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## Composites for hydraulic structures: a review

Yingxiang Lu

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# **Composites for hydraulic structures: a review**

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Problem report submitted to the  
College of Engineering and Mineral Resources at  
West Virginia University in  
partial fulfilment of the requirements  
for the degree of

**Master of Science  
in  
Civil Engineering**

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# ABSTRACT

## Composites for hydraulic structures: a review

Composites have evolved over the years and are making major in-roads into the marine, aviation and other industries where corrosions and self-weight are the major impediments to advancing the state-of-the-art. Civil Works engineers have been reluctant to make use of these composite advantages, partially because of the absence of well documented success stories, accepted design and construction practices or specifications, and limited understanding of composites, higher initial costs and others. A few navigational structures using FRP composites have been designed, manufactured and installed in the United States of America and Netherlands, recently. US Army Corps of Engineers is embarking on higher volume applications of composites for navigational structures.

This report is aimed at summarizing the state of the art of fiber reinforced polymer (FRP) composites for hydraulic structures including design, construction, evaluation and repair. After a brief review of history and introduction of fundamentals of composites, their manufacturing techniques, properties, and recent field applications are presented, including FRP rebar for bridge decks, other highway and railway structures, gratings, underground storage tank, pavement, sheet and pipe piling, FRP wraps, moveable bridges, utility poles, etc. Focus is placed on applications of composites in waterfront, marine, navigational structures including lock doors, gates, and protection systems. Design of hydraulic composite structures is presented for the cases available, such as design of FRP recess panel, Wicket Gates, Miter Gates, FRP slides and repair of corroded steel piles. This report also reviews engineering science issues such as fracture and fatigue, durability, creep and relaxation, UV degradation, impact resistance, and fire performance. The report concludes with summary remarks and recommendations after a discussion on operation and maintenance guidance including nondestructive evaluation inspection techniques. Intention is to provide up to date information on composite design, manufacturing and evaluation methodologies that are applicable for fabrication and maintenance of navigational structures.

This report is a living document with advances taking place with time as waterborne transport infrastructure community makes progress with FRP systems. This report is expected to be useful for those decision-makers in government, consultants, designers, contractors, maintenance and rehab engineers whose focus is to minimize traffic interruptions while maximizing cost effectiveness.

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Morgantown, October 2018

Yingxiang Lu



## **Disclaimer**

Case studies and applications provided herein are compiled from references and materials provided by the members of PIANC (The World Association for Waterborne Transport Infrastructure) WG 191 and other researchers. The contents of this report reflect the views of the original authors, who are responsible for the facts and accuracy of the information presented herein.

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# 1 GENERAL ASPECTS

## 1.1 Introduction

Composites have evolved over the years and are making major in-roads into the marine, aviation, and auto industry. Composites offer many and varied material property advantages, some of those advantages are strength-to-weight ratio, corrosion resistance, ease of construction, and others. Civil Works engineers have been reluctant to take advantage of these properties, partially because of absence of well documented success stories, accepted design and construction code or specifications, and limitations of composites, difficult to design due to their complex behavior, higher initial costs and others.

A few navigational structures using FRP composites have been manufactured and installed in the United States of America, Netherlands and other countries like China. USACE is embarking on additional applications using composites for navigational structures.

For any successful and sustainable use of new materials, guidance must be provided in terms of properties of constituent materials, mass-manufacturing, design, fabrication and field implementation, standardized test methodologies to establish chemo-thermo-mechanical properties, nondestructive evaluation and maintenance in the field, and finally repair and rehabilitation techniques that will be implemented easily in field.

This report is aimed at providing general guidelines and recommendations for the applications of fiber reinforced polymer (FRP) composites in navigational structural systems.

## 1.1 Structure of Report

This report can be summarised as follows:

**History:** A brief history of alternative materials (composites) describing how and why these materials are being investigated and implemented.

**Fundamentals of composites:** Define of polymers, resin and fibers, and describe how their properties are involved in the composites.

**Fabrication:** Describe how the composite materials are fabricated and assembled. Discuss and describe the methods of material fabrication and joining/connections mechanisms. Elaborate on the advantages and disadvantages of the various connections.

**Characteristics:** List the major pros and cons of using composite materials in terms of a number of topics (thermo-mechanical, physical, chemical properties, fire, durability, cost, repair and maintenance etc.) Provide examples and comparisons as needed to justify the pros and cons.

**Recent advances:** Present latest advances in materials and recycling of FRP composites.

**Applications:** Part I focuses applications in general areas while Part II identifies applications involved in large scale marine and civil projects: locks, dams, levees and pump stations, valves, gates, walls, piling, mooring facilities, etc.

**Design and testing:** List relevant codes for the design and construction of composite structures. Describe the industry standards for testing of composite materials.

***Inspection, operation and maintenance:*** Describe the process for inspecting structures fabricated with composite materials. Provide more emphasis in the testing of the various connections.

## 2 HISTORY OF COMPOSITES

The history of composites can be traced back thousands of years to Mesopotamia including the use of mud and straw in bricks and asphaltic bonded copper sheets and decorated inlays set with natural resins. Halfway into the second millennium, decorative pieces made of cloisonnes were produced in Asia and Europe. All the above have one important thing in common, i.e. they were made with at least two distinctly different constituent materials combined into one final product of improved performance. Even thousands of years ago, organic polymers from tree and plant secretions, fossilized resins, bituminous materials and those prepared from fish and animal offal were used in practice (Seymour & Deanin, 1986).

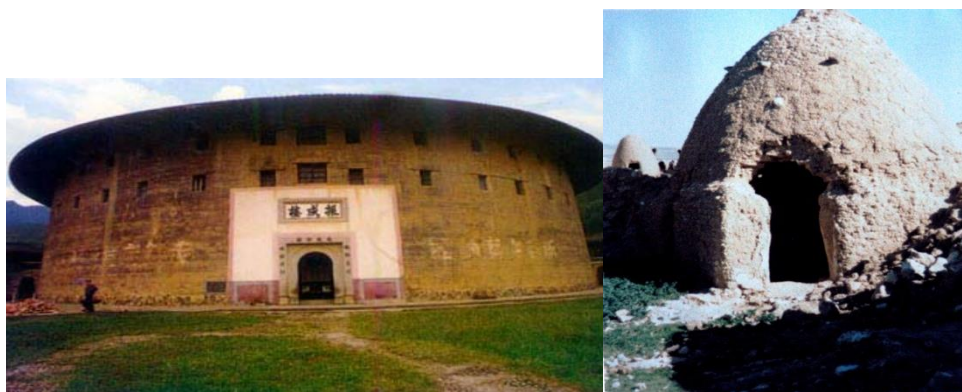
As the knowledge base kept improving, fine copper wires were most prevalent and even gold alloy filaments have been used effectively coupled with polymeric fibers such as silk for decorative purposes. Textiles and metal fibers woven as fabrics have been preserved under dry conditions for thousands of years (Sinopoli, 2003). Cotton, wool and linen are natural organic fibers that have been decorated with fine gold threads as has been utilized in India. The inclusions of metallic wires to reinforce non-metallic applications are many. For example, decorative organic plastic and paper pulp were used to make canes and umbrella handles in late nineteenth century in Europe (Seymour & Deanin, 1986).

The first range of thermosetting resins to make their mark in the modern composite age were unsaturated polyester resins, which were introduced in the UK in 1946 by “Scott Bader” and by “Marco” in the USA. Development was rapid and by 1947 the first British cold-curing polyester resin had been introduced, followed, in 1949, by the first non-air-inhibited resins, paving the way for cheap, simple, open mould production methods. (University of Delft)

### 2.1 Hakka Round House

*Sophisticated applications of composites have been identified in nature from time immemorial and man-made composite applications such as straw reinforced adobe or brick in Tulou houses of China (*

Figure 2.1- Tulou House)(Liang, GangaRao, & Stanislawski, 2011), beehives ((left) Beehive House) (Chernick, 2009), etc. have been identified in the past thousands of years ago. A typical beehive house of high domed structure with adobe brick was found to be extremely durable, and provide excellent service as a significant heat sink due to favorable thermal properties for hot countries.



*Figure 2.1- Tulou House(left) Beehive House (right)*

## 2.2 Polymer Composites

After World War Two, US manufacturers began producing fiberglass and polyester resin composite boards and the automotive industry introduced the first composite vehicle bodies in the early fifties (Tang, 2011). Modern composites are made primarily of glass, carbon and/or aramid reinforcements. More recently, FRP (Fiber Reinforced Polymer) composites are formed as load bearing structural components of aircraft and marine structures. The surfaces of marine structures are protected through a class of polymer coatings including sacrificial coatings (lead or silver). For example, the protection of ship hulls against marine growth has been accomplished through these novel coatings. As recently as 2012, the US Navy and Air Force (SERDP & ESTCP, 2012) are demonstrating a novel protective coating to reduce wear on compressor airfoils on gas turbine engines significantly increasing fuel efficiency and reducing maintenance requirements. These coatings are made of multilayer ceramic-metal matrix composites using vapor deposition process. Other notable examples made of composites appeared in thousands of household washing machines, refrigerators, drains, etc.

## 2.3 Natural Composites

Henry Ford first exhibited finished soybean car (left) Soybean Car in 1941 at the Dearborn Days Festival in Dearborn, MI (Soybean car.2012). Ford invested millions of R&D dollars developing quarter inch thick plastic car panels reinforced with tubular steel but he could not make an economically viable automobile at the time. However, natural fiber composites are just beginning to make some in-roads into high volume applications. These fibers are bound together with a variety of resin systems such as esters, urethanes, phenolics and others. In addition, a variety of additives and fillers are used in composites to improve performance such as the bonding characteristics between the fiber and resin, manufacturing process improvement, colors, fire protection and cost reductions.



From the collections of The Henry Ford (THF103652)

*Figure 2.2- Damascus steel (left) Soybean Car (right)*

## 2.4 Nanocomposites

More sophisticated composites appeared in ensuing years including Damascus Steel varieties (Inman, 2006) revealed that nanowires and carbon nanotubes in a blade were forged from Damascus Steel. This discovery provides a lesson that it is preferable to incorporate nanomaterials as an integral means of mass manufacturing for their maximum effect on properties as opposed to using nanomaterials as additives to enhance chemo-thermo-mechanical properties. A few additional

examples of recent origins of polymer composites are reinforced rubber tires, aerospace components, laminated polymer parts, laminated electroplated components and others. Similarly, polymer coated metal hardware appeared in the markets in the last 70-80 years such as polymer insulated copper wires.

## 2.5 Innovative Composite Applications

Recent research efforts on FRP composites have been focused on marine, aerospace, civil and military infrastructure applications such as deck houses for ships, airplane components, wind turbines blades, cold water pipes for Ocean Thermal Energy Conversion (Figure 2.3), high pressure composite pipes for natural gas transmission (Figure 2.4), transmission towers, utility poles up to 120 feet in height, Boeing Dreamliner 787 (Figure 2.5) of 80 vol% or 50 wt% FRP of the construction materials, Titan (Figure 2.6) that is one of only five known manned submersibles in the world capable of reaching a depth of 4,000m, oil and gas riser (Figure 2.7). More applications will be discussed in chapter 7.

FRP composites have recently been applied for hydraulic structures such as the navigational gates (Figure 2.9-Figure 2.13), movable bridges (Figure 2.14-Figure 2.19), seawater front gratings, decking, and walkways (Figure 2.20-Figure 2.24), Lifting and slide gates (Figure 2.25) and minehunter ships (Figure 2.26), Additipnal applications will be discussed in chapter 8.

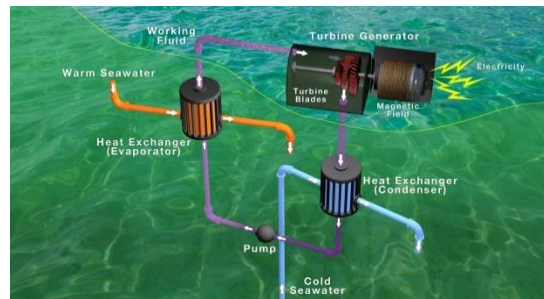


Figure 2.3- Lockheed OTEC

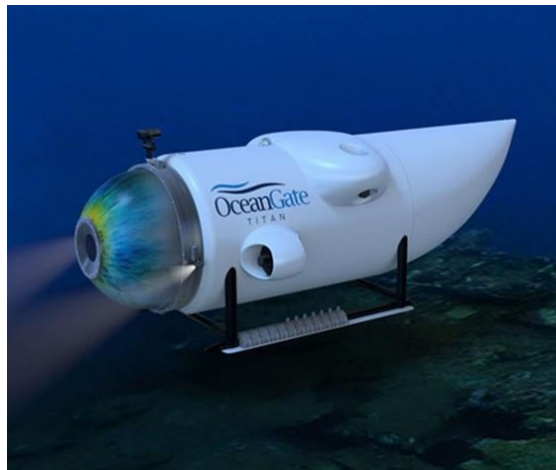


Figure 2.4-Pipe Section During Testing

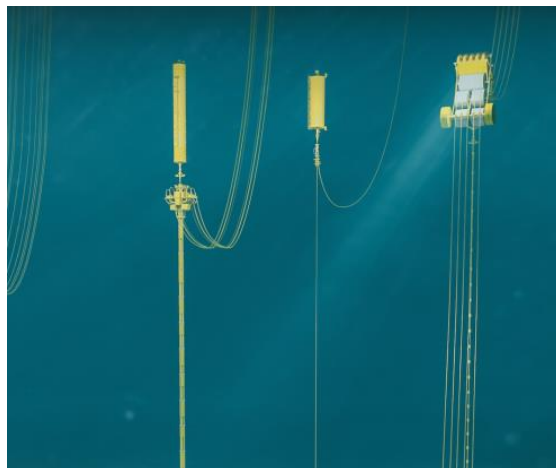




*Figure 2.5 35 tons CFRP of fuselage, wings, tail, doors, and interior in each 787*



*Figure 2.6 OceanGate (Everett, WA, US) announced June 27 the successful unmanned depth test of the manned submersible, Titan, to validate the hull to a depth of 4,000m (13,123 ft)*



*Figure 2.7 Airborne Oil & Gas TCP Riser for deep-water and dynamic applications for a major operator in South America*





*Figure 2.8 Startlink House. Startlink is a pultruded glass reinforced composite component kit which can be rapidly assembled into a wide variety of low-rise building forms without metal fastenings*



*Figure 2.9 Lorient, (France 1998)*



*Figure 2.10 Spieringsluis – Biesbosch, (The Netherlands, 1999)*



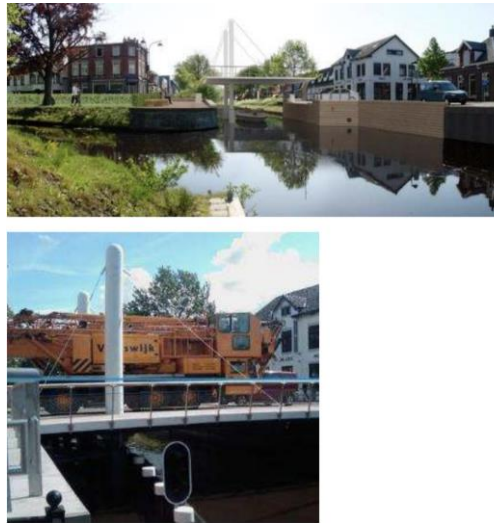
*Figure 2.11 Spaarsluis Emmen, Ter Apel, (The Netherlands 2012)*



*Figure 2.12 Lock Doors Wilhelminakanaal Tilburg, (The Netherlands, 2016)*



*Figure 2.13 Bonds Mill bridge (UK, traffic bridge, 1994)*



*Figure 2.14 Bridge Oosterwolde, (The Netherlands, 2010)*



*Figure 2.15 Bridge Fredrikstad, 60 m span pedestrian bridge, (Norway, 2018)*



*Figure 2.16 Pont y Ddraigh Rhyl Harbourbridge, (UK, 2013)*



*Figure 2.17 Pijlebridge, Meppel, LM 1 traffic bridge, (The Netherlands, 2015)*



*Figure 2.18 Elburgerbrug,, LM1 Traffic class FRP deck in existing lift bridge, (The Netherlands, 2015)*



*Figure 2.19 Mandelbridge Alkmaar, LM1 traffic bridge, (The Netherlands, 2016)*





*Figure 2.20 FRP gratings/decking and handrails*



*Figure 2.21 Jetty and catwalks*



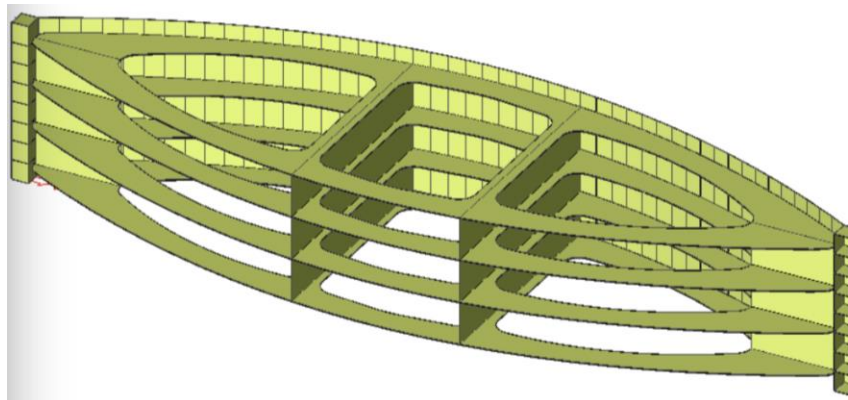
*Figure 2.22 Coating of concrete structures with glass-fiber reinforced polyester*



*Figure 2.23 Kreekrak sluices.*



*Figure 2.24 Spiering sluice*



*Figure 2.25 FRP concept for lifting slide in the Hartel barrier*



*Figure 2.26 'Alkmaarklasse' - minehunters*

## 3 FUNDAMENTALS OF COMPOSITES

### 3.1 Definition

#### 3.1.1 Definition of Polymer

The word "polymer" comes from the Greek language: poly means many and mer means part. Polymers are made up of monomer repeat units. The degree of polymerization, DP, denotes the number of monomer units jointed together in a polymer. A monomer has a DP of 1. When two monomers react and join together, a dimer with DP of 2 is formed.

#### 3.1.2 Definition of Fibers

Fiber is a natural or synthetic substance that is significantly longer than its width or diameter. Fibers are often used in the manufacture of other materials. The strongest engineering materials often incorporate fibers, for example carbon fiber and ultra-high-molecular-weight polyethylene.

Synthetic fibers can often be produced very economically and in large amounts compared to natural fibers, but natural fibers provide some benefits for clothing, such as comfort, when compared with synthetic fibers such as nylon.

#### 3.1.3 Definition of Composite

A composite material is a heterogeneous combination of two or more materials (reinforcing elements such as fibers, binders such as resins of polymers), differing in form or composition on a macroscale. The combination results in a material that maximizes specific performance. The constituents do not merge or bond completely and normally exhibit an interface between one another.

#### 3.1.4 Role of Fibers and Resins in Composites

The fiber network is the load-bearing component. Roles of resin include: dissipate loads to the fiber network, maintain fiber orientation and protect the fiber network from damaging environmental conditions such as humidity and high temperature. The resin often dictates the process and processing conditions and even with interlaminar shear strength.

### 3.2 Polymers

Polymers can be classified according to their thermophysical behavior. Those which soften and flow upon heating are termed thermoplastic; those which do not soften under higher than ambient temperatures ( $>40^{\circ}\text{C}$ ) are called thermoset polymers. The characteristics of thermoplastic polymers include linear or branched structure, polymer melting and flowing upon heating, easy to process with application of heat and heat sensitive properties.

#### 3.2.1 Thermoplastic polymers

A polymer can have any of three basic molecular shapes. The shape is determined by the functionality of a monomer which makes up the polymer. The three shapes are: long, linear polymer chains, long chains with arms coming from branch points and long chains linked together by crosslinking arms to form a crosslinked network of chains.



Some examples of thermoplastic polymers are polyethylene, polypropylene, nylon, polymethyl methacrylate and polystyrene.

The advantages of thermoplastics includes unlimited shelf life -won't undergo polymerization during storage, easy to handle (no tackiness), recyclable -- they undergo melt and solidify cycles, easy to repair by welding, solvent bonding, and postformable. The disadvantages of thermoplastics are that they are prone to creep and poor melt flow characteristics

### 3.2.2 Thermoset polymers

The characteristics of thermoset polymers include that liquid resin becomes rigid via curing process upon application of heat; thermoset polymer is less temperature sensitive than thermoplastics; crosslinked network structure (formed from chemical bonds) exists throughout a finished part under ambient conditions; crosslinking provides thermal stability such that polymer will not melt or flow upon heating. Some examples of thermoset polymers are epoxy, unsaturated polyesters, vinyl esters, phenol formaldehyde, bismaleimide and urethane.

The advantages of thermosets include low resin viscosity before cure, good fiber wet-out, excellent thermal stability (once polymerized) , good chemical resistance and creep resistance. The disadvantages of thermosets include that they are brittle; they are non-recyclable via standard techniques and that the polymer must be molded in shape of final part--not post formable.

### 3.2.3 Polymerization Reactions

There are two fundamental polymerization reactions: chain polymerization and step polymerization. This classification is of particular importance to thermosetting systems because polymerization reactions between thermosets and thermoplastics are distinct in that thermosets undergo polymerization reaction during the manufacturing process, whereas thermoplastics are polymerized prior to final part manufacture.

Chain polymerization is characterized by the presence of a few active sites which react and propagate through a sea of monomers. Polymerization may occur by any of the three mechanisms given below: free radical, cationic and anionic reactions and additional details on this subject can be found in references. Vinyl monomers frequently undergo chain polymerization. Polymers formed via this process include: polyethylene, polystyrene, polypropylene and polymethyl methacrylate.

In a step reaction mechanism, monomers can react with any nearby monomer. In contrast to chain polymerization, no special activation is needed to allow a monomer to react. Frequently these reactions are copolymerizations, where two types of monomer are present and each reacts only with the other (and not with monomers like itself) This type of polymerization is also called condensation polymerization because water is often liberated when the polymer bonds form. Example reactions include polyester formation and polyamide formation. In polyester formation, the monomers are called diols and diacids. The acid groups react with the alcohol groups to form ester linkages. In polyamide formation, amine groups react with carboxylic acids. These reactions both yield linear polymers.

### 3.2.4 Chain Crosslinking

A thermosetting system is set to cure when a crosslinked network of polymer chains is formed. In step polymerizations, crosslinks are formed with the use of monomers of multi-functional groups. Monomer functionality determines the form of the polymer (linear, branch, or network).

Functionality is the number of reactive ends or parts of monomer. For homopolymerizations, the effects of average functionality (f) are: f less than 2 relates to low molecular weight; f equal to 2 is linear polymer; and f greater than 2 relates to branched or crosslinked polymer.

A variety of monomers are available so it is possible to "design" a polymer product and its properties based on monomer type. Selecting ratio of reacting species allows us to control the degree of polymerization and the degree of branching and crosslinking. This in turn leads to some control in terms of the gel point and the material properties.

The gel point is defined as the onset of gelation. Gelation occurs when the weighted average molecular weight of the polymer approaches infinity. The gel point is of critical importance to processing thermoset systems.

Chain polymerization of vinyl monomers yields linear polymers. Monomers with two or more double bonds (for example, divinyl monomers) may lead to crosslinking. The functionality requirement differs from step polymerizations, where a functionality of three is needed for branching to occur.

A crosslinked structure can arise in either of two ways: the network structure may be formed initially from multifunctional monomers, or it may be formed via two-step process, where a polymer with unsaturation is first formed (a thermoplastic formed via step polymerization), and then these unsaturated sites are reacted with a crosslinking agent in a second step to produce the final structure. Examples of the latter type of systems include unsaturated polyesters and vinyl esters.

### 3.2.5 Unsaturated Polyesters

The ester linkage gives polyesters their name: Polyester resins are manufactured by a step polymerization reaction of glycols with unsaturated or saturated acids or anhydrides. 
$$-\overset{\text{O}}{\parallel}{\text{C}}-\text{O}-$$
 Polyesters are subdivided into three classes: aliphatic -thermoplastic, aromatic -thermoplastic and crosslinked - thermosetting.

Unsaturated polyesters provide the foundation for developing crosslinked polyesters. The unsaturated polyester is formed via step polymerization reaction. The "polyester monomer" required for making crosslinked polyester is formed from antifreeze (ethylene glycol). The important characteristic of this component is that the hydroxyl groups are on both sides of the carbon molecule. The important property of ethylene glycol in this reaction is that it acts as an organic base. Thus, the polyester reaction can be thought of as an acid-base reaction. The organic acid is a vinyl diacyl chloride. The reaction, a condensation polymerization, implies a base reacting with an acid to form an ester. HCl is released as a condensation product. Each end continues to react to form a polyester which is the new material for crosslinking.

