CECW-ED

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

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Technical Letter
No. 1110-2-548

31 March 1997

Engineering and Design
COMPOSITE MATERIALS FOR CIVIL ENGINEERING STRUCTURES

1. Purpose. This engineer technical letter (ETL) provides basic information and references on background, evaluation, and design of fiber-reinforced plastic (FRP) materials to assist structural design engineers who are considering the use of FRP on civil works projects. This information will help the engineer evaluate the suitability of FRP materials for structural applications, and will be useful in preparing performance specifications for procurement of suitable composite components and structures.

2. Applicability. This ETL applies to HQUSACE elements and USACE commands having responsibilities for the design of civil works projects.

3. Background. Composite materials, as discussed herein, refer to fiber/matrix combinations such as fiberglass/epoxy and are commonly referred to as fiber-reinforced plastics. This ETL is intended for use by design engineers who are considering the use of composite materials on civil engineering projects. Structural applications are the primary focus of the ETL.

4. Policy.

a. Applications. Applications of composite materials can be categorized as nonstructural, secondary structural, or critical structural applications. Nonstructural and secondary structural applications of composite materials can be utilized when they offer cost or performance advantages. Critical structural applications shall not be used except in consultation with and as approved by CECW-E. Details regarding the various types of applications are included herein.

b. Procurement specification. Sufficient attention must be given to the design requirements, design quality assurance, and fabrication quality assurance during the development of a performance specification and contract drawings. Details with respect to these items are also included herein.

FOR THE DIRECTOR OF CIVIL WORKS:

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Chapter 1
Introduction

1-1. Purpose

This engineer technical letter (ETL) provides basic information and references on background, evaluation, and design of fiber-reinforced plastic (FRP) materials to assist structural design engineers who are considering the use of FRP on civil works projects. This information will help the engineer evaluate the suitability of FRP materials for structural applications, and will be useful in preparing performance specifications for procurement of suitable composite components and structures.

1-2. Applicability

This ETL applies to HQUSACE elements and USACE commands having responsibilities for the design of civil works projects.

1-3. References

Required and related references are listed in Appendix A.

1-4. Discussion

a. Applications. FRP composite materials are becoming more affordable and more widely used in consumer products, industrial applications, and construction. For example, many gratings, handrails, and storage tanks are currently made from FRP materials. Applications investigated and used by the Corps of Engineers are described in Appendix B. FRP composites offer potential advantages in weight, strength, and corrosion resistance. These must be balanced against the possibility of higher initial cost and lower stiffness and other differences in material behavior, when compared to more traditional materials. Much of the basic information necessary for an initial evaluation of composites as an alternative material for civil engineering applications is provided herein. Engineers considering use of composites should review the information provided and that in the referenced publications. Since composites technology is evolving rapidly, engineers should also review the latest literature. As technology and applications evolve, additional Corps of Engineers guidance will be developed for use of FRP materials.

b. Standards. Currently, there are no national consensus standards for design of composites; however, there are many military specifications and American Society for Testing and Materials (ASTM) standards concerning FRP materials. These provide minimum requirements for various fibers and resins, for some processed composite materials, and for testing of material coupons to obtain basic material properties. Development has started on an ASTM standard for FRP composites for use as concrete reinforcement. Final properties of FRP are more dependent on the production process than some other materials. Properties of FRP are also dependent on the thickness, because surface materials experience a different processing environment than the interior materials. For these reasons, designers must be careful when specifying materials requirements. Because of the lack of design standards, procurement of FRP components will usually be based on a performance specification, possibly including verification testing.

1-5. Background

a. Composite materials, as discussed herein, refer to fiber/matrix combinations such as fiberglass/epoxy and are commonly referred to as fiber-reinforced plastics (FRP). This ETL is intended for use by design engineers who are considering the use of composite materials on civil engineering projects. Structural applications are the primary focus of the ETL.

b. This ETL identifies potential advantages of using FRP. It lists applications where composites may be suitable for use on Corps of Engineers projects. It presents background on the development and use of FRP. It includes data on the properties and behavior of selected component materials and several generic fiber/matrix combinations. A key element of this ETL is the list of references (Appendix A), which a designer must consult to obtain detailed information.

c. Composite materials take advantage of a combination of materials with different properties to result in a designed material with desired overall properties. Civil engineers have been using more traditional composites for years. These include laminated wood, reinforced concrete, and steel/concrete bridge girders. These materials have gained wide acceptance and have proven performance. FRP composites are currently gaining wider acceptance in civil engineering applications as they are proving to be effective on numerous demonstration projects.

d. Civil engineers are accustomed to using consensus design standards such as building codes and steel and concrete design codes. Similar standards for composites are not yet available. Therefore, designers cannot use a traditional civil/structural design approach when designing with FRP. This ETL provides some of the information required to develop a performance specification for procurement of suitable FRP components and structures. Quality assurance is more critical in the design, production, and construction process for FRP than for steel or concrete. This is true for several reasons. Designers and contractors have less experience with these materials; there is less extensive performance history; failure mechanisms for infrastructure applications are not yet thoroughly researched; there is a much greater choice of materials and properties; final properties are dependent on the production process; and the anisotropic properties of FRP require unique design considerations. This ETL provides information on appropriate quality assurance methods during the design and construction process.

1-6. Scope

a. Applications.

(1) Nonstructural applications. Composite materials may be used in appropriate nonstructural applications. This includes the purchase and use of existing commercial products.

(2) Secondary structural applications. When composite materials offer cost or performance advantages, they may be used for secondary structural applications. Generally such applications should be relatively small, inexpensive, and easily replaceable. Examples of such applications include handrails, grating, ladders, light posts, large pipes, small gates, and minor temperature reinforcement in thin concrete sections. Components such as these may be included in construction contracts as performance specified items, to be designed and certified by the supplier. The performance specification should identify the functional requirements, exposure conditions, durability requirements, and any restrictions on material selection. Generally, the designer should specify generic products based on consultations with several potential suppliers to determine the availability and suitability of products for such applications.

(3) Critical structural applications. Composite materials shall not be used for critical structural elements except in consultation with and as approved by CECW-E. This includes any application where failure of the composite would significantly impact life safety, or the overall structural integrity or function of the project. Examples include large gates or hybrid girders of wood/FRP or concrete/FRP. Since there are no national design codes for composite materials, each design is unique and will require special studies and design procedures, and possibly special contracting methods. This will require the involvement of suppliers, contractors, designers, and reviewers during development of the design. The project management plan should include appropriate funds and schedule for this special design effort, including appropriate expert consultation. A reliable quality assurance plan is essential for design, fabrication, and erection. To ensure acceptability of the final product, specific verification, testing, and monitoring requirements should be developed.

b. Procurement specification.

(1) Design requirements. The performance specification, along with the contract drawings, must clearly identify the following requirements for any FRP component: (a) size and shape limits, (b) strength or loading, (c) durability under given exposure conditions for a given length of time, (d) restrictions on material selection, (e) reference standards for materials and testing, and (f) design factors of safety. Because of potential property variations, design factors of safety should be relatively large. An example of a performance specification is provided in Appendix C.

(2) Design quality assurance. Due to the lack of consensus design standards, each supplier may have a unique approach to design of FRP components and structures. Generally, this approach will be based on previous test data for similar materials and joint configurations. It is critical that the supplier submit the assumptions and methods used for design, including the appropriate test results, so that the Corps can ensure there is an adequate technical basis for the design. These test results should include data from durability testing under appropriate environments to ensure long-term adequacy, and the basis for extrapolating short-term or accelerated testing results to predict long-term behavior.

(3) Fabrication quality assurance. Since FRP properties are very dependent on processing parameters, it may also be appropriate to perform verification testing on actual materials produced for the contract. For nonstructural or for secondary structural applications, quality assurance may usually be limited to a manufacturer's certification that specified shapes, materials, properties, or strengths have been provided. For critical structural applications, the design engineer must develop a more thorough quality assurance plan, sufficient to verify the adequacy of the FRP in terms of life safety or overall project function. This plan must include coupon tests of materials and connections, or verification tests of

completed structures. In addition, once the FRP has been placed in service, there should be a plan to monitor performance at appropriate intervals. The level of detail of the testing and inspection program should be adjusted to conform to the complexity and degree of importance of the FRP application. The designer should rely on an expert consultant for assistance in developing an adequate quality assurance plan for critical applications.

Chapter 2
Reasons to Consider FRP Composites

2-1. General

There are many different reasons to consider using FRP composites in civil engineering applications. The most relevant of these reasons as applied to engineering are discussed below. The main criteria for engineers to use any material to satisfy the requirements of a job are durability, corrosion resistance, cost, weight, material properties, and ease of construction. FRP composites are attractive alternatives to conventional construction materials for these and several other compelling reasons, as follows.

2-2. Structural Considerations

The items presented in this section are a brief presentation of structural considerations. Many of the items are discussed in more detail in the latter sections of Appendix B.

a. Tensile strength. FRP composites provide a number of structural properties that make them an attractive alternative to many conventional engineering materials. Their tensile strength can range from about the strength of mild reinforcing steel to stronger than that of prestressing steels. As such, they offer good incentive for use in situations where high tensile strength is an asset. FRP composites generally exhibit linear tensile stress-strain behavior throughout their load-carrying range and as such do not change their modulus over their loading history. Since FRP composites are materials composed of structural fibers in a plastic matrix, the fibers can be custom-oriented to suit individual needs. A number of good examples of this unique capability are provided in Chapter 5.

b. Fatigue. Research to date indicates that FRP composites exhibit good fatigue resistance in tension-tension cycling (American Concrete Institute, State-of-the-Art Report on Fiber Reinforced Plastic (FRP) for Concrete Structures). Research has yet to document the effects of temperature, moisture, reverse loading, long-term and compression load cycling, and holes on fatigue resistance. Long-fiber composites generally retain a high proportion of their short-term strength after 10^7 cycles. Carbon-fiber composites exhibit the highest fatigue resistance, followed by aramid and then glass (Neale and Labossiere 1991).

c. Low mass. Excessive structural mass is often a reason to consider alternate materials which will provide high load-carrying capacity as well as low density. FRP composites have densities in the range of 1,200 to 2,600 kg/m^3 (75 to 162 lb/ft^3) which make them attractive alternatives to structural materials such as steel with a density around 7,850 kg/m^3 (490 lb/ft^3).

d. Specific strength. The specific strength of materials, defined as the yield strength divided by the density, is often used to make comparisons between materials on the basis of strength and mass. FRP composites, because of their high strength and their very low density, have specific strengths which are up to 60 times that of high strength steels. The high specific strengths associated with FRP composites are very useful in applications such as structural cladding panels, low-density framing materials, and vehicle components. Their low weight makes the assembly and disassembly of temporary structures much easier and less time-consuming than similar structures made of wood or steel. Cost of many of the FRP composites, although higher than conventional construction materials on a pound-per-pound basis, are competitive when the specific strength of the materials is taken into consideration. Final construction costs can even be lower than conventional materials if such factors as more efficient design, transportation costs, and lifting equipment costs are taken into account.

e. Vibration damping. The specific modulus of FRP composites, defined as the modulus of elasticity divided by the density, is also high and provides characteristics such as low vibration in situations where vibration may be a problem (Grace, Bagchi, and Kennedy 1991). Steel has a high density, high modulus, and low damping characteristics whereas composites have low densities, moderate moduli, and high damping characteristics. Use of composites in floors and bearing pads where damping of vibration is of concern can reduce these problems.

f. Repair using composites. Structural repairs of conventional materials using FRP composites can be advantageous from the standpoint of ease of installation and reduced maintenance costs. Conventional techniques for externally strengthening cracked concrete structures call for steel plates or bars to be installed across the crack to carry the structural loads no longer carried by the concrete. FRP plates can be structurally bonded across such cracks to replace the steel repair components. The low mass of these materials makes their handling more convenient, and their noncorrosive nature eliminates the need to protect them from rusting deterioration. Some of these techniques have been used in the European engineering community for over 20 years. Some repair applications using FRP composites are presented in Appendix B.

g. Corrosion resistance.

(1) One of the most convincing reasons to consider the use of FRP composites is their resistance to corrosive elements. The plastic resins that form the matrix of most composites are resistant to deterioration from many chemicals as well as the effects of acidic, salt, and fresh waters. Acidic, salt, and fresh waters are corrosive to ferrous metals. In Corps of Engineers structures, high-maintenance corrosion-susceptible components would be appropriate candidates for the use of FRP composites. The benefits of composites over steel in terms of resistance to corrosion are greatest in the areas of maintenance and life-cycle costs. Components in marine construction such as piling, docks, and submerged construction would be applicable uses. Currently, the Corps, in cooperation with the Navy, is demonstrating the use of these materials by constructing a portion of a pier at Port Hueneme, California. This demonstration pier is constructed of concrete piles prestressed with carbon-fiber-reinforced-plastic (CFRP) tendons, vinyl ester/glass tendons for pile caps, and CFRP tendons in the deck section. The facility has an all-composite deck section as well. Details of this demonstration project are given in Appendix B.

(2) Storage structures for corrosive liquids are suited to FRP composite materials. Fiberglass tanks have been used for storage of chemicals for many years. One documentable example is a fuel storage tank, built in the late 1960's, using E-glass fiber in a vinyl ester matrix. The fibers were wound over a steel skeleton, resin was applied and allowed to cure, and the process repeated a second time. The tank has been in service for over 20 years and has developed no leaks in that time. Building components that are exposed to industrial chemicals either in the air, immersed, or through spray contact will not deteriorate as would steel, concrete, or wood components. Applications where FRP composites would be appropriate would include storage tanks, cover plates, walkways, pipes and culverts, and any other metallic component exposed to corrosive chemicals.

2-3. Production Options

a. Fabrication. The variety of fabrication techniques that are available with FRP's provide for many custom properties. Multiple types of fibers can be combined to produce materials with the advantages of each component; fibers can be oriented in specified directions to better suit specialized loading conditions; and material properties such as strength and stiffness can be controlled to meet the user need. Special molding techniques allow complicated pieces to be fabricated as one unit, eliminating joint conditions which can be a source of weakness. One method of producing FRP composites is by a technique known as pultrusion, a process much like extrusion. In the pultrusion process, the FRP materials are pulled through dies while the matrix is being cured and is in a moldable condition. These dies can be in the form of an I-beam, a channel section, or any custom cross section. Examples of some of the cross sections currently produced are shown in Figure 2-1. Other processes that are commonly used include filament winding, autoclave molding, and scrimp and are described in more detail in section 4-4. Another good example of the custom fabrication capabilities of these materials is demonstrated in custom fabricated sandwich panels. In these panels, load-bearing, FRP, honeycomb core structures are sandwiched between FRP skin plates producing a very strong, lightweight structural component.

b. Custom geometry. The length and geometry of a given pultruded cross section can be custom designed as well. The pultrusion process lends itself to custom fabrications. The length of the fabricated shape does not have to be a predetermined length. The designer can work with the fabricator to produce products in lengths and shapes needed for specific applications.

c. Color and coating. Since the matrix of FRP composites consists of resins that begin in the liquid state, many architectural treatments can be added before they harden. For example, custom coloring can be added to the resins in the manufacturing process, thereby eliminating the need for and cost of painting or other color application after the fact. Since the color is integrally mixed in the matrix, it cannot be scraped off or abraded during its lifetime. It is also possible to embed sand or other nonslip surface treatments as a secondary operation, and the treatment will become part of the component. Nonslip gratings and walkways are an example of this type of application.

2-4. Economic Considerations

a. Life-cycle costs. While the initial cost of composite materials is usually higher than alternative construction materials, there are a number of economic considerations which make their use feasible and economic. Corrosion protection was mentioned as an area where composites are beneficial to the cost of maintenance. Many life-cycle costs could be eliminated or drastically reduced with the use of FRP composites. The costs associated with periodically repainting steel to protect it against corrosion are maintenance costs that would

Figure 2-1. Cross sections of pultruded FRP components

be eliminated if materials that did not require such coatings were used. The costs of rehabilitating structures damaged by corrosion, such as blast cleaning of steel to remove corrosion products, would be eliminated with noncorrosive composite materials. In general, periodic maintenance of structures would be reduced and replacement costs would be delayed through greater use of FRP composites. Some FRPs could require coating protection for aesthetic reasons or for exceptionally harsh environments.

b. Construction and transportation costs. Construction and transportation costs can be reduced with use of the low density composites. Since many charges for freight are based on weight, the low densities of FRP composite components reduce shipping costs and require less need for heavy construction handling equipment at sites. Fabrication costs will be reduced in two areas. Through increased ease of handling of components, smaller crews can be utilized to handle components assembled in the field. Further, preassembly of some components can reduce field assembly costs. In addition to reduced costs, faster construction times can be realized through the improved handling capabilities.

2-5. Environmental Considerations

a. Reduced environmental toxicity. Many of the building materials that we presently use are harmful to our environment in some way or another. Examples of such materials are lead-based paints, creosote and other petroleum products used in piling to kill or ward off marine borers and shipworms. The components of FRP materials are, for the most part, inert and will not leach into the environment. The use of conventional maintenance coatings on structures can be toxic to the environment. The use of FRP's eliminates some of these hazardous chemicals. Piling made from FRP materials do not rot nor are they attacked by marine organisms so there is no need to treat pilings with harmful chemicals such as creosote.

b. Recycling. Many of the plastic materials that we use as food containers and composite components of automobiles can be recycled when no longer needed. These recycled plastics and glass fibers can be reused to make FRP composite components, thereby reducing the volume of waste we put in our landfills. Marine piles are currently being produced from recycled materials (Taylor 1994). High density polyethylene plastics that are recycled from milk jugs, juice containers, and detergent bottles are being combined with fiberglass pultruded reinforcing elements to produce these piles. As many as 15,000 containers can be recycled into one 18-m (59-ft) pile. FRP composites themselves can be recycled when their useful life is through. These components can be reprocessed to recover most of their original materials and the materials reused.

2-6. Material Property Considerations

a. Magnetic properties. FRP composites possess some properties that are not available from more conventional materials. Because their components are plastic resins coupled with glass, carbon, and aramid fibers, they are immune to magnetic forces. FRP materials are used in several of the designs for vehicles and guideways of magnetically levitated transportation systems to eliminate any adverse forces that would be induced through proximity to the magnets used for levitation and locomotion. Components of vehicles where magnetic compasses are employed often use composites in the vicinity of the compasses to eliminate any magnetic influence in the guidance systems. Special facilities that employ electromagnetic technology often are built entirely using composites. A dramatic architectural use of FRP composites is seen in the structure used to hide radio antennae on top of the Sun Bank Building in Orlando, Florida (Figure 2-2). Glass fiber structural shapes and cladding panels were used to construct four, three-story-high housings to contain the antennae. The structures were designed to resist hurricane force winds.

b. Conductivity. Electrical conductivity is a hazard in many construction environments. High voltages, passing through metallic construction materials acting as conductors, can cause injury or even death. Most FRP composites (including glass and aramid fiber composites) are electrically nonconductive. This makes them good candidates for construction materials where the threat of electrocution is a consideration. For many years stepladders have been made from fiberglass composites for their non-conducting properties. Electric cable trays, walkways in the vicinity of exposed electric conductors (such as at power plants), and booms of bucket trucks are all examples of FRP composites used to eliminate electrocution hazards and other electrical problems.

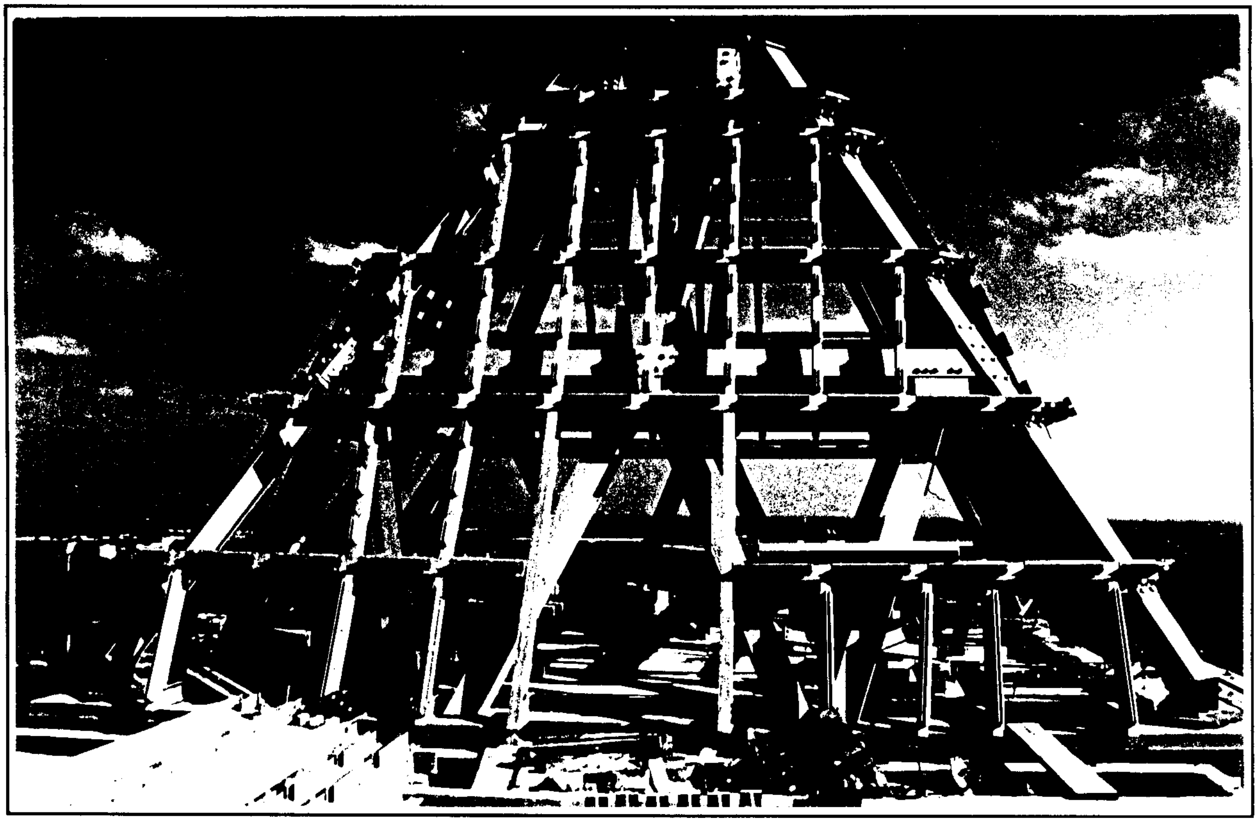

Figure 2-2. FRP materials used as electromagnetically transparent housings

Chapter 3
Potential Applications

3-1. Application Categories

FRP composites were initially used in advanced technology applications, such as the aerospace industry. Presently composite materials are being used in a number of civil engineering applications including Corps of Engineers projects as described in Appendix B. It is expected that additional applications will be possible on future projects. The various types of applications possible with FRP composites are shown in Table 3-1 and are classified as immediate, short term, and long term. As can be seen, a large number of applications are included in the immediate and short-term categories which indicates that implementation of FRP composites is possible on projects nearing the design phase. Applications listed in the short- and long-term categories will not be widespread primarily due to the lack of codes and standardization. Also, listing items in the short- and long-term categories is not intended to discourage the implementation of innovative concepts using FRP composites on demonstration projects. The meanings of immediate, short-term, and long-term are provided in the paragraphs below.

