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Section VI

Special Topics

51
Applications of Composites in Highway Bridges

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51.1 Introduction

Building a functional transportation infrastructure is a high priority for any nation. Equally important is maintaining and upgrading its integrity to keep pace with increasing usage, higher traffic loads, and new technologies. At present, in the United States a great number of bridges are considered structurally deficient, and many are restricted to lighter traffic loads and lower speeds. Such bridges need to be repaired or replaced. This task may be achieved by using the same or similar technologies and materials used originally for their initial construction many years ago. However, new materials and technologies may provide beneficial alternatives to traditional materials in upgrading existing bridges, and in the construction of new bridges. Composite materials offer unique properties that may justify their gradual introduction into bridge repair and construction.

The difference between industrial or commercial composites and advanced composites is vague but based primarily on the quality of materials. Advanced composites utilize fibers, such as graphite and Kevlar®, and matrix materials of higher strength and modulus of elasticity than industrial composites, which usually are fabricated with E-glass or S-glass fibers and with polyester or vinyl ester matrices. Advanced composites use polymer matrix materials, such as modified epoxies and polyimides, or ceramic and metal matrices. More-sophisticated manufacturing techniques are generally required to produce advanced composites. Industrial composites require little or no special curing processes, such as the use of autoclaves or vacuum techniques for advanced composites.

Composites are herein limited to materials fabricated with thin fibers or filaments and bonded together in layers or lamina with a polymer matrix. The polymers discussed are primarily polyesters and epoxies. The fibers considered include glass (E and S type), graphite, and Kevlar. The filaments may be of short fiber length (such as chopped fibers which may be less than 25 mm long) or continuous filaments. The ability to orient the fibers in any desired direction is one of the truly great advantages of composite materials as opposed to isotropic materials such as steel. The anisotropic nature of composite materials enables an engineer literally to custom design each element within a structure to achieve the optimum use of material properties.

Composite materials have been successfully utilized in many other industries in the past 50 years. The leisure industry, primarily boating, was probably the first industry to successfully and overwhelmingly adopt composite materials in the construction of pleasure craft and small ships. In the industrial application fields, pipes, tanks, pressure vessels, and a variety of other components manufactured primarily with fiberglass, composite materials have been used for over 50 years. In the defense and aerospace industry, more-advanced composites have been increasingly used since the early 1960s. In all of these industries, one or several unique properties of composites were successfully exploited to replace conventional materials.

The initial study [1] on the use of composites in bridges was performed for the U.S. Federal Highway Administration in the early 1980s and had as its main objective the determination of the feasibility of adapting composites to highway bridges. This study considered the adaptability of composites to major bridge components, given the unique characteristics of these types of materials. The study concluded that bridge decks and cables are the most suitable bridge components for use of composite materials.

The purpose of this chapter is to introduce the current and future technologies and the most feasible applications of composites in highway bridge infrastructure. Basic composite material properties are presented and their advantages and disadvantages discussed. The applications of composites in bridges presented in this chapter include beams and girders, cables, reinforcing bars, decks and wearing surface, and techniques to repair or retrofit existing bridge structures. The methods and significance of nondestructive evaluation techniques are also discussed relative to the feasibility of incorporating composite components into bridge systems.

51.2 Material Properties

51.2.1 Reinforcing Fibers

Fibers provide the reinforcement for the matrix of composite materials. Fiber reinforcement can be found in many forms, from short fibers to very long strands, and from individual fibers to cloth and braided material. The fibers provide most of the strength of the composites since most matrix materials have relatively low strength properties. Thus, fibers in composites function as steel in reinforced concrete.

The most typical fiber materials used in civil engineering composite structures are glass, aramid (Kevlar), and graphite (carbon). A variation in mechanical properties can be achieved with different types of fiber configurations. A comparison of typical values of mechanical properties for common reinforcing fibers is provided in Table 51.1.

TABLE 51.1 Typical Fiber Design Properties

Property	E-Glass (Strand)	S-Glass (Strand)	Kevlar-49 (Yarn)	High-Modulus Graphite (Tow)	High-Strength Graphite (Tow)
Tensile strength (MPa)	3100	3800	3400	2200	3600
Tensile modulus (GPa)	72	86	124	345	235
Specific gravity	2.60	2.50	1.44	1.90	1.80
Tensile elongation (%)	4.9	5.7	2.8	0.6	1.4

TABLE 51.2 Typical Properties of Polymer Resins

Property	Polyester	Epoxy	Phenolic
Tensile strength (MPa)	55	27–90	35–50
Tensile modulus (GPa)	2.0	0.70–3.4	7.0–9.7
Specific gravity	1.25–1.45	1.1–1.4	1.4–1.9
Elongation (%)	5–300	3–50	—
Coefficient of thermal expansion (10^{-6} m/m/K)	70–145	18–35	27–40
Water absorption (% in 24 h)	0.08–0.09	0.08–0.15	0.30–0.50

Glass fiber has been the most common type of reinforcement for polymer matrix. Glass fibers, which are silica based, were the first synthetic fibers commercially available with relatively high modulus. Two common types of glass fibers are designated as E-glass and S-glass. E-glass fibers are good electrical insulators. S-glass fibers, which have a higher silica content, possess slightly better mechanical properties than E-glass. Some applications require fibers with better strength or elastic modulus than glass. Graphite (carbon) and aramid fibers can provide these desired properties. The use of these fibers is generally selective in civil engineering applications, given their higher cost compared with glass fibers.

51.2.2 Matrix Materials

Thermosetting polymer resins are the type of matrix material commonly used for civil engineering applications. Polymers are chainlike molecules built up from a series of monomers. The molecular size of the polymer helps to determine its mechanical properties. Thermosetting polymers, unlike thermoplastic polymers, do not soften or melt on heating, but they decompose. Other matrix materials, such as ceramics and metals, are used for more-specialized applications.

