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FEASIBILITY REVIEW OF FRP MATERIALS FOR STRUCTURAL APPLICATIONS

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REPORT
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EXECUTIVE SUMMARY

Fiber Reinforced Polymer (FRP) composites with fibers/fabrics bonded with organic polymers (resin system) are being referred to as the materials of 21st century because of many inherent advantages including market acceptance. In the United States of America, application of composites in civil infrastructure projects started in late 1980, with major advances in bridges, roads, retrofitting of structures, and marine applications. In the last decade, significant efforts have been made to develop design guidelines, and construction and maintenance standards, and specifications for FRP reinforcement, FRP wraps, and FRP shapes including standardized test methods. Various researchers and organizations have been contributing to this effort to cover a wide variety of applications. In addition to providing a greater understanding on the FRP composite design, optimization, reliability, and manufacturing feasibility, this effort has revealed the end-user willingness to implement these high-performance materials because of better durability and cost effectiveness over conventional materials.

This report deals with the feasibility of design, development, and implementation of FRP composite structural systems that are of interest to USACE. Scope of this report is limited to cursory review on FRP constituents, structural shapes and systems including their field implementation in bridges, buildings, marine structures, automobiles, aircrafts, and others. In addition, response of FRP structures under in-plane and out-of-plane forces and also under in-door and out-door service conditions are included. Description and definition of constituents, short- and long-term properties, and influence of fiber orientation on strength, stiffness, and deformation of composite products are reviewed under combined external and environmental loads. Input to this study was obtained from the European perspective regarding: i) types of applications, ii) composite and constituent material selection guidelines, test specifications, and implementation, and iii) design, testing, fabrication, inspection (NDT), and repair techniques. USACE (1997) “ETL 1110-2-548, Composite Materials for Civil Engineering Structures,” was reviewed with emphasis on revisions corresponding to individual chapters.

Appendix A provides terminologies and definition of select constituents regarding their physical, thermal, chemical, and mechanical properties. Appendix B focuses on providing recommendations to revise/replace USACE technical letter, “ETL 1110-2-548, Composite Materials for Civil Engineering Structures,” in terms of necessary changes and recommendations to each chapter. Appendix C reviews various guidelines, specifications, and test methods developed for FRP composites during the last decade. Additional work and elaboration on these aspects is necessary as discussed in the summary and recommendation section of this report to help a designer, manufacturer/fabricator, and end-user towards FRP composite implementation. Based on the work carried out in this project, CFC-WVU proposes to design, manufacture, and field implement FRP miter gates to achieve long-term service life with high performance and lower maintenance.

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1. INTRODUCTION

1.1 Introduction

Fiber Reinforced Polymer (FRP) composites with fibers/fabrics bonded together with the help of organic polymers (resin system) are being referred to as the materials of 21st century because of many inherent advantages. Some of the inherent advantages of FRPs over traditional materials are: (1) superior thermo-mechanical properties such as high strength and stiffness, and light weight, (2) excellent corrosion resistance, (3) magnetic transparency, (4) design flexibility (tailorability), and (5) long-term durability under harsh service environments. Composites can be three to five times stronger, two to three times stiffer, and three to four times lighter than metals such as steel and aluminum. In addition, composites are dimensionally stable, aesthetically pleasing and cost effective with better durability and lower maintenance than the conventional mateirals. In the United States of America, FRP composites applications to civil infrastructure started in the form of marine structures, piers, tanks and pilings for military requirement. Since then, major field implementations of FRP composites have taken place in bridges, roads, marine structures and retrofitting of structures, with great success in retrofits (Mallick, 1993; Chakrabarti et al., 2002; CFC-Polymer Composites Conference Proceedings, 2002 and 2007).

In the last decade, significant efforts have been made to develop and implement design guidelines, construction and maintenance standards, and specifications for FRP rebars, wraps, and shapes (I-section, WF section, box section, angles etc.) including standardized test methods. Various researchers and organizations have been contributing to cover a wide variety of applications. Large volume usage of FRPs in civil infrastructure is drawing increased interest including field evaluation and development of design and construction specifications. The construction of experimental and demonstration structures using FRP composites in addition to the recent advances in guide specifications has revealed the potential increase in structural efficiency and economic viability using FRP components and systems (See list of references in addition to Appendixes B and C, and ASCE LRFD draft code for FRP, 2010). In addition to providing a greater understanding on the FRP composite design, optimization, reliability and manufacturing feasibility, the research and development efforts have been resulting in extensive field implementations and an opportunity to collect field data to develop better design and construction guidelines.

1.2 Advantages and Disadvantages of FRP

In addition to superior thermo-mechanical properties, FRP composites have many advantages over conventional materials (Tables 1.1 and 1.2). These advantages are gradually being utilized in the construction industry for infrastructure applications. Some of the marine and water way applications such as miter gates will greatly benefit by the use of FRPs in terms of high strength, stiffness, corrosion resistance, ease of installation, simple repair methods, excellent durability, long service life, minimum maintenance and lower life cycle costs. Some of the advantages of FRPs are:

1. **Light weight:** a typical 8" FRP deck including wearing surface weighs 25 psf vs. 120 psf for a standard 9.5" concrete deck. Reduction in dead load results in an increased live load capacity with possible elimination of weight restrictions.
2. **Rapid installation**: FRPs can be fast implemented due to modular, pre-fabricated, and light weight units that eliminate forming and curing efforts necessary for conventional materials such as concrete decks or elaborate welding and riveting needed in heavy steel construction.
3. **Reduced interruption**: low down-time of an in-service structure by employing rapid installation procedures can lead to lower user costs, lower maintenance, higher safety, and better public relations.
4. **Good durability**: excellent resistance to de-icing salts and other chemicals results in eliminating corrosion, cracking, and spalling associated with steel reinforced concrete.
5. **Long service life**: large, non-civil FRP structures have performed extremely well in harsh environments for decades. As an example, FRP bridge decks are expected to provide service life of about 75-100 years with little maintenance.
6. **Fatigue and impact resistance**: FRPs have high fatigue endurance and impact resistance.
7. **Quality control**: shop fabrication of FRP results in excellent quality control with lower transportation cost.

8. **Ease of installation**: FRP structural systems or subsystems such as bridge decks have been used by general contractors or maintenance crew using standard details with installation time reduction of up to 80%, thus eliminating traffic congestion and construction site related accident.
9. **Cost savings**: structural rehabilitation using FRP costs a fraction ($1/15^{th}$ to $1/10^{th}$) of the replacement cost and extends the service life by additional 25-30 years. Rehabilitation also results in less environmental impact and green house gas emissions (Ryszard, 2010). Similarly, new FRP construction provides superior FRP thermo-mechanical properties and lower life-cycle costs.

Some of the disadvantages of FRPs are: slightly higher initial costs, limited experience with these materials by design professionals and contractors, lack of data on long-term field performance, and absence of full spectrum of codes and specifications similar to conventional materials.

Table 1.1 Merit Comparison and Ratings for FRP and Steel

Property (Parameter)	**Merit/Advantage (Rating)**		**Rating Scale**
	FRP	**Steel**	
Strength/stiffness	4-5	4	1: Very Low 2: Low 3: Medium 4: High 5: Very High
Weight	5	2	
Corrosion resistance/ Environmental Durability	4-5	3	
Ease of field construction	5	3-4	
Ease of repair	4-5	3-5	
Fire	3-5	4	
Transportation/handling	5	3	
Toughness	4	4	
Acceptance	2-3	5	
Maintenance	5	3	

Note: Higher rating indicates better desirability of the property

Table 1.2 FRP Merits and Suitability of Applications

Parameter	FRP Application	
	FRP	**Application**
Strength/stiffness	Very high	aerospace
	High	marine, construction, pipes, bridges, reinforcing bars, automotive
Weight	Very high	aerospace, marine, construction, pipes, bridges, reinforcing bars, automotive
Corrosion resistance/ Environmental Durability	Very high	marine, boat industry, construction industry, aerospace
	High	automotive, leisurely applications
Ease of field construction	High	buildings, bridges, pavements, kiln linings, wind mill blades, radomes
Ease of repair	High	bridges, tunnels, underwater piles.
Fire	Very high	aerospace, marine, automotive, blast resistant FRP construction.
	Medium	bridge decks, leisure products, marine boats
Transportation/handling	Very high	shapes, bridge decks, components and assembled FRP systems
Toughness and impact	High	bullet proof vests, vandalism and graffiti proof walls.
Acceptance	low	construction and aerospace industries
	Low	offshore and fire resistant applications.

Some of the marine applications with FRP use are discussed in Chapters 2, 8, and 9. Suitability of FRP usage for offshore and marine applications is listed in Table 1.3.

Table 1.3 FRP Use and Suitability for Marine Applications

Marine/ off-shore Application	FRP Suitability	
	Advantages	**Examples**
Boating/sports related	moisture resistance, ease of use and repair, high strength/ stiffness, light weight, corrosion resistance	boats, seating and storage compartments, fishing rods etc.
Naval applications	high strength/stiffness, light weight, corrosion resistance, ease of navigation, longer service life	ship decks, aircraft landing platforms, cabins, gun housings, walking platforms, rails etc.
Off-shore applications	moisture resistance, ease of use, high strength/stiffness, corrosion resistance, ease of construction, longer service life, minimum maintenance, ease of repair, fire resistance.	piles, retaining walls, pedestrian walkways, bridges, pavement panels for oil fields and off-shore structures, buoys and floats etc.
Hydraulic structures and supporting structural elements	moisture resistance, high strength/stiffness, light weight, corrosion resistance, longer service life, minimum maintenance and ease of construction.	hydraulic gates, pumps, pipes, dampers, grating structures, access structures etc.

1.3 Overview

This report focuses mainly on glass fiber/fabric reinforced polymer composites. Carbon and ceramic composites are beyond the scope of this report. Chapter 2 presents application, performance history, and feasibility of FRP composite applications. Chapter 2 describes design, development and field implementation of FRP in the form of bars, plates, shapes, and different forms of components for various types of structures. Chapter 3 provides an overview of physical, thermo-mechanical, and creep/fatigue properties of FRP composites. Relevant discussions for updating the technical letter "ETL 1110-2-548, Composite Materials for Civil Engineering Structures," are also provided within each chapter and in Appendix B. Chapter 4 includes an overview of durability of composites with specific focus on glass fiber reinforced FRP (GFRP) that is widely used in current marine structures including "hydraulic gate" structures. Chapter 5 gives a list of different test methods including brief description of micromechanics and numerical methods for analyzing FRP composite structures. Additional standards, guidelines, and reports developed by different code developing bodies, organizations, and industries are summarized in Appendix C. Chapter 6 deals with the fabrication and field implementation details of FRP composite construction and/or field rehabilitation. Chapter 7 gives a brief overview of non-destructive techniques (NDT) that can be used for evaluating manufacturing or field-service related damage and implementing QA/QC. Chapter 8 deals with repair of FRP wrapping including hand-layup methods. Chapter 9 discusses worldwide implementation of FRP hydraulic (mitre) gates and the steps to be taken for designing, manufacturing, and implementing those structures in USA. Three appendices included at the end of this report deal with i) terminology related to FRP, ii) commentary on updating ETL 1110-2-548, and iii) list of specifications/guidelines.

2. FRP TYPES, APPLICATIONS, PERFORMANCE HISTORY, AND FEASIBILITY

2.1 FRP Applications and Limitations

Since California Transportation Agency started to use composite jacketing for seismic retrofitting of bridge piers in the late 1980, FRP materials have gained popularity in various seismic repair and retrofitting applications, both for bridges and buildings. Other non-seismic repair and retrofit applications have gained increasing interest in the last decade, and numerous successful applications using FRP composites in construction have been reported (Liao et al., 1997; GangaRao and Barbero, 1991; Vijay and GangaRao, 1999; Creese and GangaRao, 1999; Gupta, 2000; Chin et al., 1999). However, in the area of new civil infrastructure, construction of structures made of 100% composites is relatively rare (Chakrabarti et al., 2002). This chapter highlights FRP constituents, FRP reinforcements for concrete, FRP shapes, and FRP wraps for inland and offshore structures as well as their applications for army and marine structures. Some of the limitations of FRPs in terms of lower stiffness, lower shear strength, lack of traditional yielding similar to metals, and higher initial costs have been creatively addressed in composite structures through smart analysis and design. Some of these measures include: i) increasing shear strength and stiffness to match those of steel structures through smart fiber/fabric and geometrical configurations, ii) economical design due to lighter self weight, for example, leading to lower costs of transportation, erection, and material usage, iii) enhancing ductility by higher energy absorption through innovative fiber/matrix stress transfer at micro-level, iv) compensating higher initial costs through evaluation of life cycle costs to achieve better durability, minimum maintenance and replacement costs during their service life.

2.1.1 FRP Constituents

FRP consists of fibers, fabrics, resins, sizing, additives, and coatings as explained in the following sections. Strength, stiffness, coefficient of thermal expansion, Poisson's ratio, density, durability, and various other thermo-mechanical properties are available in various publications such as ACI 440 guidelines, ETL1110-2-548 (reviewed in Appendix B). Similarly, test methods for composites are discussed in Appendix C and additional details are envisaged to be provided in future work/reports.

2.1.2 Fibers

Glass and Carbon are the most common types of fibers used as reinforcements in composites. Other types of reinforcements are organic fibers such as kevlar, boron, silicon carbide, ceramic and others. Fibers can be long (continuous), short, chopped, milled, or in the form of elongated single crystals. Continuous fibers come in the form of untwisted bundles as strands, or twisted bundles as yarns, and also as a collection of parallel continuous strands, which is referred to as roving.

2.1.3 Resins

Resins are the polymer binders that hold the fibers together and transfer the loads between the fibers in addition to protecting them from environmental factors and carrying shear loads. Thermoset resins (e.g. polyester, epoxy) transform in to matrix binders after curing the resin through an irreversible chemical reaction. By heating, thermoplastic resins are softened from solid state before processing (making a composite) without chemical reactions. Thermoplastics return to solid state (matrix) once processing is done (Mallick, 1993).

Although all thermosets are amorphous, thermoplastics can be amorphous or semi-crystalline. The primary advantage of thermoplastic resins over thermoset resins is their high impact strength and fracture resistance, which is exhibited by their excellent damage tolerance property (Mallick, 1993). Thermoplastic resins also provide higher strains-to-failure, which is manifested by better resistance to microcracking in the matrix of a composite. Some of the other advantages of thermoplastic resins are:

1. Unlimited storage (shelf) life at room temperature.
2. Shorter fabrication time.
3. Postformability (e.g., by thermoforming)
4. Ease of repair by (plastic) welding, solvent bonding, etc.
5. Ease of handling (no tackiness).
6. Recyclability.

7. Higher fracture toughness and better delamination resistance under fatigue than thermosets such as epoxies.

The disadvantages of thermoplastics are low creep resistance and poor thermal stability. The amorphous polymers (thermoset resins) show a dramatic drop in molecular weight at T_g, while the molecular weight drop is not so dramatic for semi-crystalline thermoplastics. In some crystalline polymers, processing temperature must exceed melt temperature, whereas the maximum process temperature could be below T_g for amorphous polymers. Reinforcing thermoplastics with fibers is more difficult than reinforcing with thermosets because of their high viscosities (Mallick, 1993). The advantages of thermoset resins over thermoplastic resins are:

i. Better creep and chemical resistance.
ii. Lower stress relaxation.
iii. Better thermal stability.

Thermosets achieve good wet-out between fibers and resins, which results in better mechanical properties in relation to thermoplastics. However, they also have some limitations:

i. Low strain-to-failure.
ii. Long fabrication time in the mold.
iii. Limited storage life at room temperature (before the final shape is molded).

2.1.4 Fiber Surface Treatment (Sizing)

Sizing is the treatment of fiber surface with coupling agents (that couple resin to fibers), to protect the fiber against moisture and reactive fluid attacks. Sizing improves wettability of the fiber surface against the matrix, therefore creates stronger bond between the fiber and matrix. It is necessary for effective transfer of stresses between the fibers and the matrix. Functions of sizing for different fibers are (Mallick, 1993):

- Improving interfacial bond of glass fibers with the matrix and to protecting the glass fibers from environmental attacks that are of main concern in the strength degradation of glass fibers.
- Promoting good chemical bonding with a binder for carbon fiber surfaces that are chemically inactive. The sizing treatment creates porous carbon fiber surface; hence

increases the surface area by creating pitting to provide large number of fiber-matrix interfacial contact point.

- Enhancing weak surface adhesion of polymeric fibers (e.g. Kevlar 49)

2.1.5 Additives and curing

Different kinds of additives and modifiers are added to modify the performance of thermoset polymers. Catalysts, promoters, and inhibitors are used to accelerate or slow the rate of polymerization. Release agents are used to facilitate the removal of composite from the mold. Other agents are used to improve processability like plasticizers or product durability. Fire retardants are used to extinguish fire upon contact. Viscosity control agents help control the flow of the resin, while air release agents reduce air voids. Toughness agents increase the toughness of fibers. Electrical conductivity agents shield conductivity from certain fibers and antistatic agents reduce static or electrical charge. Antioxidants (as additives) keep the polymer from experiencing oxidation (CISPI, 1992). For thermoplastic resins, heat stabilizers are used to protect polymers from degradation due to heat, and UV stabilizers protect polymers from UV degradation. In addition, fillers are added to both thermoset and thermoplastic resins in order to reduce cost, control shrinkage, improve mechanical and physical properties, and to provide ultra violet (UV) protection, weathering protection, surface smoothness, temperature resistance, impact strength, and fire resistance. Fillers may account for about 20% - 40% by weight of the material.

2.1.6 Coating

Coatings are applied to improve FRP performance against abrasion, fire, and environmental attacks and to improve the adhesion to other construction materials. For high weatherproof performance along with high abrasion resistance, Nishizaki et al. (2002) proposed a paint system with high abrasion resistant as intermediate coat and a high weatherproof topcoat.

2.2 Reinforcements/Plates/Wraps/Shapes

FRP can be in the form of reinforcing bars in concrete, structural plates and shapes, or wraps for concrete or timber substrates. The wraps are used for bonding materials to structural members such as concrete and wood to enhance their strength, stiffness, ductility, and durability. Several bridge girders and concrete piers have been built where concrete decks and slabs have been reinforced with non-corroding FRP bars. Since rehabilitation of structures typically involves wrapping concrete or wood members with FRP, bond between the substrate and FRP assumes great significance. Structures requiring wrapping may be bond-critical (e.g., flexural members such as beams) or contact-critical (e.g., columns requiring confinement) (ACI 440 documents, Appendix C). Effectiveness of wrapping concrete members with fiber reinforced polymer (FRP) composites to repair and rehabilitate damaged members after partially removing chemicals from the concrete and realkalizing the members has been well researched (GangaRao et al., 1995).

2.3 Civil-Inland and Offshore Structural Repairs

FRP composites are ideally suited as quick and effective structural repair tool because of their lightweight, high strength and corrosion resistance. Bridge repair using FRP composites is a major success story and many details can be found in the book authored by GangaRao, Taly, and Vijay, entitled “Reinforced Concrete Design with FRP Composites” (2007).

Storage tanks for liquids are ideal application of FRP using corrosion and solvent resistant resins. FRP tanks are easy to install, more economical than the conventional materials, and they have better service life. Researchers visualize that within a few years large number of tanks, starting from municipal water tanks to large petrochemical tanks, will be built with FRP composites (Chakrabarti et al., 2002)**.**

The availability of resins that cure under water has extended the FRP wrap application to substructure elements such as partially submerged piles that are damaged (refer to Chapter 8). Also, FRP composites have been used in offshore platforms where corrosion in the presence of seawater is a major concern. Some of the current FRP applications are (Moahmoud et al 2009):

i. Low pressure pipes
ii. Diesel storage tanks, lube tanks, and utility tanks
iii. Walkway gratings, stair steps, and handrails
iv. Cable ladders and trays
v. Fire protection panels and sections of accommodation modules
vi. Buoys and floats

vii. Strengthening of primary steel structures
viii. Helicopter landing decks
ix. Walls and floors to provide protection against blast and fire

The higher cost of constructing offshore structures with composites compared with welded steel is a concern. However, the significant through-life cost savings can be gained with composites due to reduced maintenance and premature replacement of corroded structures.

2.4 Army, Marine, and Related Applications

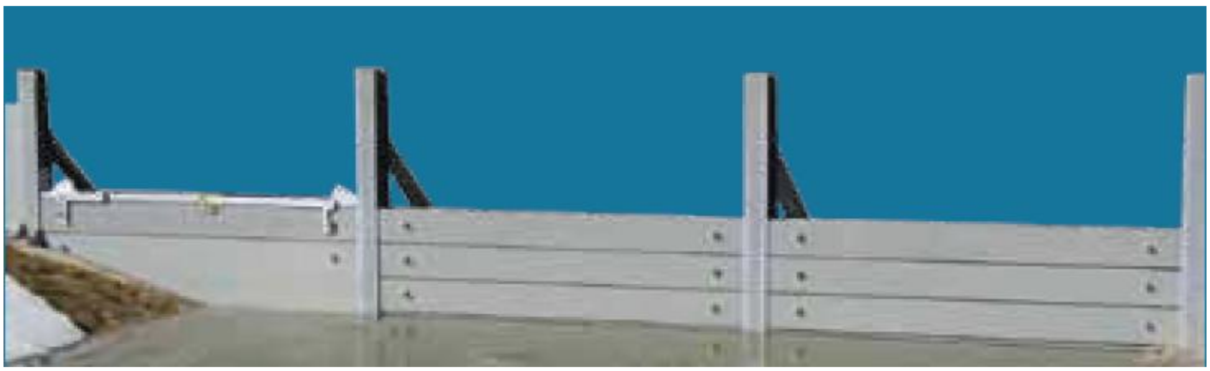
In 2000, the French Water Authority (Voies Navigables de France) introduced a new generation hybrid lock gate developed by DGA - DCN Lorient, designed for use on small or Freycinet-type inland waterway networks (locks under 6.5 meters in width with mitre-type gates). The hybrid lock gate is made of FRP material (two surface laminates of 5.2m wide and up to 8m tall with horizontal stiffeners) and strengthened with stainless steel frame and its self weight is only 40% of steel (Advanced Material and Composites News, 2000). Light weight results in easy transportation, placement, and facilitates hand assembly.

Now different types of hybrid FRP gates (12'x12') with steel core are available commercially for water-flow-control applications including sluice gates, slide gates, stop gates, weir gates and flap gates. They are reported to be capable of holding water pressure up to 100ft (Plasti-Fab.com).

Submersible pump manufacturers now offer FRP packaged pump stations, for general civil works, particularly for sewage and storm water pumping, to take advantage of lightweight, and corrosion resistance properties of FRP (flygetus.com).

FRP is being used to manufacture different kinds of centrifugal pumps, designed to handle corrosive and other difficult liquids with capacities up to 5000 GPM and pressure head up to 400 feet (www.fybroc.com).


a) Different types of available FRP gates



b) FRP wall (Stop Logs)

Figure 2.1: FRP Water control products with lightweight and simple field assembly (Plasti-Fab.com)

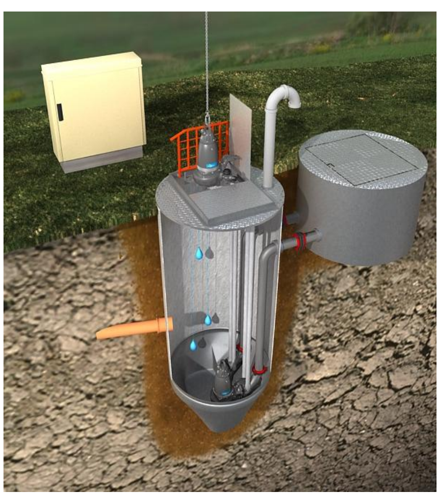


Figure 2.2: FRP packaged pump station (www.flygtus.com)

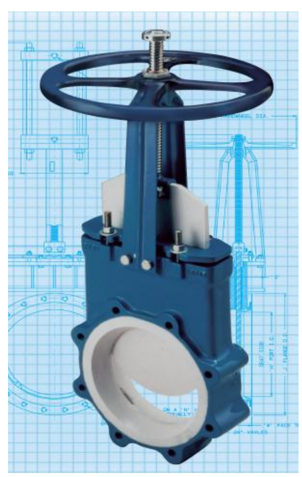


Figure 2.3: FRP lined knife gate valve (www.engvalves.com)

Figure 2.4: Different types of FRP pumps
(www.fybroc.com)

2.4.1 FRP Pipes for Marine Applications

FRP pipes such as those required for marine applications are designed with high safety factors (6 to 12), depending on the loading and application parameters such as stress levels and stress concentrations, stress (pressure) surges, operating temperatures, water hammer effects etc. FRP pipes are typically designed on allowable strain basis with due consideration provided to pressure and temperature such that repeated residual strain accumulation and damage are prevented; however, FRP structures are typically designed for deflection limit states.