The actual crosslinked network is formed via a chain propagation reaction. The unsaturated polyester formed by condensation polymerization is added to a mixture of styrene (a crosslinking) and peroxide (radical initiator). Radicals attack the unsaturated links in the polyester or the styrene vinyl groups to initiate a chain polymerization reaction which yields a crosslinked styrene-polyester copolymer. Styrene provides the crosslinks between the polyester chains to form a thermoset polymer. There are no additional products in this reaction because it is a chain addition reaction.

### 3.2.6 Vinyl esters vs. Polyesters

Polyester resins differ from vinyl ester resins in the following ways: vinyl esters have better chemical resistance than polyesters but are more expensive; vinyl esters are synthesized from an unsaturated carboxylic acid (usually methacrylic acid) and an epoxy resin; typical commercial resins are based on DGEBA and methacrylic acid. They differ from typical polyesters in having only terminal unsaturation (rather than inside the chain), pendant hydroxyl groups, and no carboxyl or hydroxyl end groups. Therefore, they are less susceptible to chemical attack.

### 3.2.7 Glass Transition Temperature

The glass transition temperature is the temperature at which the amorphous domains of a polymer takes on the characteristic properties of the glassy state-brittleness, stiffness, and rigidity. At the glass transition temperature, the solid, glassy polymer begins to soften and flow.

In glassy state, there are no large scale molecular motions and atoms move against restraint of secondary bond forces. At and above glass transition temperature, onset of liquid like motion of long molecular segments takes place and requires more free volume.

### 3.2.8 Thermoset Processing Window

Figure 3.1 illustrates the processing window in terms of time versus temperature for thermoset processes. If the molding process is not operated for a sufficiently long time, a short shot occurs. In RTM and IM, this is manifested as an incompletely filled mold because injection was not finished. In compression molding, a short shot occurs if the mold is not held closed long enough and the resin cannot distribute throughout the mold. The long-time limit for these processes is economics. If the cycle time is too long, the process cannot make enough parts to be profitable. The upper temperature limit is set by the degradation temperature. The lower temperature limit is set by the glass transition temperature. This processing window is typical for crosslinking reactions.

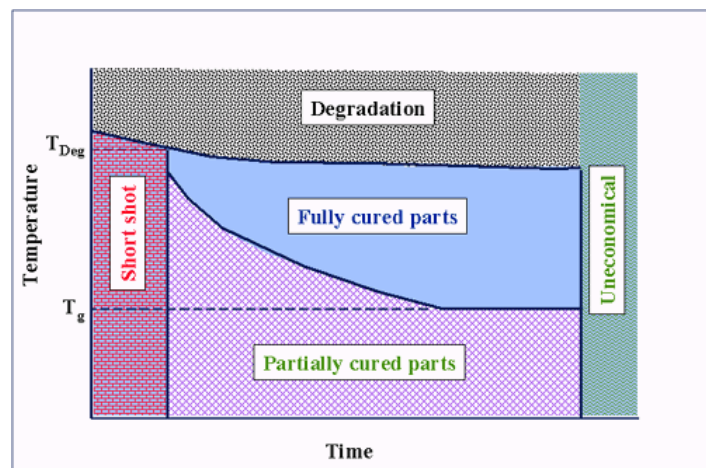


Figure 3.1 Thermoset processes

Reaction kinetics often control thermosetting systems. For any polymer system, reaction kinetics are a function of temperature, time and reactant concentration.

The issues in thermosetting polymer processing are summarized as material issues and processing issues. Material issues include process selection, resin selection, molecular weight distribution of reacting precursors and fiber selection and orientation. Processing issues include  $T_g < T_{proc} < T_{deg}$  (Thermosets have glass transitions as do thermoplastics), kinetics and economic cycle times.

### 3.2.9 Thermoplastic Processing Window

Figure 3.2 illustrates the processing window for thermoplastic processing in temperature-pressure space. The lower pressure limit is set by the short shot condition; the upper limit is the point where flashing occurs, which is polymer leaking out of the mold at the seams. The temperature limits are set by the polymer melting temperature and the degradation temperature.

The issues in thermoplastic polymer processing are summarized as material issues and processing issues. Material issues include process selection, thermoplastic selection, fiber selection and orientation and morphology. Processing issues include pressure and temperature conditions must be engineered to avoid thermal degradation, residual stress, and flash and economic cycle times

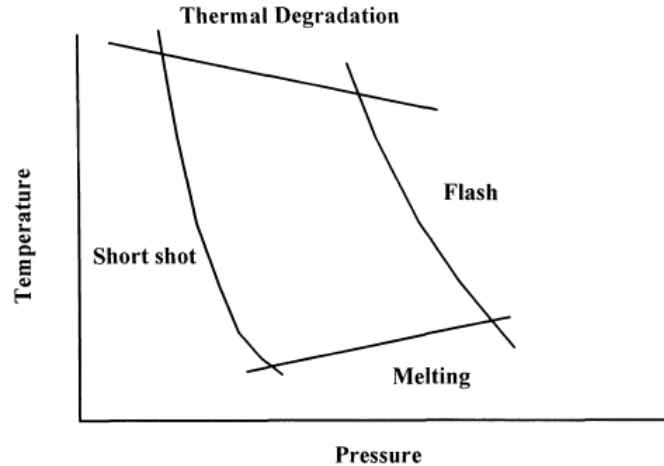


Figure 3.2 Thermoplastic temperature vs. pressure

## 3.3 Fibers

There are many types of fibers, including carbon (pitch-based or PAN-based), several types of glass (E, S, S2 or A) and Kevlar®. These are available in strands known as rovings or twisted into yarns. Selection of the reinforcing fiber is based on the mechanical requirements of the molded component, its environmental requirements and cost.

### 3.3.1 Glass Fibers

Glass fibers are the most commonly used fibers in FRP composites. Glass fibers are made from molten glass spun from an electrically heated platinum-rhodium alloy bushings (or furnace) at a speed of 200 mph. These filaments cool from a temperature of 2192 °F to room temperature within  $10^{-5}$  seconds. Glass fibers have a diameter ranging from 25 microns to 30 microns. A protective coat (called sizing) is applied on individual filaments before they are gathered together into a strand and wound on a drum. A strand is the basic form of commercially used continuous glass fibers and

consists of two hundred and four parallel filaments. Strands are combined to form thicker bundles than roving.

Sizing (protective coating) is a mixture of lubricant, antistatic agent and a binder, and performs the following functions: to reduce the abrasive effect of filaments rubbing against one another, to reduce static friction between the filaments, to pack filaments together into a strand, to reduce the damage to fibers during mechanical handling, to facilitate the molding process. Several types of commercially available glass fibers are identified below.

E-glass, which has a low alkali content and is the most common type of glass fiber for high volume commercial use. It is used widely, in combination with polyester and epoxy resins to form a composite. Its advantages are low susceptibility to moisture and high mechanical properties.

Z-glass, which is used for cement mortars and concretes due to its high resistance against alkali attack. A-glass, which has a high alkali content. C-glass, used in places that require greater corrosion resistance to acids such as chemical applications. S or R-glass, which is produced for extra high strength and high modulus applications. Low K-glass is an experimental fiber produced to improve dielectric loss properties in electrical applications and similar to D-Glass (dielectric glass).

Glass fibers offer many advantages such as: low cost, high tensile strength, high chemical resistance, relatively low fatigue resistance and excellent insulating properties.

The limitations of glass fibers are: low tensile modulus, relatively high specific gravity, sensitivity to abrasion while handling and high hardness.

### **3.3.2 Carbon Fibers (Graphite Fibers)**

Carbon fiber is described as a fiber containing at least 90% carbon obtained by the controlled pyrolysis of appropriate fibers. The term "graphite fiber" is used to describe fibers that have carbon in excess of 99%. A large variety of precursors are used to manufacture different types of carbon. The most commonly used precursors are polyacrylonitrile (PAN), petroleum or coal tar pitch, cellulosic fibers (viscose rayon, cotton), and certain phenolic fibers. Carbon fibers are distinct from other fibers by virtue of their properties and are influenced by the processing conditions, such as tension and temperature during process. In the early 1960s, successful commercial production of carbon composites was started, as the requirements of the aerospace industry, especially military aircraft, for better and lightweight materials was of paramount significance. Carbon fiber composites are ideally suited to applications where strength, stiffness, lower weight, and outstanding fatigue characteristics are critical requirements. Unlike glass and aramid fibers, carbon fibers do not have stress corrosion or stress rupture failures at room temperature. In addition, they can be used in applications requiring high temperature resistance, chemical inertness and damping characteristics.

### **3.3.3 Aramid Fibers**

Characteristics of Aramid fibers include no melting point, low flammability, good fabric integrity at elevated temperatures and para-aramid fibers, which have a slightly different molecular structure, providing outstanding strength-to-weight properties, high tenacity and high modulus.

Advantages of aramid fibers include very low thermal conductivity, very high damping coefficient, which gives superior tolerance to damage against impact and other dynamic loading.

Limitations of aramid fibers are hygroscopic, absorb moisture up to about 10% of fiber, higher specific gravity, crack internally at pre-existing microvoids at high temperature and produce longitudinal splitting, low compressive strength, loss of strength and modulus at elevated temperatures, difficulty in cutting and machining; and sensitive to ultraviolet lights (uv) leading to mechanical property deterioration with time.

For applications, aramid fibers are used for flame-resistant clothing, protective vests and helmets, asbestos replacement, hot air filtration fabrics, tire and mechanical rubber goods reinforcement, ropes and cables, sail cloth, sporting goods and composites.

### 3.3.4 Preforms

A preform is the assembly of reinforcing fibers that is preshaped and oriented by placement in a mold to its near-net configuration, prior to the introduction of resin. Preforms may be constructed with any combination of continuous fiber, fiber mats, woven and non-woven fabrics and cores.

#### Random mats

Random mats consist of continuous or chopped fibers laid randomly and held loosely together by a binder adhesive. Advantages of this form include high permeability and hence the ready flow of resin in the infusion step for thorough wet-out, easy handling for placement in the mold and good structural integrity. Limitations are: relatively poor stiffness and strength; lack of control of fiber orientation; and inability to achieve only limited fiber volume fractions.

The random fabric consists of loose strands laid together. Because of the randomness, the mat is isotropic with ease of fluid flow prediction. Furthermore, random fiber orientation is that draping the fabric over a tool does not cause much preferential orientation.

Advantages of random fabric include high permeability, ease of infusion, ease of handling, high degree of structural integrity (used as a base). Disadvantages of random fabric include poor stiffness, limited strength, no orientation control and limited fiber volume fractions.

#### Unidirectional Fabric

Unidirectional Fabric consists of parallel filaments held loosely in place by stitches in a plane.

Advantages of unidirectional fabric include high stiffness and strength in filament direction. Disadvantages of unidirectional fabrics include poor integrity that "fiber wash" may occur, and anisotropic flow and performance.

#### Two-dimensional woven fabric

Two-dimensional woven fabrics are fabricated on a loom from at least two sets of tows that are interwoven. Balanced properties in the plane of the fabric are thus achieved, although there can be some asymmetry depending on the type of weave pattern. Woven fabrics exhibit good impact resistance; but have poor conformability for placement in odd-geometry molds. Also, the weave introduces crimping (undulation) of the yarns, which degrades strength and reduces the effective stiffness of the lamina.

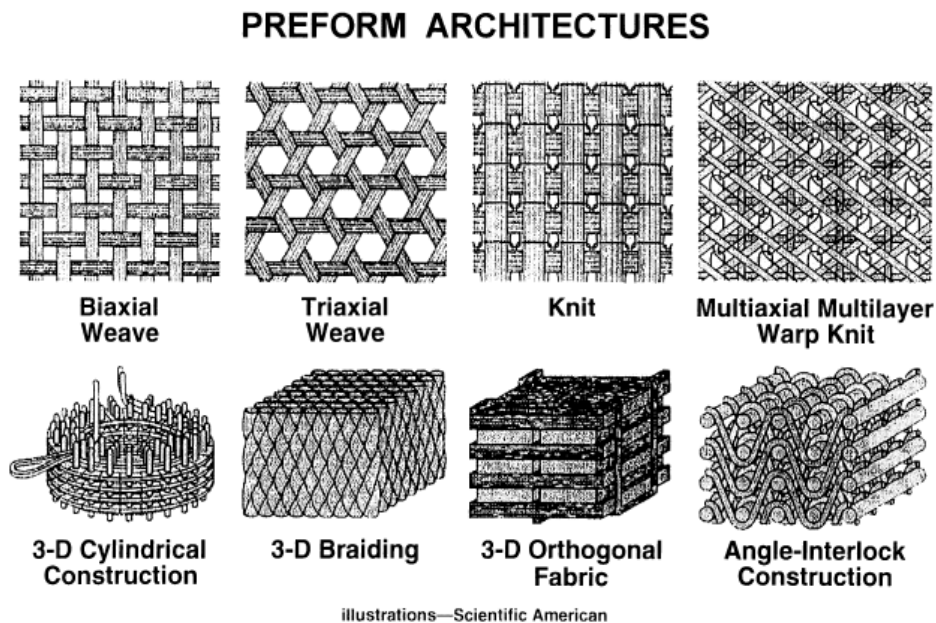


Weaves can be classified according to the spacing between the tows. Weaves with big open spaces between the tows are termed open weaves, while weaves with no space between the tows are termed closed weaves.

Advantages of weaves include balanced properties in plane of the fabric, good impact resistance and good conformability. Disadvantages of weaves include fiber undulation, asymmetry and trimming / handling.

### 3.3.5 Fabric Architecture

The fibers may be stitched or woven into various 2-D or 3-D architectures



*Figure 3.3 Fabric Architecture*

Fiber architecture (Figure 3.3) selection depends on performance issues such as modulus, strength, durability, compressibility during preforming to attain adequate volume fractions and drapability to insure proper placement of the reinforcement during preforming operations. Moreover, the selection of fiber architecture also depends on processing issues such as permeability, compressibility and drapability.

Permeability is a measure of the ability of the resin to flow through the preform, which determines key processing parameters (Fill time, Injection pressure) and is dependent upon preform architecture and resin viscosity.

Drapeability is the ability for the reinforcement layers to conform to curvature in the mold.

## 4 MANUFACTURING AND FABRICATION

### 4.1 Vacuum-Assisted Resin Transfer Molding

A vacuum-assisted resin transfer molding (VARTM) process is a process, where dry reinforcements in the form of mats, rovings or fabrics are pre-shaped and manually oriented into a skeleton of the actual part, known as preform. After the preform is inserted into a tool (typically comprised of one mold surface and one bag surface), the resin is injected at low pressures into the closed mold. During resin injection, vacuum is applied to reduce voids and assist infusion of the resin into the fabric, before allowing the resin to cure at room temperature for 12 to 24 hours. Its advantages include low tooling cost, low volatile emission, low void content, and design flexibility for large and complex parts, but the process is labor intensive and joining of VARTM panels is a challenge. Fiber content in the finished part can run as high as 70 percent. Current applications include marine, ground transportation and infrastructure parts.

### 4.2 Pultrusion

Pultrusion is a process where FRP composites are produced continuously at speeds ranging from a couple of inches to a couple of feet per minute, through a heated die of desired cross-section, i.e., no part length limitation. The reinforcements are in continuous forms such as rolls of unidirectional roving, biaxial fabric, or multiaxial fabric, which are properly positioned by a set of creels and guides for subsequent feeding into the resin bath. As the reinforcements are saturated (wet-out) with the resin in the resin bath and pulled into the forming and curing die, the heat curing of the resin is initiated from the preheated die, leading to a rigid profile. The advantages of the pultrusion process include: 1) high fiber content, 2) high cure percent, 3) minimal kinking of fibers/fabrics, 4) rapid processing, 5) low material scrap rate, and 6) good quality control. The process disadvantages are: 1) sometimes local inadequate or non-uniform fiber wet-out, 2) die jamming, 3) die size/geometry limitation, and 4) initial capital investment and die cost (Goldsworthy, 1982).



*Figure 4.1 Pultrusion of 4' Wide GFRP Composite Sandwich Panels with Integral Joint Edges.*

### 4.3 Compression Molding

Compression molding was specifically developed for replacement of metal components with composite parts. The molding process can be carried out with either thermosets or thermoplastics.



However, most applications today use thermoset polymers. In fact, compression molding is the most common method of processing thermosets.

### Compression Molding Process

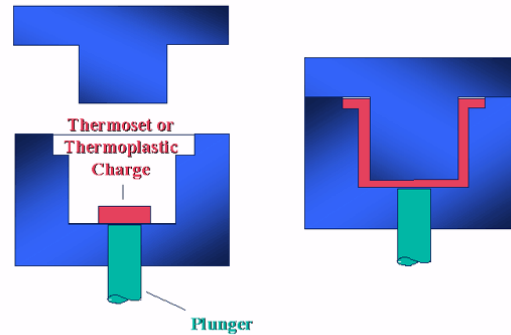


Figure 4.2 Compression molding process

The schematic (Figure 4.2) shows the compression molding process. A charge is placed in the mold, which is subsequently closed and held at a high pressure. The mold is heated to initiate the thermosetting cure reaction.

### 4.4 Injection Molding

This schematic (Figure 4.3) illustrates the process of injection molding. A hot, molten polymer is injected into a cold mold. A screw apparatus can be used to inject the polymer into the mold, as shown in the schematic. After the part cools and solidifies, the mold is opened and the part is ejected. No chemical reaction occurs during the molding process. (Any reaction that occurs would be a degradation reaction, which should be avoided!)

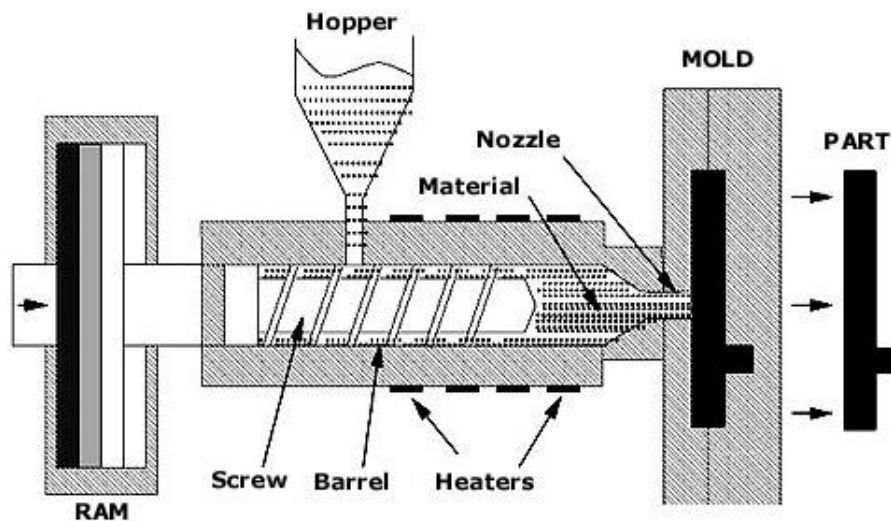


Figure 4.3 Injection molding process

Both amorphous and crystalline thermoplastic resins are used in injection molding. Short glass fibers are commonly used as reinforcements.

#### **4.5 Structural Reaction Injection Molding (SRIM)**

**RIM (Reaction Injection Molding):** A process for molding liquid chemical systems in which mixing of two to four components in the proper chemical ratio is accomplished by a high-pressure impingement-type mixing head. The mixed material is delivered into the mold at low pressure, where it reacts (cures). **RRIM (Reinforced RIM):** A reaction injection molding process with reinforcement (typically chopped fibers or flakes) added to the liquid chemical systems.

Combines multi-component thermoset monomers in a single chamber through the use of an impingement mixer. High injection pressure because of the high reactivity of the resin system (short processing-cycle times). Useful for high-volume, low-performance composite applications (e.g., spare time covers, bumper beams, satellite antennas, etc.)

Automotive industry suppliers combine structural RIM (SRIM) with rapid preforming methods to fabricate structural parts that don't require a Class A finish. Programmable robots have become a common means to spray a chopped fiberglass/binder combination onto a vacuum-equipped preform screen or mold. Robotic sprayup can be directed to control fiber orientation.

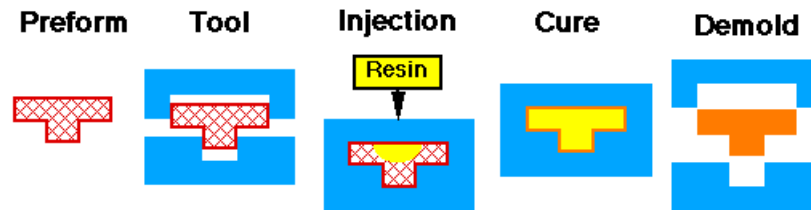
#### **4.6 Resin Transfer Molding**

Ever-increasing demand for faster production rates has pressed the industry to replace hand layup with alternative fabrication processes and has encouraged fabricators to automate those processes wherever possible.

A common alternative is resin transfer molding (RTM), sometimes referred to as liquid molding. RTM is a fairly simple process: It begins with a two-part, matched, closed mold, made of metal or composite material. Dry reinforcement (typically a preform) is placed into the mold, and the mold is closed. Resin and catalyst are metered and mixed in dispensing equipment, then pumped into the mold under low to moderate pressure through injection ports, following predesigned paths through the preform. Extremely low-viscosity resin is used in RTM applications for thick parts, to permeate preforms quickly and evenly before cure. Both mold and resin can be heated, as necessary, for particular applications. RTM produces parts that do not need to be autoclaved. However, once cured and demolded, a part destined for a high-temperature application usually undergoes postcure. Most RTM applications use a two-part epoxy formulation. The two parts are mixed just before they are injected. Bismaleimide and polyimide resins are also available in RTM formulations. "Light RTM" is a variant of RTM that is growing in popularity. Low injection pressure, coupled with vacuum, allow the use of less-expensive, lightweight two-part molds.

The benefits of RTM are impressive. Generally, dry preforms for RTM are less expensive than prepreg material and can be stored at room temperature. The process can produce thick, near-net shape parts, eliminating most post-fabrication work. It also yields dimensionally accurate complex parts with good surface detail and delivers a smooth finish on all exposed surfaces. It is possible to place inserts inside the preform before the mold is closed, allowing the RTM process to accommodate core materials and integrate "molded in" fittings and other hardware into the part

structure during the molding process. Moreover, void content on RTM'd parts is low, measuring in the 0 to 2 percent range.



*Figure 4.4 RTM process*

#### **4.7 RFI**

Resin film infusion (RFI) is a hybrid process in which a dry preform is placed in a mold on top of a layer or interleaved with layers of high-viscosity resin film. Under applied heat, vacuum and pressure, the resin is drawn into the preform, resulting in uniform resin distribution, even with high-viscosity, toughened resins, because of the short flow distance.

#### **4.8 Seeman's Composite Resin Injection Molding Process (SCRIMP)**

This molding process was developed and patented by Seemann's Composites. It is hybrid of RTM, VARI and vacuum bagging with one-sided tooling. Injection is usually achieved through the use of a high-permeability surface layer to cause through-the-thickness flow. SCRIMP can be used to fabricate large-scale parts with low void content: boat slips and infrastructure

## 5 CHARACTERISTICS OF COMPOSITES

### 5.1 Durability

FRP composites have superior performance under harsh end-use environments over conventional construction materials (steel, concrete, and wood). Such design advantages of composites have to be based on sound understanding of the durability (long term) response of the FRPs under the harsh environments and loading conditions. The durability response of composites is identified typically in terms of chemical, physical and mechanical aging and their combinations, which depends primarily on pH level, temperature, creep/relaxation, UV radiation, and externally induced thermo-mechanical stress fluctuations. The durability response is further accelerated in the presence of water or salt solutions because of their expansion under freezing (ACI 2006; Chin et al. 2001; Karbhari, 2006; McBagonluri et al., 1998; Antoon and Koenig, 1980). In terms of the above parameters, fluid absorption in and out of composites under freeze-thaw conditions has the highest influence on durability (Lesko et al., 1998).

Long-term performance determination and modeling of composites due to aging, moisture and pH, freeze-thaw, fatigue, and creep are critical for high volume applications. In-service composite structural systems are exposed to various environmental factors such as moisture, thermal (freeze-thaw cycling or elevated temperature) and other weathering conditions that affect their overall performance. The physical weathering occurs when composites are subjected to mechanical loadings such as static, fatigue, and creep (sustained stress) while the chemical weathering occurs when the material is exposed to moisture and chemicals such as alkaline or acid solutions. Under those exposures, the mechanical and physical properties (e.g., strength, stiffness, creep, fatigue life, glass transition temperature, fiber-resin bond strength) change with exposure time.

### 5.2 General Consideration

The process of physical aging of composites is dependent primarily on service temperature and sustained load, and could be substantial on composite performance. Creep of polymers involves deformation of the molecules with molecular segments changing their conformations and sliding past one another. If the deformations are large enough, molecular chain rupture (scission) may occur. As a result, the mechanical properties vary with time under load (Liao et al., 1999). The chemical aging of composites is related to: i) diffusion process, ii) polymer chemical composition, iii) temperature, iv) stress corrosion, v) fluid ion exchange, and vi) others. Polymer chain scissions and altered material chemistry are the direct result of chemical aging that lead to loss of constituent materials including physical and mechanical properties. Fluid sorption in and out of FRP composites is the most influencing factor on thermomechanical properties when a material is exposed synergistically to environmental and mechanical loads.