The most common thermosetting resins used in civil engineering applications are polyesters, epoxies, and to a lesser degree, phenolics. A summary of typical properties for resins is provided in Table 51.2. Polyester resins are relatively inexpensive, and provide adequate resistance to a variety of environmental factors and chemicals. Epoxies are more expensive but also have better properties than polyesters. Some of the advantages of epoxies over polyesters are higher strength, slightly higher modulus, low shrinkage, good resistance to chemicals, and good adhesion to most fibers. Phenolic resin is generally used for high-temperature (150 to 200°C) applications and relatively mild corrosive environments.

51.3 Advantages and Disadvantages of Composites in Bridge Applications

The rapid rise in the use of composites in many industries, such as aerospace, leisure, construction, and transportation, is due primarily to significant advantages of composites over conventional materials, such as metals, concrete, or unreinforced plastics. The following presents a brief discussion on the probable advantages and disadvantages of composites in highway bridge type applications.

The first and primary advantage of composites in bridge structures will probably be a significant reduction in weight, due to the higher specific strength (strength/density) of composites over conventional materials, such as steel and concrete. The lightweight advantage of composites in bridge decks is clearly illustrated in Table 51.3. In most short bridge applications, the lighter structural system, if adequate from the structural point of view, will probably not affect the dynamic performance of the bridge. In longer bridges, it is conceivable that a lighter-weight system may require additional design considerations to avoid dynamic behavioral problems.

The second and equally important advantage of composites is their superior corrosion resistance in all environments typically experienced by bridges throughout the world. Corrosion resistance of composites can be further enhanced by the use of premium resin systems, such as vinyl esters or epoxies in comparison with conventional resins, such as polyesters. The excellent corrosion resistance characteristics of composites, and the lower maintenance costs, may result in lower life-cycle costs than those of bridge components manufactured with steel or concrete materials. The lower life-cycle costs may be the third significant advantage of composite bridge components. However, it is anticipated that the initial cost of such composite bridge components will be considerably greater than that of conventional materials.

The fourth significant advantage of composites in bridge applications is their modular construction. It is envisioned that composite bridge deck components will be fabricated in large modules, either in the shop or at the bridge site, then assembled at the bridge site to form a desired structural system. Such modular construction will not only reduce construction costs, but also reduce the time of construction. Fifth, it is envisioned that the initial usage of composites in bridges will involve rehabilitation or retrofitting of existing bridges in large urban areas. The modular construction described above will greatly reduce the time required for retrofitting, thus reducing traffic congestion, accidents, and time delays for commuters in heavily traveled urban areas. The layered structure of composites is also an advantage that may be highly beneficial for fatigue-type loads in bridges. By placing fibers in appropriate directions, both the strength and fatigue resistance of the composite laminate is greatly enhanced. The fatigue behavior of composites when properly designed is superior to that of ductile materials, such as the conventional A36 steel.

The disadvantages of utilizing composites in infrastructure applications such as bridges are considerable, but not overwhelming. The first, but not necessarily the most significant, disadvantage of composites is their relatively high initial costs. This topic was discussed in the previous section relative to initial vs. life-cycle costs. Although graphite and other advanced fibers will probably reduce in cost with increased volume of consumption, it is very doubtful that the cost of glass fibers can be significantly reduced with increasing volume of consumption. The cost of matrices, such as polymer-based resins, will also not be reduced significantly with increased consumption.

The second disadvantage of composite structural systems is the lack of highly efficient mechanical connections. The mechanical bolted connections in composite applications are not as efficient or as easily designed as in the case of steel-type welded and bolted connections used in steel structures. To reduce mechanical-type connections, adhesive-type joints are required. However, adhesion of one part to another requires detailed knowledge of the adhesive and the bond surfaces, as well as quality control. All of these factors generally result in relatively low allowable adhesive stresses. Furthermore, many engineers tend to dislike adhesive-type connections in the presence of fatigue and vibration-type loads.

TABLE 51.3 Comparison of Dead Load (D.L.) of Deck Systems and Superstructure

Bridge Type	Bascule with 1.22 m Stringer Spacing (span = 76.2 m, width = 18.9 m)				Deck on Steel I-Girder 2.13 m Girder Spacing (span = 16.3 m, width = 8.5 m)		Deck on AASHTO Type III Prestressed Girders Spaced at 2.13 m (span = 16.3 m, width = 8.5 m)	
Deck Type	127 mm Open Steel Grid	152 mm Deep X-Shaped FRP with Sand Layer Wearing Surface	127 mm Concrete-Filled Steel Grid	152 mm Deep X-Shaped FRP with Sand Layer Wearing Surface	165 mm Thick Concrete with 5 mm Wearing Surface	229 mm Deep X-Shaped FRP with Sand Layer Wearing Surface	178 mm Thick Concrete with 5 mm Wearing Surface	229 mm Deep X-Shaped FRP with Sand Layer Wearing Surface
Deck weight only (KN)	1379	1155	5654	1155	541.4	157	583.2	157
Deck D.L. % reduction	16		80		71		73	
Girder weight (KN)	3610		3610		111.8		693.5	
Curbs and railing (KN)	300.3		300.3		166.6		166.6	
Future wearing surface (KN)	0	17.8	0	17.8	166.6	2.2	166.6	2.2
Details, stiffeners, etc. (KN)	290.9		290.9		35.7			23.8
Inspection walkway (KN)	66.7		66.7		None		None	
Total D.L. (KN)	5647	5441	9922	5441	1022	473.3	1634	1043
Total D.L. % reduction	3.6		45		54		36	

The third disadvantage is the relatively low modulus of glass fiber composites. Unless all fibers are oriented in a single direction, the modulus of elasticity of glass-type composites (E- or S-glass) will be somewhat similar to that of concrete. Since design of bridges is often governed by deflection or stiffness criteria, as opposed to strength, the cross-sectional properties of the fiberglass component would have to be nearly identical to that of concrete. The use of high-modulus fibers, such as graphite, enhances the modulus or stiffness characteristics of composites. However, even if all the graphite fibers are placed in the same direction (unidirectional laminate), the modulus of elasticity of the composite may not approach that of steel. Only with the use of very high modulus fibers (above 350 GPa), will the tensile modulus of the composite approach that of steel. To alleviate this very significant stiffness disadvantage, composite structural systems must generally be designed differently when stiffness criteria govern the design.