3-2. Immediate Category

Applications that are included in the immediate category of Table 3-1 are those applications that could be included in project designs currently being developed. Many of the items listed in Table 3-1 as immediate are currently in use on Corps of Engineers projects. Some of the items in the immediate category may not be in use yet but are included in the list because they are not critical structural items and would not compromise safety if used.

3-3. Short-Term Category

Items listed in the short-term category of Table 3-1 are applications which may be implemented in designs to be completed within the next five years. Design information beyond what is currently available will be required before they will be ready for routine use in a service environment. This may include certified test data on the materials to be used in the application or tests on a given connection detail to determine its load-carrying capacity. Approval from CECW-ED is required prior to using FRP materials for the items listed in the short-term category of Table 3-1. Should FRP materials be used for the short-term applications, sharing of information about such applications with other field offices is encouraged.

Table 3-1
Composite Material Applications

Category	Applications
Immediate	Grating
	Fenceposts
	Signposts
	Handrails
	Trashracks
	Bearing supports
	Bearing plates
	Ladders
	Small pipes
	Cable tray racks & pipe hangers
	Light posts
	Sluice gates
	Sewer pipes
	Mechanical & electrical parts
	Electrical isolation structural members
	Noncritical load-bearing structures
	Culverts at small pump stations
	Culverts at levee outlet structures
	Light-gauge sheetpile
Short term	Gates
	Gate components
	Frames made from pultruded structural members
	Concrete repair (plates and wraps)
	Noncritical reinforcing
	Heavy-gauge sheetpile
Long term	Reinforcing
	Post-tensioning
	Prestressing
	Load-bearing piles

3-4. Long-Term Category

Long-term items listed in Table 3-1 are applications which may not be appropriate for use in project designs until after the year 2000. Sufficient long-term durability data are not currently available to permit these applications, but code development is currently under way. Despite the fact that these items have significant potential for use in Corps of Engineers projects, caution should be exercised when considering FRP materials for these applications since in many cases the long-term effects have not been fully documented. As research continues on FRP composite materials, information may become available which will provide the data necessary to support the use of FRP composite materials for the long-term applications given in Table 3-1. Opportunities to use applications in the long-term category for demonstration projects or on projects that are not of a critical nature should be investigated but should not be implemented without the approval of CECW-ED.

Chapter 4
Description of Composite Materials

4-1. Terminology

a. An engineer who is not experienced in designing with FRP composite materials may not be familiar with many terms. Definitions of key terms will be found in the Glossary (Appendix D). Definitions of many key terms are also found in the ASTM standard listed below:

ASTM D 3878 Standard Terminology of High-Modulus Reinforcing Fibers and Their Composites

b. Over the years, the term *fiberglass* has been used to generically describe glass-fiber-reinforced-plastic products; for example, a *fiberglass* tank or a *fiberglass* boat. In precise terms, fiberglass is only describing the reinforcement fibers used in the composite product. However, the resin (plastic) matrix, in which the reinforcement fibers are embedded, is also an important component which greatly influences the mechanical and chemical resistance properties of the composite. Using an inappropriate resin for a given application could cause the component to perform poorly in its intended application or to prematurely fail. The acronym FRP has occasionally been used to denote fiberglass-reinforced plastic instead of just fiber-reinforced plastic. Current common usage is, however, to define FRP as fiber-reinforced plastic. Where identifying the fiber-reinforcement type is desired, a letter prefix may be added; for example, GFRP and CFRP to describe glass-fiber-reinforced and carbon-fiber-reinforced plastics, respectively. (See Appendix D for a further description of fiberglass.)

4-2. Background

a. General.

(1) In order to understand how composite materials perform in structures, it is necessary to understand some basics about their nature. Composite materials contain a mixture of two or more types of fundamentally different components. They have properties that are some combination of the properties of their components.

(2) All materials that contain more than one component are not necessarily composite materials. For example, pearlitic steel is not considered a composite, although it contains more than one component, since its various parts are of the same nature.

(3) Some materials that are considered composites are concrete, steel-reinforced concrete, fiber-reinforced polymers (like graphite/epoxy or glass/epoxy), laminated wood, and rubber tires. Concrete- and steel-reinforced concrete contain more than one type of component (aggregate, cement paste, and steel). Graphite- and glass-based FRP's contain high-strength fibers surrounded by a more ductile resin. Rubber tires contain the polymeric rubber-type material, carbon particles, and, frequently, steel or other types of reinforcement.

(4) The driving force behind the development of modern composite materials has been their high strength and stiffness when determined on a weight basis. Most of the original work on modern composites was in the aerospace industry. These industries are very weight sensitive, and a decrease in weight is a very important issue. This is the case even if the FRP parts are more expensive than the parts they replaced. Composites are now being used in the surface transportation industry. They are frequently used on automobiles and lightweight boats. Composites have also penetrated a number of consumer sports areas, such as graphite/epoxy golf clubs and skis.

(5) One way to better understand composite materials is to examine some current applications of composites. There are a number of aerospace applications. They are used as structural parts on many modern jet airplanes, such as the Boeing 767. The *Voyager* was the first airplane to fly around the world nonstop without refueling. Its superstructure was mostly made of composite materials. Similarly, the *Gossamer Albatross* became the first human-powered vehicle to fly across the English Channel. Such a vehicle could not be built with traditional metallic materials, for it would have been too heavy.

(6) Composites have also been used on land-based vehicles. For example, the auto industry has formed a consortium to do research on composite materials. They have successfully built a *Taurus* whose superstructure is composed of five composite panels that have been glued together. Glass-fiber-based composites have been used to form the hopper in railroad cars. The U.S. Army has recently designed and built an armored vehicle that has a composite material hull. The U.S. Navy has used composite materials to make mine sweeper ships.

(7) Composite materials are being used extensively in the sporting world. Glass-based FRP poles are commonly used in pole vaulting. Graphite/epoxy golf club shafts are highly desirable because of their light weight. Graphite/epoxy skis are also popular because of

their light weight. Glass-based FRPs have been used in small consumer-oriented sporting boats for many years.

(8) Composite materials are being used in civil engineering structures. The tentlike roof on the new Denver International Airport is made from a glass-based FRP that has been coated with Teflon. The same basic material has been used as the roof for a number of sports stadiums, such as the Metrodome in Minneapolis. Glass-based composites have been used in nearly 100,000 underground fuel storage tanks; this use is growing rapidly. Uses also include sandwich shell roofs for exhibition structures, large-diameter pipe, and numerous gratings and structural shapes.

b. Composite types.

(1) Particle based.

(a) There are two basic types of composites that use particle reinforcement. These two types are particle reinforced composites and dispersion-strengthened composites. Particle-reinforced composites use the particles to carry the major portion of the load. Dispersion-strengthened composites use the particles to resist deformation, while the resin carries the major portion of the load. Neither of these types of composites will typically be included in civil engineering applications, but a brief discussion is included for completeness.

(b) Particle-reinforced composites have hard particles surrounded by a softer matrix. The particles in these composites are larger than in dispersion-strengthened composites. The particle diameter is typically on the order of a few microns (a few ten thousandths of an inch). Typically the particles comprise between 20 percent and 40 percent (by volume) of the composite. In this type of composite, the particles carry a major portion of the load. The purpose of the resin matrix is to hold the particles together. Examples of particle reinforcement would be the addition of carbon black to automobile tires, and cermets (which are metal matrix composites with ceramic particle additions).

(c) In dispersion-strengthened materials, small particles on the order of 10 to 250 nanometers (10^{-9} m, which is less than a millionth of an inch) in diameter are added to the matrix material. These particles are smaller than the ones used in particle-reinforced composites. Up to 15 percent by volume of the material can be these particles. These particles act to help the matrix resist deformation. This makes the material harder and stronger. The matrix material is carrying most of the load.

(2) Fiber based.

(a) These are composite materials in which fibers have been added to increase the load-carrying capability of the material. The fibers may occupy anywhere from 40 percent to 70 percent (by volume) of the material. These fibers have relatively small diameters. For example, a typical graphite fiber diameter is on the order of 5 to 7 micrometers (10^{-6} m), while glass fibers are usually larger, on the order of 15 to 20 micrometers.

(b) The volume fraction of fibers has a significant effect upon the composite's mechanical properties. For details, see Chapter 5.

(c) Short fiber composites are fiber-based composites in which the fibers have been cut into short lengths and are randomly oriented throughout the material. These fibers are still long with respect to their diameter. The fibers are randomly mixed into the polymeric matrix. This type of composite will tend to have isotropic mechanical properties (which make it easier to design), but it means it is not as stiff nor as strong as it could be if the fibers are oriented. Complicated cast shapes can be made from this type of composite, when the resin is heated in the liquid region. The presence of the fibers will increase the viscosity of an already viscous liquid.

(3) Effect of fiber orientation.

(a) Fiber orientation will have a dramatic effect upon the mechanical properties of a fiber-reinforced composite material. Fibers can be oriented by pultrusion or by fabricating the composite from unidirectional layers of uncured material, commonly called "prepreg." A bidirectional layer, or fabric, is also commonly used. An example of unidirectional layers is shown in Figure 4-1.

(b) In most laminates, it is desirable to have a variety of fiber orientations so that the desired directional properties can be obtained. The various unidirectional layers are stacked together to form a laminate. An example of this is shown in Figure 4-2 for a four-layer laminate.

(c) Various stacking sequences (or "lay-up") can be chosen. If all the fibers are chosen to be in one direction, then the maximum possible strength for this composite will be obtained in that direction. However, a unidirectional composite will have a very low strength transverse to the fiber direction.

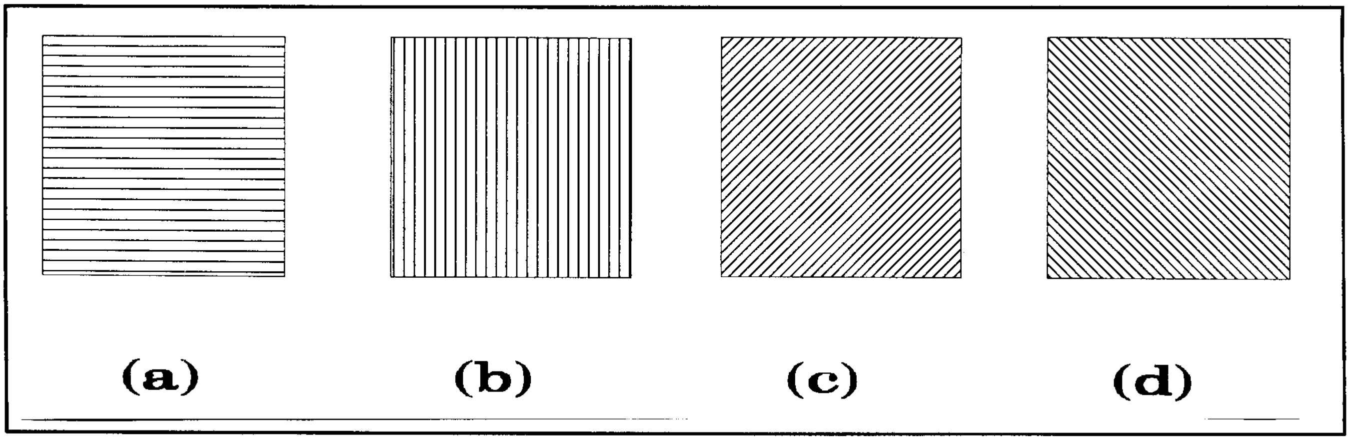

Figure 4-1. Unidirectional plies are used to fabricate a multidirectional composite
(a) Fibers are at 0°.
(b) Fibers are at 90°.
(c) Fibers are at +45°.
(d) Fibers are at -45°.

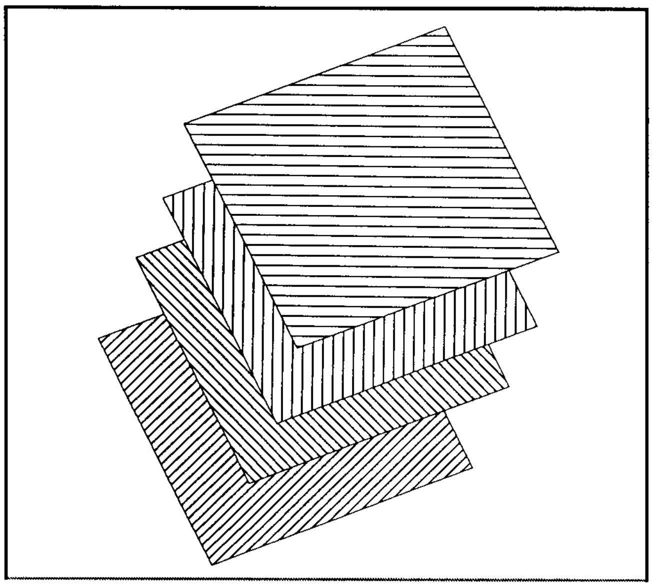

Figure 4-2. Unidirectional plies of various orientations are stacked together to make a laminate which has the desired properties

(d) Since fiber orientation dramatically affects strength and stiffness, a notation system has been developed to indicate the orientations in question. For example a 16-ply laminate that has all the fibers in the same direction is typically represented by:

$$[0_{16}]$$

The first number indicates the fiber orientation in degrees. The subscript number following the zero lists the number of layers of that particular orientation. This lay-up would have very high strength in the 0-degree direction, but very low strength in the 90-degree direction.

(e) A 16-ply laminate that has half of the fibers in one direction and half of them in a perpendicular direction could be represented by:

$$[0_4/90_8/0_4]$$

Since this lay-up is also symmetric, an alternate shorthand notation could be used. This lay-up could be written as shown below (where the S indicates that the axis of symmetry is the last ply shown in the listing):

$$[0_4/90_4]_S$$

This lay-up has the same tensile strength in both 0- and 90-degree directions, but its strength is about one half of the unidirectional lay-up in the fiber direction. In all these lay-ups, the order of the angles also represents the stacking sequence of the plies. In the one shown above, there are four 0-degree plies at both edges, surrounding a center region of eight 90-degree plies. This particular lay-up is symmetric about the center, which is usually desired in composite applications. This lay-up would tend to have a very low value of Poisson's ratio. Its shear stiffness would be the same as that for a unidirectional lay-up.

(f) If the shear stiffness needs to be maximized, then it would be most desirable to have all the fibers in the

45- or -45 degree directions. This lay-up could be written as:

$$[-45_4/45_8/-45_4]$$

Poisson's ratio for the lay-up shown is usually rather large, and for some materials it can be greater than one.

(g) One additional example lay-up should be shown. This is one in which there are equal numbers of 0-, 45-, -45-, and 90-degree plies arranged symmetrically. An example of this for a 16-ply laminate would be:

$$[0_2/45_2/-45_2/90_2]_S$$

This particular lay-up will have intermediate values for both longitudinal and shear stiffnesses. This laminate is also considered to be planar quasi-isotropic in that it will macroscopically behave as if it were an isotropic material.

(h) Historically, the quasi-isotropic lay-up was the most common one used. It is easy to design with, for its properties are the same in all planar directions. However, it does not take into account the great strength available if most of the fibers are in the same direction. It is now more common to orient the majority of the fibers in the primary load direction while retaining some plies in the other directions.

(4) Hybrid composites

(a) Hybrid composites are composites modified by the addition of another material to change their properties. A hybrid fiber-based composite could be one that is composed of an epoxy resin, carbon fibers, and glass fibers. This is an example of what might be done when the designer needed to have a composite material that was stiffer than what could be obtained from a glass-based composite but did not want to incur the additional cost to make it an all-carbon-fiber composite. By adding some carbon fibers the stiffness of the glass-fiber-dominated composite material is increased. Through hybrid composites, it is possible to tailor the stiffness, strength, and ductility of the composite to end-use requirements.

(b) A hybrid composite could also be a mixture of particle and fiber reinforcement. An example of this has been used with graphite/epoxy systems. The epoxy resin is rather brittle. In an effort to make the resin more ductile, some engineers have added rubber particles to the resin. These particles bond poorly with the resin, and act to form dull-tipped cracks. This will increase the toughness of the composite. This might be called particle weakening rather than particle strengthening. The fibers are in this system to make it strong, and the rubber particles are added to the resin to make it more ductile. Hybrid composites can also be used to improve durability. An outer layer of carbon fibers can be used to protect a core of glass fibers from breaking due to impact loads.

c. Composites versus traditional civil engineering materials. Civil engineers have experience designing with traditional materials that behave similarly to modern FRP materials. This should encourage the engineer who is somewhat apprehensive about designing with FRP materials. Two examples shown below are reinforced concrete and timber.

(1) Reinforced concrete. Steel-reinforced concrete is a classic example of a hybrid composite material. Its components of cement paste, aggregate, and steel all combine to produce mechanical properties that are considerably different from those of any of its components. Steel-reinforced concrete is very anisotropic in its strength. This is also true of most oriented fiber-based composites. When designing with steel-reinforced concrete, the engineer needs to understand how loads are transmitted through the system. The reinforcing layout that will provide very high strength in the primary reinforcing direction will also result in comparatively low strength transverse to the reinforcing direction. To safely use such anisotropic materials requires that the engineer understand the state of stress created in the system. An unanticipated load transverse to the reinforcing bars could produce a disastrous failure.

(2) Wood. Wood is a natural composite with anisotropic properties. Because of its grain structure its strength in one direction may be very much different from its strength in another direction. This type of difference is very typical of the anisotropic properties of modern composite materials. An engineer who has successfully designed a timber-based structure has designed with a material that behaves similarly to a composite material.

(3) Materials properties comparison. To better understand the differences between properties of a typical structural steel and those of FRP's such as glass/polyester and graphite/epoxy composite materials, examples of their properties are shown in Table 4-1. In evaluating composite materials the engineer should use their specific modulus and specific strength. While the steel is the stiffest material, the graphite/epoxy system has a specific stiffness that is about 1.75 times greater than that of steel.

Table 4-1
Contrasting Properties of Steel and Composite Materials

Material	Modulus GPa (10^6 psi)	Strength MPa (10^3 psi)	Density g/cm^3 (lb/ft^3)	Specific Modulus[3] GPa (10^6 psi)	Specific Strength[3] MPa (10^3 psi)
Steel[1]	207 (30.0)	248 (35.9)	7.87 (490)	26.3 (3.81)	31.5 (4.57)
Glass/ polyester[2]	27.1 (3.93)	287 (41.6)	2.13 (133)	12.7 (1.84)	135 (19.58)
Graphite/ epoxy [2]	70.3 (10.2)	683 (99.0)	1.61 (100)	43.7 (6.34)	424 (61.48)

[1] This is a typical grade of structural steel.
[2] The composite properties are dependent upon the stacking sequence chosen. These properties represent a quasi-isotropic lay-up of the composite material. Typical industry materials were chosen. See Table 5-4 for effects of ply orientation.
[3] In order to present the specific modulus and specific strength in more traditional units, the values of modulus and strength were divided by the specific gravity of the material, rather than by its density.

Although the steel is about 9 times as stiff as the glass/ polyester, it is only twice as stiff on a per weight basis. In terms of specific strength, the glass/polyester is about 12 times stronger than steel, and the graphite/epoxy is about 13 times stronger than steel.

4-3. Types of Composite Components

FRP composites consist of fibers enclosed in a polymeric matrix. Within this group there are many different types of resins and fibers that could be chosen. Several examples of these are shown in the following paragraphs.

a. Resins.

(1) There are two broad families of resins that are commonly used in composite materials. They are thermoplastics and thermosets. A thermoplastic material can be remolded into a different shape through the application of heat and force. A thermoset cannot be remolded after it has been cured. At the present time thermosets are more commonly used in FRP's. Most references to resins are for thermoset resins.

(2) Thermoplastics are composed of long hydrocarbon chains that are not chemically bonded. This system will allow one chain to slide with respect to the adjacent chain. This will produce a material that is very ductile and of relatively low strength. Thermoplastics have less resistance to elevated temperatures than thermosets. Examples of thermoplastics are polyethylene, polystyrene, polypropylene, polyetheretherketone (PEEK), polyvinyl chloride, and the acrylics.

(3) In contrast to a thermoplastic, a thermoset is a set of hydrocarbon chains where there are covalent bonds between the chains. These bonds form, or set, at higher temperatures. This produces a three-dimensional network polymer that can be very hard, brittle, and strong. The strength level can be controlled to some extent by the amount (or concentration) of these bonds between the chains. The more of these bonds between chains (called crosslinks), the stronger will be the polymer. This type of polymer cannot be reformed once cured or set. If a thermoset is reheated (in an attempt to reform it), it is likely that more crosslinking will occur, which will make it even stronger. If too much heat is applied it will decompose. Two common examples of thermosets are epoxies and polyesters. In some situations, where a higher temperature capability is required, phenolic resins are used.

(4) Sometimes the thermoset is too brittle to be easily used. Additives can be introduced into the resin to make it more ductile. As mentioned earlier, one method to accomplish this would be to add rubber particles to the thermoset. This could produce what is commonly called a toughened epoxy.

(5) Polymeric resins will absorb moisture. Since many applications are in contact with water (at least some of the time), the effect of moisture on the composite needs to be examined before it is put into place. The designer needs to evaluate each application to determine if the moisture absorption of the composite will be a problem in that specific situation.