Large FRP pipe systems with diameters up to 13ft and a minimum of 50-year design life are being manufactured for the following infrastructure applications:

- Large potable water transmission pipeline
- Slip lining of corroded large concrete sewer pipes and tunnels
- Large gravity sewer and storm water drains
- Large siphons and culverts
- River and seawater intakes and outfalls
- Power plant circulating and cooling water lines
- Large power plant penstocks

- Large irrigation pipelines
- Large pump station headers

Figure 2.5: Very large FRP pipe systems from Future Pipe Industries (www.futurepipe.com)

Figure 2.6: Very large FRP pipe T-connector (www.futurepipe.com)

2.4.2 FRP Piling

A full-scale feasibility assessment was conducted on different types of FRP composite-bearing piles at Port Elizabeth, NJ. The study consisted of the following:

- Evaluation of equivalent mechanical short-term properties of the composite material include: elastic modulus for the initial loading quasilinear phase, axial compression strength, inertia moment, and critical buckling load. These FRP composites consisted of recycled plastic reinforced by fiberglass rebar (SEAPILE™ composite marine piles), recycled thermo plastic reinforced by steel bars, and recycled plastic reinforced with randomly distributed fiberglass (Trimax), manufactured respectively by Seaward International Inc., Plastic Piling, Inc., and U.S. Plastic Lumber (Juran and Komornik, 2006).
- Response analysis of FRP piles under static and dynamic loads.
- Feasibility estimate of installing FRP piles using standard pile driving equipment, capacity, and constructability.

Figure 2.7: Composite marine piles from different manufacturers were tested. Shown in pictures: SEAPILE, PPI and Trimax piles, (Juran and Komornik, 2006)

As a result of the study related to FRP piles, Juran and Komornik (2006) concluded that FRP composite piles could be used as an alternative engineering solution for deep foundations. These authors recommended further research regarding time-dependent stress-response of composite recycled plastic material to be done before a wider spread use of these piles. One of the main concerns was that FRP piles may undergo higher deformations under sustained loads than metals

(Juran and Komornik, 2006). However, creep studies on FRP reinforced concrete members and FRP shapes have indicate an excellent creep performance of those FRP members when provided with proper fiber/fabric architecture and fiber volume fraction. Lower stiffness of FRP results in higher deformation than metals and this disadvantage has to be overcome by designing innovative shapes with higher moment of inertia (Batra et al., 2009).

2.4.3 FRP BLAST GATE DAMPERS

The FRP composite blast gates conforming to AMCA, SMACNA and NBS PS 15-69 damper/ duct requirements are made of GFRP and vinylester resins with corrosion viels. They are used in air duct systems that require simple direction /volume control with shaft seals. Some of these blast gates are typically suited for non-sophisticated and highly corrosive situations found in waste-water treatment plants, pulp and paper mills, and chemical plants.

Figure 2.8: FRP Butterfly and Blast Gate Dampers
(Industrial Plastic Systems, Inc.)

FRP platforms have found many applications in both marine and other applications. FRP beacons have been produced for offshore and ground applications.


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Figure 2.9: FRP Ground and Floating Platforms
(Industrial Plastic Systems, Inc.)

2.4.4 Other FRP applications

FRP manholes (Fig. 2.10) are commercially available with diameters up to 72 inches. Similarly, aircraft structures made of composites (Fig. 2.11) are gaining popularity because of their high strength to weight ratio.

Figure 2.10: FRP manholes for different applications (Plasti-Fab.com)

Figure 2.11: Boeing 787 *Dreamliner*, the world's first major commercial airliner to use composite materials for most of its construction (www.boeing.com)

In the 1970's, the automotive market surpassed marine market to become the number one market for the use of composites; a position it still retains. Some of the automotive milestones in terms of designing and developing fiberglass composite body, SMC, composite leaf spring, and sport-track vehicles with composite parts, are presented in Table 2.1.

Table 2.1 Automotive Composites Milestones
(*The Automotive Composites Alliance* (ACA), autocomposites.org)

1945	Owens Corning develops the Stout 46, the 1st automobile developed with a fiberglass composite body. Brandt Goldsworthy builds all-composite body for the Dutch Darrin auto.
1953	MFG launches the Chevrolet Corvette fiberglass body
1954	Heavy-duty truck hood and fender are molded in one piece. Ford Thunderbird has a composite hardtop
1960's	A new process called Sheet Molding Composite (SMC) is invented.
1966	Armstrong Rubber Co. introduces tires with glass fibers.
1968	SMC is introduced as an air deflector on the Chrysler station wagon. Ford Shelby GT makes dramatic use of composites for body panels
1970's	Transportation passes Marine as the number one market for composites
1970	Pontiac Tempest grille opening panel highlights SMC's ability to consolidate parts and reduce weight
1972	Chevrolet Corvette body panels are converted to SMC using Owens Corning Materials.
1973	Owens Corning works with Crown Fiberglass to develop first GM Heavy Truck Tilt Hood with SMC.
1973	GMC Truck designs and builds a motor home with composite body panels
1981	Composite leaf spring introduced on the Corvette, Owens Corning involved in initial spring design.
1984	Pontiac Fiero is the first high-volume composite-bodied car
1987	Mercury Tracer bumper beam is the first SMC structural part in North America
1990	General Motors APV van is the largest volume composite-bodied vehicle
1992	Dodge Viper featuring many composite parts is launched.
1993	The Corvette rear inner panel and Chrysler Ram Van interior panels are produced with recycled SMC
1996	Ford introduces SMC integrated front-end system on Taurus and Sable
2001	Ford introduces SMC pickup box (Sport Track)
2003	Tough Class-A provides Ford with SMC substrate that equals steel through paint
2004	UV stable SMC is introduced

Additional information on large-scale marine and structural applications in the US, Europe, and Japan are further described under Chapter 9.

2.5 **FRP Design, Development and Field Implementation by CFC-WVU and Others**

Some of the FRP design, development, and field implementation activities carried out by CFC-WVU are shown in Figs. 2.12 through 2.16. This design, manufacturing, field implementation, and monitoring work by the CFC-WVU over last two decades has contributed to the development and publication of design documents, specifications, various short courses, conferences, and technology transfer activities. Some of the related bridge applications in Switzerland and USA are also shown in Fig. 2.16.

Fig. 2.12 : FRP Design and Applications by the CFC-WVU, (Top L to R) – i) FRP dowels in highway pavement (Elkins, WV), ii) FRP reinforcement for concrete highway pavement (Charleston, WV), and iii) FRP thermoplastic tie for railroads (Moorefield, WV); (bottom L to R) - i) FRP pavement panels (Morgantown, WV, iii) thermoplastic FRP offset block for guardrails, (Morgantown, WV) (Courtesy: CFC-WVU).

Fig. 2.13: FRP bridge deck shapes designed and field implemented in WV and Ohio by the CFC-WVU (Courtesy: CFC-WVU)

Figure 2.14: FRP application for ship decks L); successful testing of fire resistant FRP panel at 5800 degree F with acetylene torch for 5 minute at CFC-WVU. (Courtesy: CFC-WVU)

Figure 2.15 FRP Inspection Walkway Blennerhassett Bridge, Parkersburg, WV (Courtesy: CFC-WVU)

Figure 2.16: Examples of FRP application for bridges: (Top L to R)- i) Carbon cables used in bottom chord, Kleine Emme Bridge, Switzerland (Courtesy: Dr. Urs Meier); ii) FRP pedestrian bridge over 9th Street, NY; (bottom L to R)- iii) Neal Bridge, Maine with FRP tubes (courtesy: NYTimes.com); iv) Proposed FRP Pedestrian Bridge at West Virginia University, Morgantown)

3. COMPOSITES PROPERTIES

This chapter highlights physical, thermal and chemical properties of FRP composites as well as mechanical properties including tensile, compressive, shear, and bending strengths in addition to creep, relaxation, fatigue, and bond properties. Composites have unique properties that could provide both advantages and some disadvantages, which need to be understood by the designer and taken into account by applicable codes. For example, unlike in isotropic materials such as metals, composites can be designed and manufactured with properties varying in different directions to suit the application needs; however, adjusting properties of a composite through constituent materials can be challenging and the following sections provide a rudimentary basis to potentially accomplish the above objective. This chapter provides a simple overview of the theoretical approach for composite materials properties.

3.1 Physical properties

Physical properties of composite constituents such as fibers and resins control the chemo-thermo-mechanical properties of the composite laminate.

The fiber volume fraction V_f is defined as relative volume of the fiber to the total volume of the laminate.

$$V_f = \frac{Volume - Of - Fiber}{Total - Volume} \quad (3.1)$$

The matrix volume fraction V_m is defined as relative volume of the matrix to the total volume of the laminate.

$$V_m = \frac{Volume - Of - Matrix}{Total - Volume} \quad (3.2)$$

The theoretical density of a composite is given by:

$$\rho_c = V_f \rho_f + V_m \rho_m \quad (3.3)$$

Where, ρ_c , density of composite laminate

ρ_f , density of fibers

ρ_m , density of matrix

The volume fraction of voids, V_v, can be estimated from:

$$V_v = \frac{\rho_c - \rho_{\exp}}{\rho_c} \tag{3.4}$$

Where, ρ_{exp}, density of a composite laminate measured experimentally according to ASTM-D792

3.2 Thermal Properties (Thermal Coefficient and Conductivity)

A lower coefficient of thermal expansion of glass fibers in relation to resin produces residual stresses within the material microstructure during temperature drop and during processing the composites at high temperature. In cold regions, the difference in curing and operating temperatures of the composite material may be as high as 200 °F; thus resulting in residual stresses which if high enough may cause microcracking within the matrix and matrix fiber interfaces. Matrix tensile strength reductions up to 50% may be possible because of residual stress build up under low temperature effects. As an example, for a unidirectional continuous fiber lamina, coefficients of linear thermal expansion in the 0 (α_{11}) and 90^0 (α_{22}) directions can be calculated from the following equations (Mallick, 1993).

$$\alpha_{11} = \frac{\alpha_{fl} E_f \mathrm{v}_f + \alpha_m E_m \mathrm{v}_m}{E_f \mathrm{v}_f + E_m \mathrm{v}_m} \tag{3.5}$$

$$\alpha_{22} = \left(1 + \vartheta_f\right) \frac{\alpha_{fl} + \alpha_{fr}}{2} \mathrm{v}_f + (1 + \vartheta_m) \alpha_m \mathrm{v}_m - \alpha_{11} \vartheta_{12} \tag{3.6}$$

Where, $\vartheta_{12} = \vartheta_f \mathrm{v}_f + \vartheta_m \mathrm{v}_m$ (3.7)

E_f = fiber stiffness

E_m = matrix stiffness

V_f = fiber volume fraction

V_m= matrix volume fraction

α_{fl} = co efficient of linear thermal expansion for the fiber in the longitudinal direction

α_{fr} = co efficient of linear thermal expansion for the fiber in the radial direction

α_m = co efficient of linear thermal expansion for the matrix

Temperature affects the rate of moisture absorption as well as the mechanical properties of a polymer composite. Mechanical properties of fiber reinforced polymer composites change when the material is exposed to elevated temperatures (37 °C to 100 °C). Increase in temperature may accelerate time dependent effects such as creep and stress relaxation. Similarly, evaluation of composite systems at low temperatures is essential since high strength and stiffness degradation rate under thermal cycling is observed in cold region structures. For example, higher stiffness of resins at low temperatures reduces the desirable movement of elastomeric bearing pads under bridge seats, leading to serious malfunction of the pads and consequent failure of the structure. The increase in stiffness at low temperature is attributed to crystallization and instantaneous thermal stiffening, which is dependent upon polymer type and temperature. The decrease in temperature can lead to possible increase in: 1) modulus; 2) tensile and flexural strength; 3) fatigue strength and creep resistance; and 4) adhesive strength. Also, decrease in temperature can lead to possible reduction in: 1) elongation and deflection; 2) fracture toughness and impact strength; 3) compressive strength; and 4) thermal coefficient.

3.3 Chemical Properties

Cured resins (matrix) hold the fibers together for shear transfer. Their chemical resistance against pH, strength, stiffness, and viscoelastic properties are related to their chemical structure. The presence of moisture can lead to chemical changes, potentially affecting their properties. FRP composites employed in marine applications are subjected to hygro-thermal stresses and moisture induced chemical and mechanical property variations. Water penetrates FRPs through two processes: diffusion through the resin, and flow through cracks or flaws. During diffusion, absorbed water is not in the liquid form, but consists of molecules or groups of molecules that are linked together by hydrogen bonds to the polymer. The molecules dissolved in the surface layer of the polymer migrate into the bulk of the material under a concentration gradient. Water penetration into cracks or other flaws occurs by capillary flow. Water also penetrates at the fiber matrix interface. It is reported that the primary mechanism of moisture pickup is diffusion through resin, and transfer of moisture through cracks is an after effect. Moisture pickup leads to loss of chemical energy, which is attributed to hydrolytic scission of ester groups. However, increased hydrostatic pressure reduces water uptake due to closing of micro cracks. Hence, it is important to maintain good quality control during manufacturing including complete fiber wet out and high degree of curing to achieve low void content (preferably less than 0.3%). In addition, proper design may be necessary to counter any excessive stresses or stress concentrations induced on structural materials during fabrication and service.

Diffusion of water into the resin may cause swelling stresses. The equilibrium content of water determines the magnitude of swelling stresses. The chemical composition of resin influences the solubility of water in the resin and its susceptibility to hydrolysis. Exposure of composites to moisture for longer duration results in resin (matrix) plasticization and interface bond strength reduction. Hence, surfaces of moisture exposed composites are finished with thin layer of gel coat or acrylic resins to create watertight and water-repellent surfaces.

3.4 Mechanical properties

3.4.1 Longitudinal Tensile Strength

The simplest model to predict the tensile strength of a FRP Composite is (MIL-17 Handbook):

$$F_{1t} = \sigma_{fa}\left[V_f + \frac{E_m}{E_f}\left(1 - V_f\right)\right] \qquad (3.8)$$

Where σ_{fa} is the average strength of the fiber, E_f is the modulus of elasticity of the fiber, E_m is the modulus of elasticity of the matrix, and V_f is the fiber volume fraction. Equation 3.8 is based on rule of mixture and assumes that once the fibers break, the matrix is not able to sustain the load and the composite fails. Also, Eqn. 3.8 is derived assuming all fibers have same tensile strength with no debonding from resins. For composites with a low fiber volume fraction (less than 3 to 5%), the tensile strength is controlled by the matrix,

$$F_{1t} = \sigma_{mu}\left(1 - V_f\right) \qquad (3.9)$$

where σ_{mu} is the ultimate strength of the matrix. By comparing Eqns. 3.8 and 3.9, a minimum fiber volume fraction can be determined for fiber breakage.

3.4.2 Longitudinal Compressive Strength

The compressive strength of an FRP composite in the longitudinal direction is about half of the tensile strength. The compression failure is controlled by the buckling of individual fibers, denoted as microbuckling. The microbuckling of fibers is in turn controlled by the misalignment of the fibers, the shear modulus, and the shear strength of the composite. Fiber misalignment in an FRP composite is caused by the microcatenary that is inherent in the fibers coming off a spool during production. It is also caused by the shrinkage of the polymer during the curing process, which varies anywhere from 3 to 9% by volume. As described in the report by GangaRao et al. (2001), by taking into account the distribution of fiber misalignment, along with the nonlinearity of the in-plane shear stress, the following formula for the compressive strength can be used.

$$F_{1c} = \left(\frac{\chi}{a} + 1\right)^{b} G_{12} \qquad (3.10)$$

where a and b are experimental constants and G_{12} is the in-plane shear modulus, and χ is a dimensionless number (Bullock, 1974).

3.4.3 Transverse Tensile Strength

The strength of a fiber reinforced composite transverse to the fiber direction is controlled by the strength of the matrix, the fiber-matrix interface strength, and the defects present in the matrix. Several classical models and empirical formulas (Nielson, 1967; GangaRao et al., 2001) are available to predict the transverse tensile strength with suitable correction factor for the presence of voids.

Chamis (1984) proposed the following formula for transverse tensile strength of composite which is shown with void correction factor C_v (from Agarwal and Broutman, 1990):

$$F_{2t} = \sigma_{mu} C_v \left[1 + \left(V_f - \sqrt{V_f}\right)\left(\frac{E_m}{E_f}\right)\right] \qquad (3.11)$$

where, E_f is the modulus of elasticity of the fibers and E_m is the matrix modulus. C_v (Agarwal and Broutman, 1990) is represented as:

$$C_v = 1 - \sqrt{\frac{4V_v}{\pi(1-V_f)}} \tag{3.12}$$

where, V_v is the void volume fraction.

Agarwal and Broutman (1990) used strength of materials approach to determining the transverse strength of an FRP composite, by following the assumption that the transverse tensile strength is controlled by the ultimate strength of the matrix, and modified it with a stress concentration factor (SCF) or strain-magnification factor (SMF) (Greszczuk, 1966; Kies, Rep. #5752; Schulz, 1963). A more advanced way of calculating the reduction factor, similar to that of the stress concentration and strain magnification factors, is found from the three-dimensional state of stress in the composite. From this, a suitable failure criterion such as the distortion energy criterion can be employed to determine the reduction factor (Agarwal and Broutman, 1990).

Bai and Hu (1997) developed an equation to predict the transverse strength of a unidirectional composite using the Griffith principle of virtual work and damage mechanics. Their model includes damage parameter, interface surface energy, matrix surface energy, fiber and composite dimensions, fiber volume fraction, transverse modulus of elasticity without the presence of damage, interface crack opening angle and fiber packing factor (Fig. 3.1).

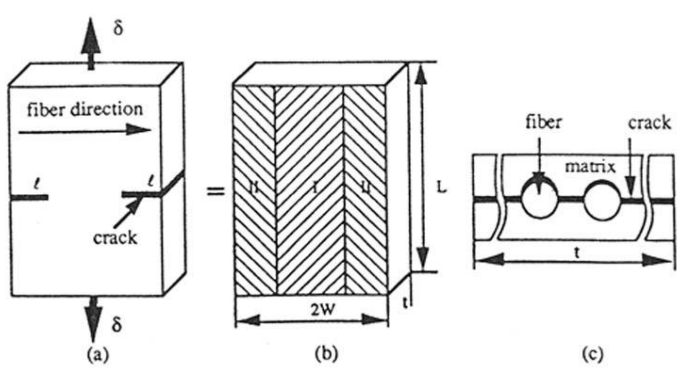


Figure 3.1: Transverse damage model of a unidirectional composite specimen for transverse strength analysis (Bai and Hu, 1997).

3.4.4 Transverse Compressive Strength

Many of the classical transverse tensile strength equations can be adapted for compressive strength as well. Equations by Nielson (1967) and Chamis (1984) can be adapted for transverse compressive strength by replacing the ultimate tensile strength of the matrix by the ultimate compressive strength. The value of the transverse compressive strength is generally higher than the transverse tensile strength for the matrix. The same is true in the full-scale composites, as well. Hence, a designer should carefully consider the fiber/fabric architectures and fiber orientations during design of structures such as mitre gates. These gates are subjected to in-plane and out-of-plane loads that lead to force couplings and stress concentrations. Therefore, combined load effects have to be considered properly in a design.

3.4.5 Bending Strength

Flexural strength is defined as the value of stress per unit length at failure on the plate surface. As described in the report by GangaRao et al. (2001), preliminary design of composite components is based on carpet plots of flexural strength. Due to the strain distribution existing in the cross section, the bending strength of fiber-reinforced composites is larger than the tensile strength. This type of behavior is seen in concrete. Typically bending to tensile strength ratio is about 1.5. This kind of relationship can be determined by finding experimental values of both the tensile and bending strengths independently. A few models have been attempted to predict the bending to tensile strength ratio for a unidirectional composite material and a model based on the Weibull distribution was developed by Bullock (1974). The ratio of bending to tensile strength of composite specimens of equal volume is:

$$\frac{\sigma_b}{\sigma_t} = \left[2(m+1)\right]^{1/m} \qquad (3.13)$$

Where "m" is the Weibull shape parameter, which is a measure of the strength variability of the specimen. Experimental data from Bullock (1974) show that the ratios of bending to tensile strengths are 1.35 and 1.49 for two different types of graphite epoxy composites. Whitney and Knight (1980) reported ratios from 1.04 to 1.33 for their testing of graphite epoxy. Composites made of glass fiber/epoxy exhibited the bending/tensile strength ratios (Bird and Trundle, 1982; Ishikawa and Chou, 1982) to be on the order of 1.30

3.4.6 Inplane and Interlaminar Shear Strength

Continuous fiber reinforced composites are orthotropic materials whose physical and mechanical properties depend strongly on the fiber direction and stacking sequence of fibers/fabrics. Composite strength value and failure behavior is influenced by the constituent material properties, fiber/matrix interfacial bond strength, and load application with respect to principal material directions. Because composites are orthotropic, their stress/strain analysis requires the knowledge of several elastic constants, which may not be readily available. In those cases, it is typical to estimate them using composite property models. This approach requires microstructural information including constituents and their elastic constants, volume fractions, fiber/fabric architecture, and stacking sequence.

Composites typically have low shear strength and shear failure could be dominant under off-axis loading. Based on fiber/fabric configuration, shear failures could occur within the plane of composite (i.e., in-plane failure) or within the plane of thickness (i.e., interlaminar failure). To avoid catastrophic shear related failures in composite structures such as mitre gates, it is necessary to evaluate both in-plane and interlaminar shear failure criteria including proper knock-down factors in the design.

Several test methods are available to evaluate the in-plane and interlaminar shear properties. The shear test method should lead to a uniform shear stress distribution on the shear plane. Depending on the structural shape, in-plane shear strength could be measured by tests such as off-axis tension test (e.g., flat plate), Iosipescu test, torsion test (e.g., thin walled tubes) (Chamis and Sinclair, 1977; Adams and Walrath, 1987; Foley and Roylance, 1989), etc. Interlaminar shear strength could be determined by short-beam test, Iosipescu test, double-notch method (Kedward, 1972, Walrath and Adams, 1983, Dadras and McDowel, 1990), etc.

3.4.7 Creep and Relaxation of Composites

When a polymeric material is subjected to a constant load, it deforms instantly. However, the deformation continues to increase with time. This phenomenon of increasing strain under constant load is known as creep. Conversely, if a constant strain is imposed on a polymeric material, it induces stress, but then the stress decreases with increasing time under constant strain which is known as stress relaxation. Both creep and stress relaxations are manifestations of viscoelastic behavior of polymeric materials. Viscoelasticity arises because polymers are long-chain molecules, and, under stress, parts of a molecule or even entire chain of molecules can rearrange and slide past each other. This is especially significant when the operating temperatures are above the polymer glass transition temperature T_g. However, rearrangement of molecules does take place in the glassy state (i.e. below T_g), albeit at a much slower rate. Furthermore, creep and stress relaxations are more pronounced in thermoplastics than in thermosets; crosslinks in thermosets restrict polymer chain mobility. The presence of fillers and reinforcements can further restrict creep. However, even in thermosets, one can observe chain rupture under large deformations.