The rate of degradation of polymer composites exposed to a fluid environment is related to the rate and quantity of fluid sorption (Bott and Baker, 1969), which are governed mostly by: i) chemical structure of the resin, ii) degree and type of cross linking, iii) state of the material including void content, iv) type, temperature and concentration of fluid, and v) applied stress and hydrostatic pressure (Antoon and Koenig, 1980). Exposure of composites to moisture and chemicals cause, which is driven by the exchange of alkali ions in glass fibers and hydrogen ions from a reactive fluid, leading to spontaneous fiber surface cracking and stress failure (Price, 1989). Diffusion of

fluids through a polymer can cause swelling due to hydrogen bond disruption and induce stresses within the composite. 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 (Karbhari et al, 2003).

Degradation of composites is compounded when exposed to other environmental factors along with freeze-thaw and fatigue (McBagonluri et al., 1998; 2000). Karbhari (2006) provided excellent insights into the effect of moisture on E-glass/vinyl ester composites through dynamic mechanical analyses. Differential scanning calorimetry (Verghese et al., 1999) data revealed the nature and presence of freezable water for each constituent material within an E-glass/vinyl ester composite (matrix and interface). Heat flow measurements during thawing were taken for a single cycle (-150°C to +50°C) on saturated, unreinforced vinyl ester resin samples, which indicated the absence of freezable water. Since this free volume size within the resin is in the order of about 6-20 Å, these voids are thermodynamically too small for water to freeze. This is due in part to hydrogen bonding in addition to geometric space constraints, thus impeding the freezing process. However, the dimensions in a cracked composite system were large enough to facilitate water freezing and damage accumulation (Verghese et al, 1999). Similarly, high damage accumulations were noted in pretensioned FRPs under marine environments (Sen et al., 1998). Life prediction model(s) for the durability of composites over a range of chemo-thermo mechanical environments has to be developed from accelerated test data and validated from field studies. For example, the work done on FRP rebars for chemo-thermo-mechanical properties by Vijay and Hota, 1999 provides a systematic basis to predict aging of composites under harsh environments...

### **5.3 Long Term Water Submersion Resistance and Moisture Uptake**

Although FRP composites other than carbon composites are not susceptible to electrochemical corrosion as with the conventional materials, debonding and strength reductions under moisture uptake still play a major role in the durability response. Depending on the polymer chemistry, the moisture absorption rate varies and leads to reversible or irreversible physical, thermal, mechanical and/or chemical changes (Bisby, 2006). As explained below, moisture absorption in FRPs is extremely complex requiring a comprehensive understanding of its influence on the thermo-mechanical behavior of FRP composites, especially with reference to interlaminar bond forces under freeze-thaw cycling and wet-dry cycling. In addition, the moisture response phenomena of FRP composites under corrosive media with various diffusion models are explained below.

#### **5.3.1 Immersion in corrosive media**

The water absorption of FRP laminates, in general (except aramid), has an adverse effect on fatigue due to hydrolysis of the resin system with no major influence from fibers or fabrics, i.e., influence of fiber type, volume fraction and fabric architecture are not influencing the composite laminates exposed to moisture.

For example, glass-carbon hybrid laminates showed excellent durability similar to carbon laminates (Nakada and Miyano 2009). Such excellent performance is mainly attributed to which are least affected by water other than electro-chemical reaction. The contact area between glass fibers and water is reduced and surrounded by carbon fibers (Saadatmanesh et al. 2010). However, glass-aramid laminates showed continued degradation with time, since moisture uptake of aramid fiber is significantly higher than that of carbon fibers (Jones, 2001). The results revealed that

unidirectional laminates had higher degradation than laminates with bidirectional fabrics because debonding along the longitudinal fibers was prone to occur in unidirectional laminates when water molecules penetrated into the interface between fiber and matrix along the fiber length direction.

### 5.3.2 Different Resins

The tensile strength of glass/epoxy composites decreased by about ~20% after 1 year exposure to seawater at room temperature and by ~30% after 1 year of exposure at 65°C. These reductions are attributed to hydrolysis and fiber/matrix separation at the interface (Mourad, et.al. 2012; Eldridge and Fam, 2014). However, the modulus of glass/polyurethane composite did not change significantly. This behavior was attributed to the highly heterogeneous materials consisting of stiff regions and soft regions due to the nonhomogeneous moisture distribution. For glass/epoxy composites under immersions for 3, 6 and 12 months at room temperature and 65°C, both the tensile strength and modulus show initial increase due to postcuring with no significant degradation. Although nonhomogeneous water distribution creates localized defects and lowers the strength of glass/epoxy composites in the initial conditioning phase, the relaxation of residual stresses can potentially improve failure strength.

Similar observations were made by Eldridge and Fam (2014). For glass/vinyl ester composites exposed to seawater at room temperature, the flexural modulus decreased 18.5% between the 3- and 6-month periods (Hammami and Al-ghuilani, 2004). Vijay and GangaRao (1999) conducted screening tests for medium reactivity isophthalic unsaturated polyester (MUPE), high reactivity isophthalic unsaturated polyester (HUPE), isocyanurate vinyl ester (IVE) and urethane-modified vinyl ester (UMVE). The results showed that GFRP bars with UMVE exhibited the lowest vulnerability under different environmental conditions, while MUPE exhibited less vulnerability to different conditioning schemes compared with D. Mounts (2007) compared durability of urethane and UMVE GFRP in an alkaline environment and showed the peak moisture content of urethane GFRP was almost five times as much as that of UMVE GFRP. This large differential may be responsible for urethane GFRP to be more severely aged than UMVE based GFRP.

### 5.3.3 Fiber Volume

Lower fiber volume fraction usually results in FRP composites to be fairly sensitive to moisture uptake and significantly affect the deterioration process over time both at the level of bulk resin and the fiber– matrix interface (Marouani, et.al. 2012). Some researchers reported that composite specimens with higher fiber volume fraction absorbed more water compared with the specimens of lower fiber volume fraction (Bian, et.al. 2012, Hammami and Al-ghuilani, 2004). This is due to the fact that relatively high fiber content may prevent the matrix from fully bonding with the fiber, resulting in high void ratio, which is a manufacturing defect. Thus microcracks appear at the interface between the fiber and the matrix. Such microcracks, under the combined action of water diffusion and hydrogen ion exchange, accelerate the degradation process. Moisture uptake and desorption response of high fiber volume fraction of pultruded carbon/epoxy composites in deionized water was observed from previous studies (Karbhari and Xian, 2009). It is shown that specimens having thickness/length ratio lower than 0.045 do not reach equilibrium within 60 days and show good correlation with Langmuir dual mode diffusion response (Karbhari and Xian, 2009). This phenomenon was attributed to hygrothermal history, including uptake and desorption of moisture, resulting in a significantly higher rate of uptake of moisture on re-immersion.



Kumosa et al. (2004) showed that moisture uptake of modified polyester and vinyl ester composites exposed to relative humidity of 80% at 50°C, followed the Fickian law. The different behavior of the epoxy-based composites cannot be analysed using single-phase method and all FRP composites do not exhibit the same moisture uptake following the single-phase Fickian diffusion model. Notched composites (Buck, et.al. 2001) and composites immersed in liquid or at high temperature saturate rapidly with time. The rapid uptake could be from void content in the resin, quality of the fiber matrix interfaces, relaxation of resin in the presence of moisture through hydrolysis and elevated temperature, water molecules binding to the molecular structure of the resin, etc.

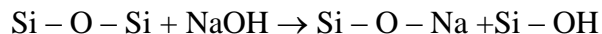
## 5.4 Chemical Resistance

### 5.4.1 Acid Solution

Acid attack on resin causes multiple cracks, resulting in resin flaking and fiber damage. Marru et al. (2014) revealed that performance of glass-reinforced epoxy (GRE) pipes in extreme alkaline medium (10% NaOH) was better than that in extreme acid medium (3% H<sub>2</sub>SO<sub>4</sub>). Further, degradation of composite pipes followed the Arrhenius principle and dependent on temperature, which controls resin reaction rates. Large strength decrease in FRP composites occurs in high concentration of acid solution. It was observed by Nakayama et al. (2004) that, after 2500 hrs in 2%, 5% and 10% sulphuric acid solution at 80°C, the flexural strength losses of GFRP (E-glass/unsaturated polyester) were about 40%, 60% and 80%, respectively. Moreover, the GFRP failed at the end of 1500 hrs in 20% sulphuric acid solution. Hammami and Ghuilani (2004) compared the durability of glass vinylester composites exposed to 2% and 5% nitric acid, and concluded that GFRP laminates decrease in flexural strength drastically with increasing acid concentration and immersion time. The corrosive fluid leads to matrix expansion and leaching which results in pits. After longer immersion time, pits may form blisters, and eventually swelling of resin and to collapse. The bond strength deteriorated with the acid concentration as shown by Kajorncheappunngam (1999, 2002). The decrease in tensile strength of glass reinforced epoxy in acid (1-M HCl) was more than that in alkaline medium (5-M NaOH), and the effect of saline water was less severe than that of acid or alkaline medium.

### 5.4.2 Alkaline Solution

Fiber cracking is found to be the main culprit in material property losses in acid-aged GFRP composites, whereas matrix cracking and fiber/matrix debonding are the major reasons for strength decay in GFRP composites aged in caustic soda and distilled water (Kajorncheappunngam, 1999). Alkaline hydrolysis tends to occur when OH reacts with ester bonds which are the weakest part in chemical structure of the polymer (Chin, et. al., 1997). Actually, alkaline solution not only attacks the matrix but also glass fibers. The chemical reaction of silica in glass and alkaline solution cause hydroxylation and dissolution, followed by notching which is caused by the formation of calcium hydroxide crystals on the glass surface (Yilmaz and Glasser, 1991). Moreover, caustic soda (pH>9) can attack the backbone of the glass molecules through the following chemical reactions (Sonawala and Spontak, 1996):



Many researchers have demonstrated the tensile strength of GFRP decreased dramatically in high concentrations of alkaline solution with time, whereas the modulus was not significantly influenced by alkaline solution. The results show pH =12.5 has the most effect on the GFRP composites compared to pH of 10, 7 and 2.5. Moisture absorption of GFRP bars was strongly dependent on tap water, saltwater and alkaline conditioning. Alkaline conditioning doubled in moisture gain by weight when compared with tap water and saltwater conditioning of GFRP composites. (Vijay, 1999) For sand-coated bars, maximum strength reductions in salt and alkaline conditioning at room temperature were 18.5 and 32.2% respectively, over 15-month duration. Over a 30-month duration, for ribbed glass composite bars, maximum strength reductions in salt and alkaline conditioning at room temperature were 24.5 and 30% respectively. However, carbon laminates have superb durability qualities and unaffected even after long-period of exposure to high pH solutions (Saadatmanesh, 2010).

## 5.5 Ultraviolet Resistance

Exposure to UV radiation causes photochemical damage of FRP composites near the exposed surface, leading to discoloration and reduction in molecular weight that results in the degradation of composites. The surface flaws can lead to stress concentrations and aggravate resin erosion under environmental attacks (GangaRao and Kumar, 1995). Moreover, effects of UV radiation appear to be exacerbated by other factors such moisture, chemical media, elevated temperature and thermal cycling (Bisby, 2006). Therefore, need protective coatings against UV after manufacturing and installation of FRP composites.

### 5.5.1 Independent Effect

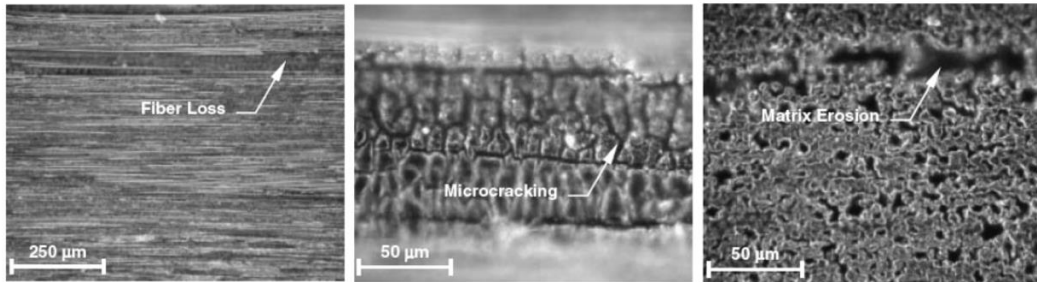
Homam and Sheikh (2000) investigated the durability of carbon/epoxy and glass/epoxy composites exposed under UV-A lamp radiation at 156 watt/m<sup>2</sup> and 38°C. For the 1200 to 4800 hrs of UV radiation exposure, the tensile strength and stiffness of the exposed FRP specimens remained slightly higher than those of the control specimens, and the strain at rupture was reduced slightly. Several studies have shown that the matrix-dominated transverse properties can undergo severe deterioration due to chain-scission induced by photo-oxidation from UV radiation.

### 5.5.2 Coupled Effect

When exposed sequentially to UV radiation followed by condensation, the CFRP/epoxy composite specimens initially lost weight during UV radiation cycle and subsequently gained weight during the condensation cycle (Kumar, et. al., 2002). The actual change in weight was a simple time-shifted linear superposition of results obtained for individual exposure conditions. However, when the specimens were cyclically exposed to both UV radiation and condensation, the specimens exhibited continuous weight loss at a steady rate throughout the exposure duration. After 1000 hrs of cyclic exposure to UV radiation and condensation (6 hrs cycle), an average of 1.25% decrease in specimen weight was observed. Micrographic observation confirmed that UV radiation and condensation operate in a synergistic manner leading to extensive matrix erosion, matrix microcracking, fiber debonding, fiber loss and void formation (Figure 5.1). The transverse tensile strength of the CFRP/epoxy composite specimens decreased 21% and 29% after exposure of 1000 hrs of UV radiation followed by 1000 hrs of condensation at 50°C, and cyclic exposure to both 1000 hrs UV radiation and condensation. The moduli for either of the subsequent or cyclical exposures were same as those of unconditioned specimens. This indicates that there are some



synergistic effects that govern the changes in matrix properties when the specimens are exposed to a combination of both UV radiation and condensation (Kumar, et. al., 2002).



*Figure 5.1 Optical micrographs of CFRP/epoxy composite specimens after 1000 hrs of cyclic exposure to both UV radiation and condensation (Kumar, et. al., 2002)*

It can be seen that the UV radiation does not affect much the fiber-dominated longitudinal properties of CFRP/epoxy composites, whereas it degrades the matrix-dominated transverse and shear properties. The combined exposure of UV radiation, high-temperature cycles and high-humidity cycles had more detrimental effects on FRP than single exposure effect. In a limited manner, FT cycles can compensate any decrease in mechanical properties of FRP under the combined effects of UV radiation, high temperature cycles, high-humidity cycles along with FT cycles, because of continued post-curing of the resin.

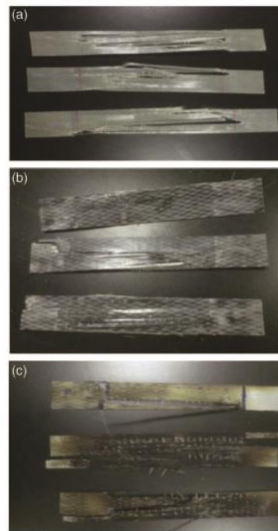
## 5.6 Thermal degradation

Although fibers are temperature-resistant up to their process temperatures and can retain most of their strength and stiffness at relatively high temperatures, most polymer matrices are susceptible to higher temperatures (Fitzer, 1980; Sauder et.al., 2004; ASTM E119, 2011; Williams, et.al, 2008). Once the temperature exceeds or even comes around 20°C below the glass transition temperature ( $T_g$ ) in-service, the strength of resin decreases. Moreover, the fiber matrix interface becomes susceptible to aggressive reactions under high temperatures, leading to matrix degradation (Ray and Rathore, 2014). However, cold temperature and freeze–thaw (FT) cycling may affect the durability of FRP composites through differential thermal expansion between the polymer matrix and fiber components or between concrete and FRP, or steel and FRP. This could result in damage to the interface between FRP composites and other materials such as concrete and steel (Bisby, 2006).

The tensile properties of CFRP sheets, hybrid carbon/ glass fiber-reinforced polymer (C/GFRP) sheets and hybrid carbon/basalt fiber-reinforced polymer (C/B FRP) sheets were evaluated at temperature ranging from 16 to 200°C (Cao, et.al., 2009). The tensile strength of carbon fibers in different FRP sheets decreased significantly when temperature increased from 16 to 55°C, and remained almost stable by retaining 67% of its original strength after the polymer exceeded its  $T_g$  (55°C). Meanwhile, at a temperature range of 16 to 200°C, the hybridization of carbon fibers with glass or basalt fibers exhibited the same variation in the tensile strength as CFRP sheets, and reduced scatter. The performance of GFRP bars (E-glass/vinylester) and GFRP reinforced concrete elements under three different elevated temperature (100, 200 and 300°C) for three different periods (1, 2 and 3 hrs), revealed no significant losses. Losses in tensile strength were proportional

to the level of temperature and exposure time. The bars with concrete cover showed higher residual tensile strength compared to their counterparts without cover, especially at 100°C for a period of 1 hr. The stress–strain relationships of GFRP and CFRP bars remained almost linear at elevated temperatures not exceeding T<sub>g</sub>, until failure. The elastic modulus remained almost unchanged until 300–400°C, but decreased dramatically beyond 400°C.

Figure 5.2 shows, three failure modes depending on the temperature range, and the FRP laminate type: (1) within the temperature range of 100–150°C, CFRP, GFRP and C/GFRP specimens have failed in a similar fashion to those specimens tested at room temperature by brittle fiber ruptures at different positions along the specimen gauge length; (2) within the temperature range of 200–250°C, the epoxy adhesives were softened and the specimens failed primarily by partial loss of epoxy adhesives followed by sheet splitting, and (3) epoxy bonds were burned and the specimens failed by rupture of the fibers at 300°C (Hawileh, et.al, 2015).



*Figure 5.2 Failure modes of CFRP, GFRP and C/GFRP composites subjected to different temperature range for 45 min (Hawileh, 2015) (a) Within 100–150°C, (b) Within 200–250°C and (c) At 300 °C.*

The different failure modes suggest the degradation of thermal stability of epoxy resin with increasing temperature, resulting in that debonding of FRP/matrix interface. Once the temperature exceeds the ignition point of resin, then the resin cannot provide protection for the fiber surfaces, lowering their mechanical behavior and shortening their useful life. In particular, the heat resistance of FRP bars made with carbon fiber and phenolic matrix is almost the same as that of steel bars (Sumida and Mutsuyoshi, 2008).

## **5.7 Hydrothermal**

Temperature may strongly affect the water absorption rate. Increase in temperature causes higher level of water diffusion; hence the onset of saturation showed advancement in the number of hours of exposure to saturation. All specimens showed an increase in moisture uptake by increasing temperature (Santhosh, 2012). After 100 hrs exposure, the moisture absorption values were found to be 0.26 and 0.29% for glass/isopolyester, 0.21 and 0.24% for carbon/isopolyester, and 0.18 and

0.20% glass/isopolyester/gel coat at 60°C and 70°C and 95% RH at the end of 100hrs, respectively. Micrographs of fractured specimens of composites confirmed that matrix/fiber bonding sustained after 100hrs of exposure at 60°C and 70°C.

## 5.8 Low Temperature and Freeze–Thaw (FT) Cycling

FRPs under lower temperature (below 0°C) exhibit mechanical property changes along with additional microcracks in FRP materials. This can further result in increase in water absorption at higher temperatures, leading to an increased matrix plasticization and hydrolysis. The expansion of frozen water results in debonding and transverse microcrack growth. Rupture elongation showed similar degradation trends to the tensile strength. For both the basalt fiber reinforced polymer (BFRP) composites and carbon basalt fiber hybrid FRP sheet, FT cycling had negligible effect on their tensile properties, which means the hybridization of carbon and basalt fibers can contribute to the stability of the tensile properties of FRP sheet in FT environments (Shi, 2014). However, both the shear and flexural strengths of saturated GFRP samples subjected to lower temperatures (between 0°C, and -60°C) were not affected appreciably. In addition, their tensile strength (Robert and Benmokrane, 2010; Wu, et.al., 2006; Wu and Yan, 2011) and flexural modulus of elasticity appeared to be stable at temperatures ranging from -40°C to 50°C.

## 5.9 Types of failures

### 5.9.1 Failure of Polymer Composites

Failures, typically, are difficult to predict. Failures depend on the shape of a composite member and structural system, connection details, i.e., solid or hollow polymer composite members of rectangular or circular rods. (Figure 5.3) Also, loading type, constituent material configuration, and environmental conditions affect the type of failure; hence leads to unexpected failures.

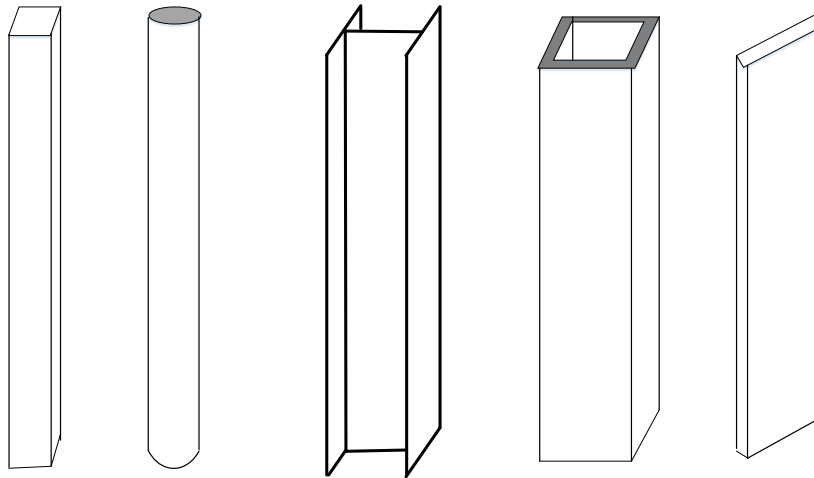


Figure 5.3 Different shapes of composite structures

Similarly, honey–comb composite structures (Figure 5.4) are prone to failure types with local failures being the most common ones. On the other hand, composite sandwich structures fail under different set of scenarios varying with the thermo-mechanical responses. Yet another set of failures may be driven by chemical and physical aging, aggravated by different load types and

environmental conditions such as high / low pH, sustained stress, fatigue, chemical reactions, and a combination of the above conditions.

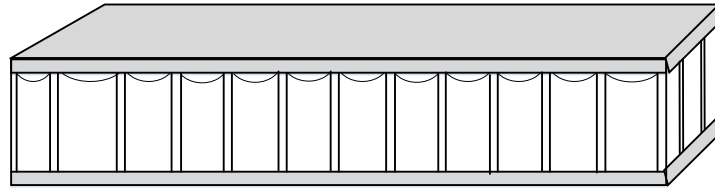


Figure 5.4 Honey comb structure

As in metals, polymer composites can fail prematurely due to inappropriate processing of polymers or inadequate temperature, or even incorrect mix proportion during production. For example, temperature, pressure and cure rate, including the polymer formulation (changes in composition of resin systems with promoters and accelerators) can affect the performance of final composite products. In addition, synergistic effects of stresses, environmental conditions and physical aging may result in premature failure. This section is focused on potential failures from:

1. Polymer processing and changes in composition, production controls, service conditions environmental cracking under the influence of stresses induced from external load applications and environmental conditions.
2. Sandwich structural failures due to limitations in strength, stiffness, local intra-cell or global buckling, shear crimping, skin wrinkling and local compression including indentation (Figure 5.5).
3. Honey-comb structures fail primarily from local and global crushing, fatigue, buckling, inadequate strength and/or stiffness, high stress concentrations at reentrant angles, and other joint failures.

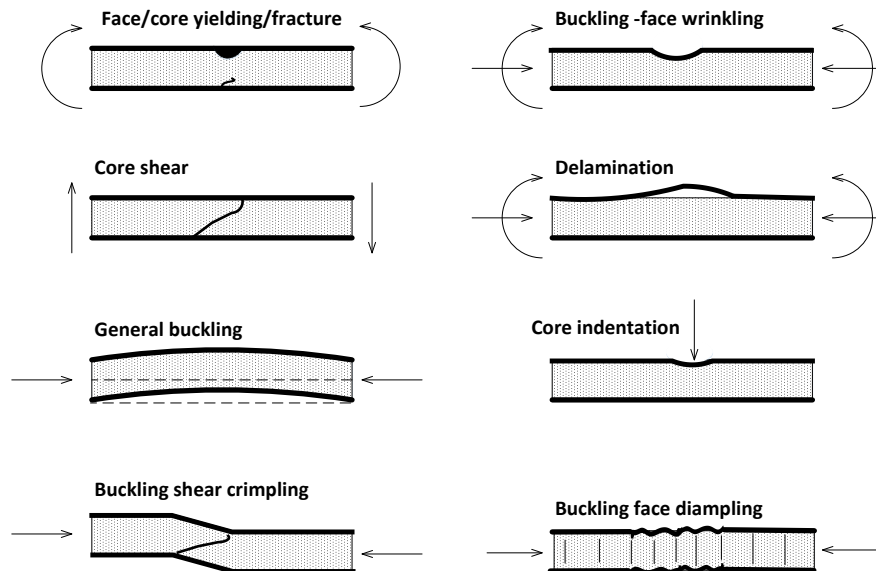


Figure 5.5 Sandwich laminate failure modes (adapted from Det Norske Veritas Offshore Standard DNV-OS-C501, Composite components, 2003)

All the above mentioned failures (and others not noted herein) can be aggravated in the presence of harsh environments such as temperatures fluctuations, pH variations, ranging from 2 to 13, chemical reactions, sustained stress (creep, also known as static fatigue) and others.