(6) Thermosets are the most widely used resin for the type of applications that will be implemented for civil engineering structures. Because thermosets are of basic importance to these types of structures, discussion throughout the remainder of this ETL will be primarily about thermoset resins.

b. Fibers. A variety of types of fibers are used in composite materials. The fibers need to be stronger and stiffer than the polymeric matrix that surrounds them. Glass fibers are probably the most inexpensive fibers, whereas carbon fibers, are the most expensive. Aramid fibers have prices in between those of glass and carbon.

(1) Carbon (or graphite) fibers. These fibers are frequently used because of their very high strength and stiffness. Carbon fibers come in many grades which vary according to their strength and moduli. Care needs to be taken so that the fibers are well bonded to the resin matrix. This is especially true for the higher strength fibers which are smoother and form weaker bonds with the surrounding resin.

(2) Glass fibers. These fibers are frequently used as a more economical alternative to carbon fibers. They have a lower modulus than the carbon fibers; however, they cost much less. There are several types of glass fibers that are commonly used in composite materials. The most common glass fiber is E glass, but others are also available. E glass fibers have better electrical resistance than do other glass types. See Chapter 6 for a discussion of how the environment can affect glass fiber properties.

(3) Aramid fibers. These fibers are made from a high strength hydrocarbon. A common example of an aramid fiber is Kevlar. Since each one of these fibers is frequently composed of even smaller groups of fibers (to give a ropelike appearance), aramid-based composites are frequently more ductile than carbon-based composites. For example, aramid-based composites are frequently used in bulletproof vests. The aramid composite stops a projectile by deforming during the impact.

c. Sizing. Sizing refers to the coating of the individual fibers before they are mixed with the resin. Graphite fibers are frequently coated with a very thin coating of an organic-type material. This coating is commonly called "sizing" or a coupling agent. The coating will act to protect the fiber itself, which is typically very brittle and easily damaged.

d. Coatings.

(1) In this context, coatings refer to a coating of the entire structure before use (but after fabrication). The purpose of the coating is to protect the underlying resin and fibers from chemical and/or abrasive attack.

(2) Coating of the entire structure has a very different purpose from sizing. This type of coating is typically applied to protect the structure from some sort of environmental damage. A coating could be applied to protect the resin from damage by ultraviolet radiation. Some coatings can reduce the amount of moisture absorption by the structure. All polymeric resins will absorb water to some extent. If the resin can be kept physically separate from water, then it will be less likely to be damaged by moisture absorption.

4-4. Processing

There are many production methods. These methods have been discussed in the literature. Two excellent references are Ashbee (1993) and Schwartz (1984). A list of several types of fabrication and curing methods is given below.

- Hand lay-up.
- Filament winding.
- Chopped fiber spray lay-up.
- Press molding.
- Vacuum molding.
- Autoclave molding.
- Injection molding.
- Resin transfer molding.
- Pultrusion.
- Vacuum-assisted resin transfer molding.

The following discussion emphasizes methods that are used to produce structural composites. For other methods, the reader should consult the references cited above. Some of the following methods are not economical without a large volume of production.

It should be noted that pultrusion and vacuum assisted resin transfer molding are becoming the primary processes used in producing structural composites for civil engineering applications.

a. Filament winding. This method is used to apply uncured and unidirectional plies to a structure that is a simple shape, such as a plate or cylinder. The fibers are wound onto the structure in one of several ways. It could be done with groups of fibers applied by themselves. If this is the case, then the resin needs to be applied later by some other means (such as spraying). As a second method, the fibers could be pulled through a bath of the resin in order to have the proper amount of resin. A third alternative is for the machine to lay down strips of prepreg, which are fibers already impregnated into an uncured resin. Once the fiber resin structure is in place, the structure must be cured.

b. Press molding. This method is used after the uncured composite has been laid up using filament winding or some other technique. The composite part is put into the press and an external load and elevated temperature are applied. The pressure and temperature act to promote chemical bonding between layers and within individual layers. This method is commonly used for simple shapes, such as flat plates.

c. Vacuum bag molding. This is an alternative method that is used to press the individual plies together to get good bonding. The entire part is placed inside a flexible bag. A vacuum is then applied to the inside of the bag. The external air pressure then acts to push the plies together. The vacuum also acts as a means to remove the volatiles that form during the curing process. This method will work if the applied external pressure does not have to be very high in order to adequately push together the layers of the composite material.

d. Autoclave molding. This method uses a furnace that can cure the composite at elevated temperature and elevated pressure. It allows more complex shapes to be formed than does the press molding method. The autoclaves can be quite large. Some aircraft manufacturers have autoclaves large enough to put an entire wing or tail assembly within it, so that the entire structure can be cured at one time. This method is frequently used along with the vacuum bagging method. In this manner there is a vacuum to remove the volatiles while there can be a large external pressure applied to push the structure together.

e. Pultrusion. This is a method in which the fibers are passed through a resin bath to coat them. The resin-coated fibers are then pulled through a die that acts to push the fibers together, thereby helping to produce a composite with a high fiber volume fraction. Dies can be fabricated so that a variety of shapes can be produced. Examples of such shapes are round bars, rectangular shaped bars, and channels. Several of these shapes are shown in Figure 2-1.

f. Vacuum assisted resin transfer molding. One example of this method is SCRIMP (the trade name). SCRIMP is the acronym for the Seemann Composite Resin Infusion Molding Process. This process is similar to the traditional resin transfer mold methods, except that it requires only one tool side and a simple vacuum bag. This allows for parts to be manufactured much more simply and cheaply than if an autoclave process had been used.

Chapter 5
Material Properties

5-1. General

Composite laminate material properties depend upon the properties of the fibers and resins from which they are made. In this chapter, the fiber and resin properties will first be discussed, and then the laminate properties. All of these discussions will concentrate on the three fiber types most likely to be used in civil engineering structures: carbon fibers, glass fibers, and aramid fibers.

5-2. Fiber Properties

a. There are various grades of carbon fiber (or glass fiber or aramid fiber). Table 5-1 lists several types of fibers and typical properties.

b. There are several things that should be noted about the data in Table 5-1. The carbon fibers have the highest modulus, but both the glass and aramid fibers have higher strength. The higher strength of the glass fibers (compared to carbon) does not translate into higher composite strengths because the glass fibers are very sensitive to small defects which can greatly lower their strength. The carbon fibers have very low ductilities. Therefore, they should not be used in applications that will require a significant amount of deformation. Compressive stiffness and strength properties are hard to obtain for pure fibers because they are difficult to test.

c. From Table 5-1 it is not possible to conclude which of the three types of fibers would produce the most efficient structure, because that would depend upon whether modulus or strength was the controlling parameter. The weight would also depend upon the fiber concentration in the composite. For a given number of fibers, the structure's mass will vary with the amount of resin.

5-3. Resin Properties

a. The properties of the resins depend upon their internal structure. Some typical resin properties are shown in Table 5-2. One type of polyester resin that is commonly used is a vinyl ester resin.

Table 5-1
Typical Values of Fiber Properties[1]

Fiber	Axial Tensile Modulus, GPa (10^6 psi)	Axial Tensile Strength, MPa (10^3 psi)	Axial Elongation at Break, percent	Density, g/cm^3 (lb/ft^3)
Carbon—low modulus	170 (24.6)	1380 (200)	0.9	1.90 (119)
Carbon—high modulus	380 (55.1)	1720 (249)	0.4	2.00 (124)
Carbon—very high modulus	760 (110)	2210 (320)	0.3	2.15 (135)
E—glass	81 (11.7)	3450 (500)	4.88	2.60 (162)
S—glass	89 (12.9)	4590 (666)	5.7	2.48 (155)
Aramid—high toughness	83 (12.0)	3620 (525)	4.00	1.44 (90)
Aramid—high modulus	131 (19.0)	3620-4140 (525-600)	2.80	1.44 (90)
Aramid—very high modulus	186 (27.0)	3450 (500)	2.00	1.47 (92)

[1] From *Engineered Materials Handbook (1987)* and *Engineers' Guide to Composite Materials* (1987).

Table 5-2
Typical Resin Properties[1]

Resin	Tensile Strength MPa (10^3 psi)	Tensile Modulus GPa (10^3 psi)	Elongation percent
Epoxy resins	103-172 (14.9-24.9)	4.83-6.21 (700-900)	< 2.0
Polyimide resins	48-83 (6.96-12.0)	2.76-5.52 (400-800)	1.7-3.2
Polyester resins	21-83 (3.05-12.0)	2.76-4.14 (400-600)	1.4-4.0
Thermoplastic resins	76-103 (11.0-14.94)	2.21-4.83 (320-700)	5-10

[1] *From Engineered Materials Handbook (1987)* and *Engineers' Guide to Composite Materials* (1987).

b. As can be seen from comparing Table 5-1 and Table 5-2, many resins contribute very little to the load-carrying capability of the composite material. However, the resins can have a big impact upon the toughness of the composite laminate. The more ductile the resin, the tougher will be the resulting laminate. The resins act to transfer load from one fiber to an adjacent fiber. When one fiber breaks, a ductile resin is more likely to distribute the load to several fibers and not just the adjacent fiber. This will act to resist further fiber failure, thus increasing toughness of the composite.

5-4. Laminate Properties

a. Strength. For a given fiber and resin combination, there are two additional parameters that significantly affect the composite's strength. These parameters are the fiber volume fraction and the fiber orientation. The fiber volume fraction is the percentage of the volume of the composite material that is occupied by the fibers. Tables 5-3 and 5-4 are for composite laminates. Table 5-3 shows properties for a unidirectional laminate. Table 5-4 shows properties for a multidirectional laminate. These are the types of data that should be used in actual designs, rather than combinations of the resin and data shown in Tables 5-1 and 5-2.

(1) Tensile strength. In Table 5-3, longitudinal refers to strength in the fiber direction and transverse refers to strength perpendicular to the fiber direction. The longitudinal tensile strengths are about 30 to 40 times greater than the transverse tensile strengths, because in the transverse direction the composite can fail without having to break any fibers. Its strength in this direction is now largely determined by the strength of the resin. The longitudinal tensile strength of a unidirectional composite can frequently be approximated by a simple rule of mixtures formulation:

$$TS_C = TS_f V_f + TS_m V_m \qquad (5\text{-}1)$$

where

TS_C = ultimate tensile strength of the composite

TS_f = ultimate tensile strength of the fibers

V_f = volume fraction of fibers

TS_m = ultimate tensile strength of the resin

V_m = volume fraction of the resin

(2) Compressive strength.

(a) It should be noted that the transverse compressive strength is higher than the transverse tensile strength for a unidirectional system. The resin itself is stronger in compression than in tension. In addition, the fibers can provide resistance to transverse compressive loads, but do not provide significant resistance to transverse tensile loads. Transverse compressive strength is also typically lower than longitudinal compressive strength.

(b) The aramid-based composite has a much lower compressive strength than tensile strength, because what appears to be a fiber in the aramid composite actually has a ropelike structure and is composed of much smaller fibers. This makes it even more likely to buckle on a microscopic level than the carbon or glass fibers, thereby leading to a very poor compressive strength.

Table 5-3
Typical Strength Terms for Unidirectional Laminates (Volume fraction of fibers is approximately 50 percent)[1]

Material	Longitudinal Tensile Strength, MPa (10^3 psi)	Longitudinal Compressive Strength MPa (10^3 psi)	Transverse Tensile Strength, MPa (10^3 psi)	Transverse Compressive Strength MPa (10^3 psi)	Shear Strength MPa (10^3 psi)
Carbon/ epoxy	1448 (210)	600 (30.5)	52 (7.5)	206 (29.9)	93 (13.5)
E-glass/ vinyl ester	610 (88.5)	215 (31.2)	49 (7.1)	49 (7.1)	16.0 (2.3)
Aramid/ epoxy	1400 (203)	235 (34.1)	12 (1.7)	53 (7.7)	34 (4.9)

[1] From Tsai and Hahn (1980) and *Delaware Composites Design Encyclopedia* (1990).

Table 5-4
Effect of Fiber Orientation on the Tensile Strength of a Typical Glass/Polyester Laminate [1]

Lay-up	Typical Strength in Zero-Degree Direction, MPa (10^3 psi)	Typical Strength in Ninety-Degree Direction, MPa (10^3 psi)
$[0_8]$	610 (88.4)	49 (7.1)
$[45_8]$	98.8 (14.3)	98.8 (14.3)
$[45_2/-45_2]_S$	120 (17.4)	120 (17.4)
$[0_2/90_2]_S$	453 (65.7)	453 (65.7)
$[0/90/45/-45]_S$	287 (41.6)	287 (41.6)
$[0_4/90_4/45/-45]_S$	393 (57.0)	393 (57.0)
$[0_6/90_2/45/-45]_S$	456 (66.1)	123 (17.8)
$[0_8/45/-45]_S$	539 (78.2)	206 (29.9)

[1] Zero-degree data are from *Engineered Materials Handbook* (1987). The remaining strengths have been calculated using Tsai-Hahn's (1980) quadratic interaction model for strength.

(3) Effect of fiber orientation on strength.

(a) Most composite laminates are not unidirectional but have a variety of fiber orientations. To illustrate what that might do to composites, strengths for a glass/polyester composite with a variety of orientations have been determined. These results are shown in Table 5-4. The lay-up notation format was described in paragraph 4-2*b*(3).

(b) The first lay-up shown in Table 5-4 is a unidirectional one. It will provide the maximum possible strength in one direction but it will have the minimum possible strength in the transverse direction. This could result in premature failure if some off-axis loads are applied to the laminate. Note how much stronger the laminate is that has both plus and minus 45-degree plies compared with the one that has only plus 45-degree plies. This is because the one that has all the plus 45-degree plies can fail along the fiber direction without having to break any fibers. The one that has both plus and minus 45-degree plies will have to break fibers before the laminate can fail.

(c) Actual lay-ups used in laminates would be similar to the last four lay-ups shown in Table 5-4. Traditionally, designers have used lay-ups that had the same number of 0-degree, 45-degree, -45-degree, and 90-degree plies. This produced a laminate that had a strength about one half that of the unidirectional one. These configurations have strengths less than the strength of a unidirectional laminate. Note that the 0-degree strength increases as the proportion of 0-degree plies increases. This increase is not proportional to the increase of 0-degree plies.

(4) Flexural strength.

(a) The flexural strength is related to both the tensile and compressive load-carrying capability of the composite. This is because bending of the composite will put part of it into compression. During flexural loading the tensile stresses are created by bending the member rather than by direct tension loading. Although flexural and tensile strength levels may be about the same, the methods of failure may be very different.

(b) Most composites are very nonisotropic, which can play a significant role if there are bending moments applied to the structure. If the ply orientations with the smallest strength are on the outside of the structure (where the flexural stresses are the largest) then they can fail at relatively low bending loads. If the strongest orientations are placed on the outside of the structure then it would have a greater flexural strength. The flexural strength can be changed by changing the order of the various plies (called the stacking sequence). The issue of stacking sequence of the plies does not play a major role if the loads are axially applied.

(5) Shear strength. As shown in Table 5-3 the shear strength of a unidirectional composite is rather low. This is because the fibers cannot resist deformation in the direction of maximum shear. However, the shear strength can be significantly increased if there are some plies added where the fibers are at ±45 degrees with respect to the applied load. If all fibers are at ±45 degrees then the composite will have its maximum shear strength. However, such a lay-up would have a relatively low tensile strength. If shear resistance is a major issue, then some plies should be placed at ±45 degrees to increase the shear strength.

b. Specific strength. Specific strength is a measure of a given mass of a material's ability to hold a given load. This is in contrast to *strength* which is a measure of a given area of a material's ability to resist a given load. Values of specific strength will vary with fiber content and fiber orientation in the same manner as does strength. If the load-carrying capability of a structure is the controlling parameter, then the composite with the highest specific strength will be the lightest weight. Since specific strength looks at the load-carrying capability of a given mass of material, the lightest weight composite may not be the one with the thinnest cross section.

c. Strain capacity.

(1) The strain capacity of fiber-reinforced polymers is typically not very high. Table 5-1 shows strain capacity for a number of fibers. Strain capacity is the strain to failure as measured by a tensile test. Carbon fibers have a very low ductility, on the order of less than 1 percent. Glass fibers are considerably more ductile, on the order of 4-6 percent. Aramid fibers have a ductility of 2 to 4 percent. As shown in Table 5-2, epoxy resins have low ductility, on the order of less than 1 percent. Thermoplastic resins commonly used in composites can be as large as 10 percent. In contrast to this, ASTM A 36 steel has a minimum ductility of 20 percent. Typical structural steel is therefore much more ductile than either the fibers or resins in these FRP's.

(2) When the fibers and resin are put together, the composite ductility is a weighted average of the fiber and resin ductility. This means that composites frequently have a low ductility (on the order of 1 to 5 percent). Some very ductile polymers can give composite ductility of up to 10 percent. If composites are to be made into complex shapes, then these complex shapes need to be formed during the initial fabrication process. Once a thermoset composite has been cured it cannot be refabricated. This is in contrast to many metals which can be cold-worked into complex shapes.

d. Modulus of elasticity.

(1) Modulus of elasticity is significantly affected by the type of fibers that are involved. Examples of this are shown in Table 5-5.

(2) Carbon/epoxy composites are intrinsically the stiffest. However, glass/epoxy composites have a better resistance to shear. The aramid-based composites are the poorest when loaded transverse to the fibers.

(3) The fiber volume fraction has a significant effect upon the modulus of elasticity. For a unidirectional system, the modulus can usually be represented by a simple rule of mixtures equation.

Table 5-5
Typical Modulus Terms for Unidirectional Composite Laminates [1]

Material	Longitudinal Modulus GPa (10^6 psi)	Transverse Modulus GPa (10^6 psi)	Shear Modulus GPa (10^6 psi)	Major Poisson's Ratio
Carbon/ epoxy	181 (26.2)	10.3 (1.49)	7.17 (1.04)	0.30
E-glass/ polyester	54.10 (7.84)	14.05 (2.04)	5.44 (0.789)	0.25
Aramid/ epoxy	75.86 (11.0)	5.45 (.79)	2.28 (0.331)	0.34

[1] Aramid and carbon data are from Tsai and Hahn (1980); glass data are from *Delaware Composites Design Encyclopedia* (1990).

$$E_L = E_f V_f + E_m V_m \qquad (5\text{-}2)$$

$$\frac{1}{E_T} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \qquad (5\text{-}3)$$

where

E_L = longitudinal modulus of the composite (in fiber direction)

E_f = modulus of fiber phase

V_f = volume fraction of fiber phase

E_m = modulus of matrix phase

V_m = volume fraction of matrix phase

E_T = transverse modulus of the composite (perpendicular to fiber direction)

(4) An engineer should not design using Equations 5-2 and 5-3. They are only first approximations, because the modulus also depends upon prior processing of the composite part.

(3) Fiber orientation also plays a big role in the composite stiffness. Figure 5-1 shows how the longitudinal and transverse moduli vary with orientation. As might be expected, the composite is stiffest when loaded in the fiber direction and least stiff when loaded perpendicular to the fibers. As Figure 5-1 shows, the relationship between modulus and orientation is not a simple one. Likewise, shear modulus is also a significant function of fiber orientation. Shear modulus reaches a maximum at 45 degrees and is a minimum at either 0 or 90 degrees. A graph of shear modulus as a function of fiber orientation is shown in Figure 5-2. Many applications have minimum requirements for both tensile and shear moduli, and some combination of 0- and 45-degree plies is frequently required.

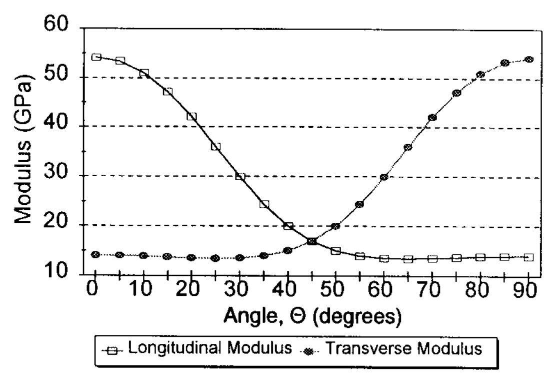

Figure 5-1. Modulus as a function of fiber orientation for a typical glass/polyester composite. Lay-up is of the form [Θ(1)/–Θ(2)/Θ(1)], where Θ is the angle in degrees

e. Specific modulus of elasticity. Specific modulus is a measure of a given mass of a material's ability to resist deformation. This is in contrast to modulus, which is a measure of a given area of a material's ability to resist deformation. The specific modulus of a material is its modulus divided by its density (or specific gravity). Values of specific modulus will vary with fiber content and fiber orientation in the same manner as does modulus. If the stiffness (or modulus) of a structure is the controlling parameter, then the composite with the highest specific modulus will be the lightest weight.

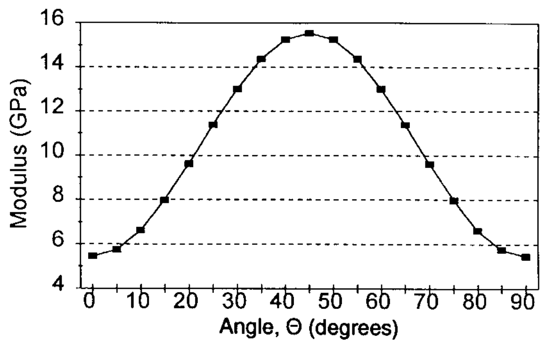

Figure 5-2. Shear modulus as a function of fiber orientation for a typical glass/polyester composite. Lay-up is of the form [Θ(1)/−Θ(2)/Θ(1)], where Θ is the angle in degrees

f. Density. Density values for various types of fibers were given in Table 5-1. They varied from about 1.4 to 2.5 g/cm^3 (88 to 156 lb/ft^3). Resin densities vary from about 1.3 to 1.8 g/cm^3 (81 to 112 lb/ft^3). Density of the composite can be calculated from a simple rule of mixtures equation.

$$\rho_c = \rho_m V_m + \rho_f V_f \quad (5\text{-}4)$$

where

ρ_c = density of the composite

ρ_m = density of the matrix

V_m = volume fraction of the matrix

ρ_f = density of the fibers

V_f = volume fraction of the fibers

Most of these composites will have densities somewhere between 1.5 and 2.5 g/cm^3 (93 to 156 lb/ft^3). This is in contrast to the density of iron, which is 7.87 g/cm^3 (490 lb/ft^3). The FRPs' low density (when compared to metals) is what gives them such high values of specific modulus and specific strength.

g. Poisson's ratio. Poisson's ratio for a given composite can vary significantly with respect to fiber orientation. When fibers are in the 0-degree direction with respect to the applied load, Poisson's ratio is frequently similar to that of most metals, being in the 0.25 to 0.35 range. However, at other fiber orientations, Poisson's ratio can vary a great deal. When the fibers are all in the 90-degree direction, Poisson's ratio can be very small, on the order of 0.02 to 0.05. This is because the very stiff fibers are resisting the resin contraction. On the other hand, with fiber orientations between 30 and 40 degrees, Poisson's ratio is often large. For some materials, Poisson's ratio can be larger than one, because the fibers are trying to align themselves with the applied load. As the fiber angles decrease slightly, they act to bring the resin in alignment with the load, which gives a very high value for Poisson's ratio. An example of this is shown in Figure 5-3.