Many experimental methods are available for creep measurement (Ferry, 1980). A sustained load is applied to a specimen in one of several standard configurations (such as tension, compression, or flexure) at constant temperature and the corresponding deformation is measured as a function of time. For FRP composites, a four-stage response is generally observed under creep: (1) rapid initial elongation of the specimen; (2) rapid reduction in response rate (primary creep, stage I); (3) steady state (secondary creep, stage II); and (4) a rapid increase in response and fracture (tertiary creep, stage III). FRP with glass fibers is expected to have very limited creep in the longitudinal direction, as compared to its transverse direction and under shear stress. For a purely elastic material, the stress-strain behavior is not dependent on time, even if it exhibits a nonlinear stress-strain relationship. This is because stress is a unique function of strain.

$$\sigma = E_0 \varepsilon$$
$$\varepsilon = J_0 \sigma \qquad (3.14)$$

This resembles the behavior of a spring. E_0 is the elastic modulus and J_0 is the elastic compliance. For a purely viscous material, such as a Newtonian fluid, the stress is proportional to the rate of strain. Polymers, as well as most real materials exhibit a combination of elastic and viscous responses, i.e., a spring and dashpot model (Maxwell model). More complex models representing the creep behavior are available and are not discussed herein.

Creep is a universal phenomenon and is exhibited by all materials, including metals, polymer composites and ceramics. For example, glass windows in churches are seen to sag over hundreds of years, i.e., long enough time of induced strain under sustained loads. It is extremely important to determine the creep coefficient of composites because of creep rupture, which becomes even more critical with increasing temperature under service (Franke and Wolff, 1988). A major mitigating factor is that all the common reinforcing fibers used in polymeric composites, with the exception of aramids, show negligible creep at room temperature and under a sustained load of about 25% of the FRP composite's ultimate rupture stress. However, the extent of creep can be influenced by factors such as, percent of sustained stress (beyond certain threshold) as a function of fiber type, rupture stress, void ratio, cure percent, temperature and exposure to moisture. These need to be accounted for in designing composites such as miter gates for their 75-100 years service life in civil applications.

3.4.8 Fatigue and Fracture

The long-term behavior and damage mechanism of FRP composite materials have been active areas of research during the past twenty years especially under fatigue loads. It is important that fatigue behavior and corresponding failure modes of FRP components and systems under long-term service must be understood properly. The behavior of FRP composites under tensile fatigue loading has been discussed by many researchers including Dittenber and GangaRao (2010).

Unlike homogeneous materials, FRP composites accumulate damage through crack propagation rather than developing localized damage, and fracture does not always occur by propagation of a single macroscopic crack. The damage accumulation in these materials is microstructural which includes fiber/matrix debonding, matrix cracking, delamination and fiber fracture (Mathews, 2000). Fatigue damage mechanism in unidirectional composites primarily depends on loading mode (e.g., tensile, compressive, bending, torsion or combinations) and on the loading direction i.e., parallel or inclined to the fiber direction. Typically, the damage mechanism in tensile fatigue is of three stages **(**Talreja, 1987) namely**:** fiber breakage, matrix cracking, and interfacial shear failure. This is true for compression fatigue, except that there could be buckling failure of fiber (Curtis and Dorey, 1986).

The damage process consists of two dominant stages: the first stage in which non-interacting cracks develop leading to Characteristic Damage State (CDS), wherein a stable crack pattern develops. The CDS is found to be independent of loading history and is determined by laminate properties, i.e., ply stiffness and ply stacking sequence. Beyond the CDS, in the second stage, the cracks of various types inter-connect with increasing rates (at lower number of fatigue cycles), causing increasing localization of cracks and consequent failure. Fatigue models are used to calculate the residual strength (R) based on the initial strength (R_0), residual strength for given number of cycles, applied stress, and material constants. In some of these models, strength degradation is assumed to result from the localized zones of damage which is conceptually replaced by a single crack capable of releasing the same amount of elastic energy as that released collectively by the various crack growth mechanisms. Residual strength is related to a characteristic dimension of the "equivalent" crack through a fracture mechanics type relationship.

Different aspects of FRP composite durability and the implication on designing structures for long-term field performance are discussed in following Chapter 4.

4. DURABILITY

Salt and moisture induced corrosion of reinforcing steel is a heavy burden on the US economy, which is of the order of $297 billion per year. It amounts to about 3% of the gross domestic product. In lieu of traditional steel reinforced concrete and steel structures with corrosion problems, glass and carbon FRP composites in the form of bars, fabrics, laminates, plates and shapes are being increasingly employed in structural applications. FRPs undergo changes in their thermo-mechanical properties with time. These changes are a function of temperature variations, humidity, freeze-thaw variations, pH variations, alternate wetting and drying, exposure to moisture in seawater applications, sustained stresses, and others. Existing literature reveals lack of adequate understanding of the several gaps in the long-term performance of Glass and Carbon Fiber Reinforced Polymer (GFRP and CFRP) composites (CERF-01 2001). This chapter highlights the parameters that affect durability of FRP products and suggests some remedial issues. The parameters that influence durability have been broadly introduced in nine different sections as discussed below.

4.1 Fiber and Resin Durability under Aging

Thermo-mechanical responses of FRPs can be significantly altered depending upon the type of resins and sizings used on fibers and their compatibility with each other. Several studies (ACI 440, CERF-01, CDCC'98, GangaRao et al. 1995, Polymer Composite Conference-2004, and several other studies) conducted over the last decade indicate that the FRP properties and performance quality vary with time. This variation is attributed to moisture ingress, freeze-thaw cycling, elevated temperature, UV exposure/ oxidation, cyclic or sustained loading, extreme temperature variation and/or chemical (e.g., alkalinity or pH variation) exposures. The degree of damage or deterioration depends on various factors such as the type and volume of fibers and resins, fiber sizing chemistry, severity of the external environmental agents such as pH and temperature values, cure conditions during manufacturing and quality control issues. Design guidelines and material selection criteria that consider the effects of mechanical and environmental loads must provide enough confidence in terms of 50-100 year service life of structural materials and systems.

The fibers in FRP composites are the main load carrying elements. The polymer matrix (cured resin) protects the fibers from damage, ensures good alignment of fibers, and allows in-plane force transfer between fibers. Fibers are selected based on strength, stiffness, and durability requirement for specific applications. Resins are selected based on the function (e.g., wet lay-up vs. factory manufactured) of FRP composite systems. Sizings, additives, and modifiers provide several functions such as fiber handling and resin wetting, durability against UV radiations, resistance to moisture transport, fire resistance and several others (GangaRao et al, 1995). Fiber types typically used in the construction industry are carbon and glass, with thermoset epoxy, vinyl ester, polyester, and urethane resins. Some advantages of GFRP and CFRP being commonly employed in structural applications include: non-corrosiveness, high strength to weight ratio, high stiffness, good thermal insulation, good impact resistance, and lightweight. Glass FRP (GFRP) is available with different types of glass fibers such as E-glass (alumino-borosilicate glass with less than 2% alkali, first used in Electrical applications), S-glass (strength glass), and others, wherein low cost E-glass is popularly used for structural applications. Carbon FRP (CFRP) is commercially available mainly as three types: high strength-low modulus, medium strength-medium modulus, and low strength-high modulus.

4.2 Moisture and Temperature Response of Composites

Moisture uptake in composites leads to matrix softening due to hydrolysis, reduction in matrix dominant properties of a composite, such as shear strength of composites, lowering of glass transition temperature and reduction in composite strength and stiffness. Mechanical property reduction is accentuated in the presence of stress and temperature (Springer, 1981). GangaRao et al. (2001) have extensively discussed relevant mathematical models, effect of aging on degradation mechanisms, and design factors related to moisture and temperature effects in their US Army Corps of Engineers Report.

Fickian or non-Fickian laws typically describe moisture ingress into FRP composites that depends on several factors: i) types of surrounding liquid/ environmental media (e.g., water, salt, acid, alkali), ii) pH concentration, iii) temperature, iv) magnitude of stress, v) amount of surface and internal voids, vi) interfacial bond between fibers, resin and “sizing”, vii) extent of fiber/ matrix debonding, viii) matrix cracking, ix) leaching and etching. For example, bulk fiber material degradation was observed in glass under alkaline environment (Adams, 1984). Mechanical properties of FRP composites decrease under elevated temperatures (40° C and higher) because of hydrolysis of resin.

4.3 Effect of Acid/Salt/Alkaline Solutions

Acid, salt and alkaline reaction of FRP composites leading to aging is a major durability factor to be considered in design. Available reports indicate the degree of severity of alkaline and acid reactions on strength and stiffness of carbon FRP. Some reports indicate that acids (e.g., hydrochloric, sulfuric, phosphoric, nitric) are more detrimental to CFRP than alkaline solutions (Kajorncheapunngam, 1999). Similarly, depending on cement content, and additives, concrete environment can be highly alkaline (~ pH=12.8) and may lead to a combination of alkali-silica reaction resulting in reduction of GFRP composite strength, stiffness, and toughness including fiber embrittlement (GangaRao and Vijay, 1998). (Ajjarapu, 1994) at CFC-WVU, suggested the rate of degradation of the composite materials under harsh environmental data conditions using an exponential form of an equation, where time (t) < 450 days. From the experimental data, it was concluded that the maximum strength reduction was 50% in 450 days. However, beyond 450 days, the strength did not change considerably. Because of GFRP composites application in marine and other structures, they are discussed with some elaboration in this section.

4.4 Durability of Glass

Glass composition, glass homogeneity, temperature, stress, and pH variation influence the changes in mechanical, thermal, and chemical properties of glass. Sizings and resins play an important role in protecting glass fibers. Chemical composition of E-Glass fibers is given by: SiO_2 (54.5%), Al_2O_3 (14.5), CaO (17), MgO (4.5), B_2O_3 (8.5), Na_2O_3 (0.5), and others (0.5%)**.** As seen, silica forms a major part of glass composition and it is the silica network that gets attacked during exposure to various environmental agents.

Alkaline attack: Alkaline attack on glass is described by two theories, viz., (1) etching (Adams, 1984), (2) hydroxilation and dissolution leading to notching. Etching is produced by an alkali attack. As the silica network is attacked, other components of the glass are released.

$$2\,x\,NaOH + (SiO_2)_X \text{ -----> } x\,Na_2SiO_3 + x\,H_2O$$

Hydroxilation and dissolution is caused by chemical hydroxilation of silica in the glass. Hydroxilation is associated with dissolution and is characterized by leaching of calcium from the glass. The leached calcium when combined with water, deposits a calcium hydroxide compound on the surface of the glass and drastically reduces the rate of reaction. Following hydroxilation and dissolution, etching (notching) is caused by the formation of calcium hydroxide crystals on the glass surface as found by X-ray diffraction analysis (Al Cheikh and Murat, 1988).

Acid attack: Acid attack leads to leaching process, where, hydrogen or hydronium ions exchange for alkali and other positive mobile ions in the glass. The remaining glass network, mainly silica, retains its integrity. It may become hydrated if the network is relatively unstable; or it may become more dense and stable than original glass. Acid reacts slowly with glass in comparison to reaction with alkali.

$$Na^+ + HCl \text{ -----> } H^+ + NaCl$$

Neutral pH solution attack: Water, salt and other solutions of neutral pH produce attack on glass similar to those of acids. Also, neutral or acidic solution attack on glass may in turn become alkali attack. Alkalies removed during acidic or neutral pH solution attack will again re-enter the solution surrounding the bulk glass and proceed to cause etching described earlier.

Effect of sizings: Glass and carbon fibers used as reinforcement in various FRP composite products such as bars, plates, cables, bridge decks, dowels and others are surface-treated with sizing agents to lubricate and protect the fibers surfaces, to modify the fiber surface such that it is more easily compatible with and wettable by resins, and to improve bonding between resins and the fiber surface.

Mechanical properties and durability of composite materials are strongly dependent on the interface between fibers and resin (Palmese, 1999, Liang, 1993). Sizings and surface treatments of fiber/fabric reinforcements play a vital role in composite performance: Surface treatment produces additional bonding sites on the fiber surface, while sizing enhances fiber processability with a protective coating on the fiber surface and can provide a coupling agent for the fiber/resin bond. Suppliers of glass fiber may offer 30 to 40 fiber products, where the primary difference between those is sizing adapted to various resin systems, molding processes and end uses (Mason, 2004). In contrast, carbon fiber manufacturers offer very few carbon products that are traditionally optimized for epoxies. The carbon/epoxy market mostly resides in the aerospace arena where qualification processes dictate what fiber, sizing, and matrix resin system are used - both in military and in many high-volume commercial applications. As carbon reinforcements find new applications including infrastructure uses, new processes and resin systems (non-epoxies) make sizing and treatment of carbon fiber as very important topics.

Optimizing a sizing for a particular fiber/resin system involves proper scientific knowledge. The sizings that work well on glass fibers with vinyl esters are designed to dissolve quickly into the resin, thus freeing up the silane coupling agents for reaction with the resin and providing good bonds. But in the case of carbon, a quickly dissolving sizing would free up the carbon fiber surface that is non-reactive to the vinyl ester, and a good interface is not formed. Hence, controlled solubility is required with carbon fiber sizing so that it partly dissolves in the resin, but does not completely leave the fiber interface (Mason, 2004).

An enhanced report is required to include FRP fiber response under environmental agents and sustained stress using principles of accelerated aging, time-temperature-stress superposition including Arrhenius temperature dependence concept, keeping in mind the relative advantages and limitations of this concept. Attempts are being made by many researchers to gain better understanding on aging of FRP composites under harsh environments (ACI 440 documents).

Effect of Nanoclay: Nanoclays consist of nanoparticles that have at least one dimension at the nanometer size. When the nanoclay is mixed with resin and exfoliated, they possess properties ideal for reducing the moisture/chemical diffusion rates. However, selection of appropriate nanoclay involves number of variables including morphology, cation exchange capacity, aspect ratio, charge density, degree of purity, ability to exfoliate, and others. Some of the advantages of nanoclays even at low concentrations of 2-6 wt % are: i) reduction of diffusion rates; ii) improvement in dimensional stability of a part; iii) increase in product stiffness; iv) enhancement of energy absorption and increase in ductility 2-4 times; and others. Some of the limitations of use of nanoclays are: i) higher resin viscosity (Chen and Curliss 2003) and ii) higher specific weight than neat resin by 1-2%.

4.5 Creep Rupture

Creep (stress) rupture also called static fatigue refers to the tensile fracture of a material subjected to constant sustained high stress levels during the service life of a structural element when the material reaches its strain limit. Time required to rupture under creep loads (endurance time) decreases with increasing ratio of the sustained tensile stress to the short-term strength of the FRP. It should be noted that carbon fibers exhibit better creep characteristics as compared to glass fibers (Vijay and GangaRao, 1998). Effect of different stress levels on the stress-strain curve (creep and recovery) need to be included or provide proper design insight into realistic application of creep factors for design purposes. Creep behavior is significantly dependent on creep properties of the resin. Resin creep behavior will be significant if the FRP sheet/ laminate is bi-directional. Many codes such as ACI typically use a conservative factor, λ, to account for creep and these should be elaborated in an enhanced report.

4.6 Fatigue

The mechanical durability of composites depends on several factors, which include constituent materials (fibers and resins), manufacturing methods, freeze-thaw fluctuations with and without external load fluctuations and others. This section focuses on the state-of-the-art of fatigue under mechanical loads and combined effects of temperature and thermal fluctuations under external loads. The failure mechanisms are very complex in composites under harsh environments, and also under variable loading with time, which include thermal and mechanical fatigue. The interaction of failure mechanisms of the constituents can lead to faster deterioration of composites than the constituents themselves. For example, moisture absorption leading to matrix swelling can degrade mechanical properties of a composite faster than the constituents. Similarly, elevated temperatures, thermo-mechanical fatigue, humidity and corrosive fluids can shorten the service life of a composite.

Proper accounting of the thermo-mechanical fatigue response is important for the durability and the safety of a structure. When a material is cyclically loaded in the presence of freeze-thaw effects and pH variations, then the term environmental fatigue is generally used. Fatigue performance is influenced by: (1) constituent material properties and their volume percents (2) fabric architecture, (3) fiber/matrix interface bonding, and (4) type of induced load (Konur and Mathews, 1989). Discernable deterioration from weathering on FRP involves exposure of fibers, surface microcracking and weight loss (Kamal and Saxon, 1967), and other influences such as pH levels and UV exposure. (Scott and Paul, 1974) concluded that three years of weathering had small (~10-20%) loss effect on strength of glass-epoxy composites, while substantial degradation was noted under long-term exposure.

Fatigue Predictions: Unidirectional composites under fatigue have been characterized by a constant degradation rate in strength and/or stiffness with the number of cycles to fatigue (Whitworph, 1987). Dharan (1975) proposed a three-stage S-N curve, each with a distinctive damage process. High stress regions lead to a shorter life (~100 cycles) with local fiber failure as the primary cause. At intermediate life (100-1000000 cycles), fractures accumulate slowly without any catastrophic failures where matrix microcracks perpendicular the loading axis develop, propagate and eventually break the fibers. However, induced stresses below the levels needed for matrix microcracks can endure more than a million cycles.

For laminated composites, generic fatigue damage patterns have been described by (Reifsnider et al, 1983). The fatigue response (S-N curve) was divided into three regions corresponding to: (1) matrix cracking through the thickness of the off-axis plies, (2) matrix crack growth along the interface resulting in ply delamination and (3) accelerated damage rate caused by delamination resulting in failure. A 10-20% sudden drop was noted in the initial stiffness of unidirectional glass composites before stabilizing to a gradual stiffness loss per cycle (Natarajan et al., 2005). For unidirectional carbon composites with epoxy, the initial stiffness drop was much less apparent than in glass composites (Hahn, 1978).

FRP composites under fatigue revealed that the internal strain energy of the material is expended as externally induced work increases. The expended strain energy or damage is accumulated through matrix cracking, fiber delamination, and eventual fiber breakage, which were observed beyond 90% of the fatigue cycles to failure (Natarajan et al, 2005). The expended energy is found to be a function of: (1) maximum induced strain, (2) strain range, (3) number of fatigue cycles, (4) loading type, and (5) properties of composite specimen.

The expended energy of a specimen under fatigue, U_f, before failure is computed from a large pool of experimental data. Natarajan et al, (2005) established that U_f is 50% higher than U_0, which is the strain energy under static mean load to failure of a composite specimen. For design purposes, the number of fatigue cycles of the test specimen corresponding to stages 1 and 2 is found to be 90% of the number of cycles to failure. Therefore, Natarajan et al (2005) have defined the design fatigue life of a glass composite specimen as 90% of cycles to failure or breakage of a specimen. The energy release rate per cycle was found to be constant for varying applied stress ranges, fabric architecture and rate of fatigue less than 5Hz; however it is the characteristic of the constitutive materials. The fatigue life of a composite has been analytically established through power law (Natarajan et al, 2005):

$$N_f = \frac{U_0}{2a\left(\varepsilon_m / \varepsilon_u \right)^b} \tag{4.1}$$

Where, U_0 is the static strain energy under tension or bending which can be computed by assuming a linear stress-strain response to failure of glass fabric reinforced polymer composites, and “a” and “b” are constants depending on type of composite and loading, ε_m is maximum strain under imposed load, and ε_u is ultimate strain. This is a very reasonable assumption since numerous researchers reported these trends and errors in life prediction models were found to be less than 10% of experimental data.

4.7 UV Effects:

The creep behavior of a variety of polymeric materials under UV exposure was investigated by (Regel et al, 1967). In their studies, specimens under sustained loads were irradiated with UV radiation from a lamp. It was found that during the short time period that the UV radiation was turned on, the creep strain increased sharply. The creep rate returned to the starting value without radiation. Similar procedures using the infrared (IR) part of the spectrum did not yield similar results. Regel et al. (1967) attributed bond breakage as the intrinsic mechanism of degradation. Their experiments involving stress-relaxation indicated that UV also increased the rate in stress-relaxation. Therefore, structures exposed to UV rays can exhibit higher strains under self-weight.

4.8 Temperature, Freeze-Thaw, and Mechanical Load Cycling-Combined effects

The combined effects of temperature and dynamic loading on composites are difficult to find in the literature. An investigation was conducted by (Kellogg, 2005) on FRP composite's effects under moisture, low temperature and load rate. Specifically, impact toughness of a pultruded glass-fiber reinforced polymer composite was evaluated on the parallel-to-the-fiber notched specimen. The results revealed that the load rate has the greatest influence on fracture sensitivity for a notched specimen where as the rate of increase of loading results in increased mean notch toughness values for wide ranges of moisture content or temperature. It was also determined that as temperatures are reduced below -25°C, the mean notch toughness increased for all test groups, which can be attributed to stiffening effects of polymer composites at low temperatures (Dutta, 1995). At room temperature, the effect of moisture is dependent upon the rate of loading. At low load rates, absorbed moisture is beneficial to fracture sensitivity, but at high load rates the absorbed moisture tends to reduce the notch toughness of the composite.

The greatest concern with temperature effects on composites is the laminate debonding under freeze/thaw cycling or fatiguing, because of moisture expansion upon freezing. Freeze-thaw in the presence of salt can also result in accelerated degradation due to the formation and expansion of salt deposits in addition to the effects of moisture induced swelling and drying (Chin et al, 2003). When exposed to other environmental factors in addition to freeze-thaw fatiguing, composite degradation is compounded. Despite the lack of a standard method, significant research has been conducted to evaluate the effects of freeze-thaw cycling on the performance of FRPs.

Time-temperature-stress Superposition Principle: Using time-temperature-stress superposition principles, polymer composite material property such as time dependent stress at one temperature can be used to find those properties under another temperature, with certain restrictions and calibrations. Arrhenius principle states that rate at which chemical degradation occurs is dependent on temperature. This principle can be judiciously employed to exploit the temperature dependence of polymers subjected to environmental aging consisting of several temperature levels.

$$k = Ae^{-E_a/RT} \quad (4.2)$$

k= Reaction rate constant with respect to a temperature T, A = "pre-exponential factor", E_a= activation energy for reaction, T = temperature in Kelvin; R=Constant.

This principle is employed to calibrate naturally aged results of FRP fibers and fabrics at ambient temperature with accelerated aging curves (Litherland and Proctor, 1986, Vijay and GangaRao 1999).

4.9 Reduction (Knock-Down) Factors:

Applying durability factors leading to reduction (knock-down) in the strength and stiffness of FRP structures is an essential element in the design of various FRP composites used as internal and external reinforcement for new and rehabilitated structures. Some of these factors have been developed by professional societies and reported in their specifications or guide-specifications (ACI, MIL, ASCE etc.). These knock-down factors have to be incorporated in the design of any FRP structures. Chapter 5 deals with micro-mechanics approach used for analyzing composites including numerical modeling

5. MICROMECHANICS, MODELING AND TEST METHODS

A brief description of micro-mechanics approach used for analyzing composites including numerical modeling is provided in this chapter along with currently available test methods. Additional details on test methods are provided in Appendix C.

5.1 Micromechanics approach

Micromechanical analysis of composite materials takes into consideration the geometry of the microstructure, and the properties of the constituents (fiber and matrix). Representative volume element (RVE) is the smallest portion of the composite material that contains all the properties of the material (Fig. 5.1). Because the composite is heterogeneous material, stresses and strains are non-uniform over the RVE. However, to simplify the calculations, the volume occupied by RVE can be replaced by equivalent homogenous material when looking at a larger scale than the RVE dimensions.

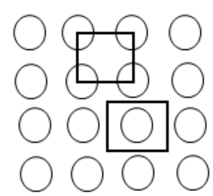


Figure 5.1: Example of RVE in composites (Mallick, 1993; Barbero, 1999).

Rule of Mixtures (ROM)

In isotropic materials, the relationship between Young's modulus (*E*), Shear Modulus (*G*), and Poisson's ratio (*ν*), is known from the classical mechanics of materials approach:

$$G = \frac{E}{2(1+\upsilon)} \tag{5.1}$$

For a given RVE, assuming that both the matrix and the fiber are elastic isotropic materials, the strain in longitudinal direction, ε_1, is defined as: $\varepsilon_1 = \frac{\Delta L}{L}$, where, ΔL is the change in length of RVE under state of stress, and L is the original length of RVE.