The fourth significant disadvantage is the relatively low fire resistance of structural composites where polymer-based matrices are used, which represent the bulk of the composites utilized outside of the aerospace industry. This disadvantage has effectively disallowed the use of polymer-based composites in fire-critical applications such as buildings. In bridge applications, fire is a relatively infrequent phenomenon. Elevated temperatures, such as in the southwestern part of the United States, may, however, affect the structural properties of composites on bridge applications.

Several additional disadvantages of composites include relatively complex material properties and current lack of codes and specifications, which tend to dissuade engineers from understanding and utilizing such materials. The presence of local defects, which are difficult and perhaps impossible to detect on a large structural system, are also viewed as a significant quality control problem.

51.4 Pultruded Composite Shapes and Composite Cables

51.4.1 Pultruded Composite Shapes

Composites are commercially available in a variety of pultruded shapes [2–4]. Some of the most common shapes available for construction purposes are I-beams, W-sections, angles, channels, square and rectangular tubes, round tubes, and solid bars. However, almost any shape of constant cross section can be pultruded.

Composite pultruded beam shapes have a potential use in bridges. However, the relatively low modulus of glass and graphite composite shapes limits their use. The effect of modulus of elasticity can be seen with the following comparison between A36 steel beams with modulus of elasticity $E =$ 200 GPa, fiber-reinforced polymer (FRP) beams with $E = 17.2$ GPa, graphite beams with $E = 103.5$ GPa, and glass fiber–reinforced polymer (GFRP)/graphite hybrid beams for a two-lane, 16.76-m-span bridge. Assuming full lateral support, a total of five beams spaced at 2.29 m, and a 178-mm-thick concrete slab, the following results are obtained.

For the case of noncomposite action between beams and concrete slab, a steel beam, W36 × 194, with cross-sectional area, $A = 36{,}770\ \text{mm}^2$, satisfies all AASHTO requirements for HS20-44 loading [5,6]. Using GFRP beams, the deflection requirement of $L/800$, which controls the design, cannot possibly be satisfied using a depth of 914 mm and a flange width of 457 mm. A GFRP I48 × 24 × 3.25 with $A = 187{,}700\ \text{mm}^2$ or I60 × 30 × 1.5 with $A = 113{,}200\ \text{mm}^2$ beam is necessary. If an all-graphite beam is used, an I36 × 18 × 1.25 with $A = 56{,}060\ \text{mm}^2$ will satisfy all requirements. A hybrid beam with a 1320-mm total depth, 660-mm flange width, and 45.7-mm web and flange thickness also satisfies stiffness requirements. For this example, the hybrid beam should have a 7.6-mm-thick layer of graphite in the center of both flanges, and for the total width of the flange.

If composite action is achieved between the concrete slab and the beams, a W30 × 99 with $A =$ 18,770 mm² steel beam is adequate for this bridge. An all-FRP I48 × 24 × 1.0 beam with $A =$ 60,650 mm² or I42 × 21 × 1.5 with $A = 78{,}390\ \text{mm}^2$ will also meet stiffness and stress requirements when composite action is included. A comparison of sizes for all the beam cross sections used in this example is presented in Figure 51.1.

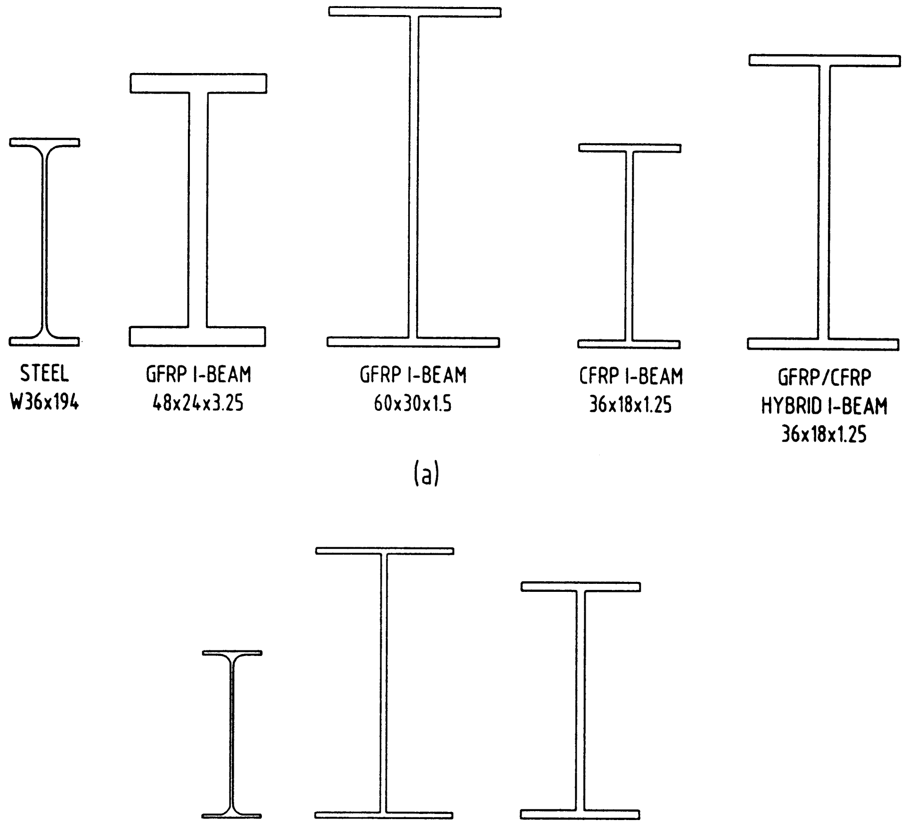

FIGURE 51.1 Comparison of different beams for a two-lane 16.80-m-span bridge, with a total of five beams spaced at 2.30 m, and a 180-mm-thick concrete slab. (a) Noncomposite action between beams and slab; (b) composite action between beams and slabs.

51.4.2 Composite Cables

Composites in the form of cables, strands, and rods have potential applications in bridges. Among these applications are suspension and stay cables and prestressing tendons. High tensile strength, corrosion resistance, and light weight are the most important characteristics that make composites strong candidates to replace steel for these types of applications. Corrosion of traditional steel cables and tendons may impose a significant maintenance cost for bridges. Composite cables, with proper selection of materials and design, may exceed the useful life of traditional bridge cables.