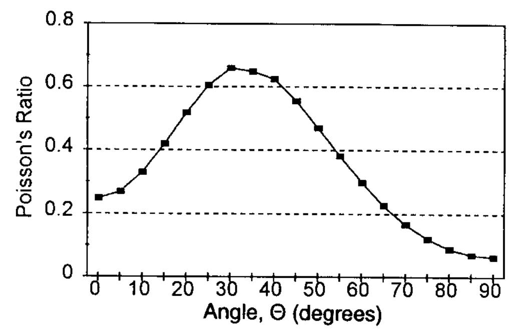

Figure 5-3. Poisson's ratio as a function of fiber orientation for a typical glass/polyester composite. Lay-up is of the form [Θ(1)/−Θ(2)/Θ(1)], where Θ is the angel in degrees

h. Coefficient of thermal expansion.

(1) Like all the other properties discussed so far, the thermal expansion coefficients are significantly affected by fiber orientation. Properties for some unidirectional composites are shown in Table 5-6. Also shown are values for steel and aluminum. Unidirectional composites are interesting in that many of them have a negative value for thermal expansion in the fiber direction. This is because the fibers resist thermal expansion of the resin in the fiber direction. Perpendicular to the fibers, the resin can expand a great deal because the fibers do not resist the expansion.

(2) It should be noted that these composites have a thermal expansion coefficient (perpendicular to the fibers)

Table 5-6
Typical Thermal Expansion Coefficients for Different Materials[1]

Material	Coefficient of Thermal Expansion Parallel to Fibers, (m/m)/°C ((in./in.)/°F)	Coefficient of Thermal Expansion Perpendicular to Fibers, (m/m)/°C ((in./in.)/°F)
Fiber-reinforced composites		
Carbon/epoxy (unidirectional lay-up)	-0.3×10^{-6} (-0.17×10^{-6})	28.1×10^{-6} (15.6×10^{-6})
E-glass/epoxy (unidirectional lay-up)	8.6×10^{-6} (4.8×10^{-6})	22.1×10^{-6} (12.3×10^{-6})
Kevlar 49/epoxy (unidirectional lay-up)	-4.0×10^{-6} (-2.2×10^{-6})	79.0×10^{-6} (43.9×10^{-6})
Isotropic (noncomposite) materials	Coefficient of Thermal Expansion (m/m)/°C ((in./in.)/°F)	
Pure epoxy resin	54×10^{-6} (30.0×10^{-6})	
Steel	11.8 x 10-6 (6.6×10^{-6})	
Aluminum	23.6×10^{-6} (13.1×10^{-6})	

[1] Data from Tsai and Hahn (1980) and *Engineered Materials Handbook* (1987).

that is considerably greater than that of steel. However, it is possible to design carbon or aramid composites with very low values of the thermal expansion coefficient because these composites have negative values of the thermal expansion coefficient in one direction and positive values in another. If a proper choice of ply lay-ups is made it is possible to obtain a thermal expansion coefficient for the structure to be essentially zero. This will allow for very thermally stable structures to be designed. However, the stacking sequence that produces a zero value for thermal expansion will probably not be the one with the highest value of strength. Therefore, the designer may have to use materials with nonzero thermal expansion coefficients.

i. Creep. Creep can occur at room temperature for many composite materials. The portion of the composite that actually creeps is usually the resin. Carbon and glass fibers do not creep a significant amount at room temperature. Creep is a function of the applied stress, fiber orientation, fiber volume fraction, and ductility of the resin. Fiber orientation is important because the more fibers that are aligned in the load direction, the lower will be the stress (and amount of creep) in the resin portion. The higher the concentration of fibers (at any orientation), the lower will be the creep rate. This is because there is less of the resin available to deform. A more ductile resin will creep more than will a more brittle one. Creep and relaxation are not usually a problem with epoxy and other thermoset resins, but can be a problem when the more ductile thermoplastics are used.

j. Relaxation. For a material to relax, it must first have deformed. The amount of relaxation that is possible is related to the initial applied stress, the fiber orientation, fiber volume fraction, and the ductility of the resin. Higher initial stress will allow for more relaxation to occur later. More fibers oriented in the load direction will decrease the amount of creep, and the amount of potential relaxation. A more ductile resin will have deformed more and will, therefore, be able to relax more than will a more brittle one.

k. Toughness. The toughness of the material is dependent upon the type of fibers, the type of resin, and the volume fraction of fibers. The stacking sequence of the plies does not appear to significantly affect the toughness of the laminate.

(1) Impact toughness (resistance).

(a) Impact tests in the traditional sense (like Charpy tests) are rarely done on composite materials. The epoxy-based composites have very low impact toughness. Thermoplastic-based composites have a somewhat higher impact toughness. The *Engineered Materials Handbook* (1987) reports impact toughness for a unidirectional glass/polyester composite of about 972 J/m (18 ft-lbf/in.)

which is contrasted to a typical aluminum of 215-647 J/m (4-12 ft-lbf/in.) and a typical stainless steel of 458-593 J/m (8.5-11 ft-lbf/in.).

(b) A more common impact test is to apply a smaller impact load to the structure that damages it but does not break it. The internal damage caused by the impact load will change the strength and stiffness of the composite. The compressive strength of the structure is measured after impact. This type of test will evaluate whether or not the structure can still be used after it has been hit with an impact load. This test has not yet been standardized.

(2) Delamination toughness.

(a) Delamination failure is a common failure for these fiber-reinforced polymers. Delamination is the separating of a composite into its original layers (or plies). This can occur because of the relatively weak bonding that occurs between the layers. Therefore the designer needs to specify a toughness sufficient for this application.

(b) Delamination toughness is largely a function of the type of resin and amount of resin (volume fraction resin). The stacking sequence of the plies does not appear to significantly affect the delamination toughness. The more ductile the resin, the higher will be the toughness. However, it is not a linear relationship. A doubling of the resin toughness will not double the composite toughness because the toughness of the composite is also affected by the resin/fiber interface. The presence of the fibers may also act to decrease the size of the resin's plastic zone. This would also decrease the toughness of the composite.

(c) Volume fraction of resin is only important for resins of medium toughness or higher (with a G_{IC} about 250 J/m^2 or 1.4 in.-lb/in^2.). For these resins, as the amount of resin increases, the plastic zone can also increase (since there are now fewer fibers to interfere with its expansion), thus increasing the toughness. For a more brittle resin, the plastic zone within the resin does not extend beyond the resin-rich region between plies. Making this region bigger will not help the plastic zone to grow at all, and the overall toughness will not increase.

(d) Another important parameter is the strength of the fiber resin interface. A poor interfacial strength will result in a lower than expected toughness. Typical resin toughness (G_{IC}) can range from 200 to 8,000 J/m^2 (1.1-46 in.-lb/in^2.). Composite delamination toughness (G_{IC}) can range from 200 to 2,500 J/m^2 (1.1-14 in.-lb/in^2.). This is in contrast to A36 steel which has a value of G_{IC} of about 13,000 J/m^2 (74 in.-lb/in^2.).

(e) One problem with laminates concerns the joining of the individual plies of the composite material. The separation of individual plies is called delamination. A number of techniques have been developed to prevent delamination. One method is to use a tougher resin matrix material. Another method is to have some occasional fiber reinforcement through the thickness. One way that has been done is by using what looks like a giant sewing machine to "sew together" the layers before they have been cured.

Chapter 6
Durability

6-1. Overview

a. FRP composites represent a new class of materials. Their durability is the primary reason for their use in many long-term applications of structural elements ranging from spacecraft to ladder rails, from aircraft wings to automobile doors, or from tennis rackets to liquid gas tanks. However, when a specific application is contemplated, it is essential for the designers to know not only the answers to questions regarding strength and stiffness, but also the question of how long the material will last under the conditions anticipated. These are the durability issues of a material.

b. In a general sense, the life of an engineering component is difficult to define. Many factors play roles in reducing the life. Most materials change characteristics by interaction with their surroundings over time. For example in the case of steel, oxidation leads to rusting. Presence of water accelerates the process. The exposure to sunlight makes nylon fiber turn yellow. Rubber ages faster and becomes brittle under the effect of ozone. Loss of water leads wood to split, and concrete degrades in harsh environment. What changes are likely to happen to FRP composites under given service conditions? If these changes are known beforehand, those changes can be accommodated in the design. And to accommodate these changes in the design, the rate of change and the effects of those changes on the behavior must also be known.

c. It is also important at the outset to define what is the limit of life; that means one must determine when the effective function of the structure ceases to exist following the period of service. For example, some materials, including polymeric composite materials, may not fail or separate under a certain service load condition, but can continue to deform or deflect beyond an acceptable limit. Thus, under these conditions the effective life ceases when a predetermined deformation or deflection limit is exceeded.

d. The mechanisms which control the durability of composites are well known. They include: (1) chemical or physical changes of the polymer matrix, (2) loss of adhesion or debonding at the fiber/matrix interface, and (3) reduction of fiber strength and modulus. Environment plays a crucial role in changing the properties of polymer matrix composites. By environment we mean here both the ambient environment and the loading environment because both can affect the durability of the composites. Considering the ambient environment we find that both matrix and fibers may be affected by moisture, temperature, sunlight (UV radiation), ozone, and presence of degrading chemicals such as salts or alkalis. Repeated excursions to very high and low temperatures (freeze-thaw cycling), too, may introduce some changes. Under mechanical loading environment, as in steel, repeated loading may introduce fatigue in composites. Sustained load over a period of time may cause the material to creep. In this chapter we will briefly summarize the effects of various service factors which may affect the durability of FRP composites.

e. It is, however, important to note that because of the relative newness of these materials there is a considerable gap in the definitive durability data of polymeric composites. Systematic investigations to predict the life of most commonly acceptable fiber composites in civil engineering construction environments are rare and in many cases the data available are not relevant to practical applications.

6-2. Physical Aging of Polymer Matrix

One of the important aspects to consider in the durability issues of composites is the role of the polymer matrix and its change. The primary role of the matrix in the composites is for it to transfer stresses between the fibers, to provide a barrier against an adverse environment, and to protect the surface of the fibers from mechanical abrasion. Although its role in tensile load-carrying capacity is minor, it has a major influence on the inter-laminar and in-plane shear load transfer. Therefore, it must be of concern and importance if the polymer matrix itself changes its characteristics with time. It is normal for all polymers to undergo an extremely slow change of chemical (molecular) structure. The environment, mainly the temperature and humidity, controls this change. The process is known as aging. The reason is that when a polymer is cooled below its glass transition temperature, the material does not achieve instantaneous thermodynamic equilibrium. Instead, its free volume equilibrium evolves over time, and during this time the mechanical properties can change (Monaghan and Brinson 1994). However, it is important to note that different groups of polymers or even different molecular configurations within the same group of polymers would respond differently to the same environment. The aging effects are less severe in the most commonly available thermoset composites than in thermoplastic composites. As a result of physical aging some polymers can become stiffer and brittle, and thus can influence the matrix-dominated properties, namely the shear and transverse response. But in most cases these effects are not critical because ultimately the major load-transfer process occurs through fibers, and the effects of aging on the fibers are minimal. While physical changes caused by aging are totally reversible once the polymeric material is heated above its glass transition temperature, this will typically not impact civil engineering structures since they will never reach the glass transition temperature.

6-3. Influence of Moisture

When exposed to humid air or water environments, many polymer matrix composites absorb moisture by instantaneous surface absorption and diffusion. Usually the moisture concentration increases initially with time and finally approaches the saturation point (equilibrium) after several days of exposure to humid atmosphere. The time to reach the saturation point depends on the thickness of the composite and the ambient temperature. Drying can reverse the process but may not result in complete attainment of original properties. The uptake of water by polymer composites in general follows the generalized Fick's law of diffusion. Figure 6-1 shows the typical Fickian behavior of a carbon-reinforced epoxy resin. In reality, however, the exact rate of moisture uptake depends on several factors including void content, fiber type, resin type, fiber orientation/architecture, temperature, applied stress level, presence of microcracks, and thermal spikes.

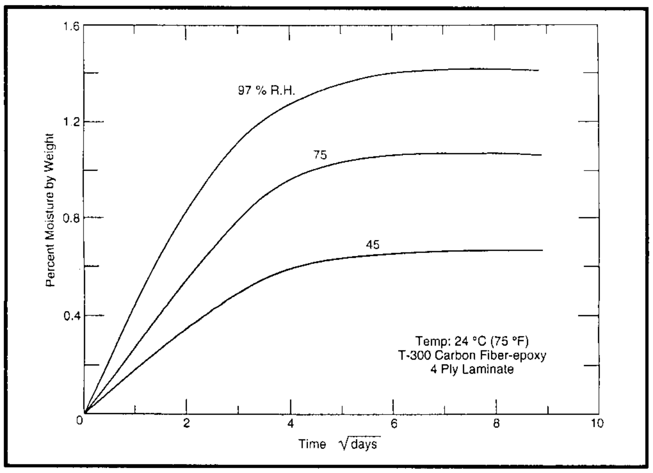

Figure 6-1. Water absorption behavior of polymer composites

a. Influence of moisture on polymer matrix. Absorption of water by resin in some instances may change the resin properties including the glass transition temperature through hydrogen bonding for the water molecules. However, this is not of major concern in civil engineering applications of composites. It is only above the temperature level of 120 °C (248 °F) that the stiffness of the composite may drastically degrade if the glass transition temperature becomes lower from moisture absorption. Moisture absorption has one beneficial effect on composites: it causes swelling of the resin. The swelling of the resin matrix in the composite around the fiber reduces the residual compressive stresses at the fiber/matrix interface caused by the curing shrinkage. This results in release of the mechanical interlocking stresses between the fiber and the matrix which in turn can have increased load-carrying capacity. Hahn and Kim (1978) reported that in improperly manufactured composites where voids are present at the fiber/matrix interfaces or in the layers of composites, the ingress of water through the voids or interfaces can cause plastification of the resin. The water trapped in voids may result in blisters. However, the problems can be eliminated by judicious selection of resin materials, appropriate surface treatment of reinforcing fibers, and manufacturing techniques.

b. Influence of moisture on fibers. It is commonly believed that glass fibers can be damaged by prolonged exposure to water. The reasons are that glasses are made of silica in which oxides of alkaline metals are dispersed. The alkaline metallic oxides are both hydroscopic and hydrolyzable. However, the most common form of glass fibers for civil engineering composite applications are made of E- and S- glass, which contain only small amounts of alkaline-metal oxides, and so are resistant to damage by water. Nevertheless, the composites of glass fibers should be well fabricated to avoid any large-scale water ingression, because presence of water at the glass-fiber interface lowers its surface energy which in turn can promote crack growth. In addition, degradation over long periods of time and at high temperatures has not been studied. Aramid fibers can absorb considerable quantities of water resulting in swelling. However, most fibers are protected by coating (sizing) which ensures good bonding with the matrix and also serves to protect it from water absorption. Moisture does not have any known degrading effects on carbon fibers (Mallick 1988).

c. General behavior of water-saturated composites.

(1) The water-saturated composites usually display a somewhat increased ductility due to a softening of the matrix. This could be a beneficial aspect of water absorption in polymer composites and could possibly be used in limited cases. Limited degradation of strength and modulus can also occur is water-saturated composites. These degradation changes are mostly reversible, so that upon

drying the composite may regain most of its lost properties.

(2) It is also interesting to note that increase of hydrostatic pressure (for example, where composites are used in underwater or sea-bed applications) does not necessarily increase the water uptake and hence does not contribute to composite degradation. Thus, most underwater polymeric structures are expected to have high durability. In fact, under the hydrostatic pressure the water uptake is reduced slightly because of consequent closing of microcracks (microvoids) and interfacial defects (Burnsell 1989). However, recent research by the Naval Surface Warfare Center indicates that a significant increase in moisture may occur in some types of composites by hydrostatic pressure.

(3) Water absorption affects the dielectric properties of the composites. Presence of free water-filled microcracks can decrease this property dramatically.

6-4. Hygrothermal Effects

Temperature plays a crucial role in the water absorption mechanism of composites and its subsequent irreversible effects. Temperature influences distribution of the water, the quantity, and the rate at which it is absorbed. As the temperature increases, the amount and rate increase rapidly, as shown by Dewimille and Burnsell (1983). They have shown that damages induced by immersion in boiling water for only a few hours produced debonding and cracking of the same degree as at 50 °C (122 °F) over a period of 200 days. At room temperature the same composite specimens showed no indication of damage. These observations led to the development of a technique for accelerated aging tests of composites.

6-5. Alkaline Environment

In using glass fiber composites in alkaline environment it is essential to ensure that high-alkali-resistant glass is used, because the alkaline solution reacts with glass fibers to form expansive silica gels. This precaution is especially important for application of glass-fiber-reinforced composite material as reinforcing bars in concrete. Glass-fiber-reinforced polyester bars are being increasingly considered to replace steel-reinforcing bars in pavements which are corroded by deicing road salt. However, during hydration of the concrete, a highly alkaline (i.e., pH > 12) pore water solution is created. This highly alkaline solution can affect the glass fiber and reduce durability of the bars. Relatively inexpensive E-glass fibers are considered not to have much resistance against the alkali attack. Use of vinyl ester resin has been observed to reduce the alkali attack by providing an effective barrier. The resistance to alkali attack can also be improved by designing the member to lower stress levels. High-alkali-resistant glass can improve the durability. There is continuing research regarding improving the long-term effects of alkaline environment on glass fibers embedded in polymer matrix. Results of the research, hopefully, will improve the FRP composite's durability in alkaline environment. It must be noted also that carbon and aramid fiber composites are not susceptible to alkaline environment degradation.

6-6. Low Temperature Effects

a. Extreme changes in temperature of composite materials result in several important effects. Most materials expand when temperature rises. In fiber-reinforced polymer matrix composites, the coefficient of thermal expansion of the matrix is usually an order of magnitude greater than that of the fibers. A decrease in temperature, due either to cooling during the fabrication process or to low-temperature operating conditions, will cause the matrix to shrink. Contraction of the matrix is resisted by relatively stiff fibers through fiber/matrix interface bonding, setting up residual stresses within the material microstructure. The magnitude of the residual stresses is proportional to the difference in curing and operating temperatures of the composite material. Except for a very severely cold environment the induced residual stresses are not of much concern. Where large temperature differentials exist (for example, in the Arctic and the Antarctic regions of the world), sufficiently large stresses may induce microcracking in the material. These microcracks in turn can reduce the stiffness of the composite, increase permeability and water ingression through fiber/matrix interface, and thus finally contribute to the degradation processes.

b. Another very important effect of lower temperatures is the accompanying change in matrix strength and stiffness. Most resin matrix materials become stiffer and stronger as they are cooled. These changes can influence the modes of failure. For example, Figure 6-2 shows the results of 1.5-in. (38-mm) diameter cylindrical specimens tested in compression at room temperature and at -50 °C (-58 °F). At the low temperature the compressive strength increased by 17.6 percent, but the material failed more violently (Dutta 1994). The energy absorption before failure at low temperature is higher than at room temperature. This particular aspect of high energy release at failure should be considered in designing with composites where impact loadings are expected at lower temperatures.

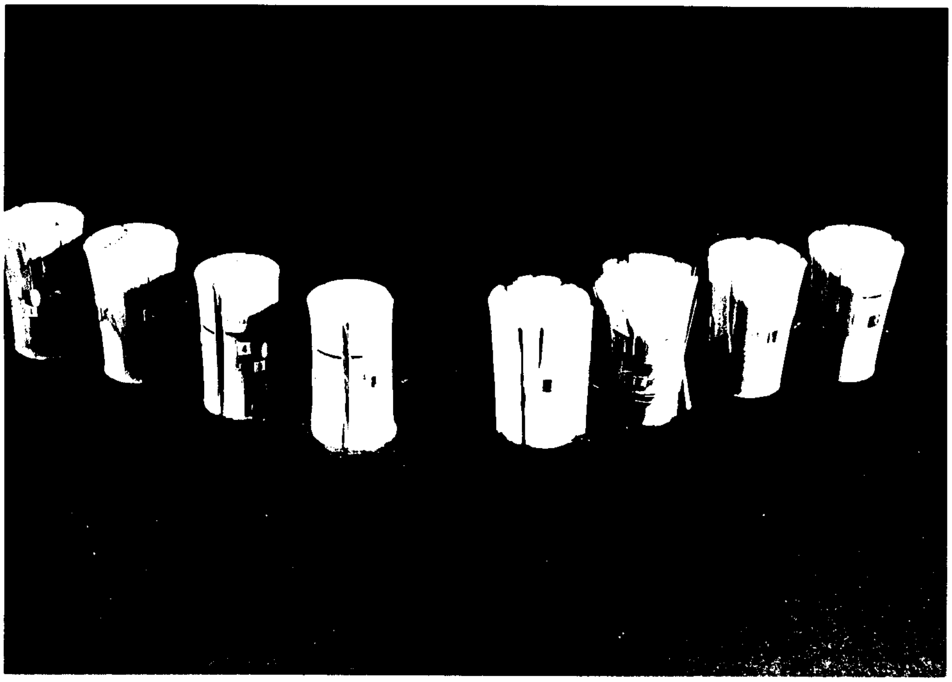

Figure 6-2. Composites failures are more violent at low temperature (right) than at room temperature (left)

6-7. Low Temperature Thermal Cycling (Freeze-Thaw) Effects

a. Unless a composite contains a significant percentage of interconnected voids that are filled with water, the freeze-thaw effects on the strength, within the normal temperature range (+30 °C to -20 °C) (+86 °F to -4 °F), are insignificant. Commercially available glass fiber composites usually contain about 0.4 percent voids, which does not allow any appreciable frozen moisture to cause any serious damage.

b. However, low temperature thermal cycling has other effects on composites. Residual stresses occur in composite materials due to differences in coefficients of thermal expansion of constituent elements in the material microstructure. Under extreme low temperature conditions these stresses can result in the formation of microcracks in the resin matrix or in the resin-fiber interface. The chances of microcrack growth under normal range of service temperatures, say between +30 °C and -20 °C (+86 °F and -4 °F), are usually remote or marginal. However, under severe thermal cycling conditions, for example, between +60 °C and -60 °C (+140 °F and -76 °F), microcracks can grow and coalesce to form matrix cracks which may propagate in the matrix or wander around the matrix-fiber interfaces (Lord and Dutta 1988). Under prolonged thermal cycling they continue to grow in number and size and can result in stiffness degradation and degradation of other matrix-dominated properties.

c. The limited number of tests conducted at low temperatures (down to -50 °C) on composites at the Cold Regions Research and Engineering Laboratory (CRREL) of the Corps of Engineers have uncovered some basic problems of designing with composites for safety and durability at extremely cold environment (Dutta 1992). It has been observed that at very low temperatures the unidirectional tensile strength of all polymeric composites tends to decrease, although the off-axis and transverse tensile strengths increase. These results are explained by hardening of the polymeric matrix at lower temperatures. Prolonged thermal cycling between extreme temperatures has also shown degradation of off-axis strength and stiffness. These characteristic changes are important for structural design in cold regions.