Therefore, the stress of the fibers and matrix can be written as:

$$\begin{aligned} \sigma_f &= E_f \varepsilon_1 \\ \sigma_m &= E_m \varepsilon_1 \end{aligned} \tag{5.2}$$

where, the cross section *(A)*, of the RVE is given by: $A = A_f + A_m$ (5.3)

The total load on RVE is: $P = \sigma_1 A = \sigma_f A_f + \sigma_m A_m$ (5.4)

$$\text{or, } \frac{P}{A} = \sigma_1 = \sigma_f \frac{A_f}{A} + \sigma_m \frac{A_m}{A} = \sigma_f V_f + \sigma_m V_m \qquad (5.5)$$

Where, V_f and V_m, are the volume fractions of fiber and matrix.

The equivalent longitudal modulus can be found as $E_1 = E_f V_f + E_m V_m$ ……… (5.6)

Similar approach can be used to fin the transverse modulus, E_2:

$$\frac{1}{E_2} = \frac{V_m}{E_m} + \frac{V_f}{E_f} \quad \ldots\ldots\ldots\ldots \quad (5.7)$$

In-plane Poisson's ratio, ν_{12}, is given by: $\nu_{12} = \nu_f V_f + \nu_m V_m$ …………………... (5.8)

In-plane shear modulus: $\frac{1}{G_{12}} = \frac{V_m}{G_m} + \frac{V_f}{G_f}$ ………………………… (5.9)

Different properties of composites and equations discussed earlier in Chapter 3 are based on the above discussed model (ROM) and other models. ROM clearly explains the different properties of composites in different directions. Further steps are necessary to find the constitutive stiffness equations of a laminate as a stack of layers in different directions and find the equivalent apparent properties for design purposes. Using the stiffness matrix of a whole laminate, one can predict the strains and stresses in the laminate and consequently, the strains and stresses in each layer. Such descriptions and corresponding equations for linear and curvilinear elements are available in several sources but are not included due to limited scope of this work.

5.2 Numerical /FE models

Macro scale analysis (Laminate level): Some current finite element software packages such as ANSYS analyze a composite structure by computing the stiffness matrix for a laminate with a given stacking order, and use it as an input for analyses. This kind of analyses is adequate to calculate the deformation response for buckling or dynamic loads and even to analyze for strain distribution throughout the laminate thickness, under certain load types. However, void content, inadequate cure, fiber misalignment etc. cannot be accounted for the stiffness matrix computations.

Meso-scale analysis (ply level): For calculation of strains and stresses at each ply, some FE packages (i.e. ANSYS) accept the input of the stacking order of a given laminate along with all the parameters for each ply including material elastic properties, thickness, and direction of each ply with respect to general laminate coordinate system. The software calculates the stiffness matrix of the whole laminate, and, eventually strain and stress components at each ply for a given geometry and loading.

5.3 Standard test methods for FRP bars and laminates

ACI 440, ASTM, CEN (European Committee for Standardization), CSA (Canadian Standards Association), and JSCE (Japan Society for Civil Engineering) provide guidelines on different test methods. These guidelines provide details about preparing the samples, conditioning the specimens, test procedures, and calculations. Some of these are listed in Tables 5.1 and 5.2. It should be noted that these tables do not provide a complete list and some related aspects and specifications are also listed in appendix C.

Some of the standard test methods available for testing FRP laminates and bars are provided in Tables 5.1 and 5.2. Brief description on these standards is provided in Appendix C. Many of these specifications have been developed after the publication of ETL 1110-2-548. These specifications are useful for both updating the information presented in ETL 1110-2-548 and design of FRP structures.

Table 5.1: Available standard test methods for FRP laminates used as strengthening or repair materials adopted from ACI 440.3R-04

Property	**Test method**	**Property**	**Test method**
Direct tension pull-off	ASTM-D4551 ACI 440-L.1	Tensile strength and modulus	ASTM-D3039 ACI 440-L.2
Lap shear strength	ASTM-D3165 ASTM-D3528 ACI 440-L.3	Bond strength	ASTM-D4551 ASTM-DC882

Table 5.2: Available standard test methods for FRP bars used for reinforcing or prestressing concrete adopted from ACI 440.3R-04

Property	Test method	Property	Test method
Cross-sectional area	ACI 440 –B.1	Longitudal tensile strength and modulus	ASTM-D3916 ACI 440-B.2
Bond properties	ASTM-A944 ACI 440-B.3	Shear Strength	ASTM-D5379 ASTM-D3846 ASTM-D2344 ASTM-D4475 ACI 440-B.4
Bent bar capacity	ACI-B.5	Durability properties	ACI 440-B.6
Fatigue properties	ASTM-D3479 ACI 440-B.7	Creep properties	ASTM D-2990 ACI 440-B.8
Relaxation properties	ASTM-D2990 ASTM-E328 ACI 440-B.9	Anchorage properties	ACI 440-B.10
Tensile properties of deflected bars	ACI 440-B.11	Effect of corner radius on strength	ACI 440-B.12
Flexural properties	ASTM-D790 ASTM-D4476	Coefficient of thermal expansion	ASTM-E831 ASTM-D696
Glass transition temperature	ASTM-E1356 ASTM-E1640 ASTM-D648 ASTM-E2092	Volume fraction	ASTM-D3171 ASTM-D2584

Chapter 6 deals with the fabrication and field implementation details of FRP composite construction and/or field rehabilitation.

6. FABRICATION/FIELD IMPLEMENTATION

Fabrication and field implementation of FRP structures consist of different operations carried out during and after manufacturing at the plant or onsite. Several FRP shapes such as wide flange beams, I-beams, channels, angles are available as standardized off-the-shelf commodities by various manufacturers. Though the dimensional configurations of these standardized shapes may be same, the fiber/fabric/resin configurations and corresponding thermo-mechanical/durability properties vary widely.

As a first step towards fabricating FRP structures, all the required components (e.g., shapes) are manufactured with or without inserts to design configurations and dimensions that conform to required specifications and tolerances with due consideration to QA and QC. Some of these fabrications may require high degree of customization including hybridization (with the use of other materials). Next step involves trimming/cutting the components to required dimensions and drilling necessary holes/openings so that the parts can be assembled in the manufacturing plant or onsite. This will be followed be joining schemes that could be a combination of mechanical fastening (e.g., bolts and rivets) or adhesive bonding. Following joining/embedment of parts, necessary final finish is provided in the form of sealing open holes or exposed fabrics to avoid moisture ingress or provide protective UV coatings or paints. Transportation and field handling of these fabricated parts are lot easier as compared to heavy materials made of steel and concrete. Above discussed fabrication steps may also involve hand-layup. Hand-layup and field application of wraps are discussed in Chapters 3 and 4.

6.1 FRP Bonded Joints

Joints are essential in FRP structures due to fabrication considerations where complex structures come in different pieces which require different attachments. In addition, design constraints due to low transverse modulus of FRP create major issues in terms of joining mechanisms (ASCE/ACMA-LRFD Draft Manual, 2010).

6.2 Adhesively Bonded FRP joints

Strength and stiffness of adhesively bonded FRP joints are affected by certain parameters and they are listed below (GangaRao and Palkamsetty, 2001):

- Bonded joints are controlled by two critical stress patterns, which are shear stress due to unequal strains of the adherents and peel stress induced at the free edge of the lap joint under eccentric loads.

- Stress concentrations at the joints are affected by thickness of the adherents, overlap length of the bond, thickness of the adhesive and stacking order of the laminate, while residual stresses during curing are considered a function of the adhesive thickness.

- Joint effectiveness is affected by adherents' thickness, fiber volume fraction, geometry, effective adhesive length, and fiber direction.

- Stiffness of bonded joints depends on the adhesive properties, adhesive thickness, stress distribution and inter-laminar shear modulus of the adherents.

- Joints may fail due to adherents' failure, which may be under peel stress or through the thickness, adhesive failure or even failure due to creep.

Additional details on a design approach for lap joints in composites and other types of connections are presented in GangaRao and Palkamsetty (2001) and Mossallam (2001).

6.3 Out-of-plane FRP Joints

Connections between two structural FRP members represent a zone of potential weakness particularly, when the two members are orthogonal to each other. In such cases, load transfer takes place in an out-of-plane mode causing stress concentrations. Two types of joints are mainly used in marine structures: top-hat stiffened single skin, and sandwich configurations.

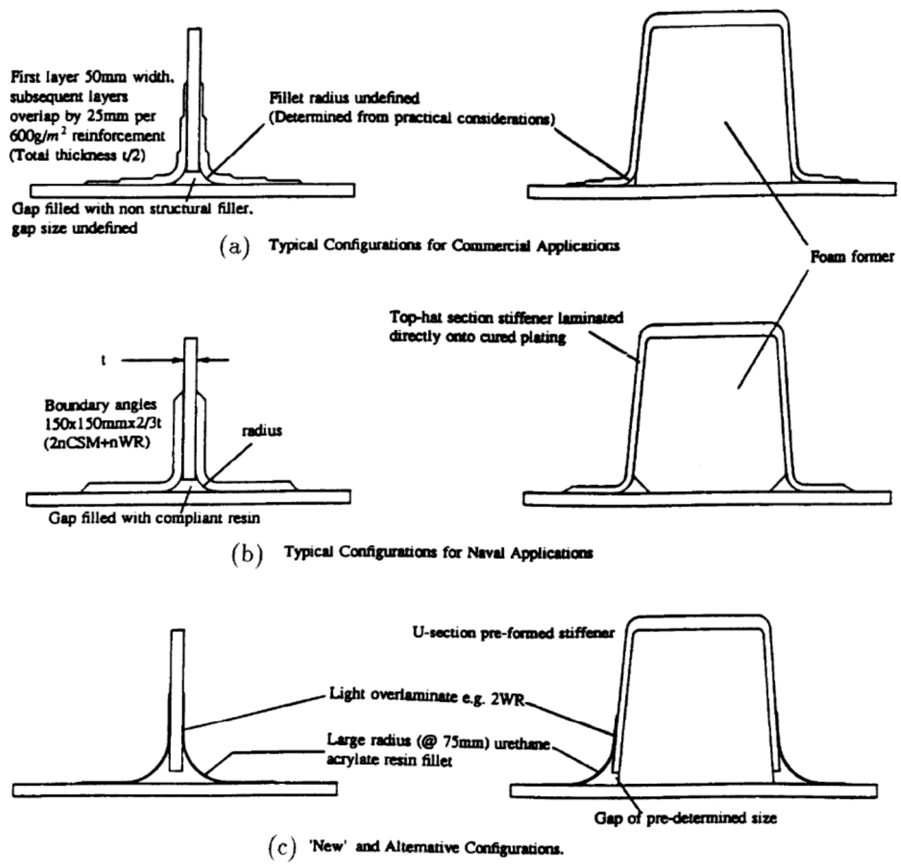


Figure 6.1: Tee-joint and top-hat stiffener configurations. (Junhou et al, 1996)

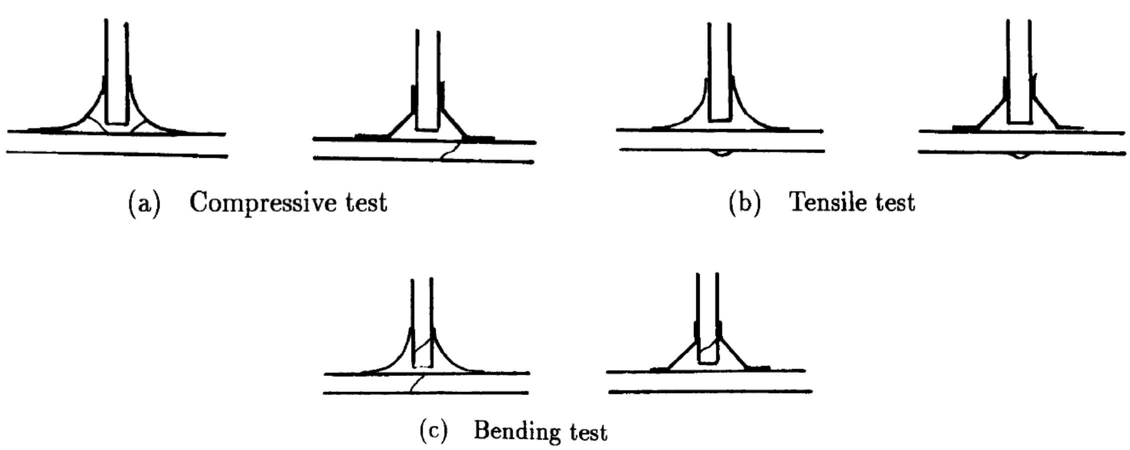


Figure 6.2: Failure modes in sandwich t-joint (Junhou et al, 1996)

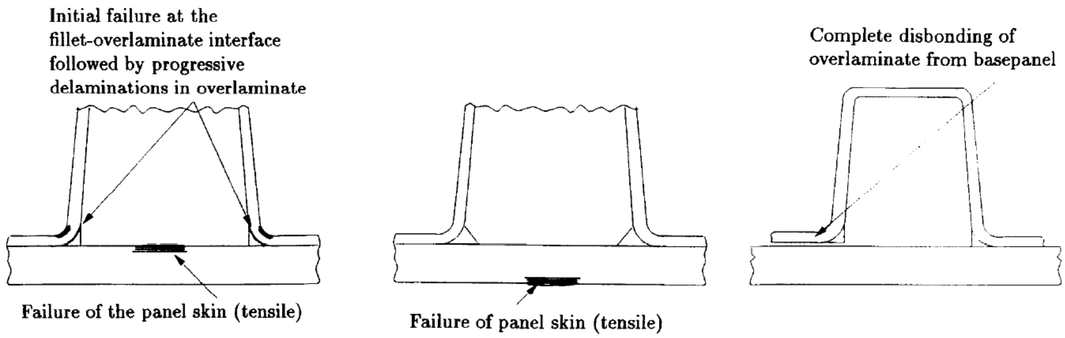


Figure 6.3: Failure modes in top-hat stiffeners (Junhou et al, 1996)

Special attention should be paid to the design of joints, since buckling is a major issue in laminates subjected to compressive stresses where the need for out-of-plane joints arises. Unlike conventional materials, unidirectional FRP composite joints are weak in transverse modulus, which are primarily dominated by the matrix properties.

6.4 Fabrication and Installation

FRP fabrication is done by several manufacturing methods. Steps associated with these methods are discussed under manufacturing and are available in several documents. Methods suitable for field fabrication include hand layup and with some modification to the scale of operation. Other methods such as filament winding could be used for large scale fabrication of parts such as cylindrical chimney liners (Fig. 6.4). Some of these methods are perfected through experience, i.e., by trial and error method.

Fabrication of these parts accounts for structural supports and connections, site and environmental conditions, and accessibility. For example, plastic pipes such as those of HDPE used as a part of marine applications can be field fabricated on ground and temperature variations could cause a dimensional change in excess of 1% due to high thermal expansion and contraction (e.g., 4" in a 32'long pipe). HDPE pipe will require more supports to prevent excessive deflection due to temperature variation. FRP pipes can be utilized for both the underground burial and above ground installations. FRP can be fabricated on both ground and on a pipe platform (supporting bridge). Stiffness (modulus of elasticity) of HDPE and FRP pipes differ by an order of magnitude, where stiffness of HDPE is about 100 ksi and that of the FRP is slightly less than 2000 ksi in the axial direction and in excess of 4000 ksi in the hoop direction.

HDPE welding (bonding) requires heavy and bulky tools, whereas fabrication of FRP pipes can be carried out with light tools. Deflection criteria are important for above ground pipes and minimizing radial stresses due to soil are important for buried pipes. Unlike unreinforced and isotropic HDPE, FRP pipes can be strengthened as required in the longitudinal and radial (hoop) directions to withstand stresses and high fatigue stresses caused by varying load cycles. Large FRP cylinders used as chimney liners are typically fabricated in manufacturing plants set up either close to the construction location or transported to the field (Fig. 6.4).

Figure 6.4: FRP composite chimney liner fabricated in field-plant through filament winding and used for smoke stack in a coal power plant, Morgantown, WV
(Courtesy: CFC-WVU)

Similar to the issues mentioned in this chapter, fabrication aspects specific to the implementation of FRP hydraulic gates including their hybridization (e.g., use of non-FRP inserts and steel frames), joining methods, transportation, field-handling, field-installation, and durability of areas subjected to wet-dry conditions require additional work with a larger scope. Chapter 7 gives a brief overview of non-destructive techniques (NDT) that can be used for evaluating manufacturing or field-service related damage and implementing QA/QC.

7. INSPECTION

This Chapter highlights different traditional NDT techniques that can be used for FRP inspection and as a QA/QC tool. These techniques include visual inspection, tapping, acoustic emission (AE), thermography, ultrasound, and x-ray radiography. Some examples of application of NDT techniques to FRP structures is also provided in this section.

7.1 Visual Inspection

Visual inspection is the most important and simplest technique. The inspector should consider the overall visual appearance of the entire structure for general appearance, noting the presence of discoloration that may be the result of improper wet out or overheating. Improper curing and even accidental resin substitutions could be detected by large-scale changes in color. In addition, large-scale debonding of a subsurface ply may be visible as lighter/darker areas. On the other hand, the inspector should look for local defects. The ASTM-D2563 “Standard Practice for Classifying Visual Defects in Glass Reinforced Plastic Laminate Parts” specifies three different categories of quality through visual inspection.

7.2 Tapping

By tapping the structural surface, an inspector can detect changes in the emitted sound due to tapping. This technique can be employed for detecting many common FRP imperfections by combining it with visual observations. This approach provides immediate clue for further inspection, with methods that are more accurate. Modern tap hammers are instrumented with electronic output devices that provide quantitative recordable readouts that can be correlated to delaminations in the structure.

Figure 7.1: *Electronic Digital Tap Hammer* from WichiTech Industries, (wichitech.com)

7.3 Acoustic Emission (AE)

Acoustic emission testing identifies and locates active defects in laminates by detecting minute acoustic impulses that are generated as a defect propagates under load. A major advantage of this procedure is its ability to monitor an entire part of a structure.

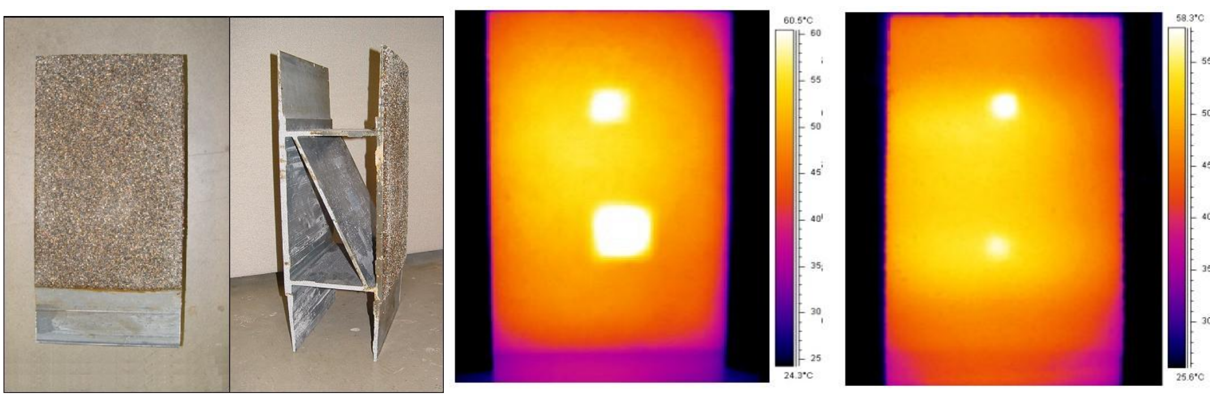
The system consists of a specialized mixer and amplifier that feed sensor data to a signal analyzer. Most current systems can monitor 20 transducers simultaneously and analyze the input signal for arrival time, amplitude, and duration. This information can be organized and displayed graphically. Guidelines for procedures related to AE on FRP are provided by ASTM E2478-06a, ASTM E1067-07, ASTM 2076-05, ASTM F1430, ASTM E1888-07, and ASTME1118-05 (Re. Appendix C of this document).

Figure 7.2: Single channel handheld AE device with sensor and accessories, (www.envirocoustics.gr)

7.4 Infrared Thermography

NDT techniques such as infrared thermography have been developed as potential tools for detecting in situ condition of FRP bridge decks (shapes) and detection of subsurface defects. Presence of subsurface defects such as debonds and delaminations formed during initial construction and in service can adversely affect the structural integrity and service performance of the FRP bridge decks. IR imaging allows a fast, non-contact overview of structure, provides a global assessment of potential defects, such as large inner-surface thickness irregularities and voids in the laminate, and does not require expensive equipments (Figs. 7.3 and 7.4, Halabe et al., 2007).

The infrared technique was used to detect these embedded subsurface defects. Surface temperature-time curves were established for different sizes of delaminations and debonds. In addition, field study was conducted on a FRP bridge deck to detect debonds between the wearing surface and the underlying deck. The laboratory and field testing results show that infrared thermography is a potentially useful tool for defect detection in FRP composite bridge decks. This technique can be potentially used for several other applications such as quality control during pultrusion of new FRP composite shapes (in factories) including those for miter gates, during field construction, and for field inspection of in-service FRP structures (Halabe et al. 2007).



(a) (b) (c)

Figure 7.3 (a) Front and c/s views of the GFRP bridge deck specimen with wearing surface (left picture); Infrared image of the GFRP bridge deck specimen (b) air-filled debonds (2” to 3”) and (c) air-filled debonds (1/2” to 1”) (Halabe et al. 2007)

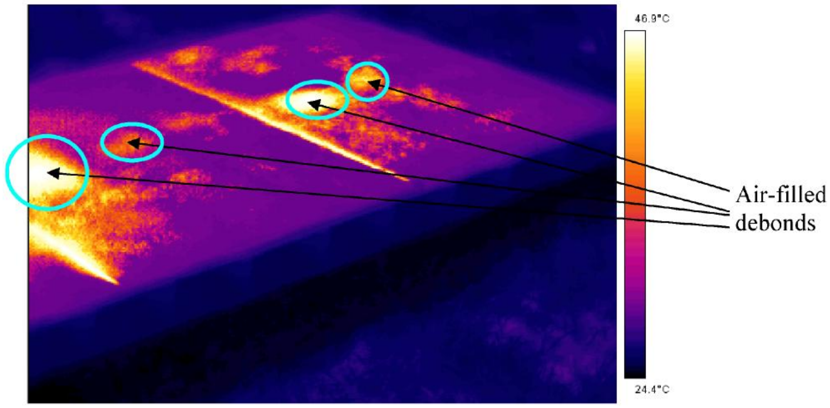


Figure 7.4: Debonds in FRP bridge deck detected by IR camera, (Halabe et al, 2007)

7.5 Ultrasonic

Digital ultrasonic thickness measurement instruments are available to quickly and accurately measure the thickness of FRP parts without access to both sides of the laminate. This technology depends on the fact that ultrasonic waves penetrate materials at different speeds depending on their density and type. In case of cracks or voids, ultrasonic devices can pickup arrival time of the reflected waves and estimate the location of voids. It also can be used for thickness measurement (Ray et al, 2007).

Figure 7.4: On-site ultrasonic inspection, (www.olympus-ims.com)

7.6 X-Ray Radiography

The X-ray technique used on FRP is relatively low power and produces high-resolution results allowing differentiation between the corrosion barrier and structural wall. Gauge blocks in the image plane are required for valid thickness measurements. It is also noted that X-ray differentiation techniques are commonly used for micro-level study of aged FRP.

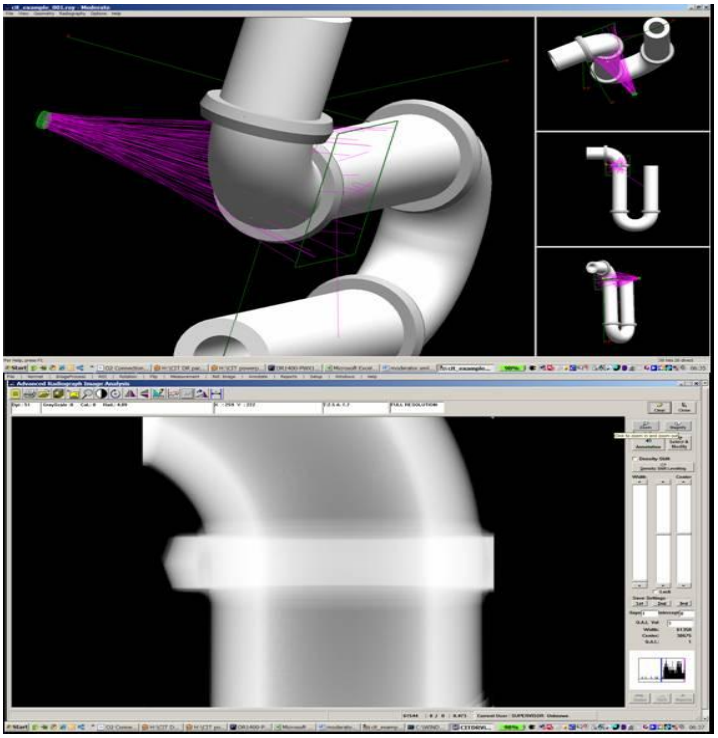


Figure 7.5: Illustration of typical radiographic inspection of a pipe, (www.cituk-online.com)

NDT techniques discussed in this section and other methods under consideration for FRP applications should be included in any future revisions to the document ETL1110-2-548. Chapter 8 deals with repair of FRP wrapping including hand-layup methods.