Carbon fiber–reinforced polymer (CFRP) composite cables have been used for cable-stay bridges [7]. Compared with steel, carbon composites can provide the equivalent tensile strength with only a fraction of the weight. GFRP tendons have been used to prestress concrete bridge girders. The computation of section strength using GFRP tendons is very similar to the methods used for steel tendons. In the case of post-tensioned structures, an adequate anchorage system must be used to minimize prestressing losses. One of the advantages of GFRP compared with steel tendons is that a lower modulus of elasticity is translated into lower prestressing losses, due to creep and shrinkage of the concrete.

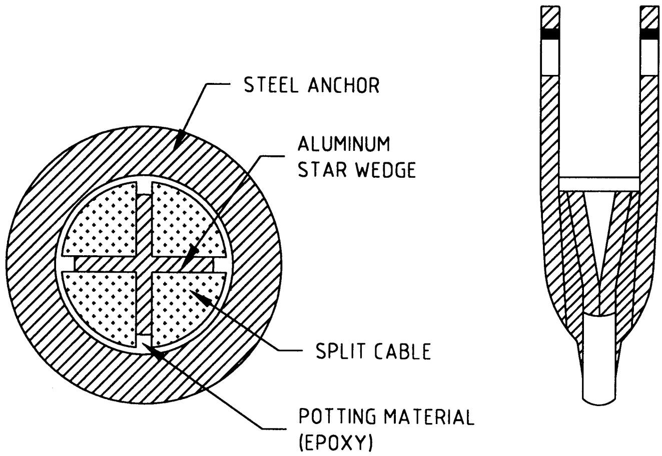

FIGURE 51.2 Potted end anchorage assembly for composite cables; cross sectional view (left) and longitudinal view (right)

A key issue in the design of composite cables is the anchoring system. Development of the full tensile strength of the composite cable is not yet possible; however, a good design of the anchors can allow the development of a large percentage of the total available cable strength. A potted-type anchor is shown in Figure 51.2 [1]. This assembly utilizes a metal end socket into which the composite cable is fitted and subsequently potted with various polymers such as epoxies. The load is transferred from the cable to the metal anchor through the potting material by shear and radial compressive stresses. The aluminum wedge is used to split the cable into four equal sectors to create greater wedging action, but this also creates large radial compressive stresses. Since the largest stresses at the stress transfer region occur at the cable perimeter, several related parameters affect the strength property of such potted anchors and, therefore, the ultimate strength of the cable system.

Another type of anchoring system [7], specifically designed for CFRP cables, utilizes a conical cavity filled with a variable ceramic/epoxy mix (Figure 51.3). The variable formulation is designed to control creep and rupture of the cable.

51.5 FRP Reinforcing Bars for Concrete

Fibers such as glass, aramid, and carbon can be used as reinforcing bars (rebars) for concrete beams. The use of these fibers can increase the longevity of this type of structural element, given the corrosive deterioration of steel reinforcement in reinforced concrete members. Tests have shown that a higher ultimate strength can be achieved with FRP rebars than with mild steel rebars. This strength can be achieved due to the high tensile strength of most fibers. The lower stiffness of FRP fibers, such as glass, will result in larger deflections compared with steel-reinforced concrete.

An important factor in the use of FRP bars is the bond between the bar and the concrete [8]. The use of smooth FRP bars results in a significant reduction of flexural capacity. Thus, smooth FRP bars must be surface-treated to improve bonding by methods such as sand coating. Test results have also shown that smaller-diameter FRP rebars are more effective for flexural capacity than larger-diameter bars. However, in general, bond characteristics are variable due to the variations in FRP reinforcing bar products. Other factors that affect the bond characteristics are concrete strength, concrete confinement, type of loading, time-dependent effects, amount of concrete cover, and type and volume of fiber and matrix. In the State-of-the-Art Report 440R-96 on FRP Reinforcement for Concrete Structures [9], the American Concrete Institute (ACI) recognizes the need for additional testing data to develop expressions that will be valid for different conditions, and can be included in a design code. Some expressions for FRP bar development lengths have been proposed recently.

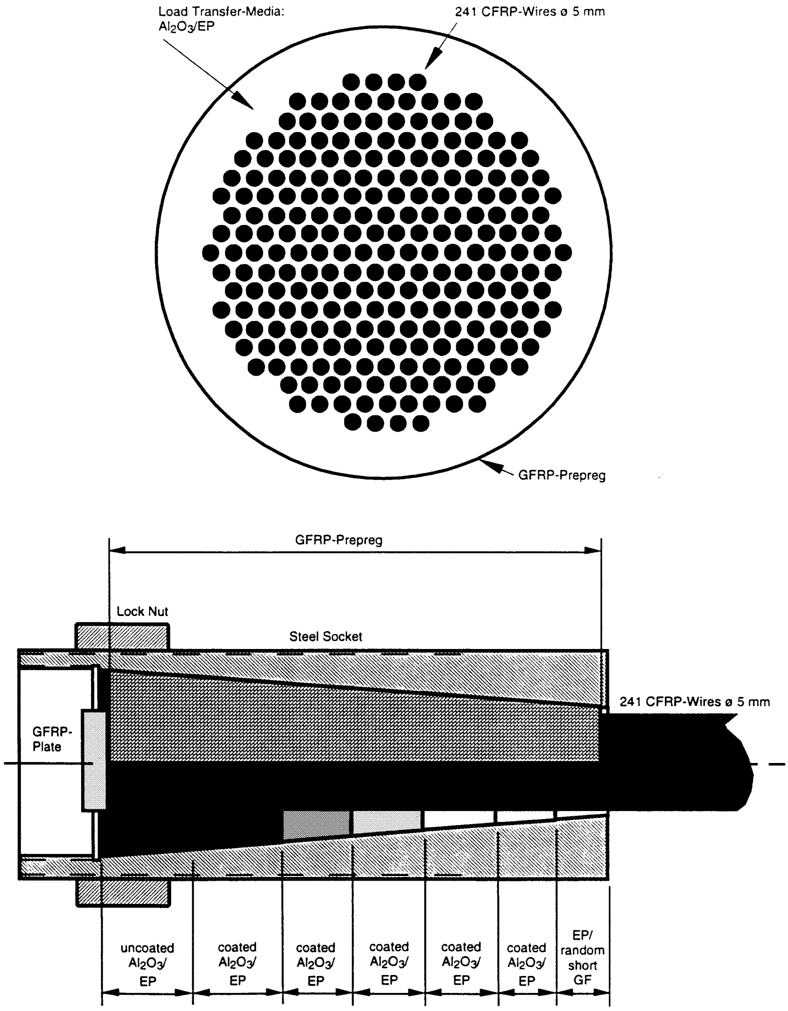

FIGURE 51.3 Specifically designed conical-shaped anchor enhances load transfer to the carbon cable.