### **5.9.2 Failures from Process and Production Variabilities**

Process failures and production variables and the variabilities in constituent materials are many in composites. One must realize that all polymers, however carefully produced, have a small fraction of monomers that do not fully react or polymerize. This would result in inadequate cure (say, << 1% uncured monomer) which could be a source of crack initiation. For example, polyvinylchloride (PVC), may have a very small amount of health-hazardous vinyl chloride monomer (1 to 5 parts per million) without cure, which can be a hazard. However, stringent process regulations cause lowering mass-production rates including cost effectiveness of a product.

Another health hazardous is the plasticizer in PVC (Dioctyl Phthalate (DOP)) which was found to be ingested by babies. DOP is banned in some countries due to health issues. Any plasticizer in PVC must have good compatibility with PVC for proper bonding with substrate. Many failures due to inadequate bond are noticed in practice.

Hazards of incomplete polymerization in small quantities, may affect children (more so than adults), as in the case of polycarbonate baby bottles containing bisphenol A (BPA). A better fire resistant halogenated (bromine or chlorine) organic compound, can result in chlorine or bromine separating from the polymer, especially under the exposure of humidity and at higher temperature such as 150 °C or above. Such process temperatures are common and may result in serious health problems; thus leading to acidic environment and corrode and/or erode the processing equipment. Changes in environment can cause failures in terms of adhesive bond failures or other forms of distress. Industry has noted hydrogen evolution in a 2-part silicone adhesive, under certain formulations, thus causing a part to bulge in a hermetically sealed system. Such scenario has to be overcome by modifying the formulation of the adhesive. For example, excess use of hydrocarbons or plasticizers can result in binding together of the parts, which can be overcome by modifying the plasticizer formulation and minimizing its use.

### **5.9.3 Failures under Environmental Variations**

FRP composites are susceptible to degradation under both the physical and chemical aging. To encourage wide use of FRPs in infrastructure, understanding of this chemo-thermo-mechanical behavior under harsh environmental conditions with time is essential. Accelerated aging test data to predict the degradation rates and service life of FRP composites have been generated by many researchers and companies. Arrhenius approach with activation energy as the focus of aging study is commonly employed to correlate durability response data with field responses over limited service durations (GangaRao, et.al., 2006). However, the Arrhenius approach has certain limitations and needs modifications to account for non-thermal degradation mechanisms under different environmental conditions. For additional details on Arrhenius or modified Arrhenius approaches, reader is suggested to refer to (GangaRao, et.al., 2006, and “Accelerated aging and life time prediction: review of non-Arrhenius behavior due to two competing process”, M.Celina, Gillen, Assink, Polymer degradation and stability journal, 2005, pp. 395-404).

A few environmental related failures of GFRP composites are:

- 1) In electric transmission lines, the insulators act as non-conductive elements, attached through metal fittings at their top as well as the bottom. These glass insulators have a tendency to fail above or below these metal fittings. A close observation of the rod and the metal fittings revealed that the fitting were holding rain, snow and corrosive materials of environment, and rusting the fittings and resulting in failures.
- 2) Polyester based insulator rods absorb moisture, resulting in molecular weight loss in addition to severe acidic (environment) reaction of E-glass fibers in the insulators, thus reducing the strength of the insulators gradually and resulting in eventual failure. Other potential causes of failure are the stress concentration on insulators at the metal fitting locations, inadequate design to carry wind and thermal loads, and even prestressing effects caused by the movements in the transmission lines.
- 3) If UV inhibitors are not added to resin systems, the UV light from Sun or fluorescent light can attack the resin and exhaust the antioxidant in the resin resulting in cracking. When antioxidants are exhausted in a resin system, the classic oxidative degradation would set in. The best approach to avoid such degradation is to provide adequate amount of UV inhibitors, which are available routinely in the market.
- 4) Damage to composite pipes can be attributed to water under pressure (resulting in sustained stress), temperature fluctuations (potentially  $>T_g$ ), exposure to acidic environment and even stress cracking under complex loading conditions. For example, polybutylene pipes used to transport water failed under water pressure. The failure can be accentuated when they are bent. Such bents can result in local stress concentration due to kinking in the composite material. In addition, excess pressure exerted at the fittings can cause stress concentrations and even cut into the pipe material, and even accentuated by moisture uptake.
- 5) Fiber debonding, or brittle resin failure at very low temperature is common. At higher temperatures, say 150 °C, polymers crystallize and lead to serviceability problems including failures.

Multiple loads acting on a composite specimen can lead to many types of failures. Some of these failures are quantified in the following sections.

Failures of polymer composites can be of many forms under varying mechanical, thermal and other environmental loads. For economical and safe designs and acceptable durability levels, accurate prediction of failure strength and failure locations are extremely important. A good design under a given set of load conditions must consider all possible failure scenarios. In all cases, cost and safety versus benefit evaluations have to be performed including even the worst case situations.

Unlike metals, polymer composites have many variables coming from varieties of polymers and fibers available in the market and also their process parameters. A few of the classic failures are enunciated (certainly not a complete set) above so that designers can appreciate the importance of accurate prediction requirements of polymeric material failures while designing complex composite parts.

## 5.10 Friction and Wear Resistance

Moisture acts as a plasticizer in cured thermosets, generally resulting in a reduced stiffness modulus and glass transition temperature. Water acts as a plasticizer by causing physical swelling of the polymer, which can lead to increased internal stresses and micro cracking in the material. Water absorption results in plasticization which disrupts van-der-Waals bonds in the polymer. Water absorption leads to reversible physical uptake of water by the material, whereas hydrolysis is the irreversible chemical degradation of the polymer by absorbed moisture.

In general, vinyl esters are the most resistant to water absorption in comparison to epoxies and polyesters. All polyesters are hydrolysable. The unreacted parts in pultrusion process due to high temperature cure, are very limited; thus making esters suitable for marine environment.

Aramid fibers are susceptible to water absorption and swelling which precludes their use in marine environments. Phenolic resin is precluded to use in a marine environment because of excess absorption of moisture.

Degradation of long term water submerged composites without protection can take place in a rapid pace resulting in lower mechanical properties. Therefore, coating of composites is essential to protect them in marine environments.

Bonded carbon FRP systems are sensitive to water and deterioration can occur after a short exposure, which depending on the adhesive type.

Similarly, GFRP patrol boats deployed by USCG since 1960s, have been performing well. Ten and twenty years test data of the USCG Patrol Boat show no degradation due to water and chemicals. The Thickness of the laminate was limited to 9.5 mm for the sides and 19 mm for the bottom.

The sensitivity from water absorption can be minimized by maximizing the fiber volume content and by minimizing the non-reacted parts of the resin and preventing air inclusions. High quality manufacturing is the key to preventing degradation due to water absorption.

## 5.11 Fire Resistance (FR)

FRPs lack adequate structural performance at high temperature, including fire. A common polymer in a composite undergoes rapid deterioration even at moderately high temperatures ( $> 150^{\circ}\text{F}$ ). However, exceptions are available at premium prices. If exposed to flames or high heat flux, commonly available polymers decompose and may even catch fire releasing heat, smoke, toxic gases and soot.

The fire resistance and fire performance of the FRPs can be improved using two main approaches. First approach relies on increasing the fire resistance of FRP materials through flame retardant additives in the resin system which slows down the thermal decomposition of the polymer resin. In the second approach, fire resistant barriers such as coatings and insulations are used to protect FRP composites from fire and heat. Intumescent coatings, insulation boards and cementitious layers are recommended as barriers. These barriers prevent rapid rise of temperature in FRP, allowing them to sustain their mechanical integrity for longer period of time, after exposure to fire.



Herein, various flame retardant materials including intumescent materials are discussed along with the mechanisms of degradation of composites under fire, smoke and toxicity. Important test methods are identified and described in terms of fire resistance (FR) performance evaluations in FRP composites including measurement and control of smoke and toxicity. Before concluding the research needs in fire resistance, needs for improved test methods are identified.

#### **5.11.1 Thermal degradation or decomposition of polymers**

According to ASTM E176, thermal decomposition is defined as “a process whereby the action of heat or elevated temperature on an item causes change to chemical composition”. Resulting in a loss of physical, mechanical, or electrical properties. Combustion in condensed and gas phases, involves heat and mass transfer processes simultaneously, thus resulting in the production of new chemical species. Thermal decomposition can be induced by heat or oxidation, and the general chemical breakdown mechanisms are: chain scission (random or end-chain cleavage in the polymer backbone), chain stripping, and cross-linking. Random scission occurs on supplying the bond energy of monomer, and this results in the formation of monomers or oligomers. Polyethylene, polypropylene, polystyrene, and polymethylacrylate decompose in this manner. End-chain scission, also called unzipping, produces monomers, especially in the presence of large side groups. Polymethylmethacrylate, polyoxymethylene, poly- $\alpha$ -methylstyrene, and polytetrafluoroethylene exhibit end-chain scission. Chain stripping is the result of elimination of small molecules which are formed by side groups of main chains. Under heat, elimination of hydrogen chloride in polyvinyl chloride is an example of chain stripping. Cross-linking is due to the bonding of main chains of intermediate molecules. When cross-linking occurs, the materials become more thermally stable, insoluble, and stiff. In polyacrylonitrile, cyclization reactions occur, and the linkage between nitrogen and carbon on adjacent side groups participates in cross-linking. (Delbourgo, 1982; Kashiwagi, 1994).

#### **5.11.2 Smoke and toxicity**

In the event of fire, the most serious threat to human life comes from the burning buildings and also from incapacitation caused by smoke and toxic gases. The presence of smoke causes reduction in visibility resulting in disorientation while toxic gases affect nervous and pulmonary system causing choking and irritation of lungs, skin and eyes while in some cases loss of consciousness and even life. In FRP composites, the problem of smoke and toxicity is further compounded by inhaling of fibers and fillers which get liberated during combustion.

At the simplest level, a polymer can be a high molecular weight compound of H and C (polyethylene, for example). In the presence of sufficient oxygen, one can expect FRP to combust releasing CO<sub>2</sub> and H<sub>2</sub>O and other gases associated with nitrogen and sulphur. Furthermore, polymers are blended with many additives (e.g. lubricants, flame retardants, fillers, antioxidants, catalysts, etc) and result in products of combustion that are mixtures of myriad of chemical compounds. For further details readers are requested to refer research by Lipscomb et. al (1997) and others.

##### **5.11.2.1 Mechanisms and behavior of FR materials**

Polymer composites are not intrinsically flammable as solids. However, when polymers are exposed to high temperatures, they decompose and produce gaseous products which burn. In particular, these decomposition products react with radicals, such as H, OH, or O by chain



reactions and release heat which goes back into the solid phase to continue the decomposition of polymers and produce even more gaseous products. Thus, there are three ways to reduce flammability of polymers:

1. Addition of chemicals which can produce radicals of low molecular weight and low chain reaction activity at high temperature. These are able to disrupt the propagation of chain reactions. Halogen-containing additives are the most commonly used ones for this purpose.
2. Incorporation of additives to produce char on the surface of the solid phase so that one has heat and mass transfer barrier. Oxygen-containing polymers are easy to protect by this method.
3. Use of additives that evaporate at high temperature and produce non-combustible gases in an endothermic manner. The result is dilution of the combustible materials in the gas phase with the simultaneous removal of heat. Metal-containing flame retardants, such as magnesium hydroxide and alumina trihydrate, are commonly used for this purpose.

The phenomenological flammability reduction discussions were elaborated by Song et al, 2012.

### **5.11.2.2 Intumescent flame retardant systems**

To find substitutes for halogenated flame retardants, studies have been devoted to intumescent systems. Intumescent systems, which give a swollen multicellular char on heating, can protect flammable substrates by preventing them from reaching ignition temperatures. The suggested mechanism of fire retardance is that the swollen multicellular char acts as a barrier against heat and oxygen transfer from the gas phase to the condensed phase and also stops the release of combustible gases. In this system, there are four components involved: resin binder, catalyst, carbonific compound, and spumific compound. An important characteristic of the resin binders is that they melt or soften at reasonably low temperatures. Therefore, vinyl polymers and styrene-butadiene polymers are preferable to be used as resin binders. A catalyst, which is used to trigger the first reaction, functions mainly to dehydrate the carbonific compounds. Three inorganic acids, which are sulfuric, boric, and phosphoric acids, are commonly used as intumescent catalysts. Carbonific compounds, which are polyhydric organic compounds, are the major source of protective char. The characteristics of an effective carbonic compound are high carbon and hydroxyl contents, and the carbonic compounds must decompose after the acid is available to play the dehydration action. The spumific compound decomposes to give a large amount of volatile gases, such as ammonia, water, and hydrogen chloride, and these gases cause the carbonaceous char to foam into a protective layer. The decomposition temperature range of the spumific compounds should be in the temperature that the carbonaceous char is still in a molten state. Otherwise, there will no intumescence (Kuryla and Papa, 1978).

On the basis of coating technology, intumescent systems have been incorporated into polymeric materials as fire retardants. The preparation of intumescent polymeric materials involves blending polymers with additives, which show the intumescent behavior on heating. General guidelines are (Camino et al., 1989):

1. Additives must be thermally stable at the polymer processing temperature.
2. Gases from thermal degradation of polymers must not interfere with the intumescence process.
3. Protective char layer must cover the entire surface of the burning polymer.
4. Additives must not interact with fillers or other additives, such as stabilizers.

Epoxy resins are often used as binders for intumescent coatings for application on steel or concrete structures. These can also be applied as thick coatings on the exposed surface of FRP wraps retrofit materials of concrete structures. Main components other than binding agents are acid catalysts to promote charring.

### 5.11.3 Standard test methods for evaluating FRP materials for FR performance

Table 5.1 Standard test methods for FR performance evaluation provides a list of ASTM standard tests that are relevant for evaluating the performance of FRP and FRP containing materials under fire conditions.

*Table 5.1 Standard test methods for FR performance evaluation*

<b>ASTM Standard</b>	<b>Description</b>
D635	Flammability of the rigid plastics
E84	Tunnel test for surface burning characteristics of building materials
E176	Standard terminology of standard fire tests
E119	Test methods for fire tests of building construction and materials
E136	Test methods for vertical burning behavior at 750°C (excluding laminated or coated materials)
E1591	Obtaining data for deterministic fire models
E662	Specific smoke density from burning solid
E1354	Cone calorimeter test for heat release rate and smoke release
E1995	Smoke density test for burning of horizontal sample from a radiant heat source
E1929	Determining ignition temperature of plastics
D3801	Determining burning rate of plastics in vertical position
E814	Test method for fire tests of fire penetration of firestop systems
D2863	Limiting oxygen index for candle like burning of plastics
E162	Surface flammability of materials using radiant heat source
E906	OSU calorimeter test for heat release and smoke density
D3675	Surface flammability of flexible cellular material using radiant heat

E1321	Method for determining material ignition and flame spread
E1678	Method for measuring smoke toxicity for fire hazard analysis
E800	Measurement of gases present during fires
E648	Critical radiant flux for floor covering using a radiant heat source
E970	Critical radiant flux for exposed attic insulation using radiative heat
E1317	Flammability of marine surface finishes
E2058	Test for measurement of polymer flammability using flame propagation apparatus

A wide variety of flammability tests have been developed over the years by standards organizations such as the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), Underwriters Laboratories (UL), National Fire Protection Association and the International conference of Building Officials. Many of these tests are small-scale tests due to the fact that they require relatively small amounts of material and also because they are inexpensive and easy to conduct. Some of them are multiple versions that differ in only minor ways in the specimen size, apparatus used and the procedure employed. However, these tests may not simulate phenomena that might occur under actual fire conditions during a large-scale fire, especially the massive effect of heat and pressure that might be generated in such an event. The different tests, though, may provide information on different aspects of flammability. Thus, there are tests of ignitability, of ease of extinguishment, of flash-fire propensity, and of flame spread. Other tests measure smolder susceptibility, the rate of heat release, fire endurance, smoke generation and the evolution of toxic or corrosive gases. It is for this reason that one may not compare data obtained from one test with data obtained from a different test. Furthermore, some tests are used primarily in materials research while others are required for field implementation of complete systems; in the former situation, the tests are of relatively low severity, while those in the latter situation are generally of high severity.

#### 5.11.4 Prescriptive vs. Performance-based test methods

Various test methods provided in standard codes are prescriptive in nature in that the test conditions are carefully controlled and strictly defined. The main concern is regarding the assumption that the test results obtained from individual structural elements tested in a controlled fire furnace can be applied to real life fire situation where design parameters may have significantly different characteristics. Some of the important parameters of interest are (Kodur, 2008; Rini and Lamont, 2008)- loading, connections, end-restraints, structural connections and temperature distribution. For example, structural connections may lead to release of loads or alternate load distribution path preventing the collapse of the structure. Non-uniform temperature distribution may add to the complexity of the thermal strains and failure criteria. Similarly, ventilation conditions may play an important part in the development of the fire behavior and the resulting temperature profile. Performance based design analysis is followed to study (Milke, 2006):

1. Real life fire exposure accounting for potential fuel load and ventilation effects.
2. Heat transfer analysis to predict temperature distribution and corresponding mechanical properties.
3. Structural analysis to determine deflections and failures under fire weekend conditions.

Insights gained from this analysis will help in improving the building design by identifying the weak spots and making the necessary design changes in terms of structural design and fire protection systems (Rini and Lamont, 2008) based on valid acceptance criteria. Performance based design approach relies heavily on finite element based computer simulations. Main obstacle in that regard is the non-availability of simulation tools and material data. As discussed earlier, parametric studies on FEM simulations have shown that the material properties such as thermal conductivity, heat of reaction and load-strain curves have strong effect on the simulation results. Therefore, it becomes imperative to generate a database of structural material properties which can be used in simulation studies. NIST (Kodur et al., 2007) published a study on the research needs in the structural fire safety design. Some of the salient recommendations for future research needs are given below:

- Development of high-temperature constitutive material models.
- Development of new sensor technology for fire tests.
- Collection and generation of test data for model verification.
- Development of acceptable tools and criteria for undertaking structural fire design.
- Defining proper fire loads (scenarios) for developing numerical models and design guidelines.
- Performing sensitivity analyses and parametric studies to identify factors governing global structural response.

### **5.12 Fatigue Evaluation**

Fatigue life prediction in composites is complex due to the inhomogeneity and anisotropy of the material. Fiber type, matrix type, reinforcement structure, stacking sequence, manufacturing quality, loading conditions, environmental conditions, boundary conditions, and long-term behavior can all significantly affect fatigue behavior (Degrieck and Van Paepegem, 2001). In unidirectional composites, the fibers carry virtually the entire load; one would expect that the fatigue behavior would depend solely on the fibers, which have good resistance to fatigue. However, experimental results have shown that the fatigue behavior is determined principally by the strain in the matrix (Curtis P. T., 1989). When the weakest location in a composite fails, the surrounding fiber/matrix interface experiences increased local stresses, which can lead to eventual fatigue damage. The weakest location is, more often than not, caused by material defects, such as misaligned fibers, voids, resin-rich regions, or simply fibers with strengths located at the lower end of the statistical distribution present in all fibers. Because of all of these additional considerations, the fatigue behavior of composites is generally quite different from the behavior of isotropic materials.

Fatigue damage in FRP composites is progressive and cumulative in nature at the micro level (Reifsnider, 1990). For metals, the damage due to fatigue is more localized at the macro level (Degrieck et al., 2001) and can be identified visually and by micro graphs of fracture surfaces (Rakow and Pettinger, 2006). Unlike metals, composites accumulate damage at various locations under fatigue. However, the potential defects present in the material (matrix cracks, broken fiber, fiber wrinkling, inadequate cure, etc.) at the time of manufacturing are higher in FRP composites than in metals. When subjected to fatigue loading, these defects lead to crack initiation, crack growth and interconnection of cracks with eventual failure. Figure 5.6 Cracking initiation and growth of a sandwich sample under 3pt bending fatigue, leading to eventual failure at the corner shows a sandwich panel under 3 points bending fatigue where crack initiation occurred at locations of fiber wrinkling.



*Figure 5.6 Cracking initiation and growth of a sandwich sample under 3pt bending fatigue, leading to eventual failure at the corner (WVU-CFC)*

Fatigue studies on composites under combined thermal and mechanical loads are sketchy and limited research has been performed by Lesko et al (1998), Kellogg (2005), and a few others (Dutta, 1995). The load rate has the greatest influence on fracture sensitivity for a notched specimen where the rate of increase of loading results in increased mean notch toughness values for wide ranges of moisture content or temperature.

In order to predict the fatigue behavior of a material, the remaining strength or the remaining number of cycles, the material properties, and the environmental/loading conditions must be related to the damage modes that the material is likely to experience. The fatigue behavior of resin-matrix composites depends on the interlaminar and intralaminar shear resistance, which in turn depends on the lamina properties, laminate stacking sequence, the environmental conditions (moisture, temperature), the testing frequency, and the stress ratios (min/max and max/ultimate) (Sendecckyj, G.P. 1990). There have been numerous fatigue life prediction models for composite materials published in the past few decades (Degrieck and Van Paepegem, 2001, Hashin and Rotem 1973, Mouritz 2005).

### **5.12.1 Strain Energy-Based Fatigue Life Prediction Equation**

One model that has been shown to match and predict the fatigue behavior of a number of different materials and layups is a strain-energy based model developed and implemented at the Constructed Facilities Center at West Virginia University (WVU-CFC) (Dittenber and GangaRao, 2010). The

WVU-CFC model takes into account the similar patterns of strain energy release rate observed among different glass fiber reinforced composites along with the initial strain energy of the unstressed sample to predict the number of constant amplitude fatigue cycles to failure for a particular coupon or component. The model, shown in Equation 5.1, relies on two constants,  $a$  and  $b$ , that can be either determined experimentally or approximated with reasonable accuracy based on similar experimental data. Additionally, in Equation 5.1,  $N_f$  is 90% of the number of cycles to failure,  $U_0$  is the initial strain energy, and  $(\sigma_{max}/\sigma_{ult})$  is the normalized maximum stress over the ultimate stress.

$$- N_f = \frac{U_0}{2a \left( \frac{\sigma_{max}}{\sigma_{ult}} \right)^b}$$

*Equation 5.1*

The stress range in Equation 5.1 is the ratio of the maximum stress to the ultimate stress ( $\Delta S = \sigma_{max}/\sigma_{ult}$ ). For small values of  $\sigma_{min}$ , the two stress ranges are approximately equal. Throughout the rest of the derivations the max stress ratio is represented as  $\Delta S$  unless otherwise noted.

In bending (simply supported, with the load concentrated at the center), the initial strain energy can be calculated as shown in Equation 5.2, where  $\sigma_{ave}$  is the average fatigue stress,  $I$  is moment of inertia of the section,  $L$  is the span length,  $c$  is the distance to the neutral axis, and  $E$  is the modulus of elasticity.

$$- U_0 = \frac{(\sigma_{ave})^2 IL}{6c^2 E}$$

*Equation 5.2*



*Figure 5.7 Example of FRP structural shape in 3-point bending (WVU-CFC)*

The accuracy of the WVU-CFC model was checked by applying the model to a large amount of glass FRP coupon fatigue data, some of which was generated by the WVU-CFC, but the majority of which was generated by Montana State University (Samborsky and Mandell 2005). The model



was found to be able to fit 80-90% of over 1200 fatigue tests to within  $\pm 5\%$  logarithmic error on their respective  $\Delta S - N$  curves. To predict fatigue life of glass-polyester FRP coupons to within  $\pm 5\%$  logarithmic error using only two empirical data points with 75% success – more empirical data further improved the accuracy. The model was able to, on average, predict the number of cycles to failure to within 3.6% on the logarithmic scale with a standard deviation of 3.0% on the logarithmic scale, which is reasonable for conservative fatigue life prediction. The identical procedure performed on the FRP Box and WF beams resulted in predictions within  $\pm 2.5\%$  log error, indicating a potential for even better accuracy when applied to full size FRP components.

Table 5.2  
 $\bar{m}$        $\bar{c}$

<b>BOX BEAM</b>	10	90
<b>WF BEAM</b>	10	460

From looking at the coupon test results (75 total samples of 7 FRP pultruded glass-polyester material combinations), the “b” constant varies from about 11 to 16 while the “a” constant varies from approximately 113 to 11300 (N-mm). If “b” is assumed to remain approximately 12 for FRP components and “a” is varied across the range seen in the pultruded coupons, is populated, where R is the average value of (experimental  $\Delta S$ ) / (calculated  $\Delta S$ ) for each set of constants.