6-8. Influence of Ultraviolet (UV) Radiation

The effect of ultraviolet light on polymeric compounds is well known. On prolonged exposure to sunlight the matrix may harden and discolor. The problem is generally overcome by applying a UV-resistant coating to the composites. Of major concern is the degradation of reinforcing polymeric fiber such as aramid. An example strength loss of 50 percent is reported for aramid fabric of light weight, 75 g/m² (0.25 oz/ft²), after five weeks exposure in Florida sunshine (Larsson 1988). However, the effect is a self-screening type--that means only the skin of the composite structure is affected. So, in thicker composites the degradation effect is minimal on structural properties. For applications where surface properties are important, consideration should be given to reduce surface cracking due to sun rays.

6-9. Creep Behavior

a. Creep is the increase in strain with time at a constant stress level. Creep occurs because of the combination of elastic deformation and viscous flow. When the stress is removed after a period of time, the elastic deformation is immediately recovered, but the deformation caused by the viscous flow recovers slowly to an asymptotic value, called the recovery strain (Figure 6-3).

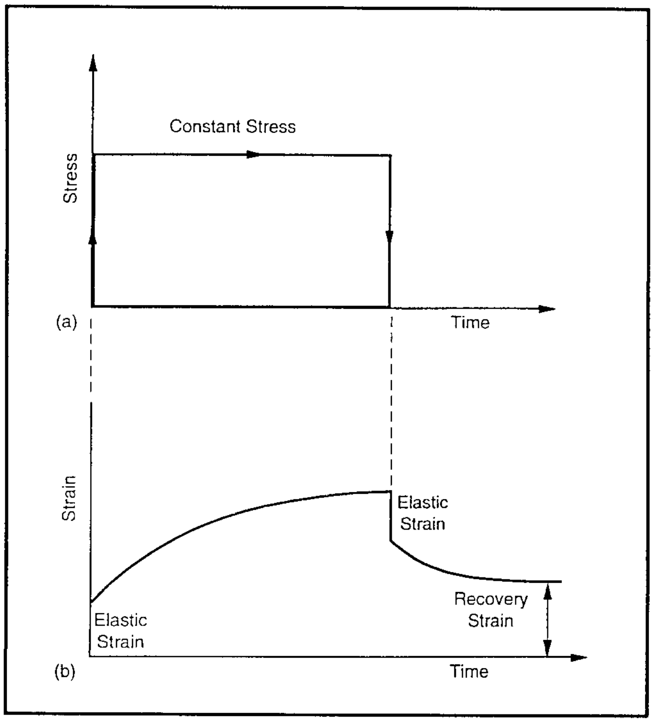

Figure 6-3. Schematic of the creep behavior of polymer composites

b. In composites, the creep strain depends on the stress level and temperature and is a function of both distribution of stress between the fiber and matrix. In general, highly cross-linked thermosetting polymers exhibit lower creep rates than thermoplastic polymer composites. With the exception of aramid fibers, commercial reinforcing fibers such as glass and carbon do not creep appreciably at normal loads.

c. Creep data for composites can be generated by conducting a tensile or flexural creep test over a period of a few hours, and from these data the long-term creep behavior can be predicted by the time-temperature superposition method.

d. The modulus of a polymer (E) at time t and temperature T_o can be related to its modulus at time t_1 and temperature T_1 by the following equation (Mallick 1988).

$$E(t,T) = (\rho_1 T_1/\rho_o T_o)E(t_1,T_1) \qquad (6\text{-}1)$$

where ρ_1 and ρ_o are the densities of the polymer at absolute temperatures T_1 and T_o, respectively.

e. Figure 6-4 shows the tensile creep curves for a composite at various stress levels. For fiber orientation $\theta = 0^o$ creep is nearly constant, indicating that creep in the longitudinal direction of 0^o composites is negligible. However, at other fiber orientation angles creep strain can be significant. Thus, it is important in polymer composite designs to recognize the influence of creep when the stresses are significantly large off-axis to fiber orientation.

f. Over a prolonged period of time a sustained load can induce a complete failure in a creep-prone material. The time at which the failure occurs is termed the "lifetime" or "stress rupture time." For a given composite material, stress rupture tests are usually performed to determine a range of applied stresses and lifetimes within which the material can be considered "safe" in long-term static load applications. The relationship between the applied stress level and lifetime is often represented as

$$\sigma_u = A - B \log t \qquad (6\text{-}2)$$

where σ_u is the static tensile strength, and A and B are empirical constants.

g. Glass and aramid fibers over a long period of time exhibit failure by stress rupture. Carbon fibers are relatively less prone to stress rupture. Glaster and co-workers (1983, 1984) have generated extensive stress rupture data for S-glass and aramid composites.

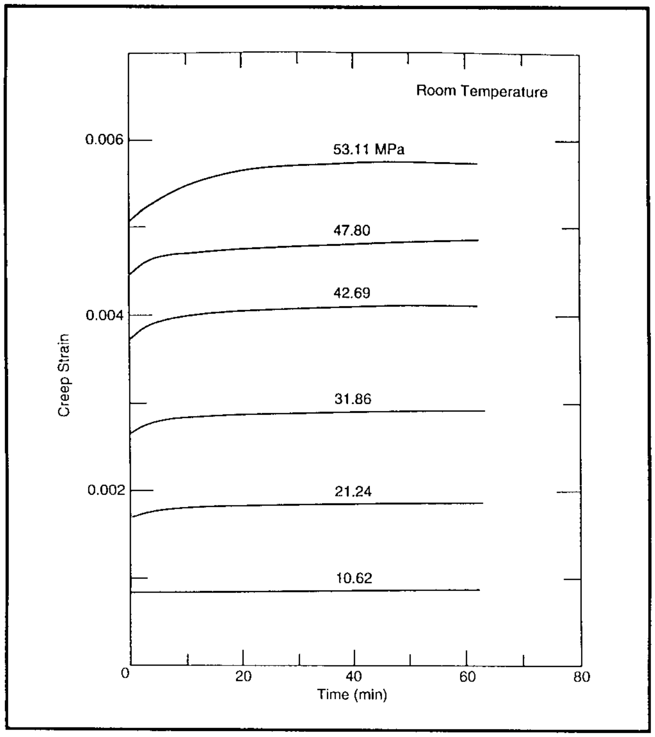

Figure 6-4. Tensile creep curves for a vinyl-ester/glass composite at various stress levels (after Mallick 1988)

6-10. Fatigue Properties

a. The fatigue properties of a structural material represent its response to cyclic loading. Repeated cyclic loading usually results in a decrease in the strength properties of metallic materials. Composites, on the other hand, generally are considered to have excellent fatigue response.

b. The fatigue behavior of a material is usually characterized by an *S-N* diagram representing the relationship between the stress amplitude (*S*) and the number of cycles (*N*) to failure on a semilogarithmic scale (refer to Figure 6-5). In general, the number of cycles to failure increases continually as the stress level is reduced. For mild steel, a fatigue limit is of the order of 10^5-10^6 cycles at 50 percent of its ultimate tensile strength. Below the fatigue limit, the likelihood of fatigue failure occurring is very low, so that the material has essentially an infinite life.

c. One of the major problems of predicting fatigue failure limit of composites is the complexity in assessing the modes of failure. The most commonly used fatigue test on composite materials is the tension-tension cycling.

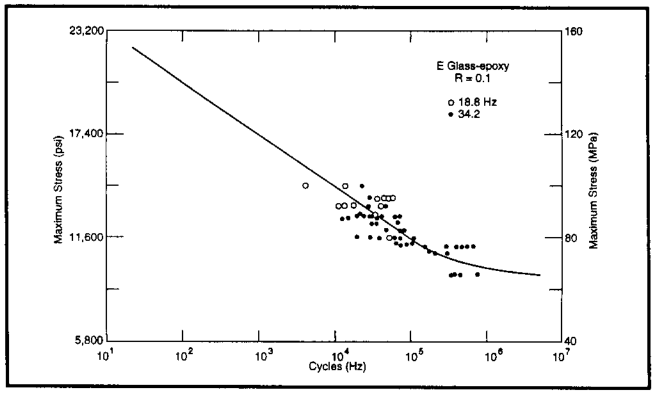

Figure 6-5. A typical fatigue behavior of an E-glass-epoxy composite

Tension-compression cycling by flexural fatigue tests are also being reported. The tension-tension fatigue cycling test procedure is described in ASTM D 3479.

d. The compression-compression fatigue performance of composites is generally less satisfactory than the tension-tension performance. In flexural fatigue loading, therefore, the initial damage usually develops on the compressive side of the specimen.

e. A unique feature of a fiber composite material in fatigue testing is that it exhibits a gradual softening with increased cycling. Thus, tests are sometimes done not to a failure represented by the separation of the specimen, but to a limit of specimen stiffness or residual strength which is predetermined.

f. The *S-N* curve for the fiber composites can be represented by a straight-line relationship given by

$$S = \sigma_u (m \log N + b) \qquad (6\text{-}3)$$

where

S = maximum fatigue stress

σ_u = static strength

m, b = constants

N = number of cycles to failure

Values of *m* and *b* for E-glass/epoxy 0-degree fiber orientation are 0.1573 and 1.3743, respectively (Lorenzo and Hahn 1986).

g. It has generally been observed that in tension-tension fatigue tests the unidirectional carbon and aramid composites exhibit exceptionally good fatigue strength. On the other hand, when the fibers are oriented in off-axis directions the fatigue strengths often depend on the proportion of fibers aligned with the loading axis, stacking sequence, and parameters of cycling. It should be noted that a tension-compression cycling may produce a steeper *S-N* plot than the tension-tension cycling. The fatigue performances of both E- and S-glass fiber-reinforced composites are poorer than those of carbon or aramid composites. Results of a tension-tension fatigue test for a 0-degree E-glass-epoxy laminate are shown in Figure 6-5.

6-11. Fire Hazards and Flammability

a. FRP composites used for any structural construction must comply with the local construction code requirements including fire resistive and other life-safety specifications. At present the coverage of structural composites in building or other construction codes is not extensive. It is, therefore, imperative for designers to work closely with the building or construction authorities early in the selection process to establish the fire-resistive requirements of the selected composites which may have to be verified by fire tests. Where fire hazard exists, the fire-hazard characteristics (including the intended use of the structure to be designed, potential ignition sources, potential mode of flame and smoke spread, and means for detection, suppression, and extinguishment) must be identified and the proper building code and other fire code requirements determined. The specific standards for plastics in a model building code have been summarized by Heger (1981). The following is a typical example:

> The approved plastic materials shall be those that have self ignition temperature of 650 ºF or greater when tested in accordance with the Uniform Building Code (U.B.C.) Standard 52-3 (ASTM D 1929) and a smoke density rating not greater then 450 (ASTM E 84). Approved plastic shall be classified in accordance with U.B.C. Standard 52-4 (ASTM E 84).

b. Fire tests for FRP composites are to be based on end use, quantity, location, and special requirements by the owner. After identifying the fire hazard, a suitable test method must either be selected from standard tests or developed for the specific need. These include ignition tests, flame spread tests, extinguishment, smoke evaluation, and tests for toxicity and fire endurance. Table 6-1 summarizes some of the standard fire tests. A review of industry literature on FRP composites shows that flammability properties are usually specified by the manufacturers. Typical values recorded by some manufacturers are given in Table 6-2.

Table 6-1
Fire Tests of Building Materials

Test Type	Test Methods	Object
Ignition tests	ASTM D 1929	Measures flash-ignition temperature
	ASTM E 136	Material is classified as combustible or not
Flame spread tests	ASTM E 84 (Tunnel test)	Measures surface flame spread, smoke generation, and total heat release
	ASTM D 635	Measures horizontal burning rate
	UL-94	Measures inflammability in vertical bar specimens
Tests for smoke evaluation	NFPA 258	Measures maximum optical smoke density
Tests for fire endurance	ASTM E 119	Determines flame penetration on unexposed face and structural collapse

Table 6-2
Typical Inflammability Properties Reported in Industry Literature

Fire and Flammability Properties	Test Method	Material[1]	Value
Flammability classification	UL 94 V-O	Extren 525 and 625 Pultrex 1525	Pass
Tunnel test	ASTM E 84	Extren 525 and 625 Pultrex 1525	25 Max 25
NBS smoke chamber	ASTM E 662	Extren 525 and 625	650-700
Flammability	ASTM D 635	Extren 525 and 625 Pultrex 1525	Self-extinguishing No ignition

[1] Names used were obtained from industry literature for the purpose of identification only. See references of these in Appendix A.

Chapter 7
Engineering Guidance

7-1. Manufacturer's Guidelines

Many commercial FRP products are designed by FRP suppliers to suit their own processing capability and their unique applications experience. There is some limited standardization of available sizes, but almost no standardization of properties. Some manufacturers publish their own test results and design guidelines. In the absence of a national design standard, such information is valuable to the design engineer. However, the designer must recognize that such guidelines may reflect results obtained from limited applications and processes. The same guidelines may not be suitable for a different application or another manufacturer's process. Since federal procurement regulations usually prohibit sole-source procurement, the designer will usually not know which supplier will produce the FRP. When the designer is relying on manufacturer's data to determine the adequacy of a composite material, the specification should require certification of material properties by the manufacturer.

7-2. Military Handbooks

Military Handbooks are available which discuss the design and analysis of composite materials as well as quality assurance and generation of property data. Many of these documents were intended for use on aircraft and aerospace vehicles and combat vehicle applications but the information presented is not limited to these applications. Some of these handbooks are discussed below.

a. Military Handbook, MIL-HDBK-17-1D. MIL-HDBK-17-1D, "Polymer Matrix Composites; Volume 1, Guidelines," focuses on characterization of fibers, matrix materials, and laminates and evaluations of prepreg, joints, and notched/damaged laminates. Chapter topics include objectives in generating property data, evaluation of reinforcement fibers, matrix characterization, prepreg materials characterization, lamina and laminate characterization, structural element characterization, and the analysis and presentation of data.

b. Military Handbook, MIL-HDBK-17-3D. MIL-HDBK-17-3D, "Polymer Matrix Composites; Volume III, Utilization of Data," discusses processes, quality control, and design and analysis. Topics are also included on behavior of structural joints, structural reliability, thick-section composites, and design for repair.

c. Military Handbook, MIL-HDBK-1002/6. MIL-HDBK-1002/6, "Aluminum Structures, Composite Structures, Structural Plastics and Fiber-Reinforced Composites," contains design information for fiberglass-reinforced plastics, thermoplastics, and glass-fiber-, steel-fiber-, and organic-fiber-reinforced concrete. Numerous references are provided as design standards and guidelines, and an appendix includes information on desirable characteristics, limitations and design cautions, and quality control.

7-3. Design Approach

Design with composite materials is different from design with traditional isotropic materials. It is important to take advantage of the anisotropic behavior that is intrinsic with fiber-reinforced composite materials. Several different theories can be used when designing with composite materials. Some of them are the maximum stress theory, the maximum strain theory, and the Tsai-Wu quadratic interaction theory. Fracture mechanics approaches are also commonly used in the design process. These approaches are described in composite materials textbooks, such as those by Gibson (1994) and Ashbee (1993). However, structural design engineers in the Corps are usually not familiar with actual design of FRP members. Therefore, when FRP components are used in a project, the USACE engineer will prepare a procurement specification for the component, which will then be designed by a subcontractor or the FRP supplier.

a. Performance specification. The typical USACE approach to design with composite materials is to utilize performance specifications, rather than designing from component material properties. In this situation, the supplier would need to furnish a structural component that would perform in a particular manner, but the details of how this was to be achieved would be left to the supplier. An example of this is the design of the composite wicket gate by the Louisville District. An example of a performance specification is given in Appendix C.

b. Material selection.

(1) Evaluate application. Material selection is more complicated than it is with traditional materials. The processing of the material greatly influences the properties of the fabricated component, which will then change its potential applications. Any time the application is changed, both the base materials and their processing need to be re-evaluated. Since the processing (and fabrication) of composite structure affects its properties, the designer

must include the processing and fabrication effects on properties during the design phase.

(2) Economical considerations. Composite materials that produce the least expensive structure commensurate with good design should be used. The designer is trying to produce the lowest cost structure. Usually this means that the lowest cost fiber, glass, will be used. A glass-fiber-based composite is likely to be the cheapest on a per pound basis. However, the designer should note that a carbon-based composite will be stiffer than glass-based ones with the same area. Therefore, if the application is controlled by stiffness, carbon composites may be more cost-effective in some cases. In another situation, if the structure needs to have a significant amount of ductility, an aramid-type composite may be the only one that really meets this requirement.

c. Standard components. One way to save costs in both design and fabrication is to use simple components that are repeated wherever necessary. For example, the designer might design the skin plate of a gate to be made of a set of standard sized composite plates. In this manner the small panels could be easily fabricated and shipped. They could then be attached at the project site. Using standard components would also make it easier to replace broken or damaged parts at the site. Some specific shapes can allow for prebuilt components, such as a honeycomb panel, to be used.

7-4. Connections

Components of a composite structure are usually joined by either mechanical or adhesive joints. No national joint design standards for FRP's now exist. Therefore, each prospective type of joint should be tested before use to ensure that it will carry the required loads. Various types of mechanical joints have been created and are discussed below. The adhesive joint bonds the two parts chemically by some type of adhesive. This joint will be as strong as the matrix material (since many matrix materials are themselves some type of epoxy) but not as strong as the structure itself. Combinations of mechanical and adhesive joints can be used in some applications.

When planning the layout of the structure's components, compressive joints are preferable. Elimination of tension connections through larger parts may be used to assist in achieving compressive joints. Since failure often occurs at a joint, a structure with fewer joints is likely to be stronger. For example, consider the manufacture of a triangular-shaped box beam, a structural element that could be used in many applications. One method of construction would be to make three flat panels, and then join them by some type of bonding method. An alternate would be to create a triangular-shaped mold, and then create the structure as inherently one composite piece. The unidirectional layers can then be wrapped around the entire structure, thereby providing fiber reinforcement at what otherwise would have been the joints between different plates. These joints then will be virtually as strong as the composite structure itself.

a. Mechanical joints.

(1) Mechanical joints usually have some type of bolt holding together the different pieces of the structure. Examples of three different types of bolted joints are shown in Figures 7-1 through 7-3. Figure 7-1 shows a single lap joint. This is the simplest type but has the disadvantage that it tends to twist when an in-plane load is applied to either of the two plates. The double lapped bolted joint (shown in Figure 7-2) will not twist, but it is more complicated. Figure 7-3 shows a strapped bolted joint. The strength of this joint depends upon the strength of the strapping, the strength of the bolt, and the strength of the composite.

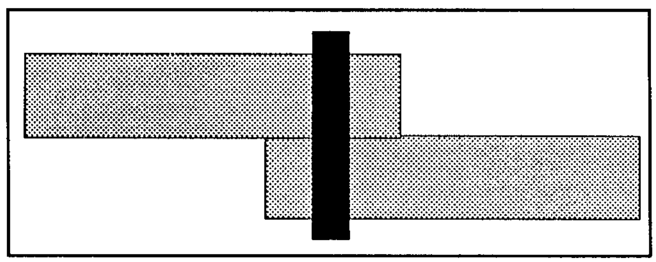

Figure 7-1. Single lap bolted joint

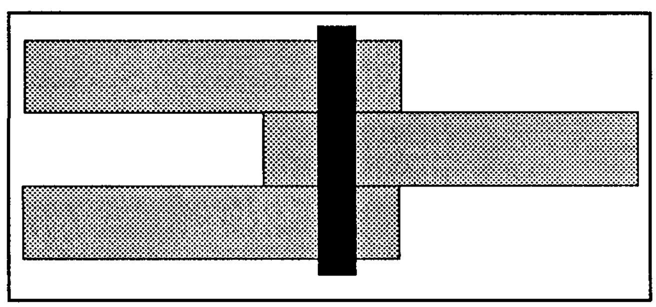

Figure 7-2. Double lap bolted joint

(2) In each of these bolted joints, the holes made in the composite plates should be coated if the joint is to be exposed to water. This coating will help to avoid water absorption through the joint region. Typically the bolts

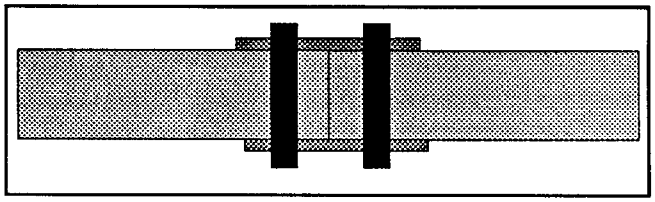

Figure 7-3. Strapped bolted joint

themselves will be made from a traditional metallic material, such as stainless steel or monel.

(3) Mechanical joints have two advantages over adhesive joints. They are frequently not as susceptible to environmental damage and they are easy to disassemble and reassemble, making it easier to perform quality control inspections and to replace damaged plates without having to replace the entire structure.