51.6 Composite Bridge Decks

51.6.1 Advantages and Disadvantages

The bridge deck appears to be one of the most suitable bridge components for use of structural composites in highway applications [1]. The primary advantages of composite bridge decks are their relative lighter weight, corrosion resistance, and fabrication in modular units which may be rapidly installed without the need for shoring and formwork.

Reference [1] provides the results of a study of bridge dead loads with various types of conventional and composite bridge decks. Table 51.3 provides a summary of this comparison for a 76.2-m-long bascule bridge and two 16.3-m-span conventional bridges. The deck used for the comparison is the X-shaped cross section yielding truss-type deck behavior. The last row of Table 51.3 indicates that for bascule-type bridges with an open steel grid deck, the composite deck would not appreciably reduce the total dead loads of the bridge superstructure (deck, stringers, and girders). However, if the steel grid is filled with concrete, the total dead-load reduction with a composite deck is 45%. Similarly, for conventional bridges, the composite deck reduces the total dead load of the bridge superstructure by up to 54%. If a comparison of bridge decks alone is considered, composite decks are typically about 20 to 30% of the weight of conventional concrete decks as shown in row 3 of Table 51.3. The reduced weights of bridge decks could be translated into:

1. Increased allowable live loads that result from moving traffic on the bridge;
2. Increased number of lanes with the same girders, columns, or piers, resulting in the same total dead and live loads;
3. Continued use of bridge without reducing its load capacity;
4. Reduced construction costs, because a lighter bridge deck requires less construction time and effort than heavier conventional decks.

A composite deck may be made of prefabricated modular units quickly assembled at the bridge site. Due to economics and the need for minimization of joints, it would be desirable that deck sections could be fabricated as large as possible. Modular construction may also translate into relatively short erection time. The quick field assembly will greatly reduce traffic routing costs, a significant advantage in urban areas.

The disadvantages of composite decks include possible higher initial costs, greater deck and girder deflections, and lower bridge stiffness. Although the lighter composite decks will reduce dead loads on the girders, columns, and piers, other structural factors must also be considered. First, the reduced mass of the deck will result in different bridge vibrational characteristics. For long bridges, the reduced mass and stiffness may result in possible vibrational problems and excessive deflections. For short spans, such problems should not occur. On the positive side, composite materials provide higher damping, thereby reducing these vibrational tendencies.

51.6.2 Composite Deck Systems

The choice of a deck configuration should be made on structural and economic feasibility considerations. Structurally, the deck should carry dead loads and specified live loads, and also satisfy deflection requirements. Economically, a composite deck should be cost-effective if it is to replace conventional decks.

The transfer of traffic loads through a composite deck can be achieved mainly by flexure or truss action. The effectiveness of these load-transfer systems depends greatly on the mechanical properties of the materials. Studies [1] have shown that AASHTO stiffness or deflection requirements for decks are difficult to satisfy with low-modulus materials such as GFRP. It was also shown that truss-type load-transfer elements (Figure 51.4a through e) are preferable to sandwich or flexural-type structural elements (Figure 51.4f).

51.6.3 Truss-Type Deck System

A composite deck system that transfers the traffic loads to the stringers and girders mainly by truss action in the transverse direction of the bridge has been developed [1]. Several shapes were studied and evaluated based on AASHTO requirements in order to determine an economical and structurally efficient deck cross section. A deck with a total depth of 229 mm satisfied the stress and stiffness requirements for all the cross sections considered and shown in Figure 51.4. The X-shaped cross section (Figure 51.4b) is the optimum design from the viewpoint of stiffness and dead load. The X-shaped deck transfers live loads primarily by truss action, which provides less deflection than flexure-type members.

In addition to analytical studies, an extensive experimental program has proved the feasibility of the X-shaped cross section for a composite deck [1,10,11]. Specimens were fabricated and subjected to static and fatigue testing under AASHTO loads and the heavier "alternate military load." These specimens sustained over 30 million fatigue cycles without failure or degradation, and suffered only minor overall stiffness loss.

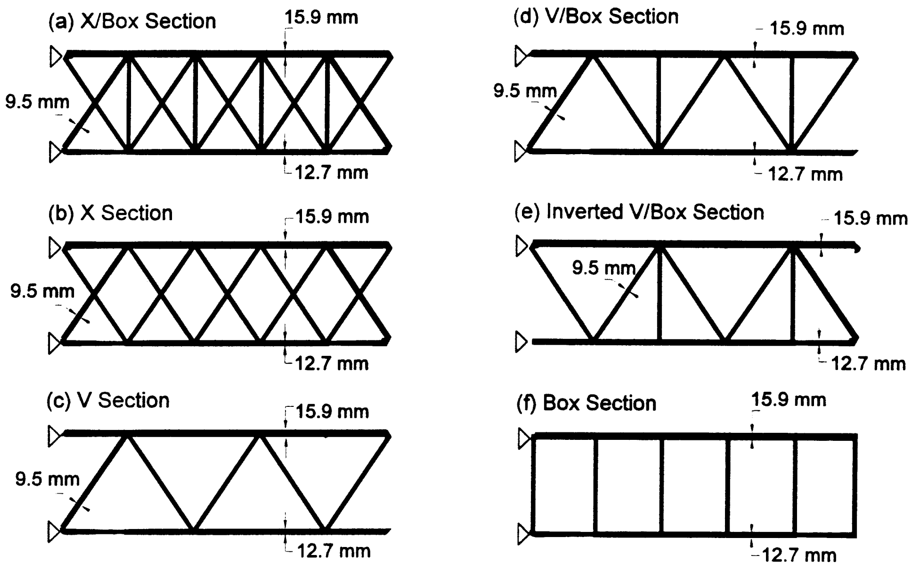

FIGURE 51.4 Shapes considered for design of a truss-type composite bridge deck. (a) X/box section; (b) X section; (c) V section; (d) V/box section; (e) inverted V/box section; (f) box section.