8. REHABILITATION/REPAIR OF FRP

FRPs have been used to repair structural elements because of their high strength to weight ratio. In addition, the emergence of resins that can cure under water and allow FRP to be bonded to wet concrete has made it possible to extend the application of FRP for emergency repair to substructure elements (Figs. 8.1 and 8.2).

In 2007, Sen and Mullins reported the applications of FRP wraps to repair submerged bridge piles. In the case of Friendship Trails Bridge, FL, 77% of its 254 piers needed repair which is an indicator of very aggressive environment. They used Aquawrap® Repair system with water activated urethane resin, and Tyfo® SEH-51A with Tyfo® SW-1 underwater epoxy.

Figure 8.1: Damage to pile requiring emergency repair (Courtesy FDOT), Sen and Mullins, 2007

Some of these Aquawrap systems used for underwater applications consist of resin saturated fabrics that can be bonded to the concrete substrate. Figure 8.3 summarizes the results of the pullout tests performed 2-years after the wrapping had been completed to evaluate the FRP-concrete bond. The results from the bond tests showed that the wet lay-up system performed better particularly in the partially wet and submerged regions.

Figure 8.2: Underwater repair using a boat and divers (Courtesy Air Logistics), R. Sen and G. Mullins, 2007

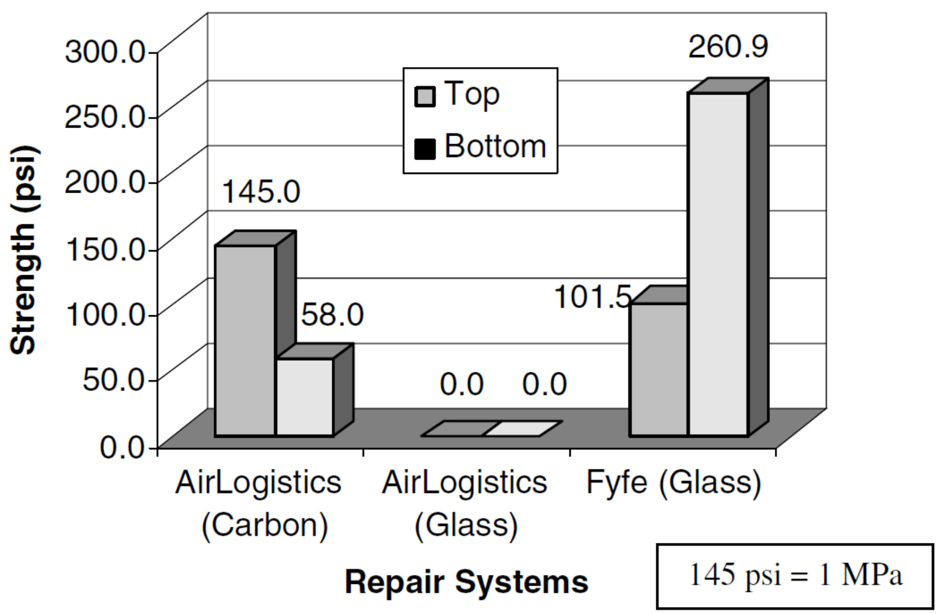


Figure 8.3: Maximum residual bond strength after 2 years, (R. Sen and G. Mullins, 2007)

Rehabilitation of concrete and timber bridge and viaduct structures carried out by CFC-WVU using glass or carbon fabric FRP in the last decade are shown in Fig. 8.4. These measures were implemented at a fraction of the replacement cost and resulted in significant cost savings.

Fig. 8.4 Design and field implementation of FRP wrap rehabilitation of timber piles, precast concrete beams, and concrete viaduct (various locations in WV, USA) by the CFC-WVU (Courtesy: CFC-WVU)

8.1 Material Selection

Depending on the application (underwater repair or dry conditions), materials could be selected for wet-lay up or open-and-use prepreg (fabrics pre-impregnated or pre-saturated with resins) kits. The most commonly used types of fibers in civil structures are glass and carbon. They can be selected as uni- or bi-directional woven fabric, and most commonly used resin systems are polyesters, vinyl ester, epoxy, and phenolics. Vinyl esters provide higher strength than polyesters, while epoxy resin is considered to be a high performance resin.

8.2 Access and Repair Equipment

Access equipment: The major equipment required for repair operation is the one that can provide access to the location of the repair (Fig. 8.5). A bridge might need special scaffolding, crane, or truck mounted bucket platform for access under a bridge deck or for the sides of a bridge. For under water repairs, boats and divers could be needed.

Repair equipments: Normally they are simple equipment like pressure wash machines, sanders, grinders, mixers, and lay up rollers.

Figure 8.5: Bridge inspection using truck mount bucket, (www.facelift.co.uk)

8.3 Repair Procedures for Concrete Substrate and Evaluations

Generally, the repair consists of following six steps and additional details can be found in respective repair guidelines and specifications provided in Appendix C. Post-repair evaluation can be done immediately by visual inspection to make sure that there are no apparent voids that need to be fixed. Using any of the NDT methods discussed in Chapter 7 assures that the cured product meets the design requirements. Following are the general steps used while repairing concrete or timber structures with FRP.

1. Cleaning the repair location using pressure wash or suitable equipment.

2. Sanding the surface of the structure at the repair location to remove damaged surface, and sharp angles.

3. Grinding the surface to provide roughness, vacuuming and dyeing the surface for better bonding of fabric to concrete substrate.

4. Applying primer coat.
5. Applying resin coat, and then fabric/fiber layers alternatively to build the required thickness for strength and stiffness, if necessary.
6. Applying protective topcoat.

Following repair/rehabilitation procedures, representative samples are taken for lab-testing and complying with governing codes. It should be noted that repair of FRPs with FRPs is not as prevalent and need to be properly evaluated with respect to compatibility of repair materials.

8.4 Repairing of FRP Structural Shapes

FRP structural shapes with local damage can be easily repaired. Repair can be either local or piecewise (sectional) replacement to match or exceed the existing strength/stiffness levels of the damaged section. Similarly, rehabilitation can also be carried out easily on undamaged sections to meet new operational requirements to restore accidental damages caused during their service life or increased load capacities of a structure, i.e., hydraulic gates. Failure can be due to: i) increased stress levels than original design and/or design inadequacies, ii) abrasions, impact/collision or other extreme force, iii) joint/connection failures, iv) manufacturing defects including QA/QC issues, v) aging of constituent material or bond between fiber and matrix, and vi) others.

Some of the damage types and their repairs commonly carried out on composites used in boats and marine applications are illustrated in Figs. 8.6 to 8.9 including sandwich composites (Green E., 1999). Localized damages that are not a serious structural threat can be corrected by using FRP fabrics and resins by removing loose materials, patching with fabric and resin, and localized curing with heat or RF (radio frequency). To correct a serious structural damage/failure or to accommodate increased design loads or design inadequacies, a thorough reevaluation of the stress distribution in a structural element is needed to determine proper repair scheme. When the failure is caused by an unusual or catastrophic event, repair work should evaluate the merits of sectional replacements or laminate bonding as appropriate. For example, FRP box section crushed under truck load on a WV farm bridge will need sawing of the crushed part and partial replacement (Fig. 8.10). Careful planning, design, material selections, and proper FRP member preparation at the repair site are essential for the success of repair. A field repair procedure requires stringent surface preparation with no dirt deposition before repair, proper surface temperature, and application of localized pressure. Sometimes local vacuum bagging will help create the necessary resin flow and fiber saturation, including pressure application to perform an effective repair.

8.4.1 Planning for Repair and Selection of Materials

After evaluating the damage type and extent, types of materials for repair are carefully selected. It is intuitive to carry out FRP repair by using the same materials used in the original laminate. Vinylesters, polyesters, and epoxies are commonly used for such repairs. It should be noted that these resins are available in different grades with different additives (e.g., fire retardants) or modifiers. These resins themselves may not be compatible with each other and should not be interchanged during repairs. If original fiber/fabric configurations and constituent material details are unavailable, it is important to select the repair schemes and materials that provide better compatibility with the existing materials. Depending on the structural importance, DSC and burn-off tests may be conducted on a small field sample to evaluate existing fiber volume fraction and degree of cure are satisfied according to the design modifications.

8.4.2 General Preparation and Repair Procedures

Every composite repair job can be unique to some extent. Important elements to carry out successful repair are:

1. Assess the nature, location (core, shell, or through thickness) and extent of damage.
2. Evaluate the structural type, service loads and conditions (e.g., types of structural stresses, stress concentrations, joining schemes in the system, environmental loads etc.)
3. Develop a repair scheme specific to the job
    - Select the fiber/resin/additives (catalysts, fillers, fire retardants etc.)
    - Design the fiber/fabric configuration for local damage (e.g., in-situ fiber/resin curing with supporting mold templates) or design the partial/component replacement scheme with appropriate fiber/fabric and resin configuration (e.g., use of FRP prepreg jackets, connecting two FRP sections with sleeves, using

plate bonding, glass fabric bonding across two sections etc.)

4. Prepare the damaged section for repair.
   - Clean the salt exposed surface with necessary solution and dry the surface such that moisture levels are brought down to very low levels (about 0.1%-0.2%). For underwater applications, evaluate the feasibility of repairing the section under dry conditions or utilize underwater compatible specialty resins.
   - Prepare the damaged location with necessary diamond saw cutting, grit disk smoothening, and rotary grinding and if necessary arrive at regular geometrical configurations such as rectangular, square, circular etc. with necessary tapered scarf or butt joints.
   - Clean the surface with air brushing or vacuuming and apply resin coatings such that cross linking between old and new resins are promoted, especially using an appropriate primer.
   - Make sure all the constituents are available to the required dimensions and volume ratios including specified temperature levels.
5. Apply the patch or carry out repair/replacement of the damaged laminate section as necessary for the chosen repair scheme with the help of trained personnel such that uniform fiber wetting is done without resin rich pockets and air bubbles.

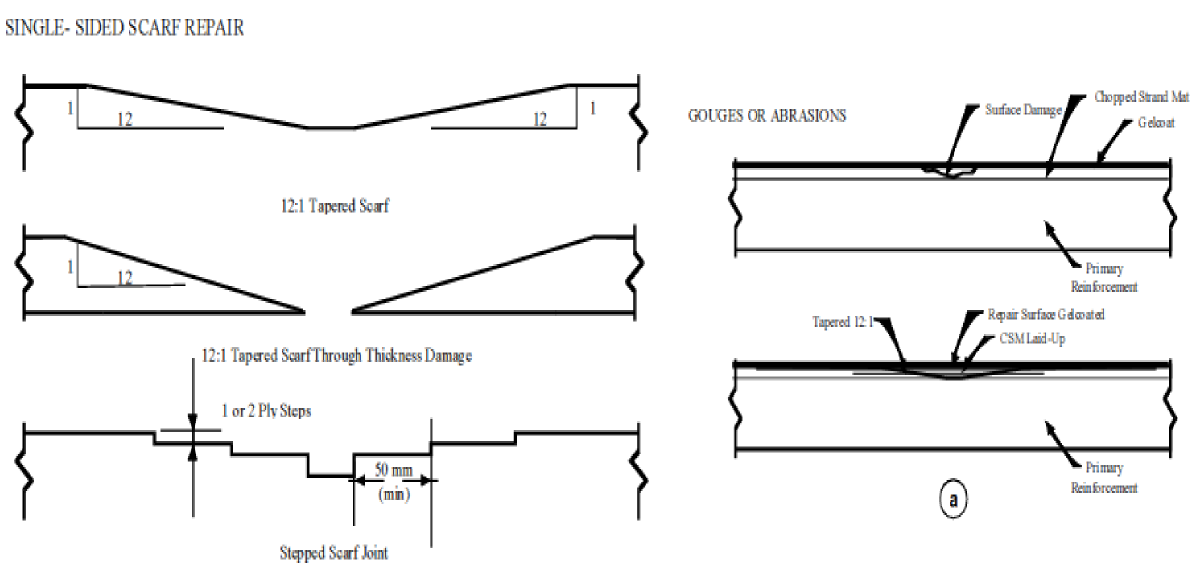


Fig. 8.6 Single and Double Sided Scarf Joints (left); Surface damage (gouges/abrasions and surface cracks) repair (right) (Source: Green E., 1999)

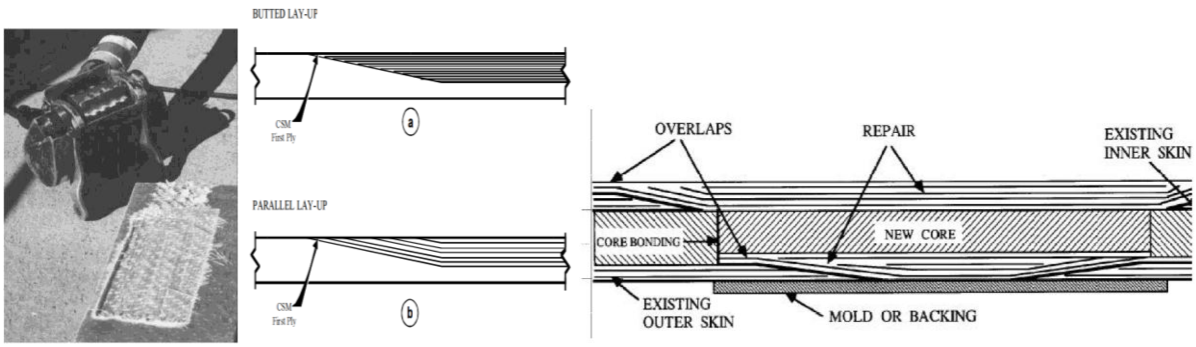


Fig. 8.7 Osmotech laminate peeler after one pass (left); butted and parallel lay-up of repair fabrics (middle); sandwich composite repair (right) (Source: Green E., 1999)

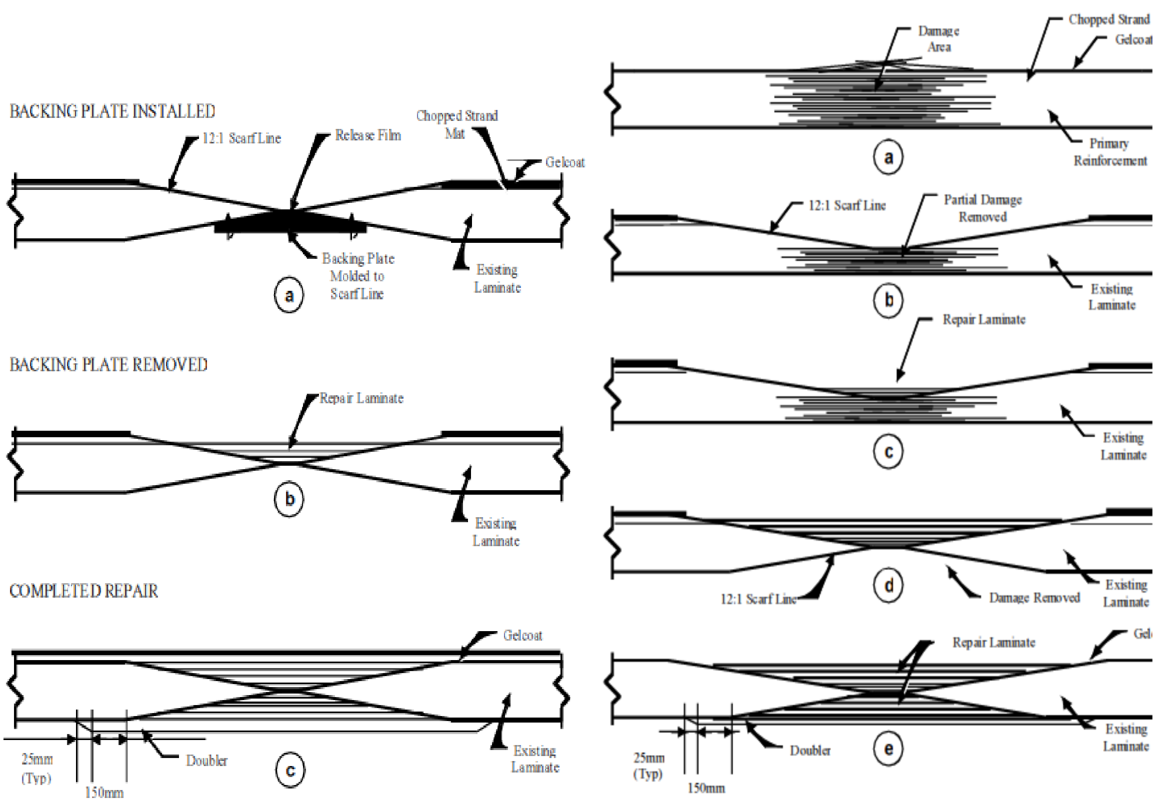


Fig. 8.8 Repairing through the thickness damage repair Scarf Joints (left); Surface damage (gouges/abrasions and surface cracks) repair (right) (Source: Green E., 1999)

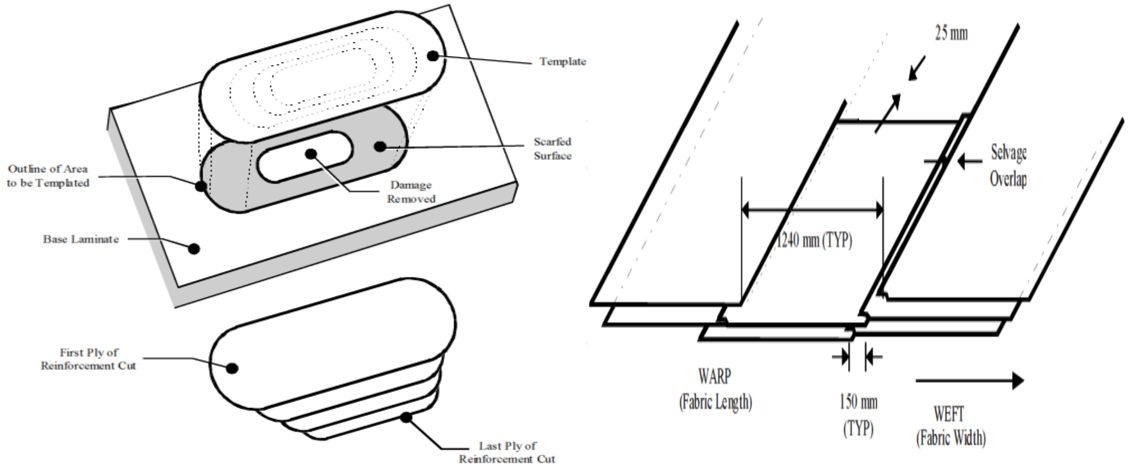


Fig. 8.9 Templating of repair fabrics (left); overlapping of fabrics (right) (Source: Green E., 1999)

Fig. 8.10 FRP box section guardrail on a WV farm bridge (crushed under truck load on right) in need of guardrail replacement

Chapter 9 discusses worldwide implementation of FRP hydraulic (mitre) gates and the steps to be taken for designing, manufacturing, and implementing those structures in USA.

9. **WORLDWIDE FRP HYDRAULIC (MITER) GATE IMPLEMENTATION AND RELATED COMPONENTS**

Application of hydraulic gates worldwide is discussed in detail by PIANC reports 105 and 106 (2009) including innovations to those lock gates. Mitre gates that are of interest to us from the perspective of FRP application, typically consist of two gate leaves that form a three-hinged arch when the gates are in the closed position. The three-hinged arch reactions are transformed into the supporting piers by hinges or quoin posts at the support and spot bearing blocks at the miter ends of the horizontal girders (Fig. 9.1).

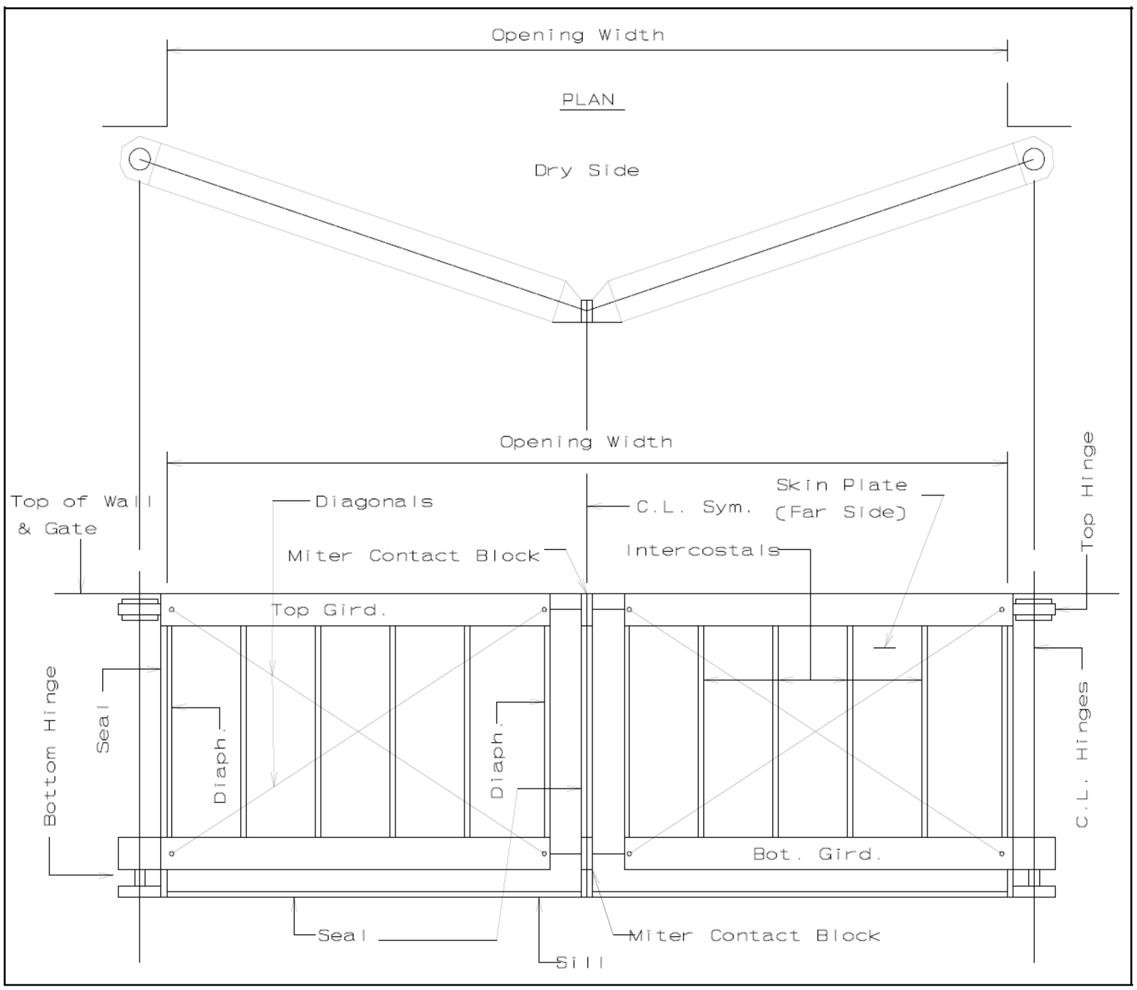


Figure 9.1: Miter gate closure structure (EM 1110-2-2705, 1994)

Supporting structures and their foundations are designed to minimize deflections at the gate hinges or quoin posts under hydrostatic pressure so that the gate can function properly. J-seal assemblies are provided for water tightness. Some of the FRP gates implemented worldwide are discussed in this section.