(4) There are three major disadvantages of mechanical joints. The first is that the joint is frequently less stiff than the base plates it is connecting. Another major disadvantage is that the creation of the bolt holes can produce small cracks in the vicinity of the hole. These cracks can act to create large concentrated stresses near the hole, which could result in premature failure of the system. Another disadvantage of using bolted joints is that the ply orientation lay-up near the bolt hole may need to be modified so as to avoid the problem of fiber pull. Whenever installation procedures require cutting through the reinforcement fibers of the composite, additional considerations must be given. A hole cut through the composite system, for example as part of a joint connection, will cut the reinforcing fibers and produce a weak joint at that location. The exact effect of the hole depends on the fiber orientation at the location of the hole as well as the location of the hole relative to the edge of the component.

(5) One way to strengthen mechanical joints is to add more material to them, so that a larger force is needed to break the system. An example is shown in Figure 7-3 for a strap bolted joint. The strapping material's strength is what holds the joint together. It can frequently be of some material other than a composite. Additional ways to strengthen mechanical joints are to make the regions in the vicinity of the bolt thicker than the base plates, thereby reducing the stress in the joint and allowing it to carry a higher load.

b. Adhesives.

(1) An adhesive joint is one in which some type of adhesive material is placed between the two plates that are to be attached together. Most adhesives are able to withstand shear loading more than tensile loading. This means that if adhesives are used, they should not be designed for use in tension. Examples of adhesively bonded joints are shown in Figures 7-4 through 7-6. These joints are the same basic three shapes that were discussed under mechanical joints, except that bolts have been replaced by the adhesive material. As was discussed before, double lap bonded joints are preferable to single lap bonded joints because the tendency to twist has been reduced.

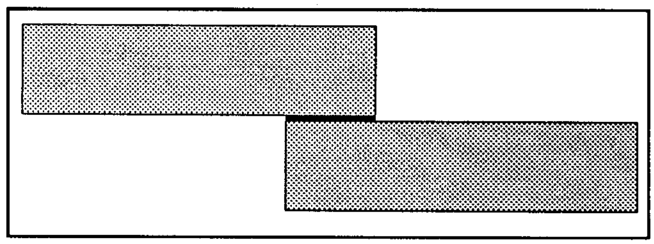

Figure 7-4. Single lap bonded joint

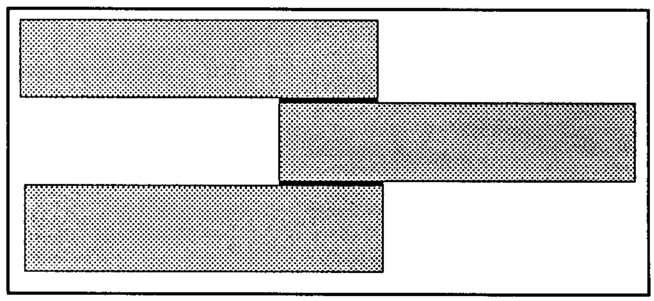

Figure 7-5. Double lap bonded joint

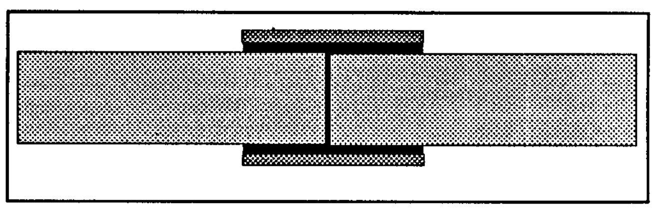

Figure 7-6. Strapped bonded joint

(2) Figure 7-6 shows a strap bonded joint. In this type of joint the adhesive holds the materials together at their ends, and also holds the plates to the strapping material. Most of the load is carried by the strapping material and the adhesive that bonds the strapping to the plates. The strength of this joint is some function of the strength of the adhesive and the strapping material.

(3) One common design issue that might be faced by engineers using composite materials to design gates would be the attachment of the skin plate to the supporting beams behind it. One method of doing so is shown in Figure 7-7. This might be considered a type of strap joint, except that the strapping material is itself an integral part of the structure. A box girder is shown in this figure since it would be more practical for composite structures.

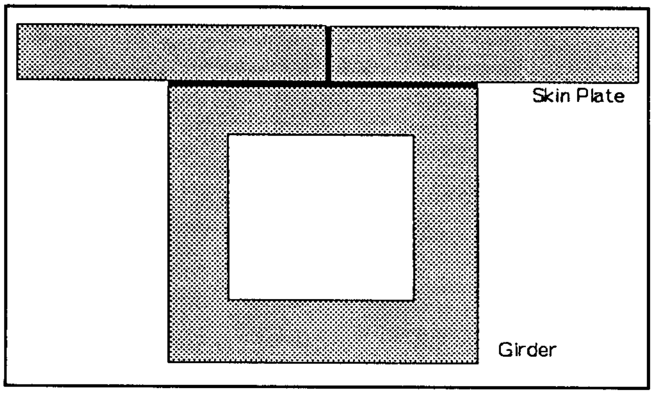

Figure 7-7. Example of an adhesive joint that is a partially lapped joint and a partially strapped joint

(4) Adhesive-bonded joints are typically stiffer than mechanical joints, because in lapped or strapped bonded joints there can be a very large surface area on which to bond. However, anything that can damage the composite resin will also damage the adhesive in the same manner. It is not possible to state that mechanical joints or adhesive joints are always superior. Which one is superior depends upon the specific application.

(5) Another approach is to use adhesive joints in a manner analogous to the welding of metals. In thermoplastic-based composites the plates can be welded together by applying a localized heat at the interface. As the resin partially melts, and then resolidifies, a very strong joint can be created. For thermoset-based composites (such as ones based on epoxies), such welding techniques cannot be used.

c. Using anchors for prestressing.

(1) FRP materials have been studied for use as prestressing tendons in prestressed concrete. To date, demonstration projects using concrete beams pretensioned and posttensioned with FRP tendons have been conducted in the United States, Europe, and Asia. Carbon-, aramid-, and glass-fiber-reinforced plastic tendons have been used in these demonstrations. These materials are well suited to the process of prestressing because of their lower modulus of elasticity. Even though the tendons experience greater strains in reaching the applied level of prestress, the lower modulus works to the advantage of the beam through lower prestress loss after locking off the stress.

(2) Despite the suitability of FRP to prestressing applications, care must be taken with anchorage devices. Due to their anisotropic nature, FRP tendons have great longitudinal tensile carrying capacity, but very low shear capacity. Consequently, loading FRP composites perpendicular to the longitudinal axis can cause failure at very low loads. This is precisely the loading condition that occurs when tendons are gripped with conventional anchors or grips that pinch the tendon to apply the prestressing loads.

(3) Wedge-type grips that rely on pinching the FRP generally are unsuitable as anchors or loading grips. These devices apply lateral load along the length of the tendon or the grip with the greatest shear loading at the mouth of the grip. The high lateral loadings in these areas can fail the tendons in shear long before the longitudinal, tensile-carrying potential of the material is realized.

(4) In the case of pretensioning where the grips are only used to apply the pretensioning load, the greatest danger caused by failure is personal injury that might occur during the prestressing operation. If sufficient care is taken in choosing the anchor, the lateral stresses on the tendon will be minimized and the tendon will not fail. As soon as the concrete has hardened around the tendon, these anchor stresses can be removed. However, in the posttensioning technique, where the anchor and its accompanying loads become part of the permanent loading configuration, the danger is always present that the shear loads could fail the tendon at some future time when the tendon is in service.

(5) For these reasons, special anchorage devices have been developed which minimize the lateral loads that

grips put on the FRP tendons. There are a number of suitable designs which have been employed. They fall into two categories, potted and wedge designs. The potted designs consist of placing the FRP tendon inside a steel collar, and filling the collar with a polymer resin to anchor the tendon inside the collar. In most of these designs, the inside surface of the collar is tapered as in a conventional wedge anchor such that the tension on the tendon will try to seat the polymer wedge into the collar. There have been several attempts to find the shape which minimizes the stress on the tendon. These range from a pipe collar with a constant inside diameter to a collar with a parabolic-shaped inside surface. Other designs are the wedge type. These differ from the conventional steel wedge designs either through the use of polymer wedges or some sort of protective sleeve around the tendon which will help distribute the stresses such that concentrations are minimized.

(6) The results of tests on ten different FRP anchor systems conducted for the Corps (Nanni et al. 1994) indicated that:

- Potted resin anchors performed better than wedge-type anchors for sustaining prestress load.

- Wedge anchors generally caused some sort of damage to the tendon.

- Some sort of grit applied to the tendons is necessary to ensure proper anchorage with wedge anchors.

- All types of anchors had problems resisting failures in tests of the tendons to failure.

Chapter 8
Quality Assurance

8-1. Test Methods

a. ASTM standards.

(1) Compounding the design issue is the fact that not all of the mechanical tests required for determining structural capacities for composite materials have been standardized. ASTM provides test methods for steel which provide all of the necessary capacities for different grades of steel as well as test methods for determining concrete mechanical properties. Currently methods are being developed for the testing of composite materials, but all the methods being developed have not yet been standardized nor have all the tests needed been developed. The lack of proper tests makes designing with composites difficult since there is not a standard to use as a reference.

(2) ASTM standards have been developed for a number of tests that are used to evaluate mechanical properties of composite components. Among the more important ones are the ones listed below:

ASTM D 638	Standard Test Method for Tensile Properties of Plastics
ASTM D 790	Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulation Materials
ASTM D 1242	Standard Test Methods for Resistance of Plastic Materials to Abrasion
ASTM D 2344	Standard Test Methods for Interlaminar Shear Test
ASTM D 3039	Standard Test Method for Tensile Properties of Fiber-Resin Composites
ASTM D 3171	Standard Test Method for Fiber Content of Resin-Matrix Composites by Matrix Digestion
ASTM D 3410	Standard Test Method for Compressive Properties of Unidirectional Crossply Fiber-Resin Composites
ASTM D 3479	Standard Test Methods for Tension-Tension Fatigue of Oriented Fiber, Resin Matrix Composites
ASTM D 3518	Standard Practice for In-Plane Stress-Strain Response of Unidirectional Polymer Matrix Composites
ASTM D 4255	Standard Guide for Testing Inplane Shear Properties of Composites Laminates
ASTM D 5229	Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning for Polymer Matrix Composite Materials

(3) ASTM D 638 has been used extensively by the plastics industry, but may not be the best choice for some composite materials. ASTM D 3039 was originally developed for thin sectioned composite structures, such as those common in the aerospace industry.

(4) Standards that still need to be developed are for various types of fracture toughness testing, such as delamination fracture testing, free-edge fracture testing, and end notch flexure test fracture testing. There are also two fracture test methods that were developed for use with metallic materials that are commonly being used for composite materials. They are:

ASTM E 399	Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials
ASTM E 813	Standard Test Method for J_{IC}, A Measure of Fracture Toughness

b. SACMA standards. Another set of test methods is available in the Suppliers of Advanced Composite Materials Association's (SACMA) SRM Manual. The SACMA Standards may be used in combination with other standardized tests.

c. Military specifications. Numerous military specifications exist with respect to testing of composite materials. Since FRP composite materials have been utilized for some time in the military, an extensive list of the specifications used in these applications is available and can be accessed as needed.

d. State-of-the-art report from ACI. Acceptance of FRP materials within the civil engineering community will depend on the recommendations of code- and standard-writing authorities such as the ASTM and the American Concrete Institute (ACI). These organizations currently have committees devoted to bringing these materials into the engineering community. The ACI Committee 440, on FRP Reinforcement, is currently writing a state-of-the-art report on FRP materials. This report includes chapters on history of FRP's, composite materials and processes, mechanical properties and test methods, behavior of nonprestressed structural elements, external reinforcement, field applications, and research needs. This text will have many good references and will contain many appropriate answers for people interested in knowing more about FRP materials for civil engineering applications. This publication will be available from ACI before the end of 1995.

8-2. Inspection and Performance Monitoring Methods

a. Background.

(1) The acceptance of FRP composites in civil engineering applications has been slow in growth, in part because of limited performance history of composite materials in civil-engineering-type applications. Performance monitoring of composite structural elements is important for several reasons: (a) to identify any problems with the FRP composite component before catastrophic failure occurs, (b) to designate where repairs are needed to avoid premature failure and/or extend useful life, and (c) to help establish a database of performance history in actual use situations.

(2) Defects (e.g., voids) and damage (e.g., delaminations) to FRP composite materials are not always easy to detect as these conditions are not always evident on the surface. A number of inspection techniques are available for use with composite materials. Most of these methods have been used extensively in the aerospace industry. Currently there are no consensus standard practices established within the construction industry for the inspection and quality assessment of FRP composite materials. Little information is available regarding the type and extent of the defect or damage relative to any change in properties of the composite component. The following information may be used, however, to help determine the suitability of using one or more of the inspection and performance monitoring techniques described below.

b. Visual inspection.

(1) Visual inspection is a very valuable technique for monitoring performance and should not be overlooked. Many defects can be detected visually. Defects readily detected visually include: discoloration, cracking, blistering, pitting, cuts and dents, and other surface damage problems. Under certain conditions, porosity, voids, and delamination may also be detectable by visual inspection.

(2) Visual inspection is most effective in detecting defects that are at or near the surface. Internal defects are not as easily detected by visual inspections unless the system is translucent or the defect is extensive enough to show as a surface flaw. ASTM D 2563, "Classifying Visual Defects in Glass Reinforced Laminates and Parts Made From These," will provide some help in visual inspections. No matter what, if any, other methods are used, performance monitoring of the composite structure by visual inspections should be performed on a routine, periodic basis.

c. Instrumental nondestructive evaluation (NDE) methods. A variety of common NDE methods used for or originally developed for other materials have been adapted for use with FRP composites. Some of the most widely used methods include sonic testing, ultrasonic testing, radiography (X-ray), and infrared detection. Each method has its strong points as well as limitations. Table 8-1 shows the type of defects that can be detected using the different NDE methods.

(1) Sonic methods. Although electronically controlled and instrumented sonic methods now exist, they were basically derived from the simple method of tapping the item with a small tool and listening to the sound. By simply tapping the surface of the composite with a small tool or even a coin, delaminations and large voids may be detectable. A composite component free of voids and delaminations will produce a clear, sharp ringing sound. A hollow or dull sound indicates the presence of delaminations and/or voids. The effectiveness of such a technique, of course, depends a great deal on the experience of the inspector. In a more sophisticated sonic test method, the tapping apparatus is electronically controlled and the produced sound is picked up by a microphone. The wavelengths used in the sonic methods limit the detection of defects to relatively large sized defects.

Table 8-1
Types of Composite Defects Detected by Various NDE Methods[1]

Type of Defect or Variation	Sonic	Ultrasonic	X-ray	Infrared Detection
Debonding	X	X	X	X
Delamination	X	X	X	X
Undercure	X	X		
Fiber misalignment			X	
Damaged filaments			X	
Variation: in thickness,	X	X	X	
in density		X	X	
Voids	X	X	X	X
Porosity	X	X	X	
Fracture	X	X	X	
Contamination			X	

[1] From *Materials Engineer*, March 1978, page 69.

(2) Ultrasonics. The detection size limitations of sonic methods can be overcome by using ultrasonic frequencies in the range of 100 kHz to 25 mHz. Three basic ultrasonic techniques applicable to composite materials include: pulse echo, through-transmission, and resonant frequency. Although each of these methods differs in how the test is set up and conducted, they all involve the conversion of electrical energy to sound energy and back again for detection. Through-transmission techniques require access to both sides of the item being analyzed. Besides detecting blisters, voids, and delaminations, through-transmission ultrasonic techniques may be used to indicate changes in strength, modulus, and density along the cross section. Resonant ultrasonic techniques may be used to assess the quality of adhesive bonds used in the composite system. For the most accurate assessment of the data output from any of these ultrasonic techniques, specimens of the same type of material with known properties or defects must be used as standards. Baseline readings of the composite structure should be made on areas where the material is known to be sound. For most accurate results, follow the manufacturer's operational instructions for each type of equipment.

(3) Radiography (X-ray). X-ray analysis techniques used for metals and ceramic materials are applicable to FRP composite materials as well. Although almost any defect normally found in FRP composites may be detected by X-ray techniques, the method does have some limitations. Cracks, voids, and delaminations that lie perpendicular to the ray path may go undetected unless such defects are so large that they would probably be readily detectable by visual means anyway. Cost, difficulties in performing the analyses in the field, and worker safety limit the use of this technique.

(4) Infrared detection. As a composite material cools from being heated (e.g., by using a heat source such as heat lamps or from being in the sun all day), internal defects such as delaminations or voids will slow the dissipation of heat causing a temperature gradient at the surface above the defect. This resulting temperature gradient can be measured using an infrared detector called a radiometer or an infrared camera. Typical radiometers are sensitive to temperature differences as small as 0.1 °C (0.18 °F). Infrared cameras are capable of detecting temperature differences in the order of 1 °C (1.8 °F). The method has the advantage over ultrasonic techniques in that there is no need for direct contact (including coupling agents, etc.) with the item being measured. A limitation, however, is that the infrared detection method is useful mainly for detecting delaminations and relatively large voids and then only if these defects are near the surface.

d. Remote sensing and smart systems. The NDE methods described above for monitoring performance require ready, direct access to the composite component or structure being evaluated. This is not always convenient or possible for submerged components or structures in remote locations. It may also be desirable for some critical structural components to have continuous monitoring of the system to warn of possible property changes that could catastrophically affect system structural performance. Such remote performance monitoring may be accomplished by incorporating external and/or internal sensors as part of the FRP composite structure. Strain gages, fiber optics, and piezo-polymer materials may be used as remote sensors. Strain gage sensors have been routinely used to monitor and proof-test FRP composites. However, the use of fiber optics and piezo-polymers for performance monitoring of FRP composites is not yet common practice. Such systems are still undergoing considerable development and refinement in the research community. The term "smart" composite is sometimes used to describe a composite system with a built-in sensor. [By strictest definitions, a "smart material" is a material that "can sense changes in its environment and make useful or optimal response by either changing its material properties, geometry, mechanical or electromagnetic response" (Varadan, Chin, and Varadan 1992).] Research is also ongoing to develop "smart" composites using embedded particles or "tags."

(1) Strain gages. The use of bonded strain gages to measure induced strain dates to the early thirties. Today's resistance strain gages consist of a grid of strain-sensitive metal foil that has been bonded to a plastic backing material. The gage is adhesively bonded to the item to be measured. When the item is stressed, a change in electrical resistance occurs which is proportional to the strain. Strain gages may be mounted at areas of known or anticipated high stress or other locations where critical strains may occur and need to be monitored. Gage length, width, and type of gage material must be matched to the application. Gages that will be exposed to the elements must be appropriately sealed from the environment. Gages are mounted on the surface of the component to be measured. The component, along with the strain gage, may then be embedded into another material--for example, placing strain gages on reinforcement bars which are then embedded in concrete. Strain gages provide strain-related information for the item only at the point of attachment. Therefore, the placement, number, and orientation of the gage is critical for optimum information output. Strain gage manufacturers are very willing to help determine the gage type, number, recommended locations, orientations, etc., to be used for a particular application and should be consulted as needed.

(2) Fiber optics. Considerable effort is being expended in the research communities (academia, industry, and government) to develop fiber optic systems to provide mechanical property data on structural systems, especially critical structures such as aircraft components. Fiber optics can function as sensors because the light channelled through the optical fibers is altered by the state of stress around the fiber. Such fiber optic sensors can provide information regarding: (a) changes in stress, strain, or pressure, (b) excessive vibration or deflections, (c) fracture crack growth, and (d) changes in the exposure (chemical) environment. Application of fiber optics in FRP composites is still in its infancy. Guidance on location and density of fibers needed and how to interpret the data output is not yet highly refined. Although the technique has a disadvantage regarding the cabling and connections necessary, fiber optic sensors are expected to find considerable future application in FRP composite structures.

(3) Piezo-polymers. Another "smart" technology undergoing further development within the research communities is piezo-electric materials. When a piezo-electric material is deformed a voltage is produced. Such materials can act as sensors when connected to instrumentation monitoring voltage and voltage changes. When stretched, polyvinylidene fluoride (PVDF) polymer film converts from an alpha phase to a beta phase, with the beta phase exhibiting piezo-electric properties (Andreshak and Bergman 1990). As a sensor material, PVDF has several advantageous properties. It is lightweight, flexible, can be fabricated into any shape or size, and possesses a high piezo-electric voltage output. Not only will a piezo-electric material emit a voltage when deformed, it will also conversely deform when an applied voltage is induced. The output of the PVDF sensor could be used to actuate another piezo-electric material that would deform in a controlled manner. For example, a piezo-polymer sensor detects unwanted vibrations which actuates another piezo-electric material system in a cyclic manner to dampen the unwanted vibrations. Such a system would truly be a "smart" system as previously defined. As with the fiber optics, use of these piezo-electric technologies is expected to provide definite future benefits for FRP composites used in civil engineering applications. However, the technology still needs some further development and demonstration before it will find widespread use in FRP composites.

(4) Other smart systems. Given the potential benefits of employing "smart" composite systems in civil engineering applications, a great deal of interest and effort is being focused in that direction. The Corps of Engineers is currently working cooperatively with the composites industry and academia participants on the research and development of smart FRP composite systems using embedded particle "tags." This tagging technique involves embedding micron-sized particles into the composite material. The particle material is selected so that

when the component is analyzed with suitable instrumentation, a measurable signature is produced. The signatures are then correlated with material and structural conditions.

A state-of-the-art report has recently been completed as part of this cooperative effort (Rogers, Zhou, and Chaudhry 1994).

Chapter 9
Repair of FRP Composites

9-1. General

As with any construction material, FRP composites are subject to damage. This damage may be intentional or unintentional. Intentional damage can occur when the composite components or structures are cut, drilled, or otherwise manipulated during installation or fabrication of the structure. Unintentional damage can be caused by accidental impact, unexpected excessive loading, or long-term environmental exposure. It is important to note that any damage or alteration to the fibers and/or the resin matrix may alter the performance properties (e.g., corrosion resistance and mechanical strength) of the composite component. The following information addresses the repair of composite materials needed as a result of damage or deterioration due to installation procedures, accidental damage, or environmental exposures.