51.7 Wearing Surface for a Composite Deck

The wearing surface of a composite bridge deck should provide laminate protection, adequate skid resistance, and safety against hydroplaning. A thin layer of sand–epoxy mix has been developed for this purpose. The mix consists of sand retained between No. 8 and No. 30 sieves and a matrix-type epoxy. The mix is applied directly to the top surface of the composite FRP deck to a thickness of 1.5 to 3 mm after surface preparation.

The performance of this wearing surface has been evaluated with a series of tests. Freeze/thaw cycling and high-temperature tests were performed to determine the response of the system to weather conditions expected in most parts of the United States.

Simulated truck traffic was applied to evaluate the performance in terms of particle loss and abrasion. Specimens were tested using the accelerated loading facility (ALF), which consists of a frame with a set of truck tires that run along a stretch of pavement. Specimens with the sand–epoxy wearing surface were embedded in the pavement, and their integrity observed during the test. When there is a loss of sand particles, the skid resistance and texture depth of the wearing surface decreases, and the risk of skidding and hydroplaning increases. The surface deterioration was monitored using the British Pendulum method and the sand patch test [12]. Variation of the average British Pendulum Number (BPN) with number of tire passes is shown in Figure 51.5. A stabilized BPN above the minimum acceptable BPN of 60, after 1 million cycles, may indicate that the wearing surface will maintain its serviceability for an extended amount of time. The sand patch readings, shown in Figure 51.6, also indicate a reduction in the rate of mean average texture height loss at an acceptable level.

51.8 Composite Bridge Structural Systems

The use of composite materials to build an entire bridge superstructure is a possibility that is being explored by engineers. An all-composite bridge, designed to meet AASHTO HS25 loading, was built and installed near Russell, Kansas in 1996 [13]. The net span is 7.08 m and the width is 8.45 m. Three side-by-side panels connected by interlocking longitudinal joints were used to construct the

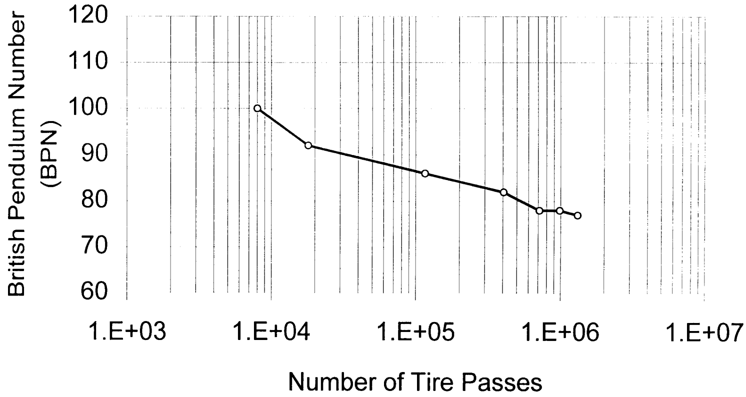

FIGURE 51.5 British pendulum readings for sand–epoxy wearing surface specimen.

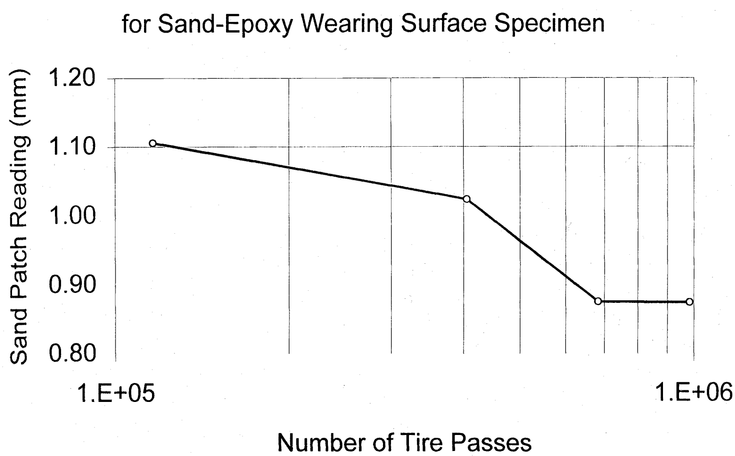

FIGURE 51.6 Sand patch test readings for sand–epoxy wearing surface specimen.

bridge. A 56-cm-deep sandwich construction was used for the panels, whose facing thicknesses were 13 and 19 mm for the top and bottom, respectively. A combination of chopped strand mat and uniaxial fibers was used with polyester resin to build the facings, which are attached by a honeycomb core. The wearing surface was a 19-mm-thick gravel–polyester resin mix.

Another all-composite 10-m-wide by 30-m-long bridge was installed in Hamilton, Ohio in 1997 [14]. This bridge, designed to meet the AASHTO HS20 specification, was fabricated with polyester resin matrix and E-glass fiber reinforcement. The bridge was delivered to the site in three sections, which consisted of two main components that formed the final box beam type of structure. The first component was a tapered U-shaped beam of approximately 0.6 m depth. The webs and the lower flange of the beam were reinforced with stitched triaxial and biaxial fabrics. The flange was also reinforced with additional unidirectional fibers. Beams, the second main component of the structure, were integral with the composite deck. A sandwich panel construction (approximately 15 cm deep) was used for the deck, with flat composite facing plates and a core of pultruded rectangular tubes oriented in the transverse direction of the bridge. The total weight of the composite bridge was approximately 100 kN, including the guardrails, but excluding the asphalt wearing surface.