9.1 Japanese/Asian Experience

In Japan, 438 FRP gates were installed between 1961 and 2002, with more than 80% installed before 1990. However, construction of FRP gates has declined in recent years (Tomiyama et al. 2006), particularly after 1990 as shown in Fig. 9.2. Reasons for decrease in the use of FRP gates after 1990 have not been discussed by the authors. Different styles of FRP gates were adopted including: slide gate, flap gate, roller gate, swing gate, miter gate, sliding gate and angle chute. Almost 90% of adopted FRP door bodies are compact in size with gate area smaller than 4.0 m^2.

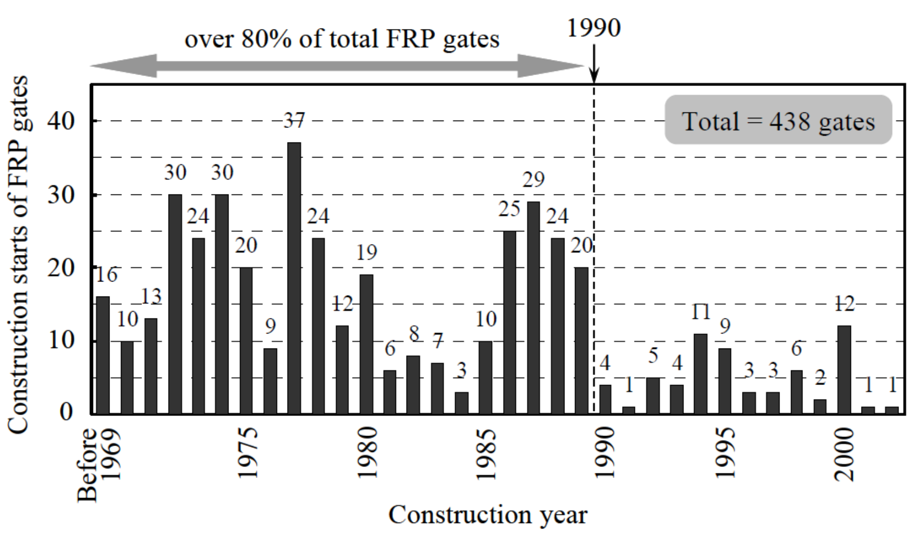


Figure 9.2: Construction of FRP hydraulic gates in Japan, (Tomiyama et al, 2006)

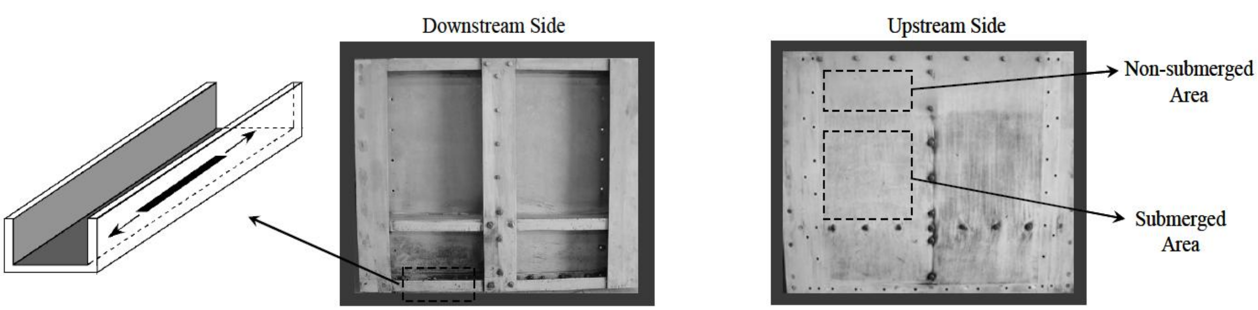
Field studies reported by (Tomiyama et al, 2006), were carried out on 53 in-service FRP gates. Results of visual inspection of all investigated FRP gates showed no major deterioration except for slight discoloration and water stain. Over 30 years, they have been maintained lightly only. Tomiyama concluded that “FRP gates seems to be more durable that steel gates after an equivalent period of time.” Despite the many advantages of FRP gates, it is obvious FRP’s great potential in terms of superior thermo-mechanical properties, ease of fabrication/transportation/handling, superior performance under constant or varying water exposure, and minimum maintenance have not been targeted by the design community and concerned authorities. Such imbalance in the utilization of FRP in civil infrastructure is gradually being eliminated through several Federal and State government sponsored FRP composite structure research and/or field implementation projects including active participation of code/specification developing organizations, private industry and end-users.

Tomiyama tested the strength of FRP sluice gate as a part of an agricultural waterway system after serving in the field for more than 35 years (Table 9.1).

Table 9.1: FRP Hydraulic Gate Selected for Strength Tests, (Tomiyama et al., 2006)

Construction Year	before 1969	
In-service Period	more than 35 years	
Gate Style	slide gate	
Dimensions	1.15m x 1.00m	
Applied FRP	door body, door stop	
Forming Method	hand lay-up	
Operating Situation	full-time operating	
Transformation by Water Absorption	N/A	
Erosion Damage	N/A	
Degradation	water stain discoloration	**Panoramic View**

Samples were cut from the selected gates as shown in Fig. 9.3, and test results were compared with test data on newly fabricated FRP samples with the same laminate composition of the gates being studied. Results were reported in Table 9.2. These results show that FRP is suitable for water-gates on long term basis. However, it is important to note the FRP gate design needs several considerations to avoid potential in-service problems.



(a) Main Girder (b) Skin Plate

Figure 9.3: Sampling of FRP Gate for Strength Tests, (Tomiyama et al., 2006)

Table 9.2: Comparison of Tensile Properties between FRP Skin Plate after Use for 35 Years and Newly Fabricated Laminate, (Tomiyama et al, 2006)

Specimen No.	After Use for 35 Years				Newly Fabricated	
	Non-Submerged Area		Submerged Area			
	Tensile Strength [MPa]	Tensile Modulus [GPa]	Tensile Strength [MPa]	Tensile Modulus [GPa]	Tensile Strength [MPa]	Tensile Modulus [GPa]
1	168.49	17.10	152.35	15.62	161.69	15.04
2	156.71	15.25	149.60	15.31	168.82	15.08
3	144.87	15.57	149.91	23.61	162.90	17.66
4	135.63	16.49	148.65	15.25	167.19	16.43
5	135.63	15.83	149.72	15.55	173.62	15.86
Average	148.27	16.05	150.04	17.07	166.84	16.02

9.2 US Experience

In 1998, Chowdhry et al. reported the test results of full-scale hydraulic wickets at the Olmsted Prototype Wicket Dam, Smithland Facility, KY. Tested prototypes included four traditional steel and one hybrid-FRP wickets. Gate schematic and operation are illustrated in Fig. 9.4.

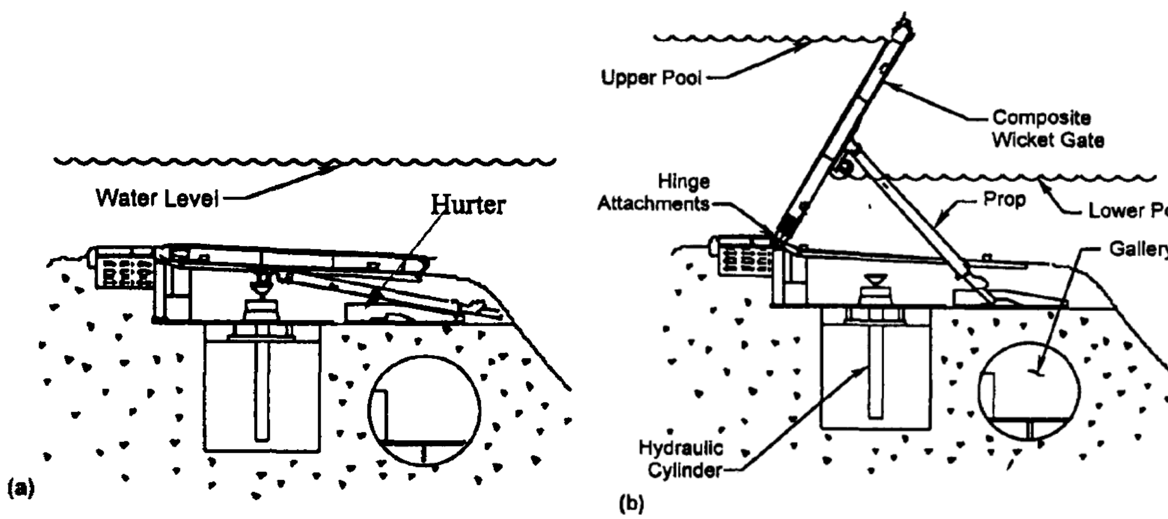


Figure 9.4: Prototype Hydraulic Wicket Gate Operation: (a) Composite wicket gate in down position. (b) Composite wicket gate in up position, (Chowdhry et al 1998)

The composite gate was designed to be interchangeable with the other steel gates, and the supporting devices were independent from the gates. The hybrid composite gate consisted of welded steel frame support with composite face and supporting I-beams. Geometry, strength, and stiffness requirements of composite gates were designed to match the steel gates (Figs. 9.5 and 9.6).

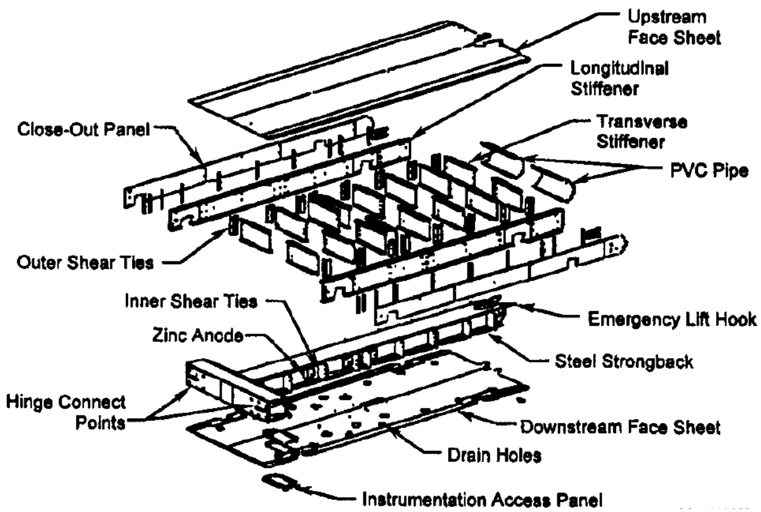


Figure 9.5: Design of hybrid wicket prototype (only t-strongback is made of steel), (Chowdhry et al., 1998)

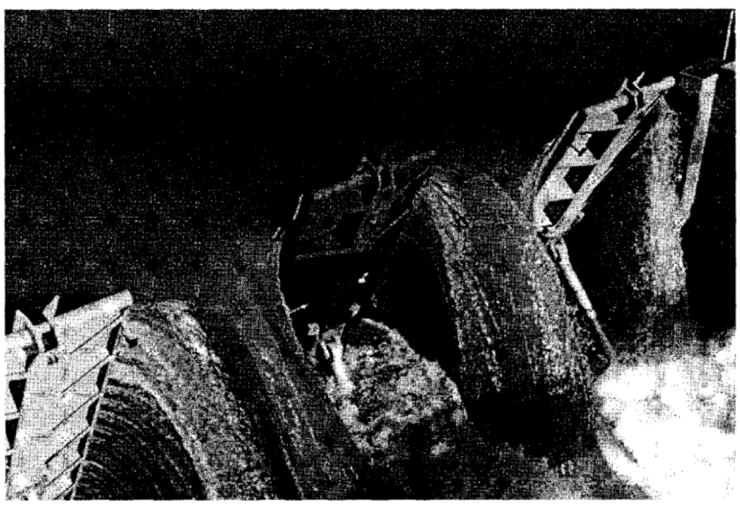


Figure 9.6: Prototype hydraulic gates in engaged position, (Chowdhry et al, 1998)

Performance Comparison of steel and hybrid-composite wickets, (Chowdhry et al, 1998):

- No major sign of distress was noted in both steel and composite gates immediately after installation.
- After 400 cycles of underwater operations (under highly abrasive and corrosive conditions) simulating 25 years of real operational cycles, long-term performance of hybrid-composite and steel gates were visually observed and compared. Composite gate seemed unaffected with minor exception of edge peel-off on both gate leaves, whereas steel gates showed extensive corrosion.

- Tests indicated that composite gates need less maintenance than steel gates.
- As stated by the authors, "the flow experiments indicate that a lighter composite gate has a higher vibrational response than the steel gate of identical flow induced hydrodynamic load history", and "an agreement of the mode shapes suggests that the dynamic motion of both wickets is expected to take similar pattern for low frequency dynamic load".
- This study recommended elimination of free edges in the design of composite gates in damage-prone areas.

9.3 European and Other Experience

PIANC WG report 105 (2009) lists several GFRP applications as alternative materials in marine structure construction. These applications utilized FRP structural shapes, FRP non-metallic reinforcements, structural strengthening materials such as FRP wraps, and hybrid structural elements consisting of conventional and composite materials. Some of these FRP applications in USA include: i) polymeric fender piles at navy pier (San Diego, California) and marine terminal (New Orleans, Lousiana), ii) recreational pier, iii) sheet pile (Masonboro Harbour, North Carolina) and sheet pile walls (Florida), iv) thermoplastic guide wall at Port Allen navigation lock (Louisina) and thermoplastic deck floating pontoon, v) tongue and groove vertical plank walls, vi) fiberglass gratings at Marina and thermoplastic lumber boardwalk, vii) pile with FRP shell and concrete core, viii) utility poles and cross beams, ix) FRP I-beams installed on underwater timber pier, x) FRP strips for concrete pier strengthening, xi) composite hybrid decks. Also, international examples of alternate composite materials usage have been presented herein, which include: i) wood-plastic composite members exposed to marine environment in Japan, ii) GFRP walkway structure in Italy, iii) GFRP reinforcement for concrete in Saudi Arabia, iv) FRP reinforcement in Nakeel's Palm Cover canal project in Dubai, and v) use of FRP reinforcement in the deck area for Ben Schoeman Quay Expansion in Cape Town, South Africa.

Figure 9.7: (L to R)- (i) Ben Schoeman Quay with FRP reinforced deck (2008), ii) GFRP reinforced concrete pier, iii) GFRP reinforcement for the concrete pier (top view) (Source: PIANC RecCom WG Report 105, 2009)

PIANC WG report n°106 (2009) consists of hardcopy and DVD report that includes a review of the 56 lock projects, a revision to their 1986 lock report, a dictionary on locks and waterways, and a worldwide list of locks. This report includes additional information and references to: i) effects of salt water intrusion effects, ii) construction process modeling, iii) hydraulic aspects, iv) gates and valves, lock equipment, and lubricants and bio oils. This report also includes reference to various other technical guidelines developed by different countries. PIANC WG report n°106 (2009) reports the benefits of application of FRP composites for mitre gates and other lock gates. Advantages of composites for miter gates as identified by PIANC WG 106 include: i) non corrosion, ii) good resistance to aging in damp environment, iii) non-requirement of finishing paint, and reduced maintenance/transportation and gate fitting costs, iii) purchasing and maintenance costs of the heavy equipment/machinery, and iv) gate positioning on the river side of the lock heads that eases maintenance and reduces the risk of collision of the gate and/or machinery.

Many of the marine construction projects reviewed in PIANC WG report 106 are suitable candidates for implementation with FRP composites (Figs. 9.7 and 9.8). Some of the new innovative concepts described in this report and related to gates include: i) folded plate for gates (Germany), ii) reversed mitre gate (Netherlands, UK), iii) suspended mitre gates (Netherlands), iv) rotary segment gates with horizontal axis (Germany), V) vertical-axis sector gates (Germany, Finland, Japna), vi) composite lock gates (France), vii) gate linings and seals (Netherlands), viii) corrosion protection measures, ix) self propelled floating lock gates, and x) rolling gates with integrated filling/emptying system. The review also includes a description of the study by CETMEF (France) on a vertical lift arch gate made out of composite materials. It is also stated that the "Spieringsluis" in the Netherlands was designed with a high strength synthetic composite material to reduce maintenance costs of wooden or steel gates.

Figure 9.8: Different types of gates with innovative design/solution: (top L to R)- i) folded plate mitre gate (Uelzen, Germany), ii) reverse mitre gate (Ijmuiden-NL), iii) suspended mitre gate (NL), and iv) rotary segment (horizontal axis) lock gate (Lisdorf lock, Germany); (bottom L to R)- v) vertical axis sector gate, vi) lifting and sliding lock gate, and vii) Golbey composite mitre gate (Source: PIANC Workshop, Oct. 2009 presentations and other publications by same Working Group).

Some examples of FRP composites for lock systems with Tenmat T814 composite (consisting of phenolic resin and polyester fibers) and polyethylene (Fig. 9.9) include: (a) use of synthetic composite bushings replaced the polyamide bearings that appeared to wear faster than originally specified in Orange Locks complex, Amsterdam; (b) use of heel bushing of Tenmat T814 composite for shaft with 316L stainless steel cap for a lock on an aqueduct ('Naviduct') in Enkhuizen, and (c) using "soft" and low friction heel cap of polyethylene (UHMPE) on a old shaft with a new 316L stainless steel cap on a high, narrow and light (timber) lock gate with low hinge loads on the Wilhelmina Canal in Tilburg (PIANC Workshop, 2009).

(a) (b) (c)

Figure 9.9: (a) Orange Locks complex, Amsterdam, (b) Lock in and aqueduct, Enkuuizen, (c) Lock in Wilhelmina Canal, Tilburg (Source: PIANC Workshop, Oct. 2009 presentations and other publications by same Working Group)

A schematic of the forces acting on miter gates during closing operation and importance of considering contact aspects of gates is described by Rigo and Ryszard (2010) and also in PIANC Workshop (2009) presentations. As shown in Fig. 9.10, flat shell action of the gate structure with in-plane forces in open position (Fig. 9.10a) starts changing when the two gate leaves meet (Fig. 9.10b) and the water head grows. At first the top hinge becomes released followed by the bottom hinge, and then the gate starts passing its loads to the heel posts (Fig. 9.10c), wherein perpendicular loads imposed on the gate along with the in-plane loads change the gate response from “flat shell” to “plate” behavior.

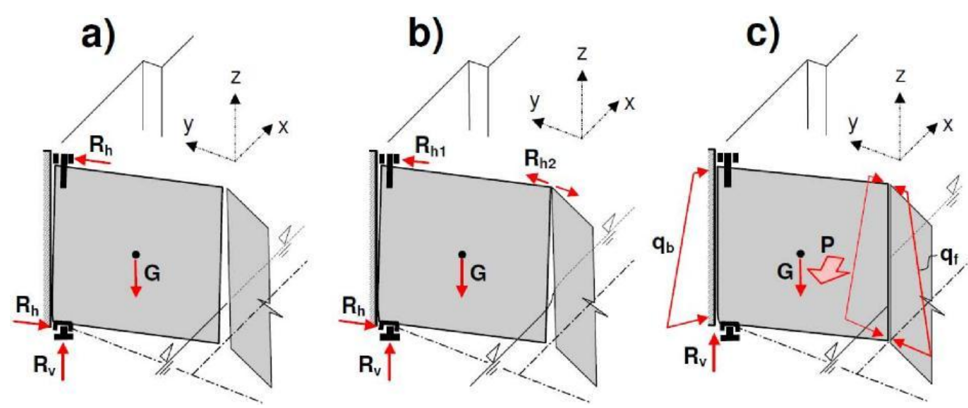


Figure 9.10. Schematic of forces on Mitre gate during operation and changing support conditions (Source: PIANC Workshop, Oct. 2009 presentations and other publications by same Working Group)

A review of these documents by PIANC including implementation of FRP materials and structural systems for marine structures in USA and Europe indicate the FRP potential as a construction material for different types of lock gates and also for their repair. CFC-WVU proposes to carry out the design, development, and implementation of mitre gates with emphasis on:

1. Design of FRP lock gates with a focus on specific types, e.g., mitre gates.
2. Selection of: i) performance based design parameters including dimensions, allowable deformations, stress-strain levels, fatigue parameters, energy absorption, and durability; ii) materials (fiber/fabric architecture, resin, additives), iii) production methods including QA & QC; iv) assembly/fabrication issues at manufacturing facility/field location; v) joining schemes and integration with other frameworks (e.g., hinges, support frame etc.); vi) transportation methods; vii) field handling and site erection; viii) field performance monitoring; and ix) life-cycle cost analysis.
3. Miter gate production and limited laboratory/analytical evaluations
4. Field implementation and monitoring.

10 SUMMARY AND RECOMMENDATIONS

The feasibility of design, development, and implementation of FRP composite structural systems with a focus on civil and marine applications is provided in this report. Scope of this report is limited to brief presentation on FRP constituents, structural shapes and systems including their durability, micromechanics, testing, fabrication, inspection, repair, and field implementation in marine and offshore structures, bridges, buildings, automobiles, aircrafts, and others. Short- and long-term properties, and the influence of fiber orientation on strength, stiffness, and deformation of composite products are described under combined external and environmental (durability/aging) loads. Necessary input is provided to this study wherein Japanese/European knowledge and practice are highlighted. In addition, composite and constituent material specifications and guidelines for the design, testing, fabrication, inspection (NDT), and repair are provided and discussed. Discussions on revisions of individual chapters of the USACE technical letter "ETL 1110-2-548, Composite Materials for Civil Engineering Structures," is provided throughout the report and also included in Appendix B. Additional work and elaboration on these aspects including field performance data analysis and major revision to the technical letter ETL 1110-2-548 are necessary.

This report includes description of hydraulic gates implemented in Japan and Europe highlighting the advancement in FRP applications. As a follow-up of our project, CFC-WVU proposes to design, develop, manufacture, and implement mitre gates as described below:

1. Design FRP lock gates with a focus on specific items, i.e., mitre gates (~40 ft.x20 ft) using available design guidelines, specifications, material selections, joining methods, and life cycle cost analysis.
2. Manufacture miter gates using: i) pultruded shapes and plates that can be assembled in field or in the manufacturing plant and/or ii) in-situ or manufacturing plant based vacuum assisted resin injection molding process.
3. Limited laboratory and analytical evaluations specific to FRP miter gates, ensuring compliance with design limit states, followed by field implementation and monitoring.

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APPENDIX A

TERMINOLOGY

The following a list of terminology summarized from various sources: ACI 440 documents , ASME RTP-1, M-11 Glossary, Several Composite Handbooks, industrial publications (Fiber Glass Sales, FGS), publications of PI and Co-PI, and others.

Accelerator - A material which, when mixed with a catalyzed resin, will speed up the chemical reaction between the catalyst and the resin. Also known as *promoter*

Acoustic Emission (AE) - In composites, a sound generated by defects within the laminate, such as plastic deformation, crack initiation or crack growth.

Barcol Hardness - A hardness value obtained by measuring the resistance to penetration of a sharp steel point under a spring load. The instrument, called a Barcol Impressor, gives a direct reading on a 0-100 scale. The hardness value is often used as a measure of the degree of cure of the plastic.

Bi-Directional Laminate - A reinforced polymer laminate with the fibers oriented in two directions in the plane of the laminate: a cross laminate. See also *unidirectional laminate*.

Binder - The agent applied to glass mat to bond the fibers prior to laminating or molding.

Blister - An undesirable rounded elevation of the surface of a plastic whose boundaries may be more or less sharply defined. The blister may contain process fluid.

Bond Strength - The amount of adhesion between bonded surfaces; a measure of the stress required to separate a layer of material from the base to which it is bonded. See also *peel strength*.

Bromine - A fire retardant (halogen) which is used to reduce or eliminate a resin's tendency to burn. Often used in conjunction with chemicals such as antimony trioxide and pentoxide to achieve a maximum Class 1 fire retardancy rating and often used in ducting systems.

Catalyst - A substance which changes the rate of a chemical reaction without itself undergoing permanent change in its composition; a substance which markedly speeds up the cure of a compound when added in minor quantity compared to the amounts of primary reactants (hardener, initiator or curing agent).