9-2. Routine Maintenance

a. A properly designed and fabricated composite system will generally not require much in the way of routine maintenance. For aesthetic purposes, soil and other similar surface contaminants may be washed off using plain water [including steam cleaning at 120 °C (250 °F) maximum] or a detergent solution. Greases and oils may require cleaning with an appropriate organic solvent (i.e., one that will not attack the resin system).

b. Composites intended for direct exposure to weathering and ultraviolet radiation generally have a surface coating to improve corrosion and ultraviolet resistance. Under long-term weathering, especially if the original coating was too thin, fiber blooming (i.e., the emergence of fibers onto the surface) can occur. If left unattended, fiber bloom can lead to reduced corrosion resistance and eventual degradation of mechanical properties.

c. If fiber bloom is identified, the damaged area must be resealed with a resin-rich layer. The damaged area must be lightly sanded and cleaned to ensure proper adhesion of the sealant. Catalyzed resins or paints (e.g., polyester, epoxy, or polyurethane) may be used. A general rule is to use a sealant material type that is the same type as on the component being repaired. Acrylic lacquer or oil base paints can also be used but will probably not provide the same level of corrosion resistance as a catalyzed resin system. As required when using any chemical system, manufacturer's instructions must be closely followed to provide an optimum repair and to minimize the exposure to potentially hazardous materials.

9-3. Repair During Installation

Sawing, drilling, grinding, routing, and other such procedures may be necessary to accomplish installation or fabrication of the composite structure. Any such procedures that cut through the resin surface sealant, or otherwise expose the reinforcement fibers, can significantly reduce the corrosion resistance of the composite system. The exposed new surface must be appropriately sealed, basically as described in paragraph 9-2. To help ensure a proper repair, residual dust or other debris resulting from the installation operations must be thoroughly removed prior to the repair procedures. For installation operations that require the cutting of reinforcement fibers (e.g., drilling holes), review the guidance presented in paragraph 7-4.

9-4. Repairs Due to Accidental Damage and/or Service Exposures

Damage to the composite component can result from impact of falling or flying objects, unexpected excessive loading(s), handling of the composite during transportation, and installation or degradation (e.g., blistering) due to service exposures. The basic steps listed below should be followed regarding repair of the damaged area:

Step 1. Identify the extent of the damaged area.

Step 2. Assess the repair options:

- a. Use as is.
- b. Repair existing component.
- c. Scrap and replace component.

Step 3. Accomplish the repair operation as required.

Step 4. Evaluate the repair.

a. Visual inspection will be the most often used method in locating damage on civil structures. Such visual inspections should be performed on a routine, periodic basis so damaged areas can be repaired before further deterioration to the composite component occurs. Ultrasonic and various other NDE methods are available to detect hidden damage as described in paragraph 8-2*c*.

b. Once the damage is detected/located and the extent of the damage determined, damage repair options must be considered. If the damage is exposed but is only a surface scratch or abrasion, the repair may be as simple as coating the area with a resin-rich coating as previously described. If hidden damage is detected and it is determined that the damaged area is not a critical load-bearing component, an assessment must be made as to whether the damaged area is likely to grow, thus warranting an immediate repair. If a repair is determined to be unwarranted at the time, the damaged area should still be monitored to assess possible growth of the damage to adjacent areas.

c. Damage to critical structural components will require immediate repair action. Basic repair options include:

(1) Patching with composite plates or overlays.

(2) Removing the damaged area or component and replacing with new material.

d. Localized minor cracks and punctures may be repaired using lay-up procedures similar to automotive body repair. The damaged area must first be sanded to roughen the surface. Lightly sand the surface 50-75 mm (2-3 in.) beyond the immediate damaged area. A fiber mat shall be cut to cover within 13 mm (1/2 in.) of the edge of the sanded area. Thoroughly wet the fiber mat with a catalyzed resin system compatible with the composite component being repaired. Multiple layers may be applied as needed. After curing, sand the area to a smooth finish and seal as described in paragraph 9-2.

e. If the extent of damage warrants the application of a plate to bridge over the damage area, the repair procedure will be similar to the procedures for making composite joints as described in paragraph 7-4. The patch plate can be bolted on, bonded on, or bonded and bolted on, as required.

f. If the extent of damage is considered beyond just applying a patch, the damaged section will need to be removed. The removed section may then be replaced with a new section or component. This may be as simple as bolting on a new beam or angle, or may require the laminating in of a new composite section. To ensure equal mechanical performance, the repair section must have the same fiber architecture (orientation and arrangement) and section thickness as the removed section.

9-5. Prepreg Kits

Composite prepreg systems are available as off-the-shelf repair kits for composite laminate systems. These kits were originally developed for field repair of composite components on aircraft. Most of these prepreg kits require the use of special equipment to provide heat and vacuum at the point of repair. Unless such repairs are expected to be made on a routine basis, purchase of the equipment and stockpiling of the prepreg kits (which have a limited shelf life) are probably not economical.

9-6. Underwater Repairs

Emergency situations or other site conditions may make it impossible to dewater or remove the composite structure from submersion in order to accomplish a repair. Under such circumstances, specially formulated resin systems and special procedures must be used for an underwater repair. Except for the repair of relatively minor damage, expert advice should be sought before attempting any major underwater repair procedures. The nonideal conditions of performing underwater repairs call for a high level of quality control during the repair process. Under most circumstances, underwater repairs should be viewed as a temporary measure until such time that permanent repairs in dry conditions can be made.

9-7. Special Considerations

a. For any repair procedures (whether part of routine maintenance or due to intentional or unintentional damage) involving the application of liquid or semicured resins, the following items must be accomplished:

(1) The surface to be repaired must be thoroughly cleaned and appropriately roughened.

(2) The fiber reinforcement mat must be thoroughly wetted with resin (already wetted with resin in prepreg systems).

(3) The catalyzed resin system must be completely mixed in the exact proportions indicated on the product container. Incorrect proportions or incomplete mixing can cause improper cure. Improper curing may result in significantly reduced mechanical and corrosion-resistant properties.

(4) Temperature extremes can adversely affect resin curing. As ambient temperatures rise, the working time of the resin mix will decrease. To increase the working time on very hot days (27 °C (80 °F) plus), the liquid resin components may need to be cooled in a refrigerator before mixing. Problems can also result when the ambient temperatures are too cold. For typical catalyzed resin systems, improper cure may result if temperatures go below 10 °C (50 °F) anytime during the first 24 hours after applying. Special catalyzed systems can be used for low temperature applications. Applying heat so the item and the surrounding air temperature are maintained above the minimum for a 24-hour period is another alternative.

(5) Handle all liquid repair materials and components with extreme care to minimize exposure to possible hazardous/toxic chemicals. Also be sure to properly dispose of all unused repair component materials.

(6) In all of the procedures presented above, carefully follow any manufacturer's directions to best ensure a successful and safe repair.

b. If there are any questions concerning damage assessment or how to accomplish an appropriate repair, seek out the advice of the composite component/system manufacturer or other expert familiar with composite damage assessment and repair.

Appendix A
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Appendix B
Examples of FRP Composite Applications

B-1. Introduction

Paragraph 1-4 of the main text outlined categories of various immediate, short- and long-term applications of FRP composites. This appendix is included to present some of the Corps of Engineers' experiences with FRP's.

B-2. Gravity Drainage Structure

a. The Harrisonville and Ivy Landing Drainage and Levee District gravity drainage structure is located in southern Illinois along the Mississippi River and is inspected by engineers from the St. Louis District. During the 1985 annual inspection, deformation to the gravity drain pipes was noted and an associated settlement was occurring at the crest of the levee.

b. Two plans were considered for rehabilitation of the gravity drainage structure. One plan specified reinforced concrete pipe and the other plan called for fiberglass pipe. Both plans had approximately the same final cost, but due to the fact that the fiberglass pipe could be placed in lengths twice as long as the reinforced concrete pipes, reducing the number of joints, a decision was made to use the fiberglass pipe. Installation of the pipe is shown in Figure B-1.

c. The specification for the fiberglass pipe was based on a performance specification. The service conditions for the fiberglass pipe required that the joints be able to withstand 137.9 kPa (20 psi) of external hydrostatic pressure and not allow any infiltration or exfiltration of soil fines through the joint. Levels of compaction were specified and agreed to by the manufacturer, since the bedding material for the pipe was not a material generally recommended for use by the pipe manufacturer.

d. The installation of the pipes appeared to be progressing well until testing of the joints began. Approximately 25 percent of the joints failed the specified internal pressure test, and some of the joints contained noticeable offsets. Subsequent to discovering the deficient joints, the pipe manufacturer submitted data requiring very tight tolerances with respect to the joint installation. The pipe manufacturer also concluded that joint difficulties resulted because of nonuniform compaction of the bedding material, but the manufacturer's definition of uniform compaction exceeded standard industry tolerances.

e. Joint repairs were made to all joints due to the large number which failed the test. The repair consisted of overlaying the joints with resin-coated fiberglass strips (Figure B-2).

f. The repairs to the joints were successful and, in general, use of fiberglass pipe in the application is favorable due to its light weight. Fiberglass also has excellent flow characteristics. With respect to the problems encountered on the Harrisonville and Ivy Drainage District project though, a careful examination should be made of what type of bedding material is to be used prior to the selection of fiberglass pipe. The tolerances in compaction for a given material may be the governing factor as to whether the fiberglass pipe can be used in that application.

g. It should also be noted that, on this project, standard FRP composite handrail, grating, and ladders were used (Figure B-3). FRP materials were selected to reduce maintenance costs to the levee district. Further details of this project are reported in a paper from the 1991 Corps of Engineers Structural Engineering Conference, "Quadruple 84-inch Corrugated Metal Pipe Repair," (Atchley 1992).

B-3. Wicket Gate

a. Hydraulically operated wicket gates were being designed for use on the dam portion of the Olmsted Locks and Dam project on the Ohio River. Because utilizing hydraulics to raise and lower the wicket gates of this size has not been used before and since hydraulically operated wicket gates have never been used in the United States, a decision was made to build a set of prototype wicket gates near Smithland Locks and Dam (also on the Ohio River) to ensure proper operation and to determine required maintenance procedures. A decision was made to include a gate constructed of FRP materials to determine the performance of these materials in a river environment.

b. Seven prototype wicket gates were constructed and, of these seven, one was constructed using FRP materials (composite wicket gate). The other gates were constructed using steel and were designed by the Louisville District. The specification for the composite wicket gate was a performance specification which limited the

Figure B-1. Installation of FRP pipe

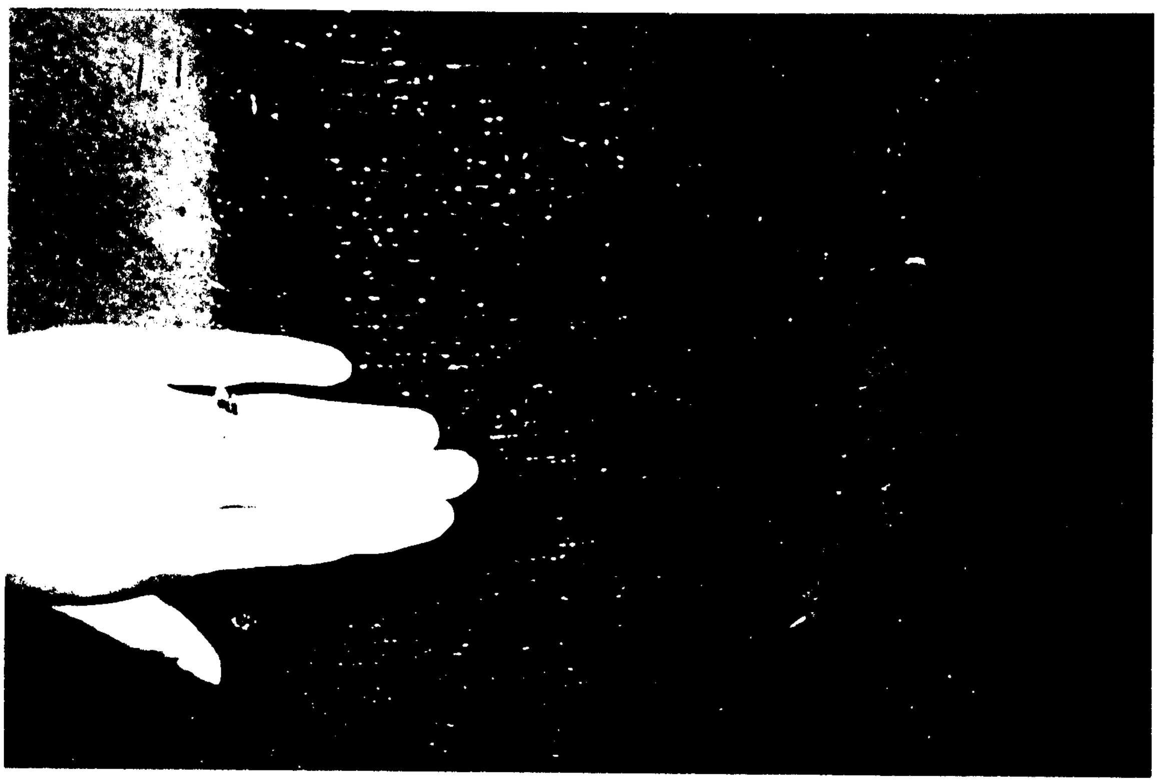

Figure B-2. Joint repair

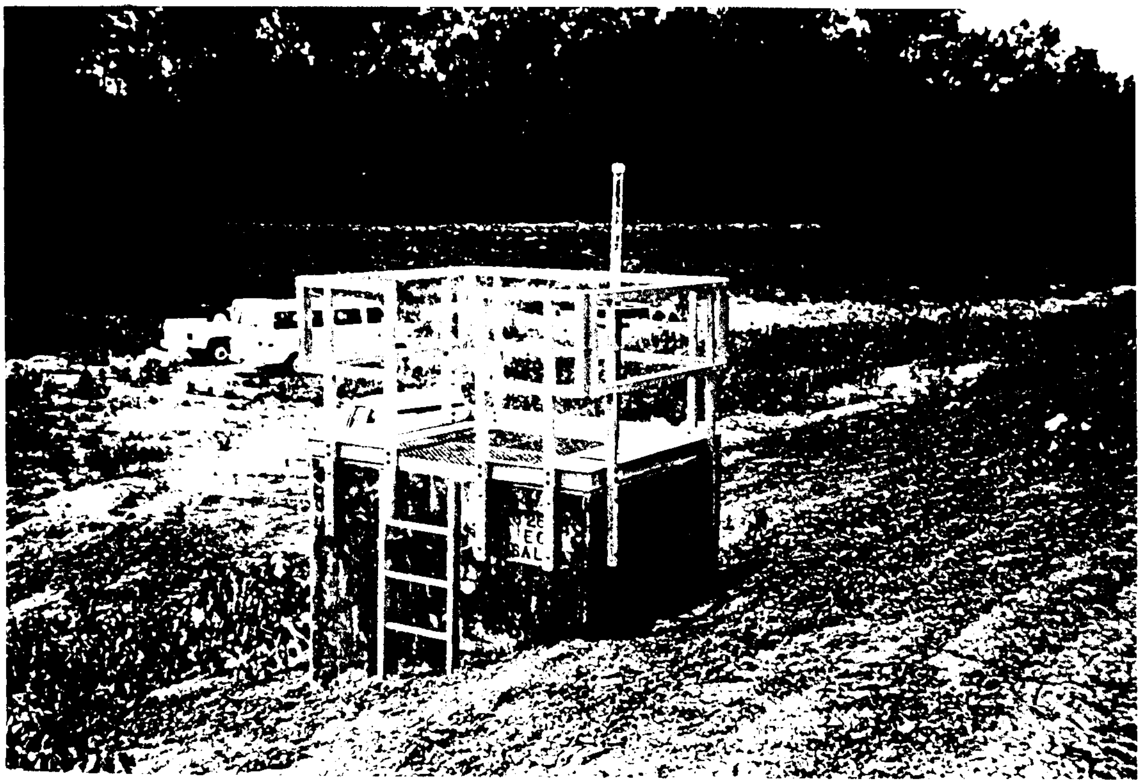

Figure B-3. Handrail, grating, and ladder fabricated from FRP materials

deflections the gate was allowed and limited stress in the gate to a percentage of the ultimate tensile strength of the FRP material.

c. The design was performed under a subcontract by McDonnell-Douglas Corporation. The resulting design was a combination of FRP materials and steel. For many applications the fact that FRP's are lightweight is advantageous and is a critical aspect in using these types of materials. The weight of the wicket gates was a design parameter because the gate had to be heavy enough so that it would not become buoyant under flow conditions. Based on this parameter a decision was made to use a combination of steel and FRP components. An exploded view of the composite wicket gate is shown in Figure B-4.

d. As can be seen in Figure B-4 the main framing member of the gate is made of steel. Steel was used for this member for two reasons. First, the steel would provide the stiffness required for the gate to meet the deflection required in the specification and second it would provide a suitable means for connecting the hydraulic arm to the gate. The remaining components are made of a glass/vinylester composite material. These components include the skin plates, the stiffeners for the skin plates, and the end sections of the gate.

B-4. Development and Demonstration of FRP Composite Materials Under the CPAR Program

Concurrently with the development of this ETL, several projects concerning FRP composite materials for civil engineering applications were being conducted under the Corps of Engineers Construction Productivity Advancement Research (CPAR) Program. The composites technologies being developed as part of these CPAR projects may be applicable to future Corps construction or maintenance activities. In order to provide an awareness of these projects and the technologies being developed and demonstrated, brief descriptions of the various ongoing projects are provided below. For additional information (including the participating Laboratory Point of Contact) about these or other additional CPAR projects regarding composite materials, contact HQUSACE element CERD-C.

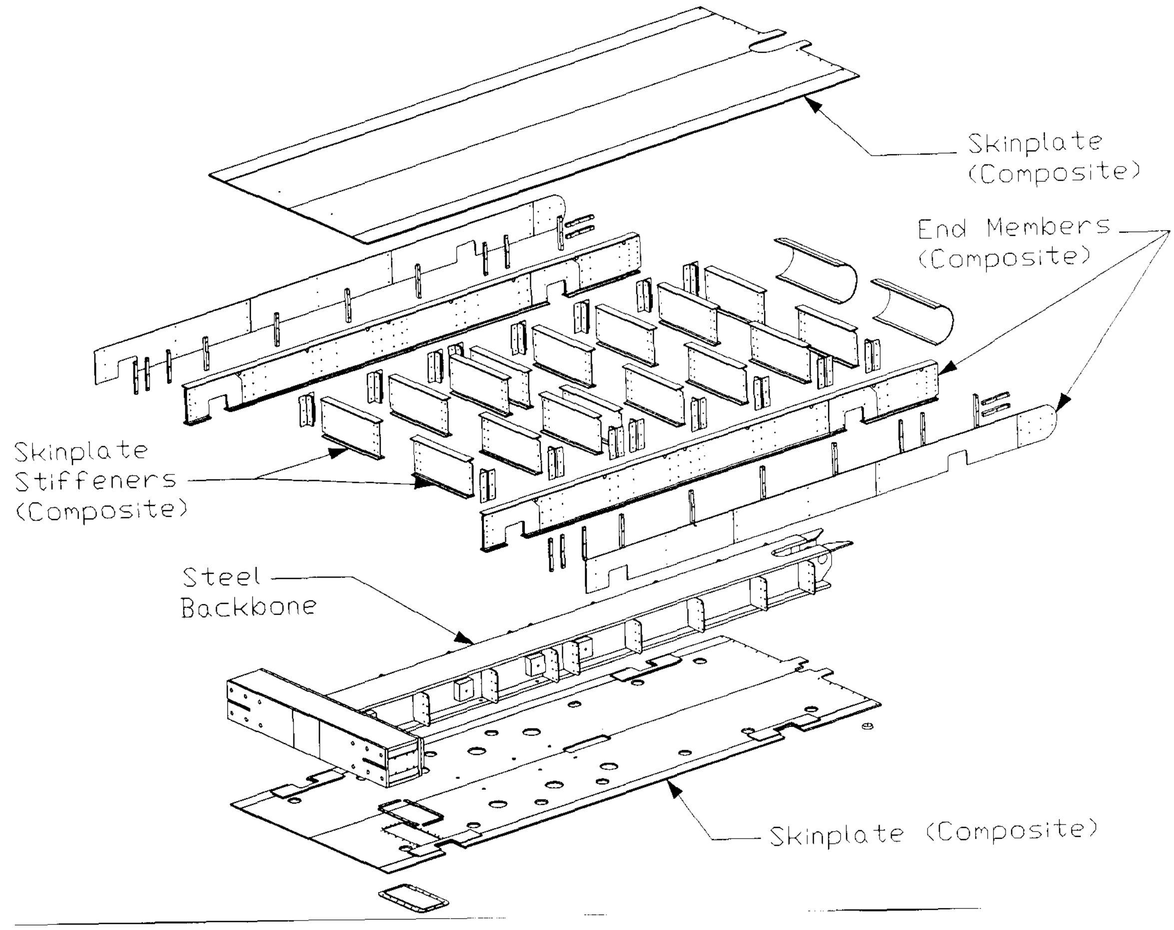

Figure B-4. Exploded view of composite wicket gate

a. Demonstration of advanced composite cables for use as prestressing in concrete waterfront structures.

(1) The objective of this project is to demonstrate the satisfactory performance and overall economy of advanced composites used as prestressing cables in concrete construction for civil-works-type structures in corrosive environments (e.g., splash zone areas, marine/saltwater exposures, water immersion, etc.). The product of the research will be advanced composite cables for use as prestressing elements in concrete structures for corrosive environments. Material specifications and design and construction guidance for the use of these advanced composite cables as prestressing structures in corrosive environments will also be developed.

(2) The Laboratory partner for this project is the U.S. Army Construction Engineering Research Laboratories (USACERL). The Industry/Academia partner is the South Dakota School of Mines and Technology. Industry/Academia partner participants include Amoco Performance Products, Owens-Corning, Neptco Inc., and the Composites Institute.