51.9 Column Wrapping Using Composites

A unique application of composite materials in bridge infrastructure is bridge column wrapping or jacketing. This procedure involves the application of multiple layers of a composite around the perimeter of columns. Since the late 1980s, column wrapping with composites was seen as an alternative to the conventional steel jackets used to retrofit reinforced concrete columns of bridges in California. Column wrapping may also be used to repair columns that suffered a limited amount of damage. Column wrapping with composites may have some advantages over steel jacketing, such as reduced maintenance, improved durability, speed of installation, and reduced interference with ongoing operations, including traffic.

A reinforced concrete column can be retrofitted using the wrapping technique to increase its flexural ductility and shear strength. A proper confinement of the concrete core and longitudinal reinforcement is highly desirable for a ductile design. Confinement has been used to prevent the longitudinal bars from buckling, even after a plastic hinge has formed in the confined region, and to improve the performance of lapped longitudinal reinforcement in regions of plastic hinge formation. The shear capacity of the column can also be increased by wrapping a column using composites.

Several materials have been used to retrofit bridges with the wrapping method. The most common types of fibers used are glass and carbon. Glass fibers have been used with a polyester, vinyl ester, or epoxy matrix, and carbon fibers are used with epoxy resins. Fibers may be applied in various forms, such as individual rovings, mats, and woven fabrics. The California Department of Transportation (Caltrans) uses its Composite Specification to establish standard procedures for selection of the system to be used, material properties, and application.

The most common techniques for application of composite column jackets are wet wrap, prepreg wrap, and precured shells. In the wet wrap technique, a fiberglass fabric is wrapped around the column as many times as required to achieve the design thickness. The fabric is saturated with resin just before or during the application process, and then allowed to cure at ambient temperature. This system is manually applied and does not require special equipment.

The second technique, prepreg wrap, involves the use of continuous prepreg carbon fiber/epoxy tow that is mechanically wound onto the column. External heating equipment may be used to cure the composite.

Another column-wrapping system uses a precured shell. These shells, usually with glass fiber reinforcement, are fabricated with the same curvature as the column. A longitudinal cut is made on one side of the shell, or it may be cut in two longitudinal sections. The cut shell is then fitted and bonded onto the column.

Experimental studies [15] have been performed to determine the effectiveness of the column-wrapping systems using composite materials as compared to steel jacketing. However, even though favorable results have been published, acceptance by bridge owners and design engineers is not yet universal.

51.10 Strengthening of Bridge Girders Using CFRP Laminates

Strengthening and repair of bridge girders have been recently achieved with the use of CFRP. This technique was initially developed in the late 1980s [16] and applied to bridge structures in the early 1990s.

The use of CFRP for girder strengthening is similar to the attachment of steel plates onto concrete girders. However, CFRP presents the advantages of easier handling, higher corrosion resistance, elimination of welded connections, and excellent fatigue behavior. An important factor to be considered when using this technique is the adhesion between the beam and the CFRP strip. The contact surfaces must be adequately prepared, and an effective bond must be developed [17].

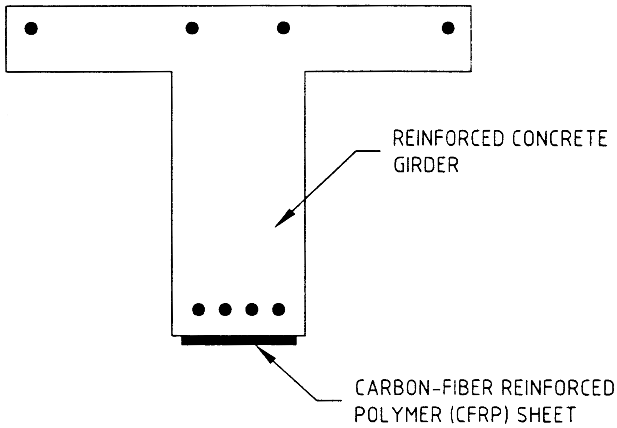

FIGURE 51.7 Strengthening of reinforced concrete girder using CFRP laminate.

In principle, reinforcing with CFRP laminates consists of a CFRP strip bonded onto the tension surface of the girder to increase or restore its original flexural capacity. The CFRP strip can be applied either nontensioned or tensioned. The high strength and stiffness of the CFRP allow the use of very thin layers to achieve the desired capacity, which can be calculated using procedures similar to those used to design traditional concrete beams. Figure 51.7 illustrates this technique.

51.11 Composite Highway Light Poles

Composite light poles were originally developed for nonhighway applications such as parking lots. Circular uniform taper along its length is the most common design. Typical pole lengths vary from 4.30 to 13.7 m. The outside pole diameter typically varies from 73 to 133 mm at the top, and from 122 to 311 mm at the base.

The most common manufacturing process for light poles is filament winding. In this process, the fiberglass filaments are wrapped around a tapered steel mandrel at specified angles to obtain the design shape with a polyester matrix. The filament winding angles vary according to the design requirements.

The primary advantages of FRP light poles are reduced weight and higher corrosion and weathering resistance compared with steel or aluminum poles. The reduced weight allows for lower shipping costs and lower installation costs. The higher corrosion resistance results in reduced maintenance costs and longer life expectancy as opposed to metal poles.

The primary disadvantages of the FRP poles are the complexity of the design and manufacturing process. For light poles, the maximum stresses are in the axial direction. Hence, the filament winding process requires more material than a process which places most or all of the fibers in the axial direction. Nevertheless, fiberglass is the most cost-effective material for use in highway light poles for heights of 7.60 to 10.7 m.

51.12 Nondestructive Evaluation of Composite Bridge Systems

The success or failure of composites in adaptation to various components in bridges greatly depends on the ability to evaluate both the short- and the long-term behavior of such composite structural elements using nondestructive evaluation (NDE) techniques. NDE and visual inspection are routinely performed on existing bridges, and new NDE technology is being developed for conventional bridge materials such as concrete and steel. Due to the greater complexity of composite materials in comparison with conventional steel and concrete, it is anticipated that existing or new NDE technology will have to be adapted to composite bridge components in order to justify their usage in critical structural elements.

NDE techniques in composites have been developed primarily in the defense and advanced technology industries. These techniques have evolved over the past 30 to 40 years, and their effectiveness in evaluating the performance of composite materials is quite impressive. However, most of these techniques require relatively sophisticated equipment, and are generally localized. Such localized NDE techniques will only describe the current and possibly predict the future behavior of the composite in a very small or localized region. In large-scale structures or structural components such as bridges, such localized techniques have limited significance in terms of the overall behavior of the structure. Therefore, NDE techniques which can evaluate the behavior and performance on a large or global scale are preferable. However, it is unfortunate that at the present time, such global techniques are not sufficiently accurate, too expensive, or not well developed technologically.

The strain gauge method of determining localized stresses and strains is well understood in civil engineering, and is widely used in the analysis of structures such as bridges, both in the laboratory and the field. The strain gauge technique is a localized type of an NDE technique and, therefore, may yield only the stress and strain levels in the lamina to which the strain gauge is attached. Strain gauge data may reveal very little about the possible delamination of inner lamina or the presence of defects within the laminate. The strain gauge method is currently used for evaluation of stresses and strains in composite tanks, pressure vessels, buildings, and various composite bridge applications which have been described here. As in other materials, the strain gauge technique is extremely beneficial in determining stress concentrations at critical locations such as the radii regions of the sections shown in Figure 51.4.

The second NDE technique is acoustic emissions (AE), which was developed more than 40 years ago, but has been successfully adapted to the evaluation of composite materials only within the last 20 years. Although this technique is described as nondestructive, the sounds or the energy emitted by the composite occur when some form of degradation of the laminate is occurring at the time of the applied loads. In simplistic terms, if no AEs are recorded, no degradation of the composite laminate is occurring. This method has been successfully utilized in the evaluation of many aerospace composite components, as well as civil engineering types of composite elements or structures, such as stacks, tanks, pressure vessels, building components, and tanker trucks. In the last application, composite tanker trucks have been evaluated on a regular basis for a period of 15 years using the AE technique. The results from these AE studies have shown the feasibility of predicting the future behavior of composite systems under fatigue loading. The bridge deck in Figure 51.4b has also been evaluated with the AE technique and the results have indicated that it is possible to predict the future behavior of such a composite bridge element utilizing AE data collected at different fatigue cycles as discussed in Section 51.6. Since AE sensors are attached at localized points on a composite structure, the data that are gathered only define the behavior of the bridge deck in a relatively localized region. However, the significant advantage of AE over strain gauges is that the behavior of the entire thickness of the laminate can be evaluated.

The continuous graphite filaments technique is a relatively simple and a global NDE method. This method essentially utilizes graphite filaments, which are electrically conductive, embedded in a glass type of composite. Glass composites are nonelectrically conductive. Since the graphite fibers can be chosen with a modulus of more than 10 times that of glass, and with a strain at failure of much less than the corresponding glass filaments, the graphite fiber will fail first within a glass fiber composite. This method is relatively inexpensive and global. The graphite filaments may be embedded anywhere within the glass fiber laminate during the fabrication of the composite structure. Additional graphite filaments may be bonded onto the surfaces of the glass fiber composite before, during, and/or after installation of the structure. This technique has been successfully utilized in determining the critical stress locations on a global scale for the extremely complex bridge deck system shown in Figure 51.4b.

When the graphite filament is broken, the electrical circuit is also broken, thus indicating high stress levels. However, the location of these high stress levels on any single graphite filament circuit is nearly impossible to predict at this time. The open electrical circuit indicates that the strain level within the fiberglass structure is excessive, but failure of the overall structure will not occur. Thus, the primary intent of such a graphite filament technique is to signal existing degradation, and possible future failure of the bridge, many truck cycles before it actually occurs. This technique may be utilized to provide a warning to the public, and cause a bridge to be shut down prior to impending failure.

The visual inspection method for composites has also been codified into an ASTM specification. Such inspections would be very similar to current periodic visual bridge inspections of steel and concrete bridges. Visual inspections are global in nature but cannot detect any possible degradation of the interior lamina within a laminate. This is a distinctive drawback to any method that involves visual inspection of external surfaces only.

Ultrasonic NDE has been widely used as an NDE technique in advanced and aerospace composites. In industrial composites, such as tanks, pipes, etc., the ultrasonic technique has been limited to determining thicknesses, detecting localized defects or voids, crack formations, and delaminations. The ultrasonic technique is a localized NDE technique and relatively time-consuming and labor-intensive. Extensive computer imaging is possible with this and other techniques discussed below which can greatly enhance the accuracy of this method.

The fiber-optics technique is analogous to the continuous graphite filament concept. The fiber-optics technology utilizes continuous fiber-optic cables which can be embedded in the laminate or on exterior surfaces. The presence of localized stress concentrations results in reduced transmission of light through the fiber-optic cable which can be related to the level of localized stresses. This technique may also predict the location of high stress levels, which continuous graphite filaments cannot do.

A variety of advanced NDE techniques are utilized in evaluation of advanced composites but are seldom used in industrial composites. Thermal NDE methods essentially use the theory of heat flow in laminates where the presence of defects, voids, or delaminations will alter the heat transfer properties. Radiographic NDE techniques utilize the transmission of electromagnetic waves through materials, and the knowledge that the presence of defects, voids, or delaminations will result in alteration of such wave transmissions. Both of these two methods may be used in local or global applications. Computer imaging may greatly enhance the effectiveness of both these techniques. However, due to the current cost, both of these techniques are economically prohibitive for periodic evaluation of large composite components as envisioned for bridges.

Other advanced NDE techniques are also available in the advanced composites industry. However, most of these techniques are currently cost-prohibitive or impractical for field evaluation of composite bridge components under less than laboratory type conditions.

51.13 Summary

The inclusion of composites into highway bridges will probably occur gradually over the next decade. Due to the strict stiffness and safety requirements, the use of composites in all structural elements of highway bridges may not be feasible in the near future. Therefore, the initial use of composites in bridges will probably be limited to those bridge elements where the unique properties of composites will result in more favorable design than with the use of conventional materials.

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