel deck suffered from a chronic fatigue problem, and Caltrans was forced to replace portions of the steel deck periodically. Due to the excellent fatigue performance of composites, the preferred choice was replacing the existing steel deck with all-composite hybrid deck system (Hranac, 2001). Small- and full-scale tests were conducted on several

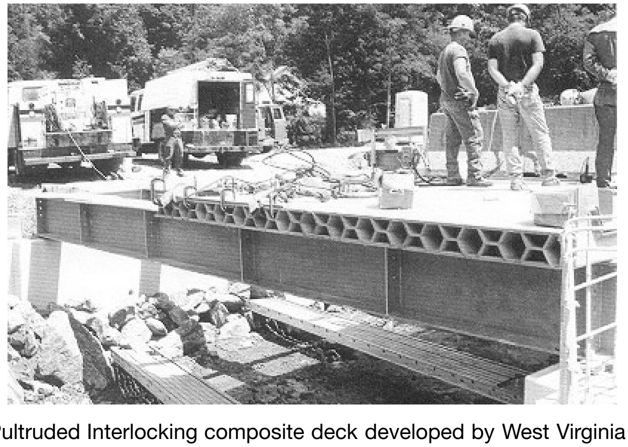

Fig. 52 Pultruded Interlocking composite deck developed by West Virginia University (GangaRao, 2000).

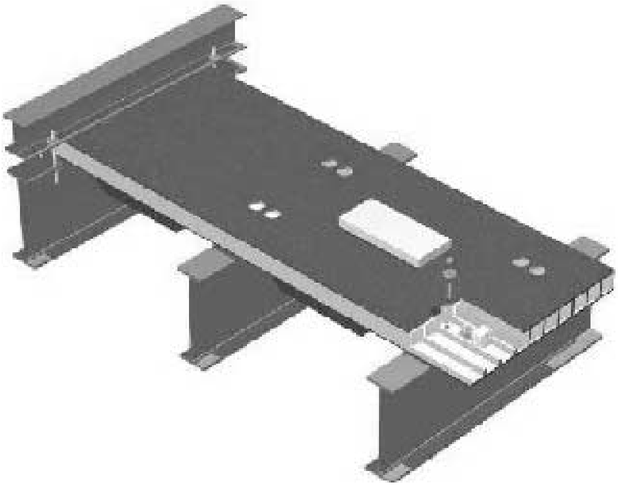

Fig. 53 All-composite hybrid deck system for the Schuyler Heim Bridge, Long Beach, California. (Courtesy of Martin Marietta Composites)

composite panels at both California State University at Fullerton and University of California at Irvine (refer to Fig. 54). Test results indicated that the FRP composite deck has exceeded both the strength and stiffness criteria required by the DOT. The composite deck will be instrumented with different measuring devices and will be monitored for a period of approximately one year. Details of the structural evaluation are reported by Mosallam and Haroun (2001). The destructive test was simulated using a state-of-the-art virtual testing/progressive analysis software called GENOA (Alpha Star, 2001) as shown in Fig. 55.

In Europe, several all-composite bridges and bridge decks have been built. The world's first all-composite cable-stayed footbridge (called the Aberteldy Bridge) was constructed in Scotland and opened on June 2, 1992. The Aberteldy

Fig. 54 Full-scale destructive tests on all-composite hybrid deck system for the Schuyler Heim Bridge, Long Beach, California. (Courtesy of University of California, Irvine, and California State University, Fullerton)

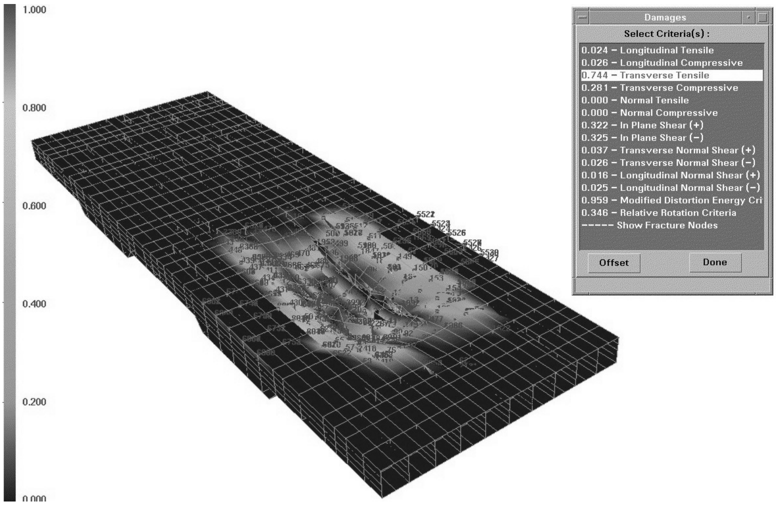

Fig. 55 Full-scale simulated destructive test using GENOA Progressive failure program. (Courtesy of Alpha Star Corporation, Long Beach, California)