Assuming the factor of safety to be applied should be three standard deviations, the number of cycles to failure for each stress level should be modified by  $3 \times 3.0\% = 9.0\%$  on the logarithmic scale. It has previously been shown that over 97% of coupons are within 10% of the logarithmic error using this fatigue model. After applying the safety factor modification to the experimental results for number of cycles to failure, it was found that the stress level should be increased by a factor between a maximum of 1.18 for a normalized fatigue stress of 0.2 and a minimum of 1.05 for a normalized fatigue stress of 0.8. Taking the value of 1.18 to be the most conservative, it can be seen in Table 5.2, that, if  $\bar{m}$  has a value of 10, “a” should have a value of around 1469 (N-mm) to provide the minimum appropriate margin of three standard deviations for both shapes. With these modifications incorporated (along with  $\Delta S$  as the maximum stress ratio instead of the normalize stress range), the pre-standard equation would include the material properties of the sections to be fatigued in flexure as shown in Equation 5.3. For undamaged FRP components, without joints, it is therefore recommended that  $\bar{m}$  should have a value of **10** and  $a$  should have a value of **1469** (N-mm) in Equation 5.3 to provide the appropriate three standard deviation factor of safety.

$$- \Delta S = \left( \frac{(\sigma_{ult})^2 IL}{48c^2 Ea N_f} \right)^{\frac{1}{\bar{m}}}$$

Equation 5.3

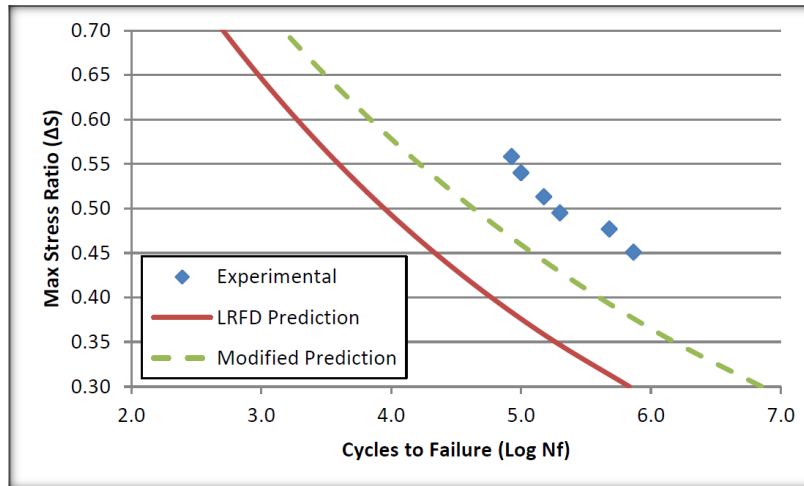


Figure 5.8 Comparison between pre-standard model and proposed modification



## 6 ADVANCES IN RECYCLING OF COMPOSITES AND GREEN COMPOSITES

### 6.1 Introduction

Recycling is discussed more in the context of recycling of thermoplastic polymers than thermosetting polymers because thermoplastics account for the majority of commercial usage. Americans use approximately 60 billion pounds of plastics each year for various applications while the annual thermosetting composites shipment is about 5 billion pounds. Waste polymeric materials exist in three sources: domestic wastes, industrial wastes and discarded plastics products. Unlike natural macromolecules, most synthetic polymers cannot be assimilated by microorganisms. In the past, most of these plastic products were not reused and thus ended up in landfills. However, over the past two decades the disposal of plastics has become a serious concern to the environment, leading to government legislation for recycling.

Although there has been increasing public demand for recycling discarded thermoplastic products, in most cases the recycling of polymers has been technically difficult and expensive. This is attributed primarily to the fact that post-consumer plastics are commingled. Mixed plastics have poor mechanical properties due to compatibility problems and thus have little value. Separating the chemically different plastics from each other, however, is expensive. Most of the implementation activities concentrate on recycling that is economically feasible, i.e., plastic wastes having slight contamination and higher resale value. These plastics can be recycled in the form of usable materials. For heavily contaminated plastic wastes which are difficult to sort into single polymer streams, a thermal recycling process is available. During this process, recovery of plastics is in the form of gaseous, liquid or solid fuels.

### 6.2 Material Recycling

Material recycling (i.e. re-use) is usually implemented in the recovery of plastics when the process can acquire large quantities of reasonably clean polymers with very good purity. Recovered plastics can be reprocessed by formulating alloys, blends or composites (known as ABC techniques) to upgrade their performance and bring them to desired levels of properties for applications (Liang, 2001). A material recycling process comprises of collecting and sorting of waste plastics, shredding, washing, drying, and upgrading. The recovered plastics are generally reprocessed by extrusion into granules for normal plastics molding. Reuse of polypropylene recovered from automobile bumpers, for example, has shown good market potential. The recovered polypropylene was reinforced during reprocessing with waste cord-yarns of the tire industry, resulting in a grade of extrudable and injection-mouldable, fiber-reinforced thermoplastics.

### 6.3 Thermal Recycling

Thermal recycling plays a key role for unwashed waste plastics or rubber wastes (often heavily contaminated, multilayered, heavily pigmented, mixed and could not be recycled in the form of materials) to recover gaseous, liquid or solid fuels, and sometimes oligomers or monomers. There are three principal thermal methods: pyrolysis, gasification, and hydrocracking. For example, the pyrolysis of acrylic polymers recover 25 to 45% gas with a high heating value and 30 to 50% oil

of rich aromatics. In addition, chemical processes such as methanolysis, glycolysis, hydrolysis, ammonolysis, and aminolysis can be employed for recycling of some types of plastics (typically polyesters, polyurethanes and polyamides). This approach involves chemically decomposing macromolecules by chain cracking into monomers that can be reused for manufacturing new polymers.

## 6.4 Material Research

Polycarbonate (PC) and Acrylonitrile-Butadiene-Styrene (ABS) are relatively expensive polymers that are used in significant quantities in the manufacture of computer, monitor and printer housings. These products are discarded after being used for only a few years. Recycling these polymers after the end of their life is receiving greater attention and tremendous progress has been made in reusing these discarded thermoplastics for a variety of applications (Vijay et al, 2000; Aditham, 2004; Kalligudd, 2010; Chada, 2012).

The objectives of the material research were to reuse these polymers in their original, high-value applications by blending with virgin polymers and/or produce acceptable, high quality, low cost, green products using as high recycle content as possible. Recycled polymers are recovered from unknown sources, approaches must be sought to minimize the batch-to-batch variations in properties in order to yield consistently high quality compounds. Four strategies can be applied: 1) blending recycled polymers with chemically identical virgin resins, 2) blending recycled polymers with chemically different virgin resins, 3) adding short glass fibers to reinforce the recycled polymer blends, and 4) using molecular weight modifiers to adjust the average molecular weight distribution. One of the findings was the “15% blending rule”, i.e., to attain excellent properties, up to 15 wt% recycled polymer can safely be added to the virgin polymer without significantly altering properties of the virgin resin if the recycled polymer has a purity level of about 99% (Liang, 2001).

## 6.5 Product Development

Both structural and non-structural applications of recycled PC and ABS polymers, with chopped or continuous glass fiber/fabric reinforcements, have been extensively investigated at WVU-CFC (Vijay et al, 2000; Aditham, 2004; Kalligudd, 2010; Chada, 2012). Some of the products developed include: guardrail post, offset spacer block, rectangular grids, rib-stiffened panels, sign posts and sign boards, dowel bars, window panels, and wood plastics composite (WPC). A couple of these products have been field-installed in the highway systems with the approval by West Virginia Department of Transportation (Aditham, 2004).

Even recycled polymers are engineered to manufacture full scale railroad crossties that use end-of-life railroad wood ties as the core and recycled polymer composite as a shell (Kalligudd, 2010; Chada, 2012). Figure 6.1 shows a recycled GFRP composite railroad tie before and after demolding. These railroad ties have been extensively evaluated under static and fatigue loads in the laboratory (Figure 6.2), followed by field installation in straight and curved locations and testing under standard locomotive loads (Figure 6.3). With over 12 million railroad ties being replaced annually in the United States, this green product is being negotiated for mass field implementation (Chada, 2012).



*Before Demolding*

*After Demoldin*

*Figure 6.1 Manufacturing of Recycled GFRP Composite Railroad Ties (Chada, 2012)*



*3pt Bending Test*

*Fatigue Test in Gravel Bed*

*Figure 6.2 Recycled GFRP Composite Railroad Tie Testing (Chada, 2012)*



*Figure 6.3 Field Testing of Recycled GFRP Composite Railroad Ties (256 Kips) on SBVR Line in Moorefield, WV (Chada, 2012)*

## 6.6 Thermosets

FRP composites with thermosets are generally believed to be more difficult to recycle than thermoplastics because liquid resin becomes rigid via chemical curing reaction upon application of heat, and cured resins will not melt or flow upon reheating. Automotive manufacturers have had good practices in recycling all the component materials used in their vehicles including composites such as sheet molding compounds (SMC) and bulk molding compounds (BMC) (SPI, 1993). A material recycling of FRP composites can be viewed as grinding thermosetting materials into particles or powder resulting in a particle size of about 1.5 mm and use these particulates as fillers or aggregates. These scrap FRP fine powders can be used as aggregate for producing panels, cement paste and mortar, as well as in asphaltic concrete. Alternatively, the thermal recycling process can be used to recover reinforcing fibers for reuse, such as carbon fibers from cured fabric/epoxy composites (Allred et al, 1996).

## 6.7 Energy Renewing

In addition, plastics including FRP composites can be collected with other combustible wastes and incinerated to recover heat value. The energy recovery of wastes by incineration could utilize all thermoplastic and thermosetting wastes under zero reuse conditions. It is reported that incineration systems with energy recovery can recover about 8000 thermies per ton of unsorted plastics (Dawans, 1992).

## 6.8 Design for Recycling

To facilitate the end-of-life recycling of polymers and composites, a “Design for Recycling” concept should be incorporated into the development of next generation products. One of the general principles is to minimize the number of material types and select compatible polymeric materials to design a new product. Another important consideration is to avoid contaminants such as labels, adhesives, nails, and metal plates. The success of composite recycling depends on the factors including government policies, industry commitment, technology, and public support.

## 6.9 Green Composites

“Green” composites are m while the term ‘natural fiber reinforced composite’ (NFRP) generally refers to natural fibers in any sort of polymeric matrix (thermoplastic or thermoset; natural or synthetic). As per Patel and Narayan (2005), a sustainable development is a “development that meets the needs of present without compromising the needs of future generations to meet their own needs.” This definition implies that sustainable development must include environmental, economic, and social factors. Biocomposites are promising sustainable composite materials due to their substitution of renewable resources for fossil fuel based polymers and synthetic fibers, lower greenhouse gas emissions, closure of the cyclical loop from raw material growth to biodegradation, potential for lower production costs, and opportunities for growth in agricultural and chemical industries including new jobs (Dittenber and Hota, 2012; Baillie, 2004). While the production of cement and other building materials results in a large amount of carbon emissions, efficiently produced natural composites would provide a minimal carbon footprint due to their natural ability to absorb CO<sub>2</sub>.



FRP composites are used in a wide range of non-structural and structural applications. FRPs are “greener” in terms of embodied energy (overall energy required in a process to make a product) than conventional construction materials. In view of durability, sustainability, energy efficiency in manufacturing and other advantages, a growing number of architects and building owners are now choosing FRP based building products over conventional materials. Several case studies have proven that FRP components for building construction are good thermal insulators, economical, strong, dent-resistant, scratch proof, having good acoustic barrier properties and user friendliness (Nadel, 2006). However, GFRP composites are made from fossil fuel based polymers and synthetic fibers. Increasing awareness about LEED (Leadership in Energy and Environmental Design) ratings has created strong demand for innovative eco-friendly materials of low carbon footprint.

### **6.10 Bioresins**

In response to growing demands to curb the usage of petroleum-based thermosetting resins due to environmental as well as economic and resource sustainability issues, researchers have been developing bio-based and sustainable resin systems for composite manufacturing. Upon processing, plant based materials such as soy, crambe, linseed and castor oil produce unsaturated triglycerides. The triglycerides constitute unsaturated and saturated fatty acids which can be polymerized to form an elastomeric network to replace petroleum based resins. With constant emphasis from markets pertaining to LEED, through the US Department of Agriculture’s BioPreferred Program, Ashland Chemicals, Inc. initiated production of soy-based (bio-based) resins for commercial applications (CT, 2008).

### **6.11 Natural Fibers**

Natural fibers used in composites are mostly derived from plant fibers. Among the natural fibers, stem-based fibers such as flax, kenaf, jute, hemp, and leaf-based fibers such as abaca rattan and sisal are considered important with respect to their specific properties and compatibility for composite manufacturing (Drazl et al, 2004). Amongst these fibers, high grade flax fiber’s mechanical properties are nearly on par with conventional E-glass fiber for composite reinforcement. Flax fibers are available on the market for half the cost of conventional E-glass fiber.

### **6.12 Pultrusion of Natural Composites**

Engineers at Bedford Reinforced Plastics (BRP) Inc. took a lead in utilizing plant-based naturally renewable fiber reinforcement with a commercially available bio-based resin system to manufacture “green” composites on an industrial scale pultrusion line (Figure 6.4), resulting in more environmentally-friendly composites having less embodied energy compared to conventional GFRP composites (Mutnuri et al, 2010). The natural fiber used was flax with two different densities, 225 gsm and 685 gsm, while Ashland ENVIREZ 70301 resin was used, which contains 22% bio-derived content and is compatible for the pultrusion process. BRP technical team explored processing variables and thermo-mechanical responses of environmentally benign natural composites. Moreover, the possibilities of using “green” composites in various applications such as thermal insulators and sound transmission barriers are being investigated for their feasibility in FRP markets (Mutnuri et al, 2010), along with those of hand layup samples. Note

that natural fibers used in pultrusion did not experience any surface treatment while the natural fibers used in hand layup samples went through treatment in alkali solution. All natural composite samples resulted in poor strength and stiffness properties under tension as well as flexure. The alkali solution treatment did not improve the properties significantly. The pultruded natural composite sample had a high fiber volume fraction but that high fiber content did not translate to good mechanical properties.



*Figure 6.4 Pultrusion of Natural Fiber Reinforced Bioresin Composite Panel (Mutnuri et al, 2010)*

Natural fiber reinforced composites offer improved sustainability and eco-friendly characteristics, and have the future potential to be lighter-weight and lower-cost than many synthetic composites, as well as being easier to handle. Natural composites are being evaluated for some automotive applications as interior paneling, but are not yet in use as primary structural elements due to their perceived lower mechanical properties and reduced environmental performance (Netravali et al, 2007; Dittenber and Hota, 2012).

### **6.13 Hydrophilic Nature of Fibers**

All natural fibers are hydrophilic in nature, which is a major limitation because excess water absorption. It is incompatible with hydrophobic polymer matrices (Mohanty et al, 2001). Glass fibers, on the other hand, are essentially moisture resistant. The most common way to reduce the moisture absorption capability of natural fibers is through the process of alkalization (also known as mercerization). Alkali treatment (usually with KOH or NaOH) reduces the hydrogen bonding capacity of the cellulose, eliminating open hydroxyl groups that tend to bond with water molecules. Alkalization can also dissolve hemicellulose. The removal of hemicellulose, which is the most hydrophilic part of natural fiber structures, reduces the ability of the fibers to absorb moisture (Symington et al, 2009).

Another process that shows promise for reducing the moisture content in natural fibers is the Duralin steam treatment process (Stamboulis et al, 2000).

### **6.14 Incompatibility of Fiber with Resin**

In addition to the data obtained by Mutnuri et al (2010), Netravali et al (2007) also noted that most 'semi-green' or 'green' composites have maximum tensile strength and stiffness in the ranges of

14.5- 29 ksi (100-200 MPa) and 0.14-0.58 msi (1-4 GPa), too low to be used for primary, load-bearing components. The main reason leading to reduced mechanical properties in natural FRPs is the poor compatibility/adhesion between the hydrophilic fibers and the hydrophobic matrix materials. Many researchers have been developing treatments to modify the surface characteristics of the fibers to improve compatibility and adhesion.

The three factors affecting the bond between two materials are the mechanical interlocking, the molecular attractive forces, and the chemical bonds. Ideally, hydroxyl groups in a resin would bond with the hydroxyl groups that are available in all natural fibers, creating hydrogen bonds. The bond strength between resins and fibers is significantly lowered by the presence of moisture while curing due to the fact that H<sub>2</sub>O molecules will bond with the available hydroxyl groups on the surface of the fiber, lessening the connections available for matrix bonding. When water evaporates, voids are left in a cured natural composite. If fibers are properly dried before a suitable matrix is introduced, then better bond ought to result and future moisture uptake ought to be limited due to the lack of available hydroxyl bonding locations (Dittenber and Hota, 2012).

There are a number of different modifications that can be made in order to improve the interface between the fibers and the matrix. Akali treatment is to overcome the aforementioned barriers to advance the development of natural composites for interior structural applications with emphasis on green structures. However, the long term goal is to evolve the natural composites as an alternative to GFRP for both interior and exterior structural applications, perhaps with focus on better sizing material.

## **6.15 Green Building**

With the world facing a crisis in terms of sustainable growth and environmental stability, the responsibility is on engineering community to develop cost effective and durable construction materials having lower embodied energy. Green building movement, science in energy and environmental design, innovation for sustainability, sustainable materials, and many other programs are established to steer the United States in a greener direction. We can envision an eco-urban habitat of zero carbon foot print. As a mid-term goal, research and development efforts on game changing technologies can aim at an urban habitat capable of breathing with ambient environment and minimizing energy and water usage. There are several projects being funded by NSF that focus on buildings of net-zero energy operation. The goal of these projects is to maximize heating/ cooling/ lighting influence of solar energy and other natural resources to reduce energy consumption and yet maintain habitable conditions, including net-zero water design for buildings. With reference to FRP composites, durable, strong and stiff composite panels made of natural fibers and natural resins with lower embodied energy and cost per unit performance than steel need to be developed and integrated with prefabricated modular sub-system design concepts for potentially zero construction waste.

## **6.16 Long-term performance prediction**

FRP composites have a potential in helping to achieve a sustainable environment because of their advantages over conventional materials (Stewart, 2011). From a life cycle assessment perspective, the selection of FRPs would require characterization of its long terms durability and development of predictive models to assess the useful life of structural components or systems utilizing



composites. Durability responses of composite materials and understanding the mechanisms have become very important topics for mass implementation of these advanced composite materials. Serviceability, durability, and cost-effectiveness are essential for wide spread use of any material. Long-term responses of composite structures under environmental loads including moisture exposure have to be established so that the accelerated aging test methodology (ATM) can be used to predict long-term performance of FRP composites through life prediction models; these data have to be calibrated with field response data, monitored from the implementation works. Thus more durable, efficient and safer FRP structures can be designed based on data collected using ATM and appropriate safety (knock-down) factors.

## 7 NONHYDRAULIC APPLICATIONS

For the past three decades, FRP implementation has touched upon a wide range of engineering applications with emphasis on enhancing performance, serviceability and durability over conventional materials. This chapter deals with FRP composites to enhance environmental protection.

The applications hereunder can be attributed to the following favorable FRP material properties: 1) higher specific (with reference to material density) strength and stiffness than steel or wood; 2) higher fatigue strength and impact energy absorption capacity; 3) better resistance to corrosion, rust, fire, hurricane, ice storm, acids, water intrusion, temperature changes, attacks from micro-organisms, insects, and woodpeckers; 4) longer service life (over 70-80 years); 5) lower installation, operation and maintenance costs; 6) non-conductivity; 7) reduced magnetic, acoustic and infrared (IR) interferences, 8) design flexibility including ease of modular construction, and 9) consistent batch-to-batch performance.

### 7.1 FRP Composites in Chemical Environmental Applications

The advantages of FRPs in terms of both the chemical and corrosion resistances over conventional construction materials were recognized since the initial development of FRPs following World War II. Their application in chemical process equipment dates back to early 1950s when the chemical process and pulp bleaching industries began using FRPs to replace expensive materials such as alloys and rubber lined steel (Kelley and Schneider, 2008). Currently, FRP composites are widely used in chemical industries, such as tanks, ducts, pipes, hoods, pumps, fans, grating, a range of other equipment for chemical processing, pulp and paper, oil and gas, water and wastewater treatment (ACMA, 2011). As per 2017 American Composites Manufacturers Association's (ACMA) data, the above applications represent 12% of total FRP composites shipments in the United States of America.

### 7.2 Underground Storage Tank

Among the success stories of FRP applications is the underground storage tank (UST) for petroleum products since its application started in late 1950s and most of the USTs are functioning well. FRP USTs came into use in the 1950s. These were made of glass fibers and isophthalic polyester resin and were proven to be a highly-engineered. A lengthy process of third-party validation and acceptance by major owners took place in the 1970s (Dorris, 2008). FRP UST designs were optimized in the late 1980s for cost-effectiveness. In the 1980s, epoxy vinyl ester resins were introduced to further increase the service life of FRP via improved chemical resistance and toughness.

USTs are regulated in the United States to prevent the release of petroleum products, contaminating groundwater. The present tanks were constructed as double or triple walled tanks – first introduced in 1984 – to catch leaks from the inner tanks and to give an interstitial space to accommodate leak detection sensors. Piping was also replaced with FRP composite pipelines of multiple-wall construction. As per the US Environmental Protection Agency (EPA) report released in March 2012, the UST program had discarded 1,762,249 steel based tanks and was regulating 587,517 active FRP USTs at approximately 212,000 sites across the country in 2011 (EPA, 2012).



*Before burial, May 15, 1963*                      *After burial, May 11, 1988*  
 Figure 7.1 The first generation FRP tank (courtesy of Al Dorris of Xerxes Corporation)

The primary methods of manufacturing FRP USTs are chopped glass spray-up, rotating mandrel laydown, and filament winding (McConnell, 2007). The FRP UST models have evolved over the years, as new requirements were identified, from single wall, to double wall, to triple wall construction. The first FRP tank shown in Figure 7.1 is a single-wall UST with a capacity of 6,000 gallon and an 8-foot diameter. Since then, changes in the UST design and construction include: 1) tank sizes are significantly larger, 8-10 ft diameter by 60-80 ft long, up to an order of 50,000 gallons; 2) majority of FRP USTs have double wall construction, ranging in wall thickness from 0.25-1.0 inch, including integral ribs; 3) resin formulations have been improved so FRP USTs can contain aggressive fuels such as ethanol; and 4) tanks now incorporate leak detection systems and containment sumps (McConnell, 2007). Typically, a double wall, multi-compartment FRP UST with a 10-ft diameter and 20,000 gallon capacity weighs about 8000 lbs, which makes it easy to handle and install these tanks underground. Currently these FRP USTs have extensive applications beyond gas stations. Many other chemical industries have been using these tanks to store and transport chemicals (Wood, 2011). The water and wastewater markets are also recognizing the merits of factory-manufactured FRP tanks that meet high performance standards for containment and longevity (LeGault, 2011).

### 7.3 FRP Rebars for Bridge Applications

Another outstanding example is FRP re-bar in lieu of steel rebar in highly corrosive environments (Malnati, 2011). Concrete is a very strong material in compression, but relatively weak in tension. To compensate for this imbalance, steel reinforcing bar is embedded into concrete to carry the tensile loads. However, steel inherently corrodes (an electrochemical reaction) under salt exposure, leading to rusting. As rust takes up a greater volume than steel, rust causes severe internal pressure on the surrounding concrete, leading to cracking, spalling, and ultimately, concrete failure in tension due to rust induce hoop stress. This is extremely serious when concrete is exposed to salt water, as in bridges where salt is applied to roadways in winter, or in marine applications.

FRP rebar appears to be the best solution to tackle this problem and offers a number of benefits to the construction of our nation’s infrastructure including bridges, highways, and buildings. It is lightweight (1/4th weight of steel), strong (about twice strength of steel), impervious to chloride ion and chemical attack, free of corrosion, transparent to magnetic fields and radio frequencies,

and nonconductive for electrical and thermal loads. FRP rebars are commercially available on the market and they are mostly made from unidirectional glass fiber reinforced thermosetting resins.



*Figure 7.2 McKinleyville Bridge with Concrete Deck Reinforced with FRP Rebars, Brooke County, WV, Built in 1996*

FRP rebar was first used in 1987 for a hospital building, but it was after nine years of research when the first vehicular bridge, McKinleyville Bridge, was built in the United States to use FRP rebars in a concrete deck (Figure 7.2). McKinleyville Bridge is located in Brooke County, the northern panhandle of West Virginia. It is a 180 feet long, 3 span, continuous integral abutment bridge accommodating two lanes of traffic. McKinleyville Bridge deck with FRP rebars has been in service for 21 years.

#### **7.4 Pavement**

The nation's first continuously reinforced concrete pavement (CRCP) test section with GFRP rebars, along with steel rebar-CRCP test segment for comparison was completed in 2007 (Figure 7.3). These test segments are located on Route 9 in Martinsburg, in the northeastern corner of West Virginia and are being studied for their performance. Field studies show that GFRP rebar offers a low life-cycle cost option for reinforcement in concrete pavements (Chen, 2008). It is anticipated that FRP rebar reinforced pavements will offer many years of additional service life as compared to steel rebar reinforced pavements. There have been many other successful field implementations, in particular using GFRP rebars in bridge deck applications in WV and many other states (FHWA, 2001; Gremel, 2007).