Composite - A homogenous material created by the synthetic assembly of two or more materials (selected reinforcing elements and compatible matrix resin) to obtain specific characteristics and properties.

Creep - The change in dimension of a polymer under load over a period of time, not including the initial elastic deformation.

Crosslink - The formation of a three-dimensional polymer by means of inter-chain reactions resulting in changes in physical properties.

Cure or Curing - To change the properties of a resin by chemical reaction, which may be condensation or addition.

Delamination - To split a laminated polymer material along the plane of its layers. Physical separation or loss of bond between laminate plies.

Discontinuity Stress - Additional stress produced where abrupt changes in geometry, materials and/or loading occur in an FRP laminate.

"E" Glass - A borosilicate glass; the type most used for glass fibers for reinforced polymers; suitable for electrical laminates because of its high resistivity.

ECR Glass - A corrosion-grade glass exhibiting corrosion resistant properties superior to "E" glass. Superior resistance to acids and alkalis is obtained through the application of special treatments and sizings to "E" fibers.

Elastic Deformations - That part of the total strain in a stressed body which disappears upon removal of the stress; opposed to plastic deformation.

Epoxy Plastics – Cured polymers based on resins made by the reaction of epoxides or oxiranes with other materials such as amines, alcohols, phenols, carboxylic acids, acid anhydrides and unsaturated compounds.

Fiber Reinforced Polymer (FRP) - A general term covering any type of plastic reinforced cloth, mat, strands or any other form of fibrous material.

Filament Winding - A process for fabrication of a composite structure in which continuous reinforcements, either previously impregnated with a resin system or impregnated during the winding, are placed over a rotating and removable form or mandrel in a previously prescribed way to meet certain stress conditions.

Filler - A relatively inert material added to a polymer mixture to reduce cost, to modify mechanical properties, to provide thixotropy, to serve as a base for color effects or to improve the surface texture.

Finite Element Analysis (FEA) - A method of analysis used in situations that are difficult to model by standard engineering techniques. The finite element method operates on the assumption that any continuous function over a global domain can be approximated by a series of functions operating over a finite number of small sub-domains. The series of functions are piecewise, continuous and will approach the exact solution as the number of sub-domains approaches infinity.

FRP - *Fiber Reinforced Polymer*

Gelation (gel) Time - That interval of time in connection with the use of synthetic thermosetting resins, extending from the introduction of a catalyst into a liquid adhesive system until the interval of gel formation.

Gel Coat - A colored resin used as a surface coat for molded fiberglass products. It provides a cosmetic enhancement and environmental protection for the fiberglass laminate underneath.

Glass Reinforcement - An inorganic product of fusion in the form of a filament which has cooled to a rigid condition without crystallizing. Glass filaments are combined, cut, woven or matted into many types of reinforcements.

Halogenated Resin - A resin combined with chlorine or bromine to increase fire retardancy. See also Bromine.

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.

Hoop Stress - The circumferential stress in a material of cylindrical form subjected to internal or external pressure.

Hydrostatic Load - Loading produced by a fluid head.

Inhibitor - A substance which retards a chemical reaction; used in certain types of monomers and resins to prolong storage life.

Isotropic Laminate - One in which the strength properties are equal in all directions, such as contact-molded laminates or metals.

Lamination Theory - An analytical procedure in which composite physical properties are predicted from an examination of the properties and interaction of the individual plies that comprise the laminate.

Mat - A fibrous material consisting of randomly-oriented chopped or swirled filaments loosely held together with a binder.

Matrix - The resin in which the glass reinforcements are distributed.

Modulus of Elasticity - The ratio of the stress or load applied to the strain or deformation produced in a material that is elastically deformed.

Monomer - A simple molecule which is capable of reacting with like or unlike molecules to form a polymer; the smallest repeating structure of a polymer.

Orthotropic - Having three mutually perpendicular planes of elastic symmetry; usually with differing properties, typically filament-wound laminates.

Peel Ply – A layer of tightly woven fabric, which is applied directly to the surface of a prepreg lay-up or pultruded section. The peel ply (which is removed after component curing) helps produce a clean surface texture and minimized surface preparation for bonding.

Peel Strength - Bond strength, in pounds per inch of width, obtained by peeling the layer. See *bond strength*.

Permeability - The passage or diffusion of a gas, vapor, liquid or solid through a barrier without physically or chemically affecting it.

Plastic Deformation - Change in dimensions of an object under load that is not recovered when the load is removed; opposed to elastic deformation. PLY An individual layer of reinforcement within a total laminate comprised of several such layers.

Poisson's Ratio - Ratio of the change in width per unit width to the change in length per unit length.

Polyester - Thermosetting resins, produced by dissolving unsaturated, generally linear, alkyd resins in a vinyl-type active monomer such as styrene, methyl styrene and diallyl phthalate. The resins are usually furnished in solution form, but powdered solids are also available.

Polymer - A high molecular weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit. Some polymers are elastomers while others are plastics. When two or more monomers are involved, the product is called a co-polymer.

Post-Cure - Additional elevated temperature cure, usually without pressure, to improve final properties and/or complete the cure. In certain resins, complete cure and ultimate mechanical properties are attained only by exposure of the cured resin to higher temperatures than those of curing.

Principle Directions - The directions in which the principle tensile, compressive and shear stresses are located in combined stress analysis. There are three principle directions which are mutually perpendicular.

Promoter - A chemical, itself a weak catalyst. See *Accelerator*.

Resin - A class of organic products, either natural or synthetic in origin, generally having high molecular weights. Most uncured resins used in open molding are liquids. Resins are generally used to surround and hold fibers. When catalyzed, the resin cures going through a polymerization process transforming the liquid resin into a solid commonly known as matrix. The cured resin and fiber reinforcement create a composite material with mechanical properties that exceed those of the individual components.

Roving (Filament Winding) - The term "ROVING" is used to designate a collection of bundles of continuous filaments either as untwisted strands or as twisted yarns. Glass rovings are predominantly used in filament winding.

Safety Factor - The ratio of ultimate stress to allowable stress, or some similar ratio of units expressing this intent.

Shear - An action or stress resulting from applied forces which causes or tends to cause two contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact. In interlaminar shear, the plane of contact is composed of resin only.

Size or Sizing - A treatment consisting of starch, gelatin, oil, wax or other suitable ingredient which is applied to fibers at the time of formation to protect the surface and aid the process of handling and fabrication, or to control the fiber characteristics. The treatment contains ingredients which provide surface lubricity and binding action but, unlike a finish, contains no coupling agent.

Stiffness - The relationship of load and deformation; a term often used when the relationship of stress to strain does not conform to the definition of Young's modulus. See also modulus of elasticity.

Strain - The elongation per unit length of a material.

Stress Corrosion - Preferential attack of areas under stress in a corrosive environment, where this factor alone would not have caused corrosion.

Stress Relaxation - Stress relaxation occurs when the stresses in the structure decrease while the deformation is held constant. Under this condition, the FRP laminate will assume a permanently deformed shape after mechanical and thermal loads are removed.

Structural Laminates - That portion of a total laminate that is designed to take the imposed equipment loads. Normally does not include the sacrificial portion of the corrosion barrier or liner.

Styrene - Unsaturated hydrocarbon used in plastics. In polyester resin it serves as a solvent and as a co-reactant in the polymerization process that occurs during curing.

Synthetic Fiber - Fiber made of materials other than glass, such as polyester.

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

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

Transverse Crack - A crack occurring in the resin matrix at right angles to the direction of the reinforcements.

Ultimate Tensile Strength - The ultimate or final stress sustained by a laminate under tension loading; the stress at the moment of rupture.

Unidirectional Laminate - A reinforced plastic laminate in which substantially all of the fibers are oriented in the same direction.

Veil - An ultrathin mat often composed of organic fibers as well as of glass fibers; used primarily in corrosion barriers.

Warp - The yarn running lengthwise in a woven fabric.

Weft - The transverse threads or fibers in a woven fabric; those fibers running perpendicular to the warp.

Weeping - A slow process of fluid passage through an FRP laminate that can occur when a leak path is established by extensive cracking.

Wet-Out - Saturating reinforcing material (glass fiber) with resin. The rate or speed of saturation is a key factor in effective and profitable molding.

Woven Roving - A heavy glass fiber fabric made by the weaving of roving and used as the primary structural material in the laminate.

Yield Point - The first stress in a material, less than the maximum attainable stress, at which an increase in strain occurs without an increase in stress.

APPENDIX B

Review Comments on Technical Letter (TL)-ETL1110-2-548

Subject		Page	Adequate	Needs improvement	Inadequate	Comments
	Chapter 1					
	Introduction				X	**Note:** Some of the comments provided in this introduction chapter are applicable to several other related chapters and may or may not have been repeated. The scope should have discussed about FRP trends under harsh environments over a service life of 50-75 years, (This is lacking). Similarly, manufacturing related issues need some attention, since the process, temperature and fabric lay-up, including fabric sequence play a major role in their mechanical properties.
1-1	Purpose	1-1			X	This technical letter needs major improvement for design purposes and deemed inadequate for design purposes. It provides basic information and related references. However, it needs to include key design details and specifications, if design is one of the key purposes of this Technical Letter (TL) published about 13 years ago (31 March, 1997). Over the past 13 years, many technical developments have been reported in the literature and special attention has to be given to these developments.
1-2	Applicability	1-1		X		Applicability of this document to USACE commands responsible for the design of civil works projects is fine, but the document needs significant improvements with latest code specifications to achieve the intended structural design. This especially true in the case of long-term property degradation under moisture, temperature, and pH variations.

Subject		Page	Adequate	Needs improvement	Inadequate	Comments
1-3	References	1-1		X		Large pool of relevant references are needed to reflect new developments particularly regarding specifications, design, aging/durability, fatigue, creep, manufacturing, and applications.
1-4	Discussion	1-1		X		Availability and applicability of new set of ACI codes and AASHTO codes need to be discussed, in addition to the information available from other countries including case studies.
	a. Applications	1-1		X		Several new applications of FRP materials have been implemented in different fields, which need to be highlighted.
	b. Standards	1-1		X		New guidelines are available, and a lot of new information has evolved since this paper was prepared and research towards development of standards is going on.
1-5	Background	1-1		X		Reference list discussed in the background needs update. PI and co-PI have actively participated in the development of standards discussed in the TL, which was not available during publication period of this TL needs to be added.
1-6	Scope	1-2			X	This cope requires a major overhaul (very inadequate). Scope need to include structural elements manufactured with FRP including some of those structural elements that are classified as critical. Specifications for QA and QC need to include new information from the codes developed after this TL release since 1997.
	a. Applications	1-2			X	Design procedure mentioned as not available for concrete structures during the publication period of this TL have been developed since then and this TL needs to be updated with availability of new information related to design of a wide range of conventional structural systems with FRP.

Subject		Page	Adequate	Needs improvement	Inadequate	Comments
	1. Nonstructural applications	1-2	X			
	2. Secondary structural applications	1-2			X	Same as in general comment of the scope.
	3. Critical structural applications	1-2		X		Application of FRP on structural elements has evolved. Repair of damaged elements using FRP and hybrid elements, or for specific applications has been tested.
	b. Procurement specification	1-2		X		
	1. Design requirements	1-2		X		Creep, fatigue, and energy absorption criteria need to be added in addition to those already specified. Need to specify reference/guidelines for design procedure, and to discuss combined efforts while designing FRP structures.
	2. Design quality assurance	1-2		X		See comments on appendix C
	3. Fabrication quality assurance	1-2		X		Need to provide method/reference of quality assurance procedure that can be field implemented for periodic structural health monitoring using latest NDT methods, in addition to using NDT while manufacturing or while repairing.
	Chapter 2					
	Reason to Consider					
	FRP Composites					
2-1	General	2-1	X			
2-2	Structural Considerations	2-1				
	a. Tensile strength	2-1		X		Revisions are necessary, particularly in Chapter 5, which is referred to in this section. Emphasis must be on establishing characteristic values.
	b. Fatigue	2-1			X	Needs to provide updates on fatigue and long term durability.

Subject		Page	Adequate	Needs improvement	Inadequate	Comments
	c. Low mass	2-1		X		Needs new table showing properties of different composites and grades of carbon, glass, aramid used as plates, bars, fabric etc.
	d. Specific strength	2-1		X		Needs new table showing properties of different composites and grades of carbon, glass, aramid used as plates, bars, fabric etc.
	e. Vibration damping	2-1		X		Needs new table showing dynamic properties (damping, natural vibrations, dynamic strength) of different composites and grades of carbon, glass, aramid used as plates, bars, fabric etc.
	f. Repair using composites	2-1		X		Update the examples in appendix B (include new codes that reflect newer design philosophies including outcome of earlier projects), and add a variety of examples related to common structural design.
	g. Corrosion resistance	2-2		X		Update the outcome of the mentioned examples along with the use of current code/specifications, including related information in appendix B.
2-3	Production Options	2-2		X		
	a. Fabrication	2-2			X	Details on fabric architecture, fabric lay-up sequences, resin chemistries, manufacturing processes and underlying micro-mechanism that affect the FRP component and system behavior including those of joints are incomplete in this section and need further elaboration through illustrative examples and comparison with experimental data.
	b. Custom geometry	2-2			X	In addition to geometry, use of inserts during production process need to be discussed.
	c. Color and coating	2-2			X	Other additives and coatings against fire and UV resistance such as intumescents need to be included.
2-4	Economic Considerations	2-2				

Subject		Page	Adequate	Needs improvement	Inadequate	Comments
	a. Life-cycle costs	2-2		X		Need to discuss the cost considerations from current field implementations and user experiences including maintenance costs and life-cycle models. Data is available in terms of maintenance cost, repair and disposal costs, including service life of certain types of composite systems. Current understanding on long-term durability better increased the life span and reduced the life cycle costs to better designs that will help in construction with FRP structures.
	b. Construction and transportation costs	2-3		X		Type of equipments and labor needed for transportation, field handling, material handling issues, and construction should be included.
2-5	Environmental Considerations	2-3				
	a. Reduced environmental toxicity	2-3		x		Applications of pavements, railroad ties, guardrails and others with thermoset and thermoplastic resins including their energy savings and environments impact with FRP needs to be discussed, in addition to case studies discussing strength and weakness of FRP structural systems in service.
	b. Recycling	2-4		X		Use of recycled polymers with engineering properties for both structural and non-structural applications including leisure with strength, stiffness, finish, and durability properties need to be discussed. Emphasis should be on thermoset composites.
2-6	Material Property Considerations	2-4				
	a. Magnetic properties	2-4	X			Additional examples that benefit from this property can be included.
	b. Conductivity	2-4		X		Application of both electrically neutral (Glass FRP) and electrically conductive (Carbon FRP) including corrosion effects of hybrids (glass and carbon FRPs) need to be included.

Subject		Page	Adequate	Needs improvement	Inadequate	Comments
	Chapter 3					
	Potential Applications					
3-1	Application Categories	3-1		X		New applications yet in-service (e.g. bridge decks, modular housing, beams, columns, retaining walls, and FRP wrapping etc.) need to highlighted.
3-2	Immediate Category	3-1		X		Additional items described under 3-1 should be considered with some emphasis on structures for USACE
3-3	Short-Term Category	3-1		X		These categories need to include additional possibilities and improvements for not only existing elements mentioned in the TL but newer applications that have been developed since 1997.
3-4	Long-Term Category	3-1		X		Same as in rest of the comments for chapter 3 since newer applications have been available and implemented since the publication of this document.
	Chapter 4					
	Description of					
	Composite Materials					
4-1	Terminology	4-1		X		List is very limited and needs expansion to include terminologies related to both thermoplastic and thermosetting resin composites with different fiber architectures including those related to testing, QA/QC, curing, resin chemistries, sizing, and nano additives, fire retardants (e.g., instumescents) etc.
4-2	Background	4-1				
	a. General	4-1		X		The auto industry has further developed applications of composites, and the Boeing Dreamliner represents a newer example in aerospace applications. Similarly, naval configurations need attention.

Subject		Page	Adequate	Needs improvement	Inadequate	Comments
	b. Composite types	4-2		X		Needs in-depth classification and explanation.
	c. Composites versus traditional civil engineering materials	4-2			X	Comparisons of composites versus conventional materials can benefit the large scale field implementation by describing or showing examples of design differences with traditional isotropic materials. Table needs to include transverse, in-plane and out-of-plane shear strength compared with other materials, and also different grades and types of fibers.
4-3	Types of Composite Components ...	4-5				
	a. Resins	4-5		X		Needs refinement including description of commonly used thermosets for structural applications such as vinylesters, polyesters, epoxies, urethanes, phenolics and their modifications including primers used for rehabilitation purposes. Special emphasis should be on resin additives such as fillers, promoters, fire retrodents etc.
	b. Fibers	4-6		X		Should add different kinds and grades of fabrics including natural fibers such as flax, kenaf, jute, and hemp.
	c. Sizing	4-6			X	Types and additional functions of sizing need to be included. Scientific discussion on type selection is needed.
	d. Coatings	4-6		X		Types, functionality, and aesthetical aspects need to be included, in addition to applicability of each type in field and resin durability.
4-4	Processing	4-6		X		Processes related to thermoplastics such as injection molding, compression molding, and extrusion would enhance the document's scope consistent with newer additions including related pictures or diagrams. Also, merits, demerits of each method need to be discussed including cost considerations. Herein, several process details are needed. For example, discussions on advances
	a. Filament winding	4-7		X		
	b. Press molding	4-7		X		
	c. Vacuum bag molding	4-7		X		
	d. Autoclave molding	4-7		X		
	e. Pultrusion	4-7		X		

	Subject	Page	Adequate	Needs improvement	Inadequate	Comments
	f. Vacuum assisted resin transfer molding	4-7		X		in resin injection dies, temperature profiles and fabric lay-up sequence.
	Chapter 5					
	Material Properties					
5-1	General	5-1	X			
5-2	Fiber Properties	5-1		X		Tables require revisions with values of currently produced fibers 9e.g., carbon fibers exhibit elongation up to 1.5%, which is not reflected in the table).
5-3	Resin Properties	5-1		X		Need to include other resins such as vinylesters and urethanes commonly used for current structural and nonstructural products, and highlight process-based resins such as polyimdes and additives that go with resins.
5-4	Laminate Properties	5-2		X		While rule of mixtures is a good approximation, in some cases, need/applicability of other models for better prediction of laminate mechanical properties has to be discussed.
	a. Strength	5-2			x	From design prospective, given tables could be used as preliminary approach for approximate design. As the design progress, different laminate stacking sequence needs to be established. Designers need to use more accurate methods to predict failure based on techniques such as FPF, or LPF. Another preliminary approach could be by using carpet plots. More such design methods and aids can be discussed/added.
	1. Tensile strength	5-2			x	
	2. Compressive strength	5-2			x	
	3. Effect of fiber orientation on strength	5-3			x	
	4. Flexural strength	5-4			x	
	5. Shear strength	5-4			x	
	b. Specific strength	5-4			x	See comments on strength above (5-4.a)
	c. Strain capacity	5-4			x	More details needed to express the behavior of multilayer multidirectional laminates under different kinds of
	d. Modulus of elasticity.................	5-4			x	

	Subject	Page	Adequate	Needs improvement	Inadequate	Comments
	e. Specific modulus of elasticity ..	5-5			x	loading and failure modes including torsion , fatigue etc.
	f. Density	5-6	x			
	g. Poisson's ratio	5-6			x	Need more details to calculate Poisson's ratio for multilayer multidirectional laminates
	h. Coefficient of thermal expansion	5-6			x	See comments above (5-4.g)
	i. Creep	5-7			x	Need to be rewritten to include results from new research in the field, including energy approach, methods available for enhancing impact and delamination toughness.
	j. Relaxation	5-7			x	
	k. Toughness	5-7			x	
	1. Impact toughness	5-7			x	
	2. Delamination toughness	5-8			x	
	Chapter 6					
	Durability					
6-1	Overview	6-1		x		A lot of research was done in this area since this document was originally written. Several ACI documents, knowledge gap documents, and plenty of publications are vailable that need to be utilized to update the information related to composite's long-term design and usage including protective coatings for civil and marine structures. Some chemical combinations of coatings and resins may interact and become inflammable at time of manufacturing, hence proper care need to be exercised. Some of the related information on hygro-thermal effects, creep, fatigue, and temperature effects are provided within the text and can be significantly enhanced depending on the scope of this project. Major advances have been made in the past 13 year. Emphasis must be on degradation rates of different composites types under different parameters (H_2O, pH, temperature, sustained
6-2	Physical Aging of Polymer Matrix	6-1		x		
6-3	Influence of Moisture	6-2		x		
	a. Influence of moisture on polymer matrix...........................	6-2		x		
	b. Influence of moisture on fibers ..	6-2		x		
	c. General behavior of water-saturated composites..................	6-2		x		
6-4	Hygrothermal Effects	6-2		x		
6-5	Alkaline Environment	6-3		x		
6-6	Low Temperature Effects	6-3		x		
6-7	Low Temperature Thermal Cycling (Freeze-Thaw) Effects ..	6-4		x		

	Subject	Page	Adequate	Needs improvement	Inadequate	Comments
6-8	Radiation	6-4		x		stress, strength degradation, or their combinations). Calibrations based on in-service fileld data is possible, however, small the data pool might be.
6-9	Creep Behavior	6-5		x		
6-10	Fatigue..	6-6		x		
6-11	Properties Fire Hazards and Flammability	6-7		x		
						New section: 6- 12: Preventive measures or procedure of how to enhance above properties should be added.
	Chapter 7					
	Design Guidance					
7-1	Manufacturer's Guidelines	7-1		x		• Discussions on currently available new guidelines including thorough revision are necessary. • Emphasis should be provided to the design of marine structures including lift gate mechanism. • Separate appendix on calculation of mechanical properties and behavior of structural properties will be very helpful. • Examples can focus on durability aspects of miter gates and lift gates used for marine applications. Design equations and guidelines that govern the connection scheme of composites and related specifications have to be updated. • A new section based on (7-5: ASCE Manual 1997+Recent+LRFD manual 2010) should be added
7-2	Military Handbooks	7-1		x		
7-3	Design Approach	7-1		x		
	a. Performance specifications.........	7-1		x		
	b. Material selection......................	7-1		x		
	c. Standard components	7-2		x		
7-4	Connections	7-2		x		
	a. Mechanical joints	7-2		x		
	b. Adhesives..................................	7-3		x		
	c. Using anchors for prestressing ...	7-4		x		

	Chapter 8					
	Quality Assurance					
8-1	Test Methods	8-1		x		• New guidelines developed by ACI, ASTM, AASHTO,ASCE and various US, Canadian, Japanese, European, industry, military, and other codes have to be included and updated. Several of these documents and information were not available when this TL was published. • NDT application to detect delamination, failure patterns, and as a QA/QC tool is an is an evolving field and the document need to updated with the latest advancements/technologies/applications including applicability and limitations of each technique.
	a. ASTM standards.........................	8-1		x		
	b. SACMA standards	8-1		x		
	c. Military specifications................	8-1		x		
	d. State-of-the-art report from ACI	8-2		x		
8-2	Inspection and Performance Monitoring Methods	8-2		x		
	a. background	8-2		x		
	b. Visual inspection........................	8-2		x		
	c. Instrumental Nondestructive evaluation (NDT) methods	8-2		x		
	d. Remote sensing and smart systems.......................................	8-3		x		
	Chapter 9					
	Repair of FRP Composites					
9-1	General	9-1		x		• Repair methods need additional focus on design methods, governing equations, and application sequences for specific concrete, timber, steel, and underwater applications. • Resins available for underwater applications and their curing need to be explained because of similarity with marine structures. • Repair of FRP with FRP in not discussed and needs to be included. • Many manuals including the ones from aerospace industry are available and need to be highlighted.
9-2	Routine Maintenance	9-1		x		
9-3	Repair During Installation	9-1		x		
9-4	Repairs Due to Accidental Damage and/or Service Exposures ..	9-1		x		
9-5	Prepreg Kits	9-2		x		
9-6	Underwater Repairs	9-2		x		
9-7	Special Considerations	9-2		x		

	Appendix A					
	References					
A-1	Required publications	A-1			X	Huge body of work is available to reference for civil engineering examples and guidelines and need to be updated.
A-2	Related publications	A-2			X	
	Appendix B					
	Examples of FRP Composite Applications			X		• Update the outcome of these mentioned projects that employed FRP is necessary including current status. This information can be appropriately utilized while designing such structures with FRP. • Needs to include measures to limit deflections when combination of steel backbone and FRP stiffnere/skin plate utilization, including the applicable allowable limits. • In addition, design aspects of FRP gates and manufacturing aspects need to be separately discussed. • Several of the design, manufacturing, environmental durability, and long-term performance lessons learnt from the bridge and construction industry needs to be included. • Section B-3 on Wicket gate needs to include major discussion on European experience on locks and potential applicability with composites.
B-1	Introduction	B-1		X		
B-2	Gravity drainage structure	B-1		X		
B-3	Wicket gate	B-1		X		
B-4	Development and demonstration of FRP composite materials under the CPAR Program.................................	B-3		X		

	Appendix C					
	Example Performance Specification for FRP Components					
	PART 1 GENERAL	C-1		X		Specify a group of materials that can be used,
	PART 2 PRODUCTS	C-4			X	require sufficient long-term property data for the used materials
	PART 3 EXECUTION	C-5			X	Provide method/reference of service life prediction, and quality assurance procedure that will be implemented
	Appendix D					
	Glossary			x		Additional terms related to revision should be added.
	Tables					Document would benefit from updating the existing tables with available information and development over the past decade plus since this TL was published.
	Figures					Document would benefit from updating the existing figures with newer implementation of FRP structures, FRP repairs, fabrication (manufacturing) methods, joining schemes, structural shapes, structural response diagrams including those related to successful functioning and failure.