Bridge is 2.2 m (7.2 ft) in width and total span of 113 m (370 ft), with a mainspan of 63 m (206 ft) between the two A-frame composite pylons, as shown in Fig. 56. The height of each composite A-frame pylon that support the mainspan with Kevlar composite fan-type cables is 17.20 m (56.43 ft). The structural components of the bridge deck, A-frame pylons, and handrails were all made of GFRP, while the cable stays were made of dry parallel aramid fibers (Kevlar 49) in polyethylene sheaths. The total cost of the bridge was about $200,000 (£120,000), in addition to some donated labor. After nearly 10 years of service, slight sagging of the bridge occurred that can be attributed to the viscoelastic nature and the low modulus of aramid cables. Table 6 presents the physical and

Fig. 56 Aberteldy all-composites cable-stay bridge. (Courtesy of Strongwell Company)

Table 6 Physical and Mechanical Properties of the Different Composite Components of the Aberfeldy Bridge

Composite Materials and Properties	Deck/Pylons	Cable Stays
Fibers	E glass	(Kevlar® 49)
Matrix	Isophthalic polyester resin	None
Manufacturing process	Pultrusion	Parallel Sheathing
Assembly	Toggle and epoxy bonding	—
Adhesives	Epoxy	—
Tensile modulus	22 GPa (3.2×10^6 psi)	127 GPa (18.4×10^6 psi)
Tensile strength	300 MPa (4.3 ksi)	1.9 GPa (276 ksi)
Ultimate tensile strain	1.4%	1.6%

From FHWA (1997).

the mechanical properties of the different composite components of the Aberfeldy Bridge (FHWA, 1997).

A similar all-PFRP-composite pedestrian cable-stayed bridge was built by Fiberline Company (Kolding, Denmark) crossing a busy rail line and was officially opened on June 18, 1997 (Fig. 57). Although the construction work was restricted to only a few hours during weekend nights due to the busy railway line, restricted installation work to only the bridge was fully installed in only three short nights. The short installation time has illustrated the clear advantages of composites.

In 1997, an all-composite bridge was installed in the mountainous region of Pontresina in Switzerland (refer to Fig. 58). The two bridge sections, each measuring 12.5 m (41 ft) and weighing a total of 2,500 kg, were placed by a helicopter, one section at a time. The load-carrying capacity of this bridge is 500 kg/m^2, in addition to a 1-ton snow-clearing vehicle allowance.

Fig. 57 Fiberline all-composite cable-stayed in Denmark. (Courtesy of Fiberline Composites A/S)

Fig. 58 Pontresina all-composite truss bridge constructed in Switzerland in 1997. (Courtesy of Fiberline Composites A/S)

Currently, a new generation of optimized pultruded profiles for a modular bridge deck is being developed through the ASSET project supported by the European Union. The pultruded sections are being manufactured by Fiberline Composites A/S of Denmark. This bridge is considered the first highway bridge that has a load capacity up to 40 tons and will be constructed across a motorway in Oxfordshire in England during the summer of 2002. Figure 59 shows one of the profiles that will be used in this composite bridge deck. A comprehensive review of other composite bridges can be found in the FHWA report (1997).

3 DEVELOPMENT OF CODES AND STANDARDS

In recent years, the construction industry started to realize the potential of using polymer composites in construction applications. Unfortunately, the construction industry and the civil engineers were faced with a tremendous amount of difficulties to utilize these materials in the same manner they are used to for the

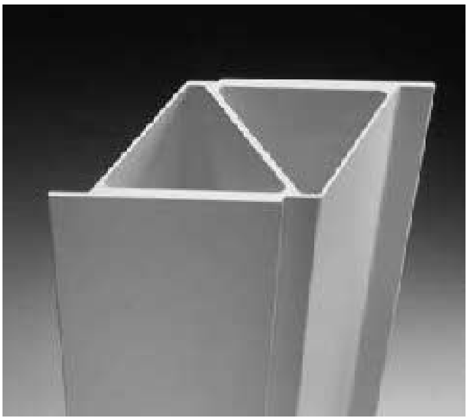

Fig. 59 Optimized patented pultruded profile for modular composite highway bridge deck applications. (Courtesy of Fiberline Composites A/S)

conventional material such as steel, concrete, and wood. The major obstacle is the lack of design standards and authoritative codes for the use of these materials in construction applications. Despite the fact that there is a great deal of research and application information available from the aerospace industry for the past four decades or so, still the civil engineers are searching for ways to convince them with the reliability, applicability, and the structural efficiency of such materials. The Structural Composites and Plastics Committee (SCAP) of the American Society of Civil Engineers (ASCE) appreciates this demand and is working to assist the civil engineers to achieve this goal.

For any structural system, design standards are one the essential requirements for professional engineers' acceptance. Both the American Concrete Institute (ACI) and the American Society of Civil Engineers (ASCE) has been involved in the development of several standard documents for different materials and systems. Since the 1960s, the ASCE has been involved in developing several engineering documents dealing with both unreinforced and fiber-reinforced polymers (FRP) materials and systems. In 1984, the ASCE Structural Plastics Design Manual (SPDM) was published (1984) by the Plastic Research Council of the Materials Division of ASCE. Starting in the late 1980s, as the demand and the acceptance of FRP materials increased, the ASCE recognized the need for more developments in this field. Jointly with the Society of Plastics Industry (SPI), a long-range, multiphase program was established in the early 1990s. The ultimate goal of this joint program is to develop accepted standards for structural design, fabrication, and erection of FRP composite systems. In 1995, the Pultrusion Industry Council (PIC) of SPI sponsored the first phase of this program to develop a design draft standard or a "prestandard" document with a view to process the prestandard upon completion as an ASCE national consensus standard in accordance with the rules of the American National Standard Institute (ANSI).

In late 1995, ASCE awarded phase I of this project to Chambers Engineering, p.c. (as the general contractor) and the author (as the subcontractor) to undertake a one-year startup and planning phase of the multiphase standard program. The scope of work of phase I was to (i) surveying and evaluating existing design and martial information. This task included researching both published and unpublished technical literature, government and university reports, performance data, standards and specification documents (ASTM, ACI, ASCE, JSCE, Eurocode, Canada), manufacturer's materials data, and current practice relative to the use of FRP composites. (ii) Development of a computerized database containing the relevant and evaluated useful technical information, (iii) using this database, identify gaps in knowledge that might impede promulgation of the standard, and (iv) developing the prestandard outline through defining the approach including recommended design philosophy and relationship of the ASCE design standard with other martial or industry standards such as AASHTO, ASTM, ISO, ICBO, and other test standards.

In 1993, the American Concrete Institute realized the potential of the polymer composites in concrete applications. For that reason, a new committee (ACI440) was formed to answer the needs of this new industry and to provide guidelines for design, specifications, and applications of polymer composites as external and internal reinforcement systems. Due to the rapid increase of new polymer composite products and applications, the ACI440 committee was divided into several subcommittees focusing on different design and application aspects of polymer composites in concrete applications. This includes subcommittees on internal reinforcements (FRP rebars), FRP prestressing, FRP external repair, education, and others. One of the active subcommittees is the ACI440 subcommittee on FRP external reinforcements (ACI440F). The ACI440 committee is currently in the final development phase of a design and construction of externally bonded FRP systems for strengthening concrete structures document that will be available shortly to the public. The information presented in the document will assist the structural engineer in properly selecting and designing an optimum and reliable FRP system. The documents also describe conditions where FRP strengthening is beneficial and where its use may be limited.

In 1997, the International Conference for Building Officials (ICBO) evaluation services produced acceptance criteria (AC125) for seismic repair and rehabilitation of reinforced concrete members and walls. Unlike the ACI current proposed document, AC125 focused more on applications related to seismic design. However, the document has been reviewed recently by the different experts and some modifications have been suggested and will be incorporated in the near future.

Lately, the author has developed the *ASCE Structural Design Manual on Pultruded Composite Joints* and will be available in 2002. The manual consists of 12 chapters covering a wide range of design topics related to joining PFRP frame structures (Mosallam, 2001).

4 NEW STRATEGY AND RECOMMENDATIONS

One of the major questions that need to be answered clearly for the structural engineer who has been dealing for decades with conventional materials such as steel and concrete is: Why should he or she select this new material? The same question was asked 40 years ago when composites were first introduced to the aerospace industry. The answer of this question to the civil engineering community is not as simple as many engineers think. The complexity lays on the apparent burden that this engineer will face and the sacrifices expected by dealing with more advanced design and relatively complex structural material. Some of these fears are: (i) the absence of authoritative codes and material specifications, (ii) the lack of simplistic design procedures similar to those that have been established for centuries for conventional materials (concrete, steel, wood), (iii) the direct involvement of the structural engineer in the manufacturing and the tailoring of the material, (iv) the lack of long-term structural and environmental test data, and lastly (v) the need of relatively skilled labors at both the fabrication and construction sites, as compared with composite materials. The effective tool to overcome these roadblocks, in the author's opinion, is education. First, the construction industry should be educated about the nature of these materials and the associated benefits, as well as the special mechanical properties of PFRP composites such as the anisotropy and the viscoelasticity. Second, a modified or new civil engineering curriculum should be established that includes several composite design courses similar to those for steel, wood, and concrete. Generation of structural engineers equipped with the skills required for adopting advanced composites. This, of course, requires the establishment of a design code and specifications. Recently, positive movements by the different engineering and industrial organizations have been initiated to pursue this important task. For example, a new subcommittee of the ASCE plastics and structural composites has been formed to initiate an initial proposal for establishing an ASCE code for composites. The Pultrusion Industry Council (PIC) of the Society of Plastic Industry has already initiated the first phase of a structural design manual project.

It is also important to identify several facts for the civil engineer who will be introduced to FRP composites for the first time. First, the fact that he or she for decades has been using some form of composites with no difficulties (e.g., reinforced concrete, natural, and laminated wood). Second, the engineer should understand that the aim of using FRP composites is neither to replace nor to compete with other construction industries such as concrete, steel, wood, etc. In contrast, these materials are here to enhance and assist the conventional materials in certain applications beyond their capabilities. In addition, these materials if used properly with other conventional materials can produce an optimum engineered structural ‘‘system’’ capable of solving many problems associated with our infrastructures. This misconception has led to both confusion and defensive position of loyal concrete, steel, and wood users. The fact is composites are the right choice in some applications when other construction materials are disqualified in part or whole. For this reason, the structural engineer should begin to look at different materials as elements of an ‘‘integrated structural system.’’

From the above discussion, a new strategy to deal with advanced construction composites is needed. Composites should not be penalizing by adopting the wrong design of sections and structures. It is important for those engineers who are willing to take advantages of these materials to learn the basic mechanics of composites. The directionally dependent, the viscoelasticity, and environmental properties need to be clearly understood. The composite industry must offer all the support and encouragement to all academic and research studies. The great attention shown lately by the different professional and federal organizations in promoting and supporting research and demonstration projects is essential. For example, the recent activities conducted by the Civil Engineering Research Foundation (CERF), the American Society of Civil Engineers (ASCE) SCAP Committee, the International Conference of Building Officials (ICBO), The American Concrete Institute (ACI), the U.S. Corps of Engineers, the Federal Highway Administration (FHWA) Transportation Equity Act (TEA-21) (Hooks, 2000), and the National Science Foundation (NSF) indicate the acceptability and the high level of awareness by the engineering communities. The need of building design codes and material specifications is a must in order for this material to enter and to survive the complexity of the construction industry. Much research data has been conducted in this area that need to be collected in a database system. The importance of this database is to evaluate these works by committee experts in this area to select the useful information for the development of unified design procedures. Experimental and analytical research work on the long-term performance of PFRP is needed to increase the confidence level of these materials. Composite education at the university level and the practical training programs for structural engineers are essential.

As we entered the twenty-first century with these advanced materials, we need advanced design tools to achieve the optimum design and the best performance of these materials. For the other conventional construction materials, the use of simplified design formulas, charts, and tables were acceptable. Fortunately, and due to revolutionary advancement in computer and computational techniques such as finite-element method (FEM), the use of computers will be the recommended tool for composites. This is due to the fact that the optimum design and performance prediction of campsites can only be achieved with more detailed calculations. Simplified equations are still important for quick estimate and as a tool for comparison. In short, advanced composites provide the structural engineers, for the first time, with the challenging opportunity to create innovative structural systems.

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