(3) To demonstrate the composite prestressing cables, a 12.2-m (40-ft) long by 5.5-m (18-ft) wide demonstration pier was selected for construction at the Navy Facilities Engineering Service Center (NFESC) in Port Hueneme, CA. Figure B-5 shows the basic layout and dimensions of the pier construction. The pier deck was designed to withstand a 1.0×10^6 newtons (225 kips) load over a 0.76-m (30-in.) square area (based on Navy requirements where their heavy cranes are in operation). Carbon-fiber reinforcing rods and cables were fabricated for the prestressing applications. Prestressed concrete

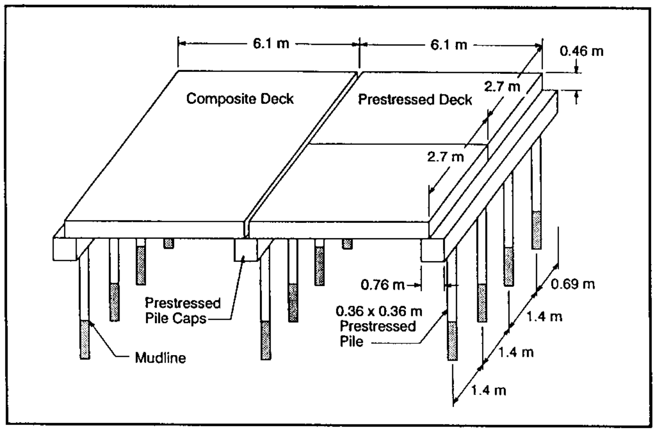

Figure B-5. Diagram of demonstration pier construction

piles [0.36 × 0.36 m (14 × 14 in.) square and 18.3 m (60 ft) long] and pier deck sections [each section was 6.1 m (20 ft) long by 2.7 m (9 ft) wide by 0.46 m (18 in.) thick] were fabricated using a pretensioned mode. One pile and deck section was tested in the laboratory to ensure that these elements met the design criteria. Glass-fiber-reinforced cables were fabricated and tested relative to design load criteria (the glass-fiber-reinforced composite cables were used in the pile caps in a posttensioned mode). The piles and deck sections were shipped to NFESC. After driving the piles, the pile caps were fabricated onsite and posttensioned. The prestressed deck sections were then placed onto the piles to span one of the bays. As an extra to the project, an all-composite deck section was fabricated using off-the-shelf pultruded composite structural elements and placed on the pile to span the second bay. The construction phase is now completed. Load testing and performance monitoring of the pier structure is under way. The project completion date is December 1995.

b. Demonstration of a full-scale concrete bridge deck reinforced with FRP composite reinforcing bars.

(1) The objective of this project is to demonstrate the advantages of the use of specially designed FRP composite reinforcing bars to improve the construction productivity and long-term durability (corrosion resistance) of reinforced concrete bridge decks. (Successful use of FRP composite reinforcing bars in a full-scale bridge deck will help demonstrate the potential for the use of FRP reinforcing bars in other concrete structures as well.) The product of the research will be FRP composite reinforcing bars for the reinforcement of concrete structures. Material specifications, design, and construction standards will be developed for the use of FRP composite reinforcing bars.

(2) The Laboratory partner for this project is USACERL. The Industry/Academia partner is West Virginia University--Center for Constructed Facilities. Industry/Academia partner participants include West Virginia Department of Highways and International Grating.

(3) During the course of the project, the following activities have been completed. Fatigue testing of concrete deck sections reinforced with composite reinforcing bars was completed in the laboratory. In cooperation with the West Virginia Department of Highways, a bridge was selected for the demonstration construction of a replacement deck using composite reinforcing bars. The bridge is on County Route 27/3 over Buffalo Creek near McKinleyville, WV. Preliminary designs for the bridge deck have been initiated. Final designs should be completed by early 1995 with construction completed by the fall of 1995. The project completion date is scheduled for May 1996.

c. Development and demonstration of hybrid, advanced design composite structural elements.

(1) The objective of this project is to develop, test, and demonstrate optimized, advanced design composite structural components (beams, trusses, profile shapes, panels, etc.) for civil engineering applications. The product of the research will be optimized composite structural components (beams, trusses, profile shapes, panels, etc.) for civil engineering applications.

(2) The Laboratory partner for this project is USACERL. Laboratory participants on this project include the U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL) and the NFESC. The Industry/Academia partner is West Virginia University--Center for Constructed Facilities. The Industry/Academia participant for this project is the Composites Institute.

(3) This project is in its initial stages of execution. Three demonstration projects have been targeted: a salt storage shed, a pier deck section, and an observation tower. Theoretical optimization of structural composite shapes was initiated. A total of 8 beams, 8 columns, and 2 deck shapes will be optimized and tested. One half of these shapes will be based on existing die shapes with optimized fiber architecture. The other half will be optimized for both shape and fiber architecture

(i.e., orientation and arrangement). The project completion date is scheduled for March 1997.

d. Development and demonstration of polymer composite piling and sheet pile systems.

(1) The objective of this project is to develop, test, and demonstrate high-performance, polymer composite structural pilings, fender pilings, and sheet pile (bulkheads) for marine/waterfront civil engineering structures. The product of the research will be high-performance, composite structural, fender and sheet pile systems for marine/waterfront civil engineering applications. Material standards, specifications, and design protocol for each type of piling system will also be developed.

(2) The Laboratory partner for this project is USACERL. Laboratory participants include USACRREL, the U.S. Army Engineer Waterways Experiment Station (USAWES), and NFESC. The Industry/Academia partner is Rutgers University. Industry/Academia participants include the Composites Institute and the New York/New Jersey Port Authority.

(3) This project is in its early stages of execution. Mechanical, physical, and cost performance goals for each type of piling system have been formulated. Composite piling systems are being fabricated to meet these target goals. The fabricated systems will be tested in the laboratory to ensure performance with the most promising systems demonstrated in full-scale field constructions. The project completion date is currently scheduled for March 1997.

e. Development and demonstration of advanced composite materials systems to enhance/protect or repair/ upgrade reinforced concrete civil engineering structures.

(1) The objective of this project is to develop, test, demonstrate, and commercialize advanced composite materials systems for in-place strengthening, repair, or upgrade of existing concrete civil engineering structures including columns, beams, and decking. Systems developed in this CPAR project will enhance structural protection against seismic damage as well as rehabilitate or upgrade deteriorated civil engineering structures. The end product of this research effort will be fiber-reinforced (glass and/ or carbon fibers) polymer composite material systems for the repair and/or upgrading of concrete columns, beams, and decking used in civil engineering structures (e.g., bridges and parking decks). Materials standards, specifications, and design protocols will be developed for each type of strengthening system.

(2) The Laboratory partner for this project is USACERL. Laboratory participants include USACRREL, USAWES, and NFESC. The Industry partner is the Composites Institute. Industry participants include the American Concrete Institute, the American Society of Civil Engineers, the California Department of Transportation (CALTRANS), and the Federal Highway Administration.

(3) This project is currently in its initial stages. A project "kick-off" meeting was held in February 1995. The project completion date is scheduled for December 1997.

Appendix C
Example Performance Specification for FRP Components

(The following example of a performance specification is loosely based on an actual specification used for procurement of a composite wicket gate for a prototype test for Olmsted Dam. This example is provided to illustrate the types of information which should be included in the specification.)

COMPOSITE WICKET GATE

PART 1 GENERAL

1.1 REFERENCES

MILITARY HANDBOOK

MIL-HDBK-17-1D Polymer Matrix Composites; Volume 1. Guidelines.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) PUBLICATION

D 2344-84	Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method
D 3039-76	Test Method for Tensile Properties of Fiber-Resin Composites
D 3410-75	Standard Test Method for Compressive Properties of Unidirectional Crossply Fiber Resin Composites
D 3518-76	Inplane Shear Stress-Strain Response of Unidirectional Reinforced Plastics

SUPPLIERS OF ADVANCED COMPOSITE MATERIALS ASSOCIATION (SACMA) PUBLICATION

SRM 3	Open Hole Compression

1.2 SYSTEM DESCRIPTION

1.2.1 General Requirements

The wicket gate shall be constructed primarily from fiber reinforced polymeric (FRP) materials. Gate components which may be constructed using steel materials are defined in paragraph 1.2.2. The wicket gate serves as a movable water control device. The main system requirements are to provide long-term performance in the river environment, with minimum maintenance. Strength and stiffness requirements for the gate are defined paragraph 1.2.4. Metal components of the gate should be limited to minimize potential corrosion. Resin and fiber materials should be selected to provide necessary properties after exposure to fresh water, temperature changes, and sunlight over a period of 20 years. Limited gate weight is not a requirement.

1.2.2 Materials

Main gate components shall be constructed using FRP materials except as follows. The following items shall not be fabricated from FRP materials: hinges; prop; attachment devices for hinges, prop, and actuator; fasteners. Fasteners may be of other materials such as metal. Metal materials shall conform to the requirements of SECTION____________.

1.2.3 Geometry

The exterior dimensions of the wicket shall conform to the dimensions shown on the drawings. This includes all locations and dimensions of attachment devices for gate operating equipment and for gate mounting to the dam sill.

1.2.4 Design

The design calculations, as required in paragraph 1.3.2, must demonstrate the ability of the gate to withstand design loads and provide required stiffness during a service life of 20 years, including up to 10,000 load cycles, and exposure to fresh water, sunlight, and site temperature variations. Strength and stiffness calculations shall be based on appropriate test data from the selected gate material, or from similar materials, as specified in paragraph 1.3.3. Test results shall be adjusted to account for changes in properties due to environmental exposure and load cycles. When used to determine gate strength and stiffness, nominal material properties shall be taken as a value which is exceeded by 95 percent of all test results.

1.2.4.1 Strength

The nominal strengths shall be reduced by a factor of 2.0 to provide an adequate factor of safety to resist the following applied loads.

1.2.4.1.1 Normal Hydrostatic Loading

Pressure applied normal to the gate surface, varying linearly from ____ at the hinge line to ____ at the top of the gate, and uniform across the width of the gate. For this loading the gate is supported at the hinges and by the prop in the raised position.

1.2.4.1.2 Maximum Equipment Loading

Pressure applied normal to the gate surface, varying linearly from ____ at the hinge line to ____ at the top of the gate, and uniform across the width of the gate. For this loading the gate is supported at the hinges and by the actuator cylinder, with the gate raised 23 degrees from horizontal.

1.2.4.1.3 Emergency Lifting

Pressure applied normal to the gate surface, varying linearly from ____ at the hinge line to ____ at the top of the gate, and uniform across the width of the gate. For this loading the gate is supported at the hinges and by a lifting hook at the top of the gate. The gate is raised 23 degrees from horizontal, and the angle of the lifting force acts upstream, 50 degrees up from horizontal.

1.2.4.1.4 Torsional Loading

Pressure applied normal to the gate surface, varying linearly on one edge of the gate from ____ at the hinge line to ____ at the top of the gate, and along the other edge from ____ hinge line to ____ at the top. The pressure varies linearly across the width of the gate. For this loading the gate is supported at the hinges and by the prop in the raised position.

1.2.4.2 Stiffness

1.2.4.2.1 Bending

When subjected to the loading defined in paragraph 1.2.4.1.1, the gate shall have adequate bending stiffness to limit deflection of the gate to ______ as measured at the center of the top edge, when supported rigidly at the hinge and prop locations.

1.2.4.2.2 Torsion

When subjected to the loading defined in paragraph 1.2.4.1.4, the gate shall have adequate bending stiffness to limit twist of the gate to _______ as measured between the hinge line and a line through the outer corners of the top of the gate.

1.3 SUBMITTALS

1.3.1 Fabrication Drawings

The contractor shall submit shop drawings which fully detail fabrication, assembly, and installation of the gate. Shop drawings shall indicate material thicknesses, dimensions, interface surfaces, connection details, and fit up criteria. The fabrication drawings must show the fiber orientation used in the FRP materials from which the gate is fabricated. Drawings shall include erection details and installation instructions. Shop drawings shall be dimensioned in accordance with SPECIAL CONTRACT REQUIREMENTS.

1.3.2 Design Calculations

The contractor shall submit design calculations which document the capability of the gate to provide the required strength and stiffness during the required 20-year service life of the gate. Calculations shall demonstrate the adequacy of all structural components of the wicket, all joints within the wicket, and all attachments between the wicket and appurtenances. Prior to performing design calculations the contractor shall submit a preliminary design concept, including a list of design calculations to be performed for approval by the Contracting Officer.

1.3.3 Test Results

The contractor shall submit test results to document the FRP basic strength and stiffness values used in the design calculations. As a minimum, results of the following tests shall be provided for each type of laminate or pultruded shape used in gate fabrication. These tests shall be performed on batches of material used for actual gate fabrication. Each test shall be repeated ____ times on different samples of the material.

Tension test, 0 degree, ASTM D 3039

Tension test, 90 degree, ASTM D 3039

Compression test, 0 degree, ASTM D 3410

Compression test, 90 degree, ASTM D 3410

In-plane shear test, ASTM D 3518

Short beam shear test, 0 degree, ASTM D 2344

Open hole compression test, SACMA SRM 3

Test results shall also be submitted to document the variation in material properties expected over the 20-year service life due to environmental exposure and loading cycles, and to document the structural capacity of all connection types used in fabrication and installation of the gate. These results may be based on tests of similar materials, rather than actual materials used for gate fabrication.

1.3.4 Certificates

1.3.4.1 Manufacturer's experience

The contractor shall certify that the gate manufacturer has been engaged in fabrication of fiber-reinforced polymeric composite structures for a minimum of five years, and has performed work of a size and load resistance of a magnitude comparable to that of the wicket gate.

1.3.4.2 Materials

The contractor shall certify the chemical composition of all fiber, resin, and other material used in fabrication of the completed gate. Where onsite repairs are made to a delivered gate, the contractor shall supply Material Safety Data Sheets (MSDS), toxicity reports, manufacturing lot numbers, and the shelf-life history of the material used in repair of the gate.

1.3.5 Fabrication Records.

The contractor shall submit a preliminary process specification describing how the components will be fabricated, machined, assembled, and inspected for approval by the Contracting Officer prior to beginning the fabrication. Nondestructive evaluation methods such as ultrasonic and/or x-ray shall be used to inspect the integrity of the gate to ensure that delaminations, severe porosity, voids, resin depletions, and foreign objects are minimal in the FRP material. Identification of porosity above ____ percent, a void larger than ____, or a delamination longer than ____ shall be cause for rejection of the gate. Upon delivery of the gate, the contractor shall submit complete fabrication records, including: fiber architecture; matrix placement and curing; component joining operations; storage; and test handling.

PART 2 PRODUCTS

2.1 MATERIALS

2.1.1 FRP Composites

The gate shall be fabricated using a fiber-reinforced polymeric composite material. The fibers shall be glass and/or carbon. The matrix shall be polymeric resins commonly used in the fabrication of composite structural elements. The chemistry, configuration, and coatings for the composite material shall be capable of ensuring the composite maintains its required strength and stiffness during 20 years of environmental exposure to loading cycles, sunlight, seasonal temperatures, and immersion in fresh water. Any joining systems, such as adhesives, used for gate assembly must also be capable of maintaining required strengths under the same exposure conditions.

2.1.2 Metals

Metals used for appurtenances and fasteners shall conform to (reference the Miscellaneous Metals specification). Painting of metal components shall conform to (reference the Painting specification).

PART 3 EXECUTION

3.1 FABRICATION

Fabrication of the gate shall conform to common practice for structural applications of FRP materials. This shall include the following quality control items:

- Ply orientation tolerance of _____

- Clean fabrication environment

- Material control system and traceability of the material lot

- Curing cycle

- Process control procedures

- Nondestructive inspection techniques, such as ultrasonic and x-ray

- Quality control inspections of fiber volume, void content, glass transition temperature, percent cure, and hardness

3.2 REPAIRS

Minor damage to any FRP component of the gate shall be repaired, subject to approval of the Contracting Officer, by addition of resin and reinforcing fibers sufficient to restore the component to its undamaged strength. Damage to any FRP material which is greater than 10 percent of the cross section of any component will be cause for rejection of the wicket.

3.3 INSTALLATION

The FRP gates shall be installed on the dam by attaching the hinges and prop. Each gate shall then be operated through one full cycle of raising and lowering. This operation shall be performed in the dry.

3.4 PAYMENT

Payment for the FRP gates will be made per gate, and shall include the gate and connections, delivery, installation, and required technical assistance during installation.

Appendix D
Glossary

This glossary was developed to provide a quick reference for terms often used in the composites industry that may not be familiar to the civil engineer. It was developed primarily from "Introduction to Composites" by the Composites Institute of the Society of Plastics Industry, Inc., New York, NY.

Additive
Any substance added to another substance, usually to improve properties, such as plasticizers, initiators, light stabilizers, and flame retardants. See also Filler.

Aramid
A type of highly oriented organic material derived from polyamide (nylon) but incorporating aromatic ring structure. Used primarily as a high-strength high-modulus fiber. Kevlar and Nomex are examples of aramids.

Autoclave
A closed vessel for conducting and completing a chemical reaction or other operation, under pressure and heat.

Bulk Molding Compound (BMC)
Thermosetting resin mixed with short-strand reinforcement, fillers, and so on, into a viscous compound for compression or injection molding.

Carbon Fiber
The element that provides the backbone for all organic polymers. Graphite is a more ordered form of carbon. Diamond is the densest crystalline form of carbon. In fiber form, carbons are used in FRP composites.

Centrifugal Casting
A production technique for fabricating cylindrical composites, such as pipe, in which composite material is positioned inside a hollow mandrel designed to be heated and rotated as resin is cured.

Composite Material
A combination of two or more materials (reinforcing elements, fillers, and composite matrix binder), differing in form or composition on a macroscale. The constituents retain their identities; that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

Compression Molding
A process wherein a mold is open when the material is introduced and that shapes the material by the pressure of closing and by heat.

Filament Winding
A process for fabricating a composite structure in which continuous reinforcements (filament, wire, yarn, tape, or other), either previously impregnated with a matrix material or impregnated during the winding, are placed over a rotating and removable form or mandrel in a prescribed way to meet certain stress conditions. Generally the shape is a surface of revolution and may or may not include end closures. When the required number of layers is applied, the wound form is cured and the mandrel removed.

Filler
A relatively inert substance added to a material to alter its physical, mechanical, thermal, electrical, and other properties or to lower cost or density. Sometimes the term is used specifically to mean particulate additives.

Glass Fiber (Fiberglass)
An individual filament made by drawing molten glass. A continuous filament is a single glass fiber of great or indefinite length. A staple fiber is a glass fiber of relatively short length, generally less than 430 mm (17 in.), the length related to the forming or spinning process used.

Glass Transition Temperature (T_g)
The reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer from, or to, a viscous or rubbery condition at hotter temperatures to, or from, a hard and relatively brittle one at colder temperatures.

Hand Lay-up
The process of placing (and working) successive plies of reinforcing material or resin-impregnated reinforcement in position on a mold by hand.

Injection Molding
Method of forming a plastic to the desired shape by forcing the heat-softened thermoplastic polymer into a relatively cool cavity under pressure or thermosetting polymer into a heated mold.

Laminate
To unite layers with a bonding material, usually with pressure and heat (normally used with reference to flat

sheets, but also rods and tubes). Also a material consisting of layers bonded together.

Lay-up
The reinforcing material placed in position in the mold. The process of placing the reinforcing material in position in the mold.

Plastic
A material that contains as an essential ingredient an organic polymer of large molecular weight, hardeners, fillers, reinforcements, and so forth; is solid in its finished state; and, at some stage in its manufacture or its processing into finished articles, can be shaped by flow.

Ply
In general, fabrics or felts consisting of one or more layers (laminates, and so forth). The layers that make up a stack.

Polymer
A high molecular weight organic compound, natural, or synthetic.

Prepreg
Either ready-to-mold material in sheet form or ready-to-wind material, which may be cloth mat, unidirectional fiber, or paper impregnated with resin and stored for use.

Pressure Bag Molding
A process for molding reinforced plastics in which a tailored, flexible bag is placed over the contact lay-up on the mold, sealed, and clamped in place. Fluid pressure, usually provided by compressed air or water, is placed against the bag, and the part is cured.

Pultrusion
A continuous process for manufacturing composites that have a cross-sectional shape. The process consists of pulling a fiber-reinforcing material through a resin impregnation bath and through a shaping die, where the resin is subsequently cured.

Reaction Injection Molding (RIM)
A process for molding polyurethane, epoxy, and other liquid chemical systems. Mixing of two or more components in the proper chemical ratio is accomplished by a high-pressure impingement-type mixing head.

Reinforced Plastics
Molded, formed, filament-wound, tape-wrapped, or shaped plastic parts consisting of resins to which reinforcing fibers, mats, fabrics, and so forth, have been added before the forming operation.

Reinforced Reaction Injection Molding (RRIM)
A reaction injection molding with a reinforcement added.

Reinforcement
A strong material bonded into a matrix to improve its mechanical properties.

Resin
A solid or pseudosolid organic material, usually of high molecular weight, that exhibits a tendency to flow when subjected to stress (e.g., polyester, vinylester).

Resin Transfer Molding (RTM)
A process whereby catalyzed resin is transferred or injected into a closed mold in which the fiberglass reinforcement has been placed.

Seeman Composite Resin Infusion Molding Process (SCRIMP)
A process which is similar in concept to RTM but requires only a single tool side and a simple vacuum bag and is capable of producing large parts.

Sheet Molding Compound (SMC)
A composite of fibers, a liquid thermosetting resin (usually polyester), and pigments, fillers, and other additives that have been compounded and processed into sheet form to facilitate handling in the molding operation.

Size
Any treatment consisting of starch, gelatin, oil, wax, or other suitable ingredient applied to yarn or fibers at the time of formation to protect the surface and aid the process of handling and fabrication or to control the fiber characteristics.

Spray-up
Technique in which a spray gun is used as an applicator tool. In reinforced plastics, for example, fibrous glass and resin can be simultaneously deposited in a mold.

Thermoplastic
Capable of being repeatedly softened by an increase of temperature and hardened by a decrease in temperature.

Thermoset
A plastic that, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble material.

Transfer Molding
Method of molding thermosetting materials in which the plastic is first softened by heat and pressure in a transfer chamber and then forced by high pressure through suitable sprues, runners, and gates into the closed mold for final shaping and curing.

Vacuum Bag Molding
A process in which a sheet of flexible transparent material plus bleeder cloth and release film are placed over the lay-up on the mold and sealed at the edges. A vacuum is applied between the sheet and the lay-up.

Wet Lay-up
A method of making a reinforced product by applying the resin system as a liquid when the reinforcement is put in place.

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