APPENDIX C

Available standards, guidelines, and reports for FRP

The following are available standards, guidelines, and reports from different organizations along with brief description as provided by them.

Issued by	Code No.	Title	Description
AASHTO	GFRP-1 GFRP-1-UL ISBN# 1-56051-458-9	AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete Bridge Decks and Traffic Railings, First Edition, 2009	The guide focuses on differences in the physical and mechanical behavior of GFRP materials as opposed to steel, unique guidance on the engineering and construction of concrete bridge decks reinforced with GFRP bars. These guide specifications offer a description of the unique material properties of GFRP composite materials as well as provisions for the design and construction of concrete bridge decks and railings reinforced with GFRP reinforcing bars.
AASHTO	GSDFPB-1 GSDFPB-1-UL ISBN# 1-56051-395-7	Guide Specifications for Design of FRP Pedestrian Bridges, 1st Edition, 2008	These Guide Specifications apply to fiber-reinforced polymer (FRP) composite bridges intended to carry primarily pedestrian and/or bicycle traffic. In addition, this guide does not supersede the *Guide Specifications for Design of Pedestrian Bridges.*
ACI	364.2T-08	TechNote: Increasing Shear Capacity Within Existing Reinforced Concrete Structures, 2008	This TechNote provides an overview of the variety of materials and methods available to increase shear capacity, including the use of external steel reinforcement, section enlargement, internal steel or fiber-reinforced polymer (FRP) reinforcement, supplemental members, FRP plates and strips, both steel and FRP near-surface-mounted reinforcement, and external prestressing.
ACI	440.1R-06	Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars, 2006	This guide offers general information on the history and use of FRP reinforcement, a description of the unique material properties of FRP, and guidelines for the construction and design of structural concrete members reinforced with FRP bars. This guide is based on the knowledge gained from worldwide experimental research, analytical work, and field applications of FRP reinforcement.
ACI	440.2R-08	Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, 2008	This document offers general information on the history and use of FRP strengthening systems; a description of the unique material properties of FRP; and committee recommendations on the engineering, construction, and inspection of FRP systems used to strengthen concrete structures. The guidelines are based on the knowledge gained from experimental research, analytical work, and field applications of FRP systems used to strengthen concrete structures.
ACI	440.3R-04	Guide Test Methods for Fiber-Reinforced Polymers (FRPs) for Reinforcing or Strengthening Concrete Structures	This document provides model test methods for the short-term and long-term mechanical, thermo-mechanical, and durability testing of FRP bars and laminates. The recommended test methods are based on the knowledge gained from research results and literature worldwide. Many of the proposed test methods for reinforcing rods are based on those found in “Recommendation for Design and Construction of Concrete Structures using Continuous Fiber Reinforcing Materials” published in 1997 by the Japan Society for Civil Engineers (JSCE). These test methods are expected to be considered, modified, and adopted, either in whole or in part, by a U.S.national standards-writing agency such as ASTM International or AASHTO.

Issued by	Code No.	Title	Description
ACI	440.4R-04	Prestressing Concrete Structures with FRP Tendons, 2004	The document focuses on the current state of design, development, and research needed to characterize and ensure the performance of FRP as prestressing reinforcement in concrete structures. The current development includes a basic understanding of flexure and axial prestressed members, FRP shear reinforcement, bond of FRP tendons, and unbonded or external FRP tendons for prestressing applications. The document concludes with a description of research needs.
ACI	440.5-08 440.5M-08	Specification for Construction with Fiber-Reinforced Polymer Reinforcing Bars (M for metric version)	This reference specification covers construction using fiber-reinforced polymer reinforcing bars that the Architect/Engineer can make applicable to any construction project by citing it in the Project Specifications. The Architect/Engineer supplements the provisions of this Reference Specification as needed by designating or specifying individual project requirements.
ACI	440.6-08 440.6M-08	Specification for Carbon and Glass Fiber-Reinforced Polymer Bar Materials for Concrete Reinforcement, 2008 (M for metric version)	This material specification covers provisions governing testing, evaluation, and acceptance of carbon and glass fiber-reinforced polymer (FRP) bars used as reinforcement for concrete.
ACI	440.7R-10	Guide for Design & Constr of Externally Bonded FRP Systems for Strengthening Unreinforced Masonry Structures, 2010	This guide offers general information on FRP systems use, a description of their unique material properties, and recommendations for the design, construction, and inspection of FRP systems for strengthening URM structures. These guidelines are based on knowledge gained from a comprehensive review of experimental and analytical investigations and field applications.
ASCE	41056 ISBN# 9780784410561	ASCE/SEI Design of Fiberglass-Reinforced Plastic (FRP) Stacks (52-10)	*Design of Fiberglass Reinforced Plastic (FRP) Stacks* outlines the important mechanical and structural engineering considerations for stacks where the primary supporting shell is made of FRP. Topics include: • considerations pertaining to wind and seismic-induced vibrations; • guidelines for the ultraviolet protection and selection of materials; • requirements for lighting and lightning protection based upon existing building and federal codes; • requirements for climbing and access based upon current Occupational Safety and Health Administration (OSHA) standards; • the important areas regarding fabrication and construction; and • maintenance and inspection following initial operation.
ASTM	D7522 D7522M-09	Standard Test Method for Pull-Off Strength for FRP Bonded to Concrete Substrate	This test method describes the apparatus and procedure for evaluating the pull-off strength of wet lay-up or pultruded (shop-fabricated) Fiber Reinforced Polymer (FRP) laminate systems adhesively bonded to a flat concrete substrate
ASTM	D5573-99 (2005)	Standard Practice for Classifying Failure Modes in Fiber-Reinforced-Plastic (FRP) Joints	This practice covers the method of classifying, identifying, and characterizing the failure modes in adhesively bonded fiber-reinforced-plastic (FRP) joints. The FRP used in developing this practice consists of glass fibers
ASTM	D5868-01 (2008)	Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding	This test method describes a lap shear test for use in measuring the bonding characteristics of adhesives for joining fiber reinforced plastics to themselves and to metals. The method is applicable to random and fiber oriented FRP.

Issued by	Code No.	Title	Description
ASTM	D5364-08e1	Standard Guide for Design, Fabrication, and Erection of Fiberglass Reinforced (FRP) Plastic Chimney Liners with Coal-Fired Units	This guide offers direction and guidance to the user concerning available techniques and methods for design, material selection, fabrication, erection, inspection, confirmatory testing, quality control and assurance.
ASTM	F711-02 (2007)	Standard Specification for Fiberglass-Reinforced Plastic (FRP) Rod and Tube Used in Live Line Tools	This specification covers insulating rods and foam-filled tubes made from fiberglass-reinforced plastic (FRP) that are intended for use in live line tools.
ASTM	E2478-06a	Standard Practice for Determining Damage-Based Design Stress for Fiberglass Reinforced Plastic (FRP) Materials Using Acoustic Emission	This practice details procedures for establishing the direct stress and shear stress damage-based design values for use in the damage-based design criterion for materials to be used in FRP vessels and other composite structures.
ASTM	E1067-07	Standard Practice for Acoustic Emission Examination of Fiberglass Reinforced Plastic Resin (FRP) Tanks/Vessels	This practice covers acoustic emission (AE) examination or monitoring of fiberglass-reinforced plastic (FRP) tanks-vessels (equipment) under pressure or vacuum to determine structural integrity.
ASTM	D7565 D7565M-10	Standard Test Method for Determining Tensile Properties of Fiber Reinforced Polymer Matrix Composites Used for Strengthening of Civil Structures	This test method describes the requirements for sample preparation, tensile testing, and results calculation of flat fiber reinforced polymer (FRP) composite materials used for the strengthening of structures
ASTM	D7337 D7337M-07	Standard Test Method for Tensile Creep Rupture of Fiber Reinforced Polymer Matrix Composite Bars	This test method outlines requirements for tensile creep rupture testing of fiber reinforced polymer matrix (FRP) composite bars commonly used as tensile elements in reinforced, prestressed, or post-tensioned concrete.
ASTM	D7205 D7205M-06	Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars	This test method determines the quasi-static longitudinal tensile strength and elongation properties of fiber reinforced polymer matrix (FRP) composite bars commonly used as tensile elements in reinforced, prestressed, or post-tensioned
ASTM	E2076-05	Standard Test Method for Examination of Fiberglass Reinforced Plastic Fan Blades Using Acoustic Emission	This test method provides guidelines for acoustic emission (AE) examinations of fiberglass reinforced plastic (FRP) fan blades of the type used in industrial cooling towers and heat exchangers
ASTM	F1825 – 03 (2007)	Standard Specification for Clampstick Type Live Line Tools	This specification applies to the clampstick type live line tools to ensure manufacturing processes and materials are compatible and no deterioration of components occur during the assembly process. Neither the FRP tube and rod, foam filling, or the bonding adhesive is allowed to deteriorate during the prescribed mechanical and electrical test. The external surface of the FRP is supposed to be uniform, symmetrical, and free of abrasions, scratches, blemishes, and surface defects. The mechanical design test and electrical design test procedures are presented in details.
ASTM	D4167-97 (2007)	Standard Specification for Fiber-Reinforced Plastic Fans and Blowers	This specification covers centrifugal and axial fans and blowers with airstream components fabricated of fiber-reinforced thermoset plastics (FRP) for corrosion resistance

Issued by	Code No.	Title	Description
ASTM	F1430 F1430M-10	Standard Test Method for Acoustic Emission Testing of Insulated and Non-Insulated Aerial Personnel Devices with Supplemental Load Handling Attachments	This test method describes a procedure for acoustic emission (AE) testing of aerial personnel devices (APDs) with supplemental load handling attachments.
ASTM	D6465-99 (2005)	Standard Guide for Selecting Aerospace and General Purpose Adhesives and Sealants	This guide is intended to assist design engineers, manufacturing/industrial engineers, and production managers in selecting the best-fit adhesive/sealant or bonding/sealing process.
ASTM	E1888 E1888M-07	Standard Practice for Acoustic Emission Examination of Pressurized Containers Made of Fiberglass Reinforced Plastic with Balsa Wood Cores	This practice covers guidelines for acoustic emission (AE) examinations of pressurized containers made of fiberglass reinforced plastic (FRP) with balsa cores. Containers of this type are commonly used on tank trailers for the transport of hazardous chemicals.
ASTM	D5041-98 (2004)	Standard Test Method for Fracture Strength in Cleavage of Adhesives in Bonded Joints	This test method covers the determination of fracture strength in cleavage of adhesive bonds when tested on standard reinforced plastic specimens and under specified conditions of preparation and testing
ASTM	C1228-96 (2009)	Standard Practice for Preparing Coupons for Flexural and Washout Tests on Glass Fiber Reinforced Concrete	This practice covers preparation of test coupons to be used in tests of plant manufactured thin-section glass fiber reinforced concrete (GFRC).
ASTM	E1118-05	Standard Practice for Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP)	This practice covers acoustic emission (AE) examination or monitoring of reinforced thermosetting resin pipe (RTRP) to determine structural integrity. It is applicable to lined or unlined pipe, fittings, joints, and piping systems.
ASTM	D907-08b	Standard Terminology of Adhesives	This terminology standard is a compilation of definitions used in the science and technology of the adhesives industry. Terms that are generally understood or adequately defined in other readily available sources are not included.
ASTM	NACE/ASTMG193-10a	Standard Terminology and Acronyms Relating to Corrosion	This terminology and acronyms standard covers and defines commonly used terms and acronyms in the field of corrosion. Related terms may be found in Terminologies D16 , D4538 , G40 , or other ASTM terminology standards
ASTM	D4475-02(2008)	Standard Test Method for Apparent Horizontal Shear Strength of Pultruded Reinforced Plastic Rods By the Short-Beam Method	This test method covers the determination of the apparent horizontal shear strength of fiber reinforced plastic rods. The specimen is a short beam in the form of lengths of pultruded rods. This test method is applicable to all types of parallel-fiber-reinforced plastic rod samples.
ASTM	D5117-09	Standard Test Method for Dye Penetration of Solid Fiberglass Reinforced Pultruded Stock	This dye-penetrant test method covers a means of evaluating solid fiberglass all-roving reinforced pultruded rod or bar stock for longitudinal wicking.
ASTM	D4476-09	Standard Test Method for Flexural Properties of Fiber Reinforced Pultruded Plastic Rods	This test method covers the determination of the flexural properties of fiber-reinforced pultruded plastic rods. The specimen is a rod with a semicircular cross section, molded or cut from lengths of pultruded rods
ASTM	C868-02(2008)	Standard Test Method for Chemical Resistance of Protective Linings	This test method covers a procedure for evaluating the chemical resistance of a polymer-based protective lining in immersion service.

Issued by	Code No.	Title	Description
ASTM	D2996-01(2007)e1	Standard Specification for Filament-Wound “Fiberglass" (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe	This specification covers machine-made reinforced thermosetting resin pressure pipe (RTRP) manufactured by the filament winding process up to 24 in. nominal size. Included are a classification system and requirements for materials.
ASTM	D4896-01(2008)e1	Standard Guide for Use of Adhesive-Bonded Single Lap-Joint Specimen Test Results	This guide is directed toward the safe and appropriate use of strength values obtained from test methods using single-lap adhesive joint specimens.
ASTM	E2533-09	Standard Guide for Nondestructive Testing of Polymer Matrix Composites Used in Aerospace Applications	This guide provides information to help engineers select appropriate nondestructive testing (NDT) methods to characterize aerospace polymer matrix composites (PMCs). This guide does not intend to describe every inspection technology.
ASTM	C297 / C297M - 04	Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions	This test method covers the determination of the core flatwise tension strength, or the bond between core and facings of an assembled sandwich panel. The test consists of subjecting a sandwich construction to a tensile load normal to the plane of the sandwich, such load being transmitted to the sandwich through thick loading blocks bonded to the sandwich facings or directly to the core.
Japan Society of Civil Engineers		Recommendation for Design and Construction for Reinforced Concrete Structures Using Continuous Fiber Reinforcing Materials	Available as free download on JSCE website: http://www.jsce.or.jp/committee/concrete/e/newsletter/newsletter01/recommendations.htm
Japan Society of Civil Engineers		Recommendations for Upgrading of Cconcrete Structures with Use of Continuous Fiber Sheets	Available as free download on JSCE website: http://www.jsce.or.jp/committee/concrete/e/newsletter/newsletter01/recommendations.htm
National Research Council Canada	NRCC BLDGCODE-05	National Building Code of Canada 2005	Design and Construction of Building Components with Fiber Reinforced Plastics
Canadian Standards Association (CSA)	CAN/CSA-S6-06	Canadian Highway Bridge Design Code	Fiber Reinforced Structures (section of code)
Canadian Standards Association (CSA)	CAN/CSA-S806-02 (R2007)	Design and Construction of Building Components with Fibre-Reinforced Polymers	This Standard provides requirements for the design and evaluation of building components of fibre-reinforced polymers (FRP) in buildings and of building components reinforced with FRP materials. It is based on limit states design principles and is consistent with the National Building Code of Canada. This Standard does not apply to the design of fibre-reinforced concrete (FRC), except for FRC/FRP cladding as defined in Clause 7.3 and Clause 13.

Issued by	Code No.	Title	Description
BSI	EN 13706-1:2002 EN 13706-2:2002 EN 13706-3:2002	European Standard EN 13706 Reinforced plastics composites. Specifications for pultruded profiles. Designation	The standard specifies the minimum requirements for the quality, tolerances, strength, stiffness and surface of structural profiles. The standard basically divides pultruded structural profiles into two classes: E23 – having the most stringent requirements to quality E17 – having more lenient requirements to quality The standard broadly consists of three parts: • EN 13706-1: Specifying the designation/labelling/marking of structural profiles with regard to selection of materials, selection of reinforcement, surface treatment, etc. • EN 13706-2: Indicating testing methods and tolerances for pultruded structural profiles. Guidelines for quality and quality assurance are also given. • EN 13706-3: Indicating minimum values for the technical properties of structural profiles in relation to the standard's two classes.
National Research Council of ITALY (CNR)	CNR-DT 200/2004	Guide for the Design and Construction of Externally Bonded FRP Systems For Srengthening Existing Structures	This document provides guidelines on strengthening reinforced concrete, prestressed concrete, and masonry structures.
National Research Council of ITALY (CNR)	CNR-DT 203/2006	Guide for the Design and Construction of Concrete Structures reinforced with Fiber-Reinforced Polymer Bars	Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars
National Research Council of ITALY (CNR)	CNR-DT 205/2007	Guide for the Design and Construction of Structures made of FRP Pultruded Elements	This document deals with structures made of FRP pultruded elements particularly with glass, carbon and aramid. The design regulations take into consideration the state of the experimental knowledge still currently being developed. Therefore, in the case of double symmetrical sections, they are based on analytical expressions, while in other cases on numerical procedures. This document also has four Appendices: Appendix A – Further study on the critical load of local instability of double T stressed pultrudes; Appendix B – Production techniques of FRP pultrudes; Appendix C – Typical technical data sheet of FRP pultrudes; material characterisation tests; Appendix D – Choice and verification of FRP pultrudes: duties and responsibilities of the designer.

Issued by	Code No.	Title	Description
International Federation of Structural Concrete (FIB) Switzerland	fib Bulletin No. 14 ISBN# 978-2-88394-054-3	Externally bonded FRP reinforcement for RC structures, 2003	This technical report constitutes the work conducted by five working groups: Material Testing and Characterization (MT&C), Reinforced Concrete (RC), Prestressed Concrete (PC), Externally Bonded Reinforcement (EBR), and Marketing and Applications (M&A) This bulletin gives detailed design guidelines on the use of FRP EBR, the practical execution and the quality control, based on the current expertise and state-of-the-art knowledge of the task group members. It is regarded as a progress report since • it focuses on those aspects that form the majority of the design problems of RC strengthening with composites. • Several of the topics presented are subject of ongoing research and development, and the details of some modelling approaches may be subject to future revisions. • As knowledge in this field is advancing rapidly, the work of the EBR WP will continue.
International Federation of Structural Concrete (FIB) Switzerland	fib Bulletin No. 35 ISBN# 978-2-88394-075-8	Retrofitting of concrete structures by externally bonded FRPs, with emphasis on seismic applications, 2006	*fib* Bulletin 35 presents the course materials developed for the short course "Retrofitting of Concrete Structures through Externally Bonded FRP, with emphasis on Seismic Applications", given in Ankara and Istanbul in June 2005. It also presents relevant provisions from three of the standardizations: EN 1998-3:2005 "Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings", the 2005 Draft of the Turkish seismic design code, and the Italian regulatory document CNR-DT 200/04, "Instructions for Design, Execution and Control of Strengthening Interventions by Means of Fibre-Reinforced Composites" (2004).
International Federation of Structural Concrete (FIB) Switzerland	fib Bulletin No. 40 ISBN# 978-2-88394-080-2	FRP reinforcement in RC structures, 2007	*fib* Bulletin 40 deals mainly with the use of FRP bars as internal reinforcement for concrete structures. The bulletin covers the issues of Ultimate Limit States (primarily dealing with flexural design), Serviceability Limit States (dealing with deflections and cracking), Shear and Punching Shear and Bond and Tension Stiffening. It provides information on state-of-the-art and ideas for the next generation of design guidelines. The bulletin ends with a discussion of a possible new framework for developing partial safety factors to ensure specific safety levels that will be flexible enough to cope with new materials.
Transportation Research Board	HRD282	Fiber Reinforced Polymer Composites for Concrete Bridge Deck Reinforcement, 2003	This digest describes the material requirements for fiber reinforced polymer (FRP) composites used as internal reinforcement for concrete bridge decks and presents test procedures for evaluating these composites. This report includes a review of current practices regarding the use of FRP composites for concrete bridge deck reinforcement, performance of laboratory and analytical investigations, monitoring of in-service bridge deck installations, and identification of protocols for the evaluation of FRP composites.
Transportation Research Board	NR609 ISBN# 978-0-309-09928-8	Recommended Construction Specifications and Process Control Manual for Repair and Retrofit of Concrete Structures Using Bonded FRP Composites, 2008	The specifications provided in this document cover the construction of FRP systems used as externally bonded or near surface-mounted reinforcement to enhance axial, shear, or flexural strength of a concrete member. The experimental investigation and the research findings supporting the recommended construction guidelines, construction process manual, and threshold values are available online.

Issued by	Code No.	Title	Description
Transportation Research Board	NR514 ISBN# 0-309-08785-6	Bonded Repair and Retrofit of Concrete Structures Using FRP Composites: Recommended Construction Specifications and Process Control Manual, 2004	This report contains the findings of research performed to develop recommended construction specifications and a construction process control manual for bonded fiber reinforced polymer (FRP) repair and retrofit of concrete structures. The material in this report will be of immediate interest to bridge construction inspectors, general contractors, FRP subcontractors, and FRP and adhesive materials suppliers.
U.S. Department of Defense	MIL-HDBK-17E	Composite Materials Handbook	Volume 1, Guidelines for Characterization of Structural Materials, Jan. 1997. Volume 2, Material Properties, Dec. 1998. Volume 3, Materials Usage, Design, and Analysis, Jan. 1997
Transportation Research Board of the National Academies	NCHRP REPORT 514	Bonded Repair and Retrofit of Concrete Structures Using FRP Composites Recommended Construction Specifications and Process Control Manual, 2004	This report deals with the recommended construction specifications and a construction process control or bonded FRP repair and retrofit of concrete structures. The three most common types of FRP repair systems are discussed: wet lay-up, precured, and near surface mounted. The novelty of the FRP technology and its subtle differences from the traditional repair systems are reflected in the proposed specifications.
Northrop Corporation, Federal Aviation Administration, DOT	NOR 86-181	Handbook: An Engineering Compendium On The manufacture And Repair Of Fiber-Reinforced Composites, 1987	This handbook is a compendium of information on fiber-reinforced composites technology. It is aimed at familiarizing the reader with the salient aspects of using composites in aviation applications and aiding FAA engineering personnel in assessing the continued airworthiness of composite parts in civilian aircraft. The contents of this handbook include: descriptions of the various fiber, matrix and composite materials; quality assurance, handling and storage of the uncured composites; prepregs; laminate fabrication processes; quality assurance of laminated structural parts; laminate definition and analysis; defect and damage tolerance of composites; and repair of composite structures.
ICC Evaluation Service, INC. icc-es.org	AC280	Acceptance Criteria For Fiber-Reinforced-Polymer-Glued-Laminated Timber Using Mechanics-Based Models, 2005	This acceptance criteria has been issued to provide all interested parties with guidelines for demonstrating compliance with performance features of the applicable code(s) referenced in the acceptance criteria.