Figure 7.3 Pavement with FRP Rebar, WV Route 9, Martinsburg, WV (Chen et al, 2008)

### 7.5 FRP Composite Deckhouse

Few materials can survive long service life under aggressive sea-waterfront environment, i.e. onslaught of sea waves, impact from vessels, corrosive salts, sand and pebble erosion, high atmospheric humidity, inter-tidal wetting and drying, sun, marine borers, and immense storm forces. Historically, steel has been the primary structural material used for ships and submarines. Steel structures make up the largest weight group of any ship, typically contributing 35% to 45% of the overall vehicle weight (Beach and Cavallaro, 2002). This fact implies that ship structures have a major influence on the overall characteristics such as displacement, payload, signatures, combat system effectiveness, and life-cycle cost. Currently, 52 percent of a ship's manpower is focused on maintenance because the existing primary construction material- steel- requires constant maintenance to avoid rapid rate of corrosion (Greene, 2003). Costs of spare parts and associated downtime needed to repair corroded structures and hardware severely drives the operational readiness of a ship.

FRP composites offer a potential solution to improve performance, survivability, and reliability of future naval ships and submarines. The U.S. Navy is currently expanding the use of composites in the first of a new family of advanced, multi-mission destroyers, known as the DDG-1000 *Zumwalt* class (LeGault, 2010). The DDG-1000 destroyer is designed to support both sea-based and land-based missions. It features a "tumblehome" wave piercing hull and an upper section deckhouse made predominantly of fiber-reinforced sandwich composites. Both the hull shape and composite deckhouse are intended to reduce the ship's radar footprint.

The all-composite deckhouse superstructure of DDG-1000 is illustrated in Figure 7.4. It is approximately 130 ft long by 60 ft wide by 40 ft high (39.6m by 18.3m by 12.2m), divided into four levels, and is made of balsa-cored glass and/or carbon/vinyl ester sandwich panels (LeGault, 2010). Each superstructure will use approximately 200,000 square feet of flat composite sandwich panels. The all-composite superstructure not only reduces infrared and radar signatures but also reduces topside weight and total ship tonnage, and lowers construction and maintenance costs.





Figure 7.4 DDG-1000 Zumwalt: Stealth Warship (LeGault, 2010)

A sandwich panel can be defined as a three layer construction, i.e. two thin face sheets (skin) and a thick core (Marshall, 1998). The skin is thin and stiff with high strength, while the core is thick and lightweight. A good sandwich construction requires the core to be strongly bonded to the skin so that the core can transfer loads from one face sheet to another; thus, the core and skins will act in unison offering greater stiffness than the face sheets alone. Typically, the thickness ratio of core to skin of a composite is in the range of 10 to 20.

## 7.6 Cold Water Pipe for Ocean Thermal Energy Conversion (OTEC)

In the last decade, the U.S. Department of Energy (DOE) and Lockheed Martin have been collaborating to develop innovative technologies to enable ocean thermal energy power generation (PRNewswire, 2008). Ocean Thermal Energy Conversion (OTEC) uses the ocean's thermal gradient to drive a heat engine (Figure 7.5). Since the ocean's temperature difference is relatively small, large volumes of seawater must be used to generate commercial levels of power. The fabrication and installation of large diameter cold water pipe (CWP) that reaches depths of thousands of feet (~3000') represents one of the largest technical challenges to successfully installing and operating an offshore OTEC system. Figure 7.5 shows a section of 4m (13ft) diameter FRP CWP at the Lockheed Martin facility. The goal is to manufacture a 10m (33ft) diameter pipe that will reach depths downwards of 1000m (3300 ft) in the bottom of the ocean (Miller, 2011). On this project, WVU researchers provide technical consultations and conducted testing and evaluation of composite materials and FRP CWP sections with emphasis on FRP durability and service-life prediction in a seawater environment (Dittenber and Hota, 2010).



Figure 7.5 Ocean Thermal Energy Conversion Cold Water Pipe (Miller, 2011)

## 7.7 FRP Composites in Coal-Fired Plants

More than half of electricity in the United States is generated from coal. Environmental concerns and increasing demand for energy have created a situation where flue gas generated by coal-fired power plants, old or new, needs to be cleaned before being rejected into the atmosphere. Early in the 1970's, the U.S. government's regulation of stack emissions from coal-fired plants led to the deployment of flue gas scrubber systems that remove sulfur dioxide and mercury from the flue gas produced when coal is burned (Figure 7.6). These flue gas scrubber systems require corrosion resistant chimney liners to resist corrosive chemicals.



Figure 7.6 No air pollution control devices (left), with air pollution control devices(right)  
(Miller, 2011)

## 7.8 Chimney Liners

FRP composites have been successfully applied as chimney liners and gas ducts in power plants for many years due to their non-corrosive properties, ease of fabrication, and cost effectiveness. Recently, more stringent requirements have led to new greenhouse gas scrubber technologies such as Jet Bubbling Reactors (JBR) and have further expanded the use of FRP composites. FRP composites have proven to be durable both structurally and chemically when used in the flue gas desulfurization (FGD) process of a coal-fired power plant (Southern Company Services, 2002). FRPs are also used in water piping, storage tanks, top ash and fly ash pipe, and cable trays in many coal-fired plants, while more than 70% of new and replacement field erected cooling towers in the



United States are constructed with pultruded FRP structures. FRP composites enable coal-fired power plants to be operated under more environmentally friendly conditions.



*Figure 7.7 Large Diameter FRP Chimney Flue Liner (courtesy of International Chimney); Module liner section (left); connection elbow (right)*



*Figure 7.8 View of Stack Liner Installation inside a Power Plant Chimney (Kelley et al, 2008)*

Again, these applications involve the mass use of FRP composites for large diameter FRP structures. A recently built coal power plant in Springfield, IL has a 440-foot (134-meter) tall concrete chimney with a FRP composite liner that is made of 27 segments that were fabricated using a filament winding method (Lucintel, 2008). Each segment is 13.5 feet tall by 15 feet in diameter. For joining in the field, the segments were aligned to within 0.25-inch (6.35-millimeter) tolerance. After surface preparation, the segments were then bonded together with interior and exterior laminates of 0.375-inch thick fiberglass/resin composite. Figure 7.7 shows a module of FRP liner and connection elbow on an International Chimney worksite near Morgantown, WV, while Figure 7.8 shows a view of stack liners installed inside a concrete power plant chimney (Kelley et al , 2008). International Chimney installed the FRP liner at Fort Martin Power Plant, Maidsville, WV in 2009. The plant has a 60' diameter x 529' high reinforced concrete chimney that took about two rows of 400' tall FRP liners that are 25' in diameter, in addition to an interconnecting elbow.

## 7.9 Cooling Towers

American Electric Power (AEP) is one of the largest electric suppliers in the United States, delivering electricity to more than 5 million customers in 11 states. AEP ranks among the nation's largest generators of electricity, owning more than 38,000 megawatts (MW) of generating capacity in the US, with individual unit ratings ranging from 25 MW to 1300 MW. There are a total of 15 hyperbolic and 30 mechanical draft cooling towers in the AEP system. These towers utilize a cross-flow or counter-flow thermal transfer design, and almost all of the cross-flow towers are treated wood structures. AEP started using pultruded glass fiber reinforced (GFRP) composite structures in cooling towers in 2008. AEP replaced four cross-flow mechanical draft towers during a period from 2008 through May 2010, and a counter-flow mechanical draft tower was built for a new unit in 2009. All five of these new towers were constructed using GFRP structures. They are the first batch of in-service FRP composite cooling towers on the AEP system (Cashner, 2011).

AEP engineering team has been working on converting a hyperbolic tower structure from a cross-flow to a counter-flow design as part of Cardinal Plant Unit 3 FGD Project that is owned by Buckeye Power Inc. (BPI). The cold water basin is roughly 385 ft in diameter with the bottom of the concrete shell measuring 262 ft in diameter. Figure 7.9 shows a general view of the tower. The heat transfer area, distribution pipes and drift eliminators are located about 35 ft above the cold water basin and are supported by a structure composed of pultruded glass fiber reinforced vinyl ester columns. The columns measure 5.2 inches square, 3/8 inch thick, and were supplied in full lengths (e.g. no splices). There are roughly 464 columns which are laid out on a 12 ft by 12 ft grid.

FRP composites have become the structural material of choice in industrial cooling towers in view of their superior performance in hostile environments (such as high temperature, wet, corrosive, abrasive, and sustained loading) and other beneficial properties. The design flexibility of FRPs has allowed new types of cooling tower to be developed which are more efficient and cost effective than previous designs with conventional materials. The modular construction systems provide structures of high integrity that can be rapidly installed. The desirable environmental properties of FRP composites also aid compliance to the increasingly stringent legislation.



*Figure 7.9 Buckeye Power Inc. Cardinal Plant Unit 3 FGD Project, Brilliant, OH*

## 7.10 Utility Poles

Utility companies rely on transmission and distribution poles (Figure 7.10) to connect to end users. Currently, there are 130 million utility poles in-service in the United States, with about 97% of them being creosote treated wood poles, less than 2% steel poles and less than 1% composite poles. More than 70% of the utility poles in use are distribution poles in class 4 or class 5 ranging to 40 ft or less in height. Both new installation and replacement markets are about \$4 billion per year (Hiel, 2001).

Wood poles require treatment with environmentally unfriendly toxic preservatives (e.g. creosote, copper chromium arsenate (CCA), penta-chloro-phenol) to resist rot, decay, etc. in order to yield a service life of about 30-35 years. However, these preservatives have been found to be hazardous to humans through leaching to the surrounding soil and water. This led to petitions for the EPA to ban the use of CCA, Penta and Creosote (Feldman and Shistar, 1997).

Utility companies are searching for alternatives to treatii wood poles. FRP poles, which represent one of three alternatives along with steel poles and concrete poles, are beginning to penetrate into both the distribution and the transmission pole markets. FRP poles have advantages such as non-conductive and non-corrosive properties over steel poles, and lighter weight, easier installation and better ductility over prestressed concrete poles. Thus, FRP poles have been receiving greater attention from electrical utility and telecommunication companies. This is especially true now because mass production of FRP poles in a more cost effective manner is made possible in order to receive a greater market share, other than niche applications beyond the mountainous terrain or corrosive soils.



*Figure 7.10 FRP Utility Poles (courtesy of Duratel)*

### **7.11 Modular Track Panels**

FRP offers lightweight, high strength, corrosion resistance, humidity resistance, impact resistance, non-sparking, long-term durability and other advantages that are essential for mining applications (Richter, 1999; Tusing, 2003). Many pultruded shapes have already found a wide range of applications in mining facilities, such as handrails, walkways, platforms, caged ladders, non-slip decking and grating.

West Virginia is the second largest coal-producing state in the United States and has over 50 coal mines in production. Mine cars often derail (two or three times daily) in coal mines causing fatal injuries, fires initiated from sparks during derailment, and costly downtimes. To improve coal mining productivity and safety of miners during transportation, WVU-CFC researched GFRP modular track panels for the mining environment. The GFRP modular track panels were comprised of two box beams bonded together with epoxy resin (Figure 7.11). The modular track panels were tested for bending behavior and load sharing characteristics, between track modules and also between rails. Tests on the panels included static and fatigue loading at discrete locations to determine the response of the beams in a simulated mine foundation. Static tests of the modular panels included both vertical and horizontal loading. Fatigue tests were used to determine the change in stiffness of the modules. The study indicated that the FRP panels would distribute load more efficiently, possess good fatigue performance, and be able to sufficiently sustain the loading. FRP panels are well-suited for field applications and the lightweight of FRP panels would allow the miners to install these panels at ease within the mine. FRP panels would alleviate the derailment and other structural problems (Tusing, 2003).



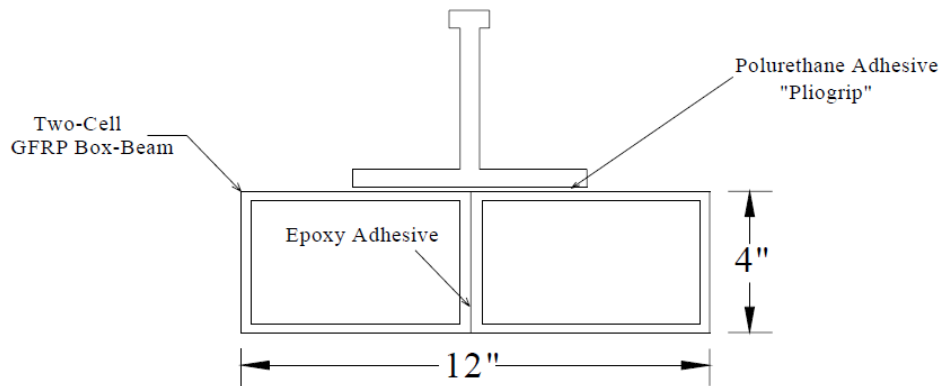


Figure 7.11 Cross-Section of GFRP Track Panel and Test Specimen (Tusing, 2003)

## 7.12 Geosynthetics

Zijin Mining group is a leading gold, copper and non-ferrous metals producer and refiner in China with gold output of 69 tons in 2010. In July 2010 two leaks of waste acid copper solution at the Zijinshan Gold and Copper Mine polluted the Ting River in Fujian province and poisoned hundreds of tons of fish. The waste acid was found to have leaked from the cracking of a GSE high-density polyethylene geomembrane liner. The company believed that the cracking was caused by a shearing force created by the accumulation of water beneath the liner. Again in September 2010, there was a deadly tailing dam collapse at its Yinyan Tin Mine that killed 4 people. The accident was later attributed to a landslide triggered by heavy rains from Typhoon Fanapi. The above accidents have alerted engineers at Zijin Mining College of Fuzhou University, Fujian, China, to re-evaluate the material requirements under specific loadings.

Zijin engineers reached out to WVU-CFC researchers for possible collaboration. For example, Zijin engineers are looking into the potential use of lightweight, high strength, corrosion resistant, durable FRP composite materials for construction of new dams or strengthening of existing dams. WVU researchers are proposing to use geosynthetics as soil reinforcements to construct a tailing dam as illustrated in Figure 15 (Wu, 1994; Koerner, 2012). Geosynthetics are available in a wide range of forms and materials, including geotextiles, geogrids, geomembranes, geofoam, geocells, or combination of the above. Each type of geosynthetic has at least one of the following functions: 1) separation, 2) reinforcement, 3) filtration, 4) drainage, and 5) containment (Wikipedia). The

tailing dam requires being strong but still allows for drainage without soil loss. The geosynthetic under consideration would be geocells that are made of strips and can be expanded into three-dimensional, stiff honeycombed cellular structures, resulting in a confinement system when infilled with compacted soil. The cellular confinement reduces the lateral movement of soil particles, thereby maintaining compaction, retaining the earth, and protecting the slope. Geogrids offer open, gridlike configurations and as reinforcement materials, play similar roles to those of geocells. In addition geotextiles are flexible, porous woven or knitted synthetic fibers/fabrics and can function as reinforcement or drainage or filtration or separation, while geomembranes are thin, impervious sheets of polymeric material and function as containment. Geomembranes are being extensively used as linings of waste acid copper solution reservoirs in Zijin Mines.

### 7.13 Pipelines

Zijin has over 270 km of various pipelines across the mine, with a typical pipeline diameter of 22 inches. They are typically HDPE pipes of half-inch thickness. FRP pipes are only used when chemical and corrosion resistance is required. Figure 7.12 shows some venting systems made of FRP composites while extensive pipelines are also seen along a tailing dam. WVU-CFC has extensive experience with design, manufacturing, testing, and in-service monitoring of FRP pipelines. Figure 7.13 shows a 16” diameter FRP pipe being tested at WVU-CFC Laboratory.



*Figure 7.12 Extensive Uses of FRP Vessels and Pipelines at Zijin Mining Group, Shanghang, Fujian, China*



*Figure 7.13 A 16" FRP Pipe Being Tested at WVU-CFC Laboratory*

Researchers at WVU-CFC are currently collaborating with Beijing Huade Creation Environmental Protection Equipment Corporation to develop FRP products for mining and environmental applications in China. Huade Corporation serves the coal mine and metal mine industries as well as coal-fired power plants. They manufacture and/or supply coal preparation equipment, fine coal preparation systems, tailing mine surface disposal and backfill treatment equipment, mill circuit clarification/de-slime/dewatering equipment, power plant flue gas desulfurization cyclones and many others. The company has manufacturing capabilities in cast polyurethane, mould-pressed rubber, spray polymer, FRP composites, precise steel structure fabrication, ceramic liner equipment and others. Huade is an associate member of NSF IUCRC Center for Integration of Composites into Infrastructures at WVU.

#### **7.14 Rock Bolting**

The products under consideration by Huade include FRP rock bolt, vessels, pipelines, duct valves and fittings, cooling tower, spiral, safety helmet, electric fan, cable pipe, railing, grating, crane span and others. Rock bolt (Figure 7.14) is widely used in underground mining to provide support to the roof or sides of the cavity. It can be used in any excavation geometry and it is simple and quick to apply, and is relatively inexpensive. The installation can be fully mechanized. The length of the bolts and their spacing can be varied, depending on the reinforcement requirements. However, in aggressive environmental conditions such as in coal mines steel bolts deteriorate in a matter of days rather than years. FRP rock bolt is particularly suitable in harsh chemical and alkaline environments because of its corrosion resistance. It is durable, lightweight, easy to install, non-conductive, dimensionally stable under thermal loading, anti-static rating, and can be cut without the danger of sparks. Currently, four production lines are being installed at the Beijing Huade facilities. On the other hand, spiral (Figure 7.15) is widely used in coal preparation equipment and fine coal washing systems, which is being manufactured based on a hand lay-up method. It is made of FRP composites with wear-resistant coating.





*Figure 7.14 Rock Bolt for Underground Mining (courtesy of Huade)*



*Figure 7.15 Spirals in Coal Preparation Process (courtesy of Huade)*

### **7.15 FRP Composites for Modular Building of Environmental Durability**

Traditional housing focuses on uses of masonry, timber, steel and concrete. FRP composites were initially used for small components, such as windows, canopies, doors, profiles, and other decorative features. The WVU-CFC team has designed, manufactured, and constructed its first innovative FRP building in Weston, West Virginia, in November 1995 (Figure 7.16). This experimental building was the result of a joint research and development effort among the US National Science Foundation, West Virginia Department of Transportation/Division of Highway and WVU-CFC. All multicellular panels were of standard size of 24 inches x 5.5 inches, with a wall thickness of 3/16 in. The cells of the panels contained polymeric insulation. The building is about 40 ft x 21 ft, with an inside height from slab to trusses of 14 ft. The weight of total FRP material used in the construction was approximately 9500 lbs.



*Figure 7.16 Multi-purpose FRP Building, Weston, WV, Nov. 1995 (photos taken on Aug 27, 2009)*



*Figure 7.17 FRP Composite House at Bedford Reinforced Plastics Inc. Facility (2008) (courtesy of Bedford Reinforced Plastics Inc)*

All the components used for this project were installed without the use of mechanical equipment such as a crane because of its lightweight nature. FRP parts were delivered pre-cut, thus speeding up the entire construction process. This building is being used as a multi-purpose facility requiring heat, insulation, electric power and ventilation. A 2009 inspection revealed that the building has been performing excellently for the past 16 years and looks new. The building with maintenance-free interior and exterior walls has demonstrated outstanding chemical and environmental durability. A newer modular unit is shown in Figure 7.17. Currently, the WVU-CFC researchers are developing FRP modular dwellings using natural composites integrated with many green concepts towards future sustainable buildings.

FRP composite houses are now readily available on the markets (CBS, 2009; Stewart, 2011). Such modular FRP houses have the following features: 1) no maintenance (no painting and do not deteriorate from weather, rot, or insect infestation); 2) lower heating and cooling cost (the modular FRP panels have built-in insulations and the dome shape further increases energy efficiency); 3) high structural strength (the curved surface of the panels reduces wind resistance, enabling the house to withstand hurricanes); 4) quick construction (modular design for ease of erection); 5) earthquake resistance (the FRP panels flex instead of breaking); 6) water resistance (completely



sealed from the ground up); 7) portability (a FRP house can be easily disassembled and relocated to a new site). These buildings serve as disaster-resistant shelters, military barracks especially at cold and high altitude locations, school buildings, industrial factory and warehouse buildings, and large dormitory settings for workers in remote locations, greenhouses, etc.

## 7.16 FRP Wraps

The infrastructure in the United States is deteriorating and aging. The constructed facilities are being used far in excess of their original design life and are close to being obsolete; these structures are vital to support the economic, transportation, and societal functions. Therefore, the most attractive alternative would be to extend the physical life of the existing infrastructure in a cost-effective manner. By extending the service life of existing structures, the need to demolish, dispose, and reconstruct existing structures is reduced, leading to lower life cycle cost, as well as minimal energy use and construction waste minimization (Edwards et al, 2009).

FRP retrofitting has been widely used to strengthen civil and military structures as an effective disaster prevention approach or to restore the damaged structures after disasters such as hurricanes and earthquakes. Recently FRP composites have been receiving more attention as a material of choice to strengthen existing structures to continue serving their functions (Mirmiran et al, 2008; Belarbi et al, 2011). In the United States, many of the existing highway or railroad bridges have either reached the end of their service life or require rehabilitation to continue in service.

### 7.16.1 STRENGTHENING OF CONCRETE STRUCTURES

WVU-CFC has been actively involved with advanced FRP wrapping technology development, including specific design methods, material selection, field installation procedures, performance requirements and subsequent inspection techniques since 1988 (FHWA, 2001). The rehabilitation of cracked reinforced concrete beams of the floor of a San Antonio, TX library building, using Tonen Carbon Tow Sheet was completed in the year 1993 after testing and evaluating the steel reinforced concrete beams stiffened with Tonen Carbon Tow Sheet at the WVU-CFC laboratory. The creep behaviour of such stiffened beams and the long term performance of bond between the concrete surface and Tow Sheet were also evaluated before field implementation. Figure 7.18 shows the details of rehabilitation of T shaped reinforced concrete superstructure girder of Muddy Creek Bridge, Preston County, WV using Carbon FRP Wraps.



(a)

(b)



(c)

(d)

*Figure 7.18 Rehabilitation of T-section Reinforced Concrete Superstructure using Carbon FRP Wraps, Muddy Creek Bridge, Preston County, WV (October 2000). (a) Blue primer coating and wrap application, (b) Pressing of wrap for full bond with concrete, (c) Carbon wrapped concrete beam, (d) Gray paint application.*

### 7.16.2 STRENGTHENING OF TIMBER STRUCTURES

WVU-CFC's research and development on repair and rehabilitation of wood railroad bridges using FRP composites began in 1999. The laboratory testing revealed that compression test of previously failed creosote treated railroad stringer, after wrapping, regained 80% of strength using GFRP wraps (Petro et al, 2002). The field work was conducted on two railroad bridges on South Branch Valley Railroad (SBVR) lines in Moorefield, WV in summer 2000. Field static and dynamic testing (5 mph, 10 mph, 15 mph) using GE 80 Ton locomotive supplied by SBVR was conducted before and after wraps. Infrared Thermography (IRT) measurements were also carried out to assess the bond status of rehabilitated members. The results turned out to be a success and the rehabilitated members have been performing satisfactorily for the past 12 years. Figure 7.19 shows a group of photos showing how damaged piles of 11 timber railroad bridges on SBVR lines in Moorefield, WV were rapidly rehabilitated and restored in-situ without affecting the rail traffic by using GFRP composites in summer 2010. These timber bridges consisted of total span lengths varying from 75 ft. to 1200 ft. with timber pile bents spaced 15-20 ft apart. The deteriorated piles were cracked, heart-rotted, and damaged to varying lengths. This rapid rehabilitation technique can be used on various other structural members including steel and reinforced concrete members in a cost effective manner to extend the service life of structural systems. West Virginia Department of Transportation, Division of Highways is embarking on rehabilitating 400-500 concrete bridges using FRP composite wraps in the next 5 years (by 2017) because of their cost effectiveness, minimal user inconveniences, and proven success.



*Figure 7.19 Retrofitting of Railroad Bridges Using FRP Wraps without Interrupting Railroad Service, SBVR, Moorefield, WV (July 2010)*



## 8 HYDRAULIC STRUCTURAL APPLICATIONS AND REPAIR METHODS

The hydraulic structural applications involve the construction and rehabilitation of facilities such as locks, dams, levees and pump stations. These projects are comprised of various elements such as valves, gates, walls, piling, mooring facilities, etc. These elements can be broken into four major categories for possible applications. These are:

**Structural Elements/Systems:** Fabricated from various composite shapes to erect a larger composite structure, such as wicket gates, miter gates and valves. These gates and valves would be operable under large loads, submersion and extreme climate and environmental conditions.

**Hybrid Structural Elements/Systems:** Structural Elements/Systems, but would be a combination of traditional materials and composite materials.

**Coatings:** sprayed or brush-painted to steel structures to inhibit corrosion.

**Miscellaneous Items:** railings, gratings, ladders, etc. These items are not subject to extreme loadings but are subject to submersion and vagaries climate and environmental conditions.

The GFRP composite system use for hydraulic structures is leading to longer service life, lower initial costs and reduced life-cycle costs with enhanced structural performance (Vijay et al 2016, Liang et al 2016). It is extremely important to note that proper selection of constituent materials (resins, fibers, fillers) for a tailor-made composite structure is essential to meet certain performance requirements (Netherlands 2015, Sahirman et al 2011). It is noted that some of the inherent limitations of GFRP composites (lowest shear strength and stiffness, complexity in tailor-making final systems, etc.) have been highlighted as well so that readers can better appreciate the advantages and limitations of composite products and systems especially applicable to hydraulic structures. Recent advances in resins with underwater curing capabilities resulted in rehabilitation of underwater structures, especially concrete structures. These are reviewed in brief to make readers aware of novel applications of FRP composites.

This chapter reviews development of wide range of hydraulic structures made of FRP products, and their field implementation.

### 8.1 Miter Blocks

The miter blocks (Figure 8.1) are inserted at the sides of each of the two miter gate leaves which come together when the gates are in closed position. These blocks provide flexibility due to low modulus of elasticity and do help minimize water leaks from the upstream side of a river or canal, after self-adjustments over 12 months of initial service period. Details can be found in Figure 8.2. These blocks are designed with high glass fiber content (~55% by volume) with vinyl ester binder (~33%), and fillers and small quantities of other additives (~12%). As per USACE requirements, the miter block was designed, tested and evaluated for a maximum compressive stress of 1400 psi under closed conditions of miter gates. In addition, the block is designed and tested for 12,000 cycles of openings and closings, with a potential life span of 30 years (Soti et al 2016).



Figure 8.1 Miter Gate (left); Miter Block (right)



Figure 8.2 Single GFRP Block (4"×2.5") with Max. Failure Load >224 (kips)

These blocks were installed in Washington Lake Lock and Dam system in spring 2015. There were a few “field-drilled” bolt holes which were sealed with waterproof sealant for longer service life. However, sealants may not provide permanent protection from moisture ingress into the core of a miter block over service life of 50+ years. Recent field inspection (2017) of these miter blocks revealed good field performance and also good durability with no visible distress.

## 8.2 Underwater Wrapping of Concrete Ports

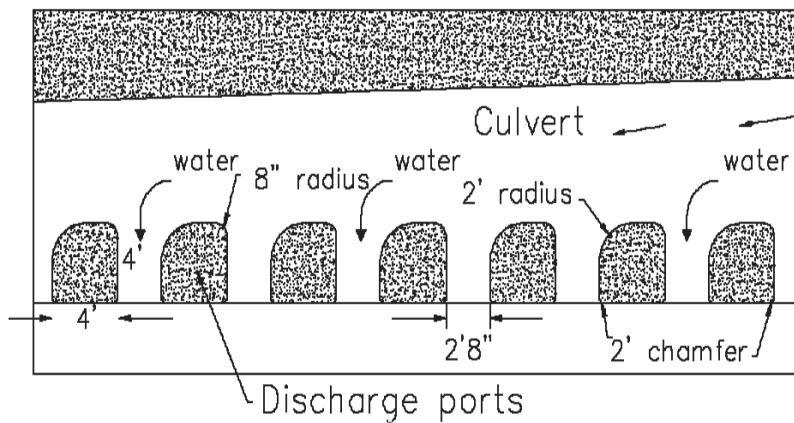


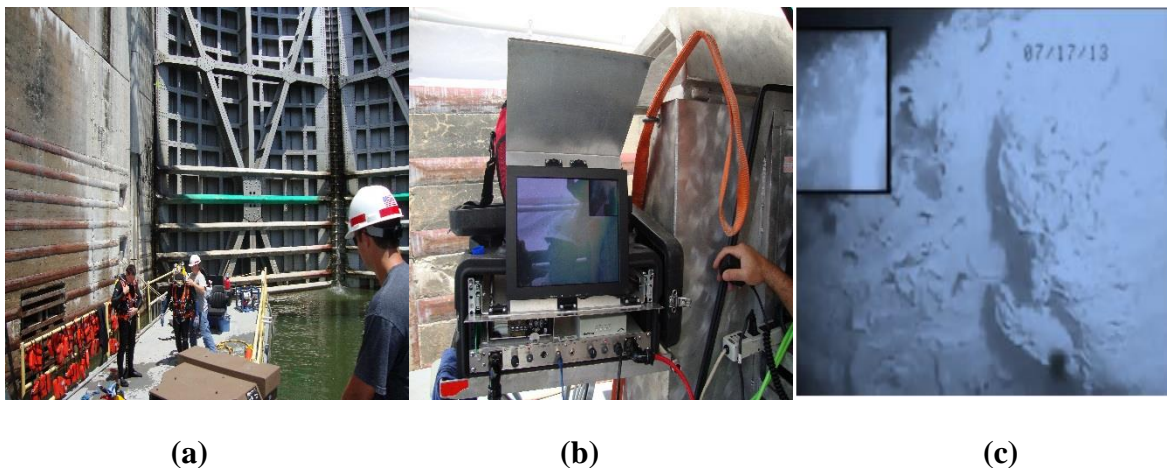
Figure 8.3 View of Discharge Ports at Chickamauga Lock and Dam, TN



To arrest concrete section loss in discharge ports as shown in Figure 8.3, a prepreg glass-resin system with underwater curable resin was selected. The field installation was selected by USACE as the main section of Chickamauga Lock, in Tennessee, USA. The main reason for selecting Chickamauga Lock and Dam was the loss of concrete which is attributed primarily to alkali-silica reaction of concrete and rapid loss of concrete mass to the fast flowing waters around the ports. In addition, high velocity water discharging through ports aggravated the erosion of concrete ports.

The prepreg system (Aquawrap) selected to rehab the ports was available in sealed foil pouches. “BP-4” primer was used for better bond between concrete and Aqua wrap (Vijay et al 2014, Vijay et al 2016). This primer mixed with microfibers performed well to resist cracking and chipping of concrete ports and provided better bond between concrete substrate and the glass wrap. After conducting several compression tests of submerged concrete cylinders with multiple layers of Aqua wrap, the WVU-CFC team concluded that the average under water concrete cylinder strength increased by about 45% to 52% per layer, for ~2ksi concrete.

The Chickamauga Lock and Dam discharge ports were wrapped with 2 layers of glass fabric in mid-2013. This operation included surface preparation of concrete ports i.e., power wash with water jets, primer application and hand wrapping by a team of divers. Figure 8.4 provides additional details including underwater primer application. This site was inspected in 2015 and 2016 and the wrap did not exhibit any deterioration since the initial installation in year 2013.



*Figure 8.4 (a) Aqua Wrap; (b) Onboard Audio, Video, and Depth Monitoring; (c) Under Water Hand Application of Primer on Discharge Ports*

### 8.3 Wicket Gates



*Figure 8.5 Deteriorated Wood Wicket Gate Pulled from Service*

A conventional wicket gate as manufactured in the United States of America with white oak logs shows extreme decay of wood, as shown in Figure 8.5. A GFRP composite wicket gate that was manufactured in cooperation with Composites One Inc. is shown in Figure 8.6. The composite wicket gate was tested in the Major Units laboratory, WVU, Morgantown, USA for structural integrity, IE, bending, shear, fatigue and push-out. Two of the three wicket gates installed over Mississippi river were bonded with ultra-high molecular weight polyethylene to prevent gouging from floating debris (Vijay et al 2016).



*Figure 8.6 Composite Wicket Gate (Left) and Prototype Gate under Bending*

Additional wicket gates were manufactured and installed at Lock and Dam #52 near Rock Island, IL USA in summer 2015. The installed product is shown in Figure 8.7.

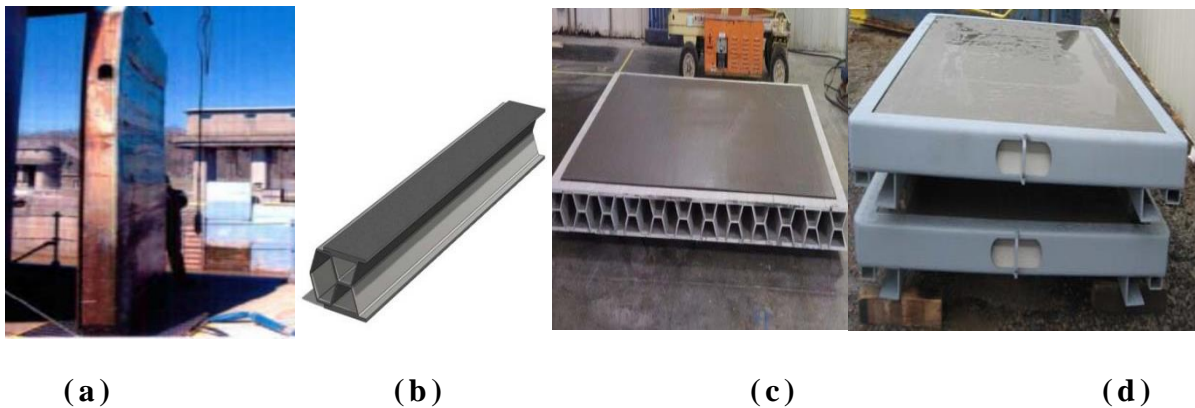


*Figure 8.7 Composite Wicket Gates in Service*

The detailed design procedure is shown in Chapter 9.3.

#### 8.4 Recess Panels

Recess panels protect the recess areas in the lock chamber from vehicular impacts, so that damage can be prevented to lock walls. In case of inoperable conditions of miter gates, emergency gates would be opened wherein recess panels protect the recess areas in the lock walls. The additional details are shown in Figure 8.8 and Chapter 9.2 (Liang & GangaRao 2016).



*Figure 8.8 (a) Steel Recess Panel; (b) FRP SuperDeck Component; (c) SuperDeck with Polyuria Coating; (d) Assembly with Steel Frame*

#### 8.5 Rehab of Corroded Steel Piles

East Lynn Lake Bridge, WV, USA was built in 1969 as a conventional 2-lane concrete deck with wide-flange steel column bents. Severe corrosion of steel due to upstream underground mine water flowing in to the East Lynn Lake resulted in corrosion of steel bents and reduced the load rating of the bridge from 15 tons to 6 tons. One of the traffic lanes of the bridge was closed for several years and eventually the bridge was made inaccessible to traffic before undergoing exhaustive rehabilitation. The additional details are shown in Figure 8.9, Figure 8.10 and Chapter 9.5.





*Figure 8.9 East Lynn Bridge Rusted and Scoured at Mudline*



*Figure 8.10 Rehabilitation Steps of Steel Piles with FRP Composites*

## 8.6 Lock Doors and Stop Logs

Netherlands, under the leadership of ‘Infra Core’ has taken a major lead in constructing many GFRP lock doors. Some of the lock doors were built in years 1999 and 2002 with each of the two doors having dimensions of about 10’ in width and 20’ in height. The installed GFRP gates can be seen in Figure 8.11, and are functioning well with no corrosion related degradation (Netherlands 2015, World’s Biggest Miter Gates).

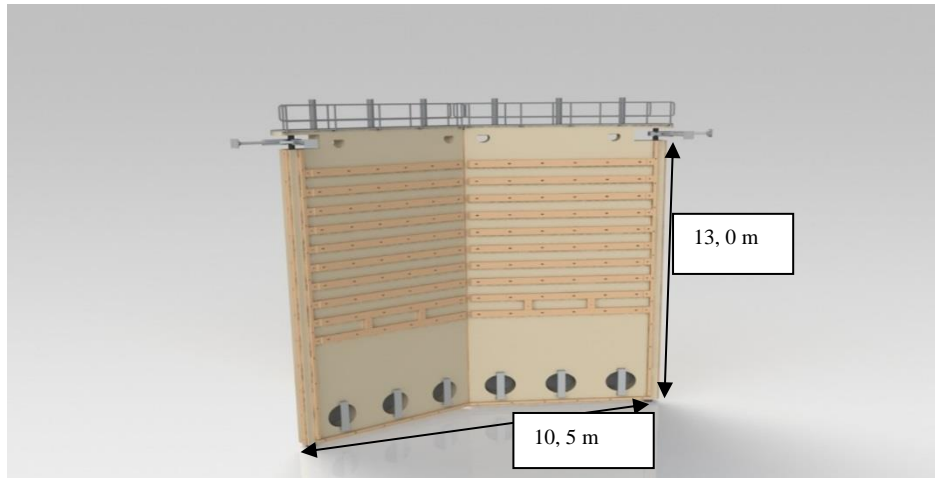


*Figure 8.11 Werkendam FRP Lock Doors*



*Figure 8.12 Eric Ter Apel Lock Doors*

These doors were manufactured using vacuum assisted resin transfer molding (VARTM) process with low void content. Later, “Infra Core Inc.” manufactured lock doors of larger dimensions, IE, approximately 11.5' in width and installed at Erica Ter Apel power plant in year 2011-2012. The principle owner is ‘Provinces Croningen & Drente’. Again, these lock doors are functioning well since 2012 and the quality of product after 5+ years of service can be seen in Figure 8.12. “Infra Core Inc.” extended their expertise in polymer composites by building the largest FRP lock doors in the Wilhelminakanaal in Tilburg in 2014. The size of the world’s largest FRP doors is approximately 17.5' in width and 43' in height. The schematic of Wilhelminakanaal is shown in Figure 8.13 was provided to CFC as courtesy of “Infra Core Inc.”. Stop logs provide obstruction to water flow. These can be made of glass fiber polymer composites (GFRP) shells wrapped over wooden cores. Also, they can be made of hollow core composite blocks of 12" to 18" depth with 1/2" to 3/4" wall thickness. Stop logs are being designed by the Constructed Facilities Center, WVU, USA.

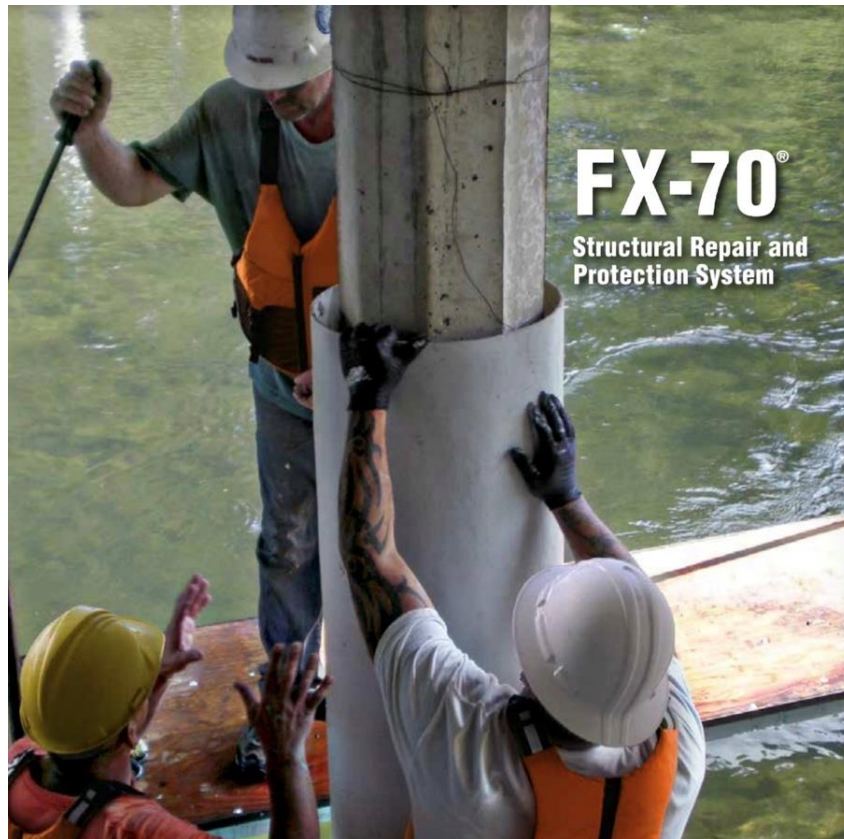


*Figure 8.13 2014 - World's Largest FRP Lock Doors in the Wilhelminakanaal*

These structures have been installed since 1999 and performing well which implies that their durability is excellent. The initial cost of GFRP structures is mostly lower than those made of conventional construction materials. Also, durability of properly designed GFRP hydraulic structures is superior to those from steel, concrete or timber. Recent advances have shown that GFRP can be employed for rehabilitation of structure built from conventional materials with low rehabilitation costs.



## 8.7 FX-70 Structural repair and protection system

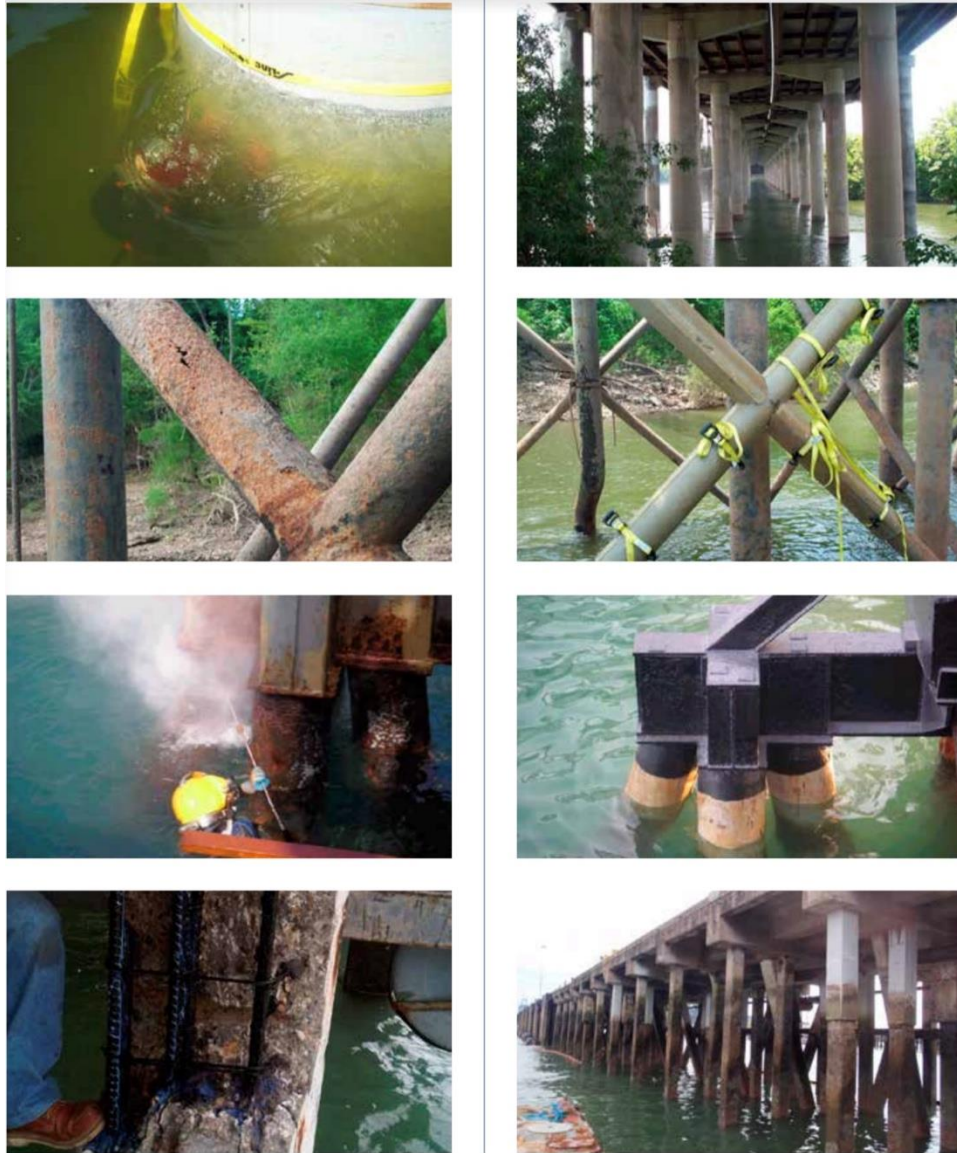


*Figure 8.14 FX-70 Structural Repair And Protection System*

In 1970, the FX-70® Structural Repair and Protection System made in-place repair of damaged marine piles possible and practical, an industry first. By eliminating the need to dewater the repair site or take the structure out of service, FX-70 dramatically reduces the overall cost of restoring the damaged structure. A corrosion-resistant system, being implemented both in the aged and new structures does extend service life with the FX-70 system. Many of the first repairs using FX-70 in 1971 are still in service today.

Advantages of structural repairs through FRP composites include: Repair the damage area in-place, no need to dewater or take structure out of service; High-strength materials bond well to various substrate materials; Corrosion-free system prevents deterioration, weathering and erosion; Accommodates piles of various shape and size; System is low-maintenance following repair; Safe for use in marine-life habitats and UV-resistant.

Over 300 concrete piles of Chesapeake Bay Bridge were repaired and protected. The dimension of Jacket is 55 in. (1.4 m) diameter, 1/8 in. (3 mm) thick, and 8 ft. (2.4 m) length, with a 1/2 in. (13 mm) annular void. The jackets were placed in splash zone and filled with FX-70®-6MP multi-purpose Marine Epoxy Grout. No dewatering was required.



*Figure 8.15 Before and after foundations repairs of Chesapeake Bay Bridge-Raymond Hollow  
(www.strongtie.com)*

## **8.8 Composite Dolphin**

The dolphins at Rosario port, used an innovative technique based on composite materials. The remodeling work of Rosario port would allow the berthing of large cruise ships or two smaller boats using caissons made of composite materials that are more resistant and environment-friendly. Pile dolphin solution was based on the assembly of precast composite panels (12m wide\*13.3m height\*84m length of dolphin line with a total of 390m). These composites reduce CO<sub>2</sub> emissions arising from steel construction by 75% and minimize the need to carry out extensive maintenance work, extending their working life. (ACCIONA Construction)



*Figure 8.16 FRP Dolphin (Fuerteventura, Canary Islands-Spain,2014)*

### **8.9 Composite Lighthouse**

Another application of a composite structure is the lighthouse. The new Valencia Lighthouse was designed by Ignacio Pascual, Infrastructure Director of the Valencia Port Authority. ACCIONA built the 32m tall lighthouse (first in the world made from composite materials) and developed composite material in Acciona Infraestructure's R&D center. It replaced the city's old lighthouse.

This five-storey structure, which weighed 19 tons, was formed by eight carbon FRP tubular columns made by pultrusion, and the 5 storeys are made of glass FRP and polyurethane octagonal sandwich panels made by resin infusion. An FRP spiral staircase is placed in the center of the structure, going from its base to its top. To increase the lateral stiffness of the structure, carbon FRP columns are connected along the structure perimeter using horizontal glass FRP pipes forming four octagonal rings. (ACCIONA Construction)



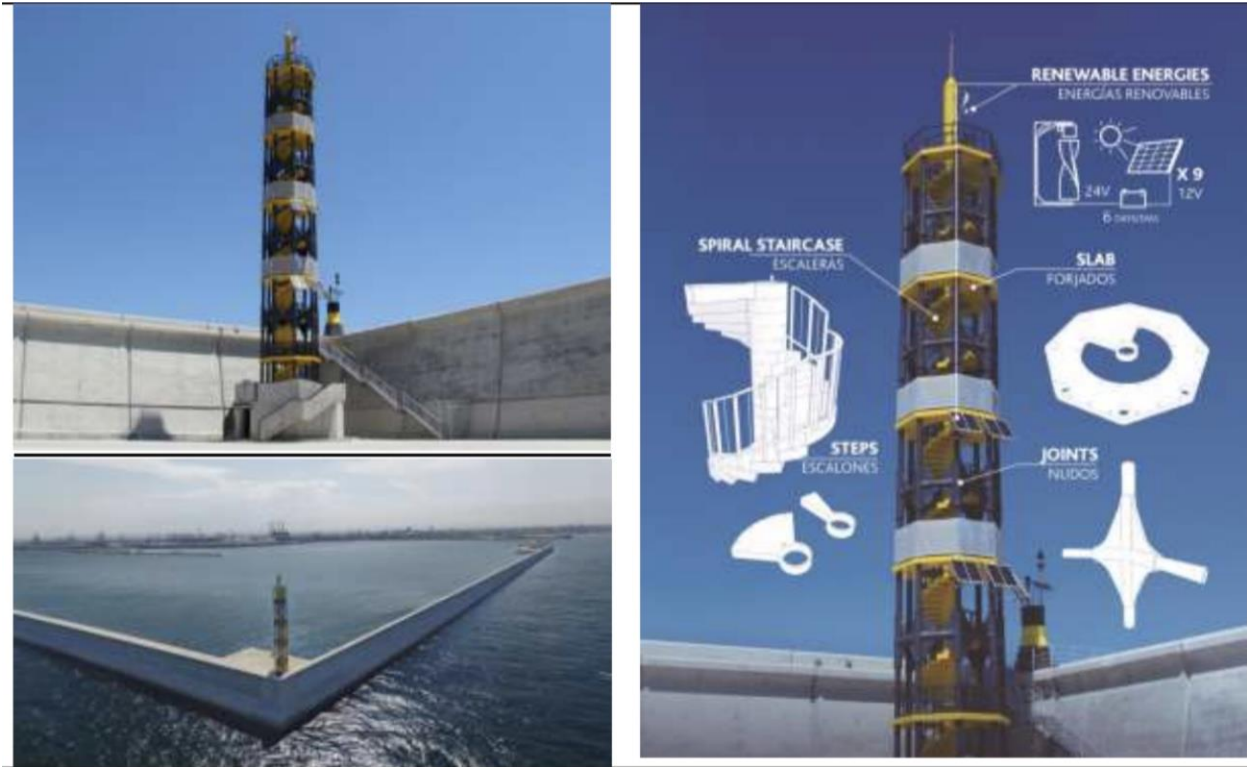


Figure 8.17 FRP lighthouse in the north extension of Valencia Port (Valencia-Spain, 2015)

### 8.10 SuperLoc Fiberglass Reinforced Polymer (FRP) Sheet Piling and Accessories

Creative Pultrusion, Inc (CPI) is the world leader in pultrusion manufacturing. As the world's most innovative leader in the FRP pultrusion industry, over the last two decades, they've developed structural systems that outperform and outlast structures built with traditional materials of construction. CPI has continued to build upon their reputation by offering a complete line of quality composite products to the marine industry, including the SuperLoc® Sheet Pile System. Developed to provide a solution for deteriorated waterfront structures subjected to the harsh marine environment, SuperLoc® is the perfect solution for shoreline protection.

This FRP composite system, is manufactured by the pultrusion process and is designed and manufactured to provide a solution for deteriorated waterfront structures subjected to the harsh marine environment. The patented SuperLoc® product line offers cost effective, long-term and low-maintenance solutions, and has been vetted for two decades as the premier solution for long-term shoreline and asset protection.

SuperLoc® Sheet Piling is manufactured with electrical grade fiberglass and high strength resins. The combination of the advanced resin and high strength glass produces a superior, highly corrosion resistant sheet pile that has been engineered to stand the test of time.

All composite sheet piles are manufactured with electrical grade E-glass reinforcements in the form of unidirectional roving, Continuous Filament Mat (CFM) and stitched fabric mats. The combination of fiber reinforcements has been engineered for optimal bending strength, as well as

superior stiffness. All E-glass reinforcements meet a minimum tensile strength of 290 ksi per ASTM D2343.

CPI manufactures the SuperLoc® sheet piles and accessories in both vinyl ester (VE) and isophthalic polyester (I) resin formulations. Proper resin selection should be based on the environmental aspects of the site conditions including the soil and water pH and chemical exposure.

SuperLoc® is an alternative construction material without many of the performance disadvantages of conventional materials such as aluminum, concrete, steel and wood. SuperLoc® will not corrode, decay, or spall thereby reducing maintenance costs and future replacements. The FRP composite system resists impact, creep, UV and weathering effects better than vinyl (PVC) materials and is easier to install in harder soils than vinyl sheet piling. Typical applications include wave breaks, retaining walls, water control, land stabilization, bridge abutments, erosion control, stay-in-place forms, storm surge/flood protection and containment/cut-off walls.

### **8.11 Composite pilings protect platinum leed site from flooding**

In 2011, Sacramento Municipal Utility District (SMUD) began construction on its East Campus Operations Center, a net zero Platinum LEED® energy site containing a five-story office building, fuel and storage areas, maintenance space, shops and felt parking. Platinum LEED® (Leadership in Energy and Environmental Design) designation was located in a flood risk area and required a flood wall. SMUD and the project's engineers, Bohler Engineering, wanted a versatile solution which was non-corrosive, possessed an extended life cycle and reduced carbon foot print while contributing to the site's durability. They selected CMI'S UltraComposite™ UC 95 profile sheet piling. Installation Contractor Blue Iron, Inc. utilized sheets which were 30 feet in length. A medium weight excavator with a vibratory hammer was responsible for the driving of 100 feet of wall length daily into the rocky and challenging soil at depths of 17 feet with 13 feet exposed for flood protection.

CMI's UltraComposite™ UC 95 profile sheet piling was manufactured in Strongwell's ISO 9001:2008 and ISO 14001:2004 certified manufacturing facility to ensure consistent high quality, design strength, durability, cost and sustainability. By using UC 95, CMI was able to reduce both product and installation costs while generating further interest in the utilization of American-made composite sheet piling. (Application Profile - Strongwell)



*Figure 8.18 CMI'S UltraComposite™ UC 95 profile sheet piling for flood wall*

## 8.12 Composite pilings alter course of erosion

Seabrook Harbor has over 400 years of maritime history and function along the New Hampshire Atlantic coastline. Over time the harbor's economic benefits were slowly being hindered due to erosion and risks associated with increased silt levels from the Blackwater River.

The U.S. Army Corps of Engineers and the National Shore- Line Erosion Control Development and Demonstration Program arrived at a solution which would repair the breach between the shore and sand flats. Water from the river had to be diverted from the town utilizing a cofferdam-like structure on the north side of the harbor.

The walls of the structure were anchored with a galvanized steel tie-back system with 18" rods and connecting turnbuckles on 6' centers and two 10' channels. To drive the UltraComposite™ UC 30 sheets, Reed & Reed Construction used an ICE 216 vibratory hammer hanging from a crane. 160 sheets or 240 feet of bulkhead were completed daily. UltraComposite™ 17' and 27' sheet piling was chosen in the place of steel because hydro-dynamic models were built to measure theoretical solutions and calculations. (Application Profile - Strongwell)



*Figure 8.19 Walls made of UltraComposite™ UC 30 sheets*

## 8.13 Fiberglass structures stand the test of time offshore

In 1986, Strongwell constructed an all-fiberglass well bay deck for 18 wellheads on Shell's Southpass 62A production platform located southeast of the Mississippi Delta in the Gulf of Mexico. The entire 20' x 40' fiberglass structure, which included grating, handrail, stairs, stair treads and superstructure, was fabricated of EXTREN® fiberglass structural shapes and special fiberglass grating.

Initially, fiberglass was selected to replace failed steel structures because of its lightweight and easy installation. It took two men five days to install a steel platform versus two days for fiberglass. Also, fiberglass is less expensive to transport and easier to handle. Fiberglass installation eliminated use of cutting torches and welding, saving downtime and the costs of shutting down well production.

Fiberglass, unlike steel, will not sag and deform due to wear and abuse. After years of service, the DURADEK®/EXTREN® structures are still level and do not have dangerous dips or bumps (common to steel platforms) that cause trip hazards.



Corrosion resistant fiberglass structures are virtually maintenance free, thereby reducing the problems of offshore painting where blasted paint must be carefully recovered in an effort to not pollute the Gulf. (Application Profile - Strongwell)



*Figure 8.20 All-fiberglass well bay deck for 18 wellheads on Shell's Southpass 62A production platform*

#### **8.14 Fiberglass structures used to reclaim beaches**

An innovative beach building and erosion control system was constructed using EXTREN® structural shapes and DURADEK® grating on the Lake Erie shoreline in Ohio.

The patented Martin Beach Builder™ is a new triangular framing system anchored to a precast concrete base. The frame, which is pre-fabricated by Strongwell, is comprised of EXTREN® Series 500 channel, angle, and square tube. EXTREN® plate bonded to DURADEK® grating forms the face of the system.

The Beach Builder™ system, which is partially submerged underwater at various distances from the shore, dissipates wave energy and then captures sand normally washed away by the receding waves. Eventually, the frame is completely covered by sand, which results in the establishment of a maintenance-free, permanent beach.

Strongwell's FRP materials was chosen instead of steel because of their superior corrosion and UV resistance and overall durability. The weight of the FRP also is an advantage over steel. The frames are light enough to be installed quickly using a standard backhoe. (Application Profile - Strongwell)



*Figure 8.21 The Martin Beach Builder™, a new triangular framing system anchored to a precast concrete base*

### **8.15 FRP products aid in the rehabilitation of endangered species**

Manatees are known as the gentle giants of Florida’s waterways. Unfortunately, the population of these peaceful creatures is diminishing because of the serious and often fatal injuries they incur from boat propellers.

Walt Disney’s Epcot Center is responding to the dwindling numbers of manatees by creating a manatee hospital to help rehabilitate the animals. Lifting and lowering platform made from Strongwell’s FRP products is a key component to the manatees’ rehabilitation.

Family Lifeguard, the manufacturer of the platform, worked with Strongwell’s engineering team to design the platform using EXTREN® beams, DURAGRID® T-1800 grating and FIBERBOLT® nuts and studs in the lifting apparatus. The platform is located on the side of a saltwater pool and allows the staff to raise the animals in and out of the water for treatment. Disney chose Strongwell materials for the product because of the loading criteria involved. Herein, Strongwell’s noncorrosive products were the perfect fit. Ease in installation and lightweight properties were added benefits as Family Lifeguard was able to install the platform in only five days. (Application Profile - Strongwell)



*Figure 8.22 FRP lifting and lowering platform made from Strongwell products to rehabilitate the manatees*

### **8.16 FRP materials guard a California pier from corrosion**

The Avila Beach Pier in California has been reconstructed using Strongwell's pultruded fiberglass structural materials. The 1,685-foot public pier was in need of a support system and large stairwell at the end, allowing public access for landing boats and unloading guests.

The pier is constantly exposed to a harsh saltwater environment and is always under attack from the corrosive elements. In fact, parts of the stairwell are entirely submerged in saltwater at all times. Strongwell's FRP support system for the base of the pier consisted of EXTREN® I-beams and channels, replacing the existing galvanized platform which was failing in the salt-water environment. DURADEK® pultruded grating and stair treads and SAFRAIL™ handrail was also installed creating the new walkway. The fiberglass reinforced materials were chosen over traditional building materials because of the superior corrosion resistance and strength that it offers. (Application Profile - Strongwell)



*Figure 8.23 The Avila Beach Pier in California reconstructed using Strongwell's pultruded fiberglass structural materials*

### 8.17 FRP arctic towers project wins top construction award

Strongwell's Fiber Reinforced Polymer (FRP) products were recently used by Wade Perrow Construction, LLC (WPC) for a Seal Observation Facilities Project on St. Paul Island, Alaska. WPC was in need of a low maintenance, high strength material to replace the rotten wooden towers and walkways. These structures were deemed unsafe for the observation of northern fur seals in the corrosive, arctic salt water environment .

WPC found that the corrosion, rot and low temperature resistant qualities of Strongwell's EXTREN® and SAFRAIL™ products proved to be an ideal replacement for the wooden structures and walkways. To ensure that the seals were not disturbed, WPC had to work during the winter months when the seals were not on land. The ease of installation allowed the FRP materials to be quickly assembled even in the midst of extreme sub-zero temperatures and high winds. This led to the project's completion a year ahead of schedule. The FRP products were easy to ship, install and maintain; and available in custom colors. (Application Profile - Strongwell)



*Figure 8.24 FRP arctic towers for a Seal Observation Facilities Project on St. Paul Island, Alaska*

### 8.18 DURADEK cut costs in Olympic pool operation

The Olympic pool in Oklahoma City, Oklahoma, shown in Figure 8.25 was completed in 1989. The "trough gutter covers" of DURADEK® run 168' long x 12" wide on each side of the pool and 75' long x 12" wide at each end of the swimming pool. The adjacent diving pool is 53'4" wide x 66'7" long and the DURADEK® trough gutter covers run the perimeter of this pool also. (A total of over 8,500 square feet of DURADEK® fiberglass grating was used for the gutter covers.)

DURADEK® grating was selected because it is corrosion resistant to chlorine, easy to install and has the strength to withstand people walking on it. The stainless steel could be the alternative but it is too expensive. (Application Profile - Strongwell)





*Figure 8.25 The Olympic pool in Oklahoma City, Oklahoma*

### **8.19 Fiberglass floating docks save high maintenance costs**

Seepage from Snohomish County, Washington landfill mounds is held in containment pits where it is treated with bacteria and agitated until effluent is purified and can be returned to surrounding land. In the past, when it was necessary to service the aerators, landfill management hired a crane to move aerators out of pits and workers went out in canoes to hook cable between the crane and aerators. This process was time consuming, expensive and dangerous to workers.

The solution to this maintenance problem is two “fiberglass floating docks” — one in each seepage pit. Constructed of EXTREN® fiberglass structural shapes and DURAGRID® fiberglass grating and fabricated by Strongwell-Chatfield Division, each 780 square foot horseshoe shaped dock is mounted on a styrofoam float. The aerators are hooked by cables to the dock and workers simply pull the aerators into the work area for service.

The dock must float to accommodate the change in effluent level and be strong enough to withstand the stress of high winds and wave action. The service docks are also used to give workers access to take samples and monitor effluent. The fiberglass docks are resistant to the extremely corrosive effluent and require little maintenance. The floating dock design has eliminated the crane rental costs and made servicing the aerators quicker and easier. (Application Profile - Strongwell)





*Figure 8.26 Fiberglass floating docks in Snohomish County, Washington*

### **8.20 Fiberglass grating stays ship shape longer**

"No Le Hace" is a 74' power boat built by Delta Marine, Seattle, Washington. The boat has made over 40,000 miles since her launching in 1988 in waters from Alaska to Mexico. DURAGRID® T-1800 1" white fiberglass grating manufactured by Strongwell is used by Delta Marine for stair treads and swim steps or platforms. DURAGRID® fiberglass grating is excellent in aggressive marine applications because it has high strength, is resistant to corrosion and UV, and has a tough anti-skid surface.

This pultruded fiberglass grating contains 70% glass fibers and mat. Glass mat results in high impact resistance to prevent chipping when subjected to a blow such as a dropped tool. The highest quality vinyl ester resins are used resulting in resistance to corrosion caused by salt water and other aggressive chemicals. Round silica grit is twice bonded to the surface of the bearing bars. This prevents slipping for the life of the grating and is comfortable to kneel or walk on. (Application Profile - Strongwell)



*Figure 8.27 Fiberglass grating manufactured by Strongwell used by Delta Marine, Seattle, WA.*

### **8.21 DURADEK platforms and catwalks save laguardia millions in maintenance costs**

Skid and corrosion resistant fiberglass catwalks and platforms extend one mile over the bay at LaGuardia Airport. The fiberglass structures have replaced timber and saved the Port Authority of New York and New Jersey \$16.5 million in maintenance costs. The non-conductive fiberglass improves worker safety and does not interfere with the mounted radar transmissions of the aircraft instrument landing systems (ILS).

The fiberglass is immune to harsh salt water environment, bird droppings and jet exhaust. Further savings were realized when the Port Authority employed its own engineers and construction personnel to design and install the fiberglass.

The grating is mounted on EXTREN® fiberglass wide flange beams that are bolted atop the wooden piers. Fiberglass wide flange beams are also used as cable supports mounted on the sides of the catwalks. The wooden walkways and catwalks previously used required six full-time workers to maintain them. However, since 1990 when the fiberglass installation began (in phases), maintenance and repair has not been required on the walkways.

The grating was pultruded in a special brown color to blend into the environment at night so aircraft would not mistake the fiberglass walkway for runways. (Application Profile - Strongwell)



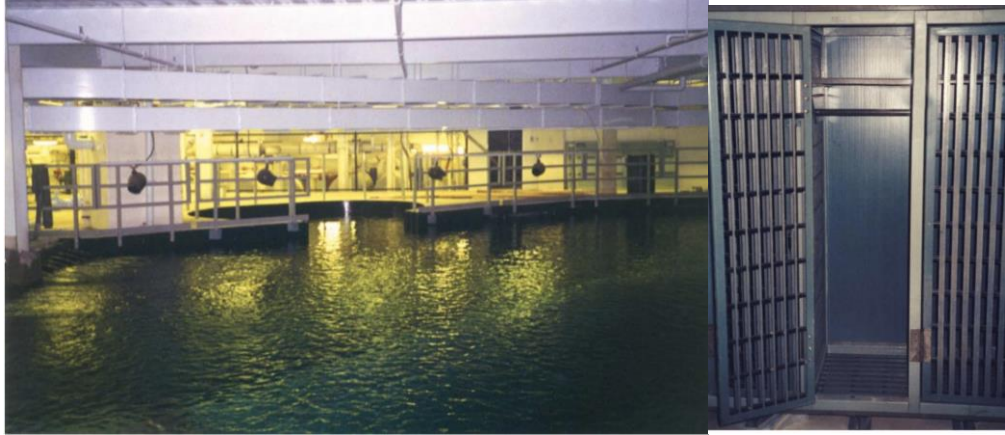
*Figure 8.28 DURADEK platforms and catwalks*

## **8.22 Fiberglass fights corrosion “underwater” and above**

The Mall of America's "UnderWater World", Minneapolis, Minnesota, is an aquatic extravaganza. The corrosion resistant walkways above as moving sidewalks take visitors through the 400 foot underwater tunnels. The walkways, of fiberglass handrails and concrete decking, are above the four aquarium holding tanks and are used by the staff of divers, biologists and lab specialists who maintain this waterworld. Designed to give years of maintenance free service, fiberglass industrial products produced by Strongwell are used throughout the support areas.

The massive installation included 600 lineal feet of SAFRAIL™ fiberglass handrail systems and five 14' SAFRAIL™ fiberglass ladders and ladder cages. The design included 200 square feet of DURAGRID® I-4000 1-1/2" grating panels in various locations such as access hatches, shelving, and drainage areas. Five 3' diameter manhole covers (fabricated from EXTREN® plate) were also used.

This was a fast paced project with everything completed and on site three weeks from order placement. (Application Profile - Strongwell)



*Figure 8.29 SAFRAILTM fiberglass handrail systems used in the Mall of America's "UnderWater World", Minneapolis, Minnesota*

### **8.23 Phenolic grating provides lightweight decking offshore**

DURAGRID® phenolic grating, developed by Strongwell, provides the weight savings necessary for floating tension leg platforms, as well as fire resistant safety with low smoke and low toxic fume emissions. More than 80,000 square feet of phenolic grating has been fabricated for primary modules on the Shell Mars tension leg platform in the Gulf of Mexico, and another 75,000 square feet was used on the nearly identical Ram Powell platform.

Innovative technologies are required to meet the challenges of the offshore oil industry's move to develop record deep oil production. In this environment, weight savings is the key design feature since the more weight that can be taken out of the structure, the more weight that can be optimized for drill pipe, riser and production equipment. Compared to steel grating at 10 lb/ft<sup>2</sup>, the phenolic DURAGRID® grating weighs 3.5 lb/ft<sup>2</sup>. Phenolic grating, which is pultruded using fiberglass reinforced phenolic resin, offers the following additional properties: high fire resistance, low emissions, low thermal conductivity, high strength and impact resistance. Noncorrosive and virtually maintenance-free, phenolic grating also eliminates the continual repainting and rust removal maintenance required with steel. (Application Profile - Strongwell)



*Figure 8.30 DURAGRID® phenolic grating used in Shell Mars tension leg platform in the Gulf of Mexico*



## 8.24 Movable pool dividers are longlasting

Movable swimming pool divider bulkheads, manufactured by Recreation Supply Company, Bismarck, North Dakota, are designed with DURAGRID® fiberglass reinforced grating for the top and sides of each unit. The bulkheads allow commercial aquatic centers to program a wide range of aquatic activities in a single swimming pool. Racing lanes can be quickly defined and divided from the diving well and casual swimmers can be separated from lesson areas.

The DURAGRID® T-1800 1" white grating has proven to be ideally suited for this application. The superior corrosion resistance of DURAGRID® resists the chlorine, heat, humidity and even sunlight that relentlessly attack pool equipment. In contrast to plastic or PVC materials, which often begin to deteriorate after just a few years, DURAGRID® remains sound years after the bulkhead is installed.

The skid resistant surface of DURAGRID® increases the safety of swimmers, coaches and judges who routinely walk across the wet surfaces of the bulkheads. The lightweight nature of DURAGRID® allows easy maneuverability of each pool divider, even in fully filled pools. (Application Profile - Strongwell)



*Figure 8.31 Movable swimming pool divider bulkheads, manufactured by Recreation Supply Company*

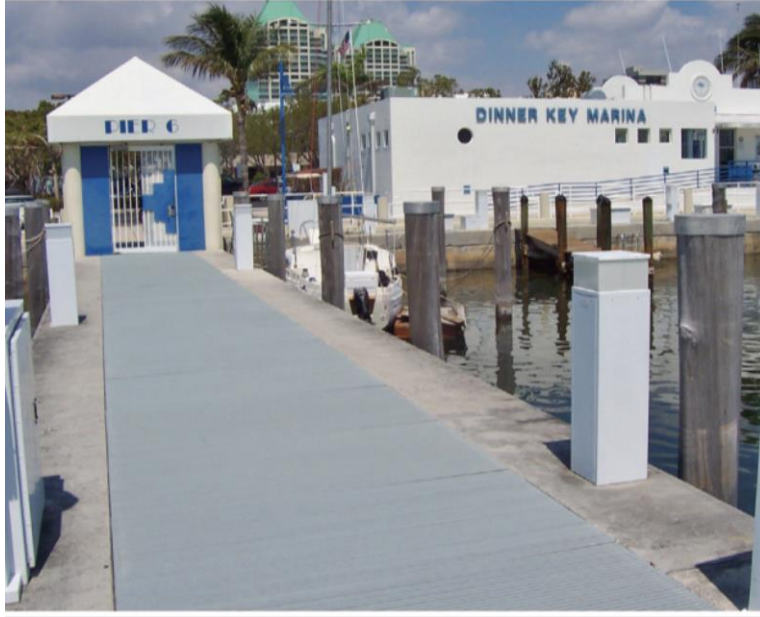
## 8.25 Strongwell's pultruded grating assists a Florida marina

Strongwell's DURAGRID® T-1700 pultruded grating was used to replace wood planks on several piers at Dinner Key Marina in Miami, Florida. The wood planks were frequently damaged during large storms and were susceptible to rotting caused by the corrosive salt-water environment.

The corrosion, rot and mildew resistant DURAGRID® pultruded grating is an ideal replacement for the wood planks while also preserving the aesthetic beauty of the surrounding area. The greatest appeal of the T-1700 grating with 2" T-bars, is that it spans the wide 5' walkway while maintaining enough stiffness to accommodate both foot and golf cart traffic.

The grating allows for easy accessibility to utilities below the walkway because the lightweight panels can be easily removed for maintenance. The grating is also easy to install and maintain, low in thermal and electrical conductivity, aesthetically pleasing, and available in custom colors. (Application Profile - Strongwell)





*Figure 8.32 Strongwell's DURAGRID® T-1700 pultruded grating used on piers at Dinner Key Marina in Miami, Florida*

#### **8.26 After 7 years, first installation of round safrailtm continues to resist corrosion**

In 2002, Fort Lauderdale, Florida received the very first installation of Strongwell's round SAFRAIL™ industrial handrail system. The SAFRAIL™ was added to a fender system located below the city's 17th Street Bridge. A strong, corrosion resistant handrail system was required for workers' safety while inspecting the fenders.

A round SAFRAIL™ fiberglass handrail system is ideal for any high traffic area where handrail is needed. The round rails are easy to grip. The handrail system meets OSHA strength requirements with a 2:1 factor of safety with five foot maximum post spacing.

In addition to strength and safety precautions, SAFRAIL™ fiberglass handrail was selected because of the product's excellent resistance to salt water. After seven years of exposure to the Florida sun and the Atlantic ocean, the photos shown here, taken in January of 2009, demonstrate the durability of the fiberglass system. (Application Profile - Strongwell)



*Figure 8.33 Strongwell's round SAFRAIL™ industrial handrail system in Fort Lauderdale, Florida*

### **8.27 SAFPLANK – The ideal material for pier deck**

Low maintenance, easy installation and minimal heat retention were key requirements for Camp Civitan officials when they began searching for materials to build a new pier at their Easter Seals camp on Lake Martin in southeastern Alabama. These requirements were easily met when they chose Strongwell's SAFPLANK® fiberglass plank system for the pier's deck.

SAFPLANK® was chosen to build the pier deck because it would remain cool enough for campers to walk barefoot on its surface. The SAFPLANK® also would be virtually maintenance free because the fiberglass material would not shrink, rot or absorb water as is the case with wood.

The deck installation time is less than two hours. SAFPLANK®'s non-skid surface, which provides campers with a safe walking surface, is another feature that made it the ideal material for the installation. Additionally, SAFPLANK® does not shrink and therefore will not create joint cracks that could cause problems for campers with wheelchairs. (Application Profile - Strongwell)



*Figure 8.8.34 Strongwell's SAFPLANK® fiberglass plank system for the pier's deck*

**8.28 STRONGDEK™ ocean FRONT fiberglass decking impervious to salt water environment**

STRONGDEK™ installed at Perdido Beach Resort in Orange Beach, Alabama in 2003 has withstood the test of time and elements. Two years after the decking installation in 2005, Orange Beach was pounded by Hurricane Dennis and several panels from the deck were blown away during the storm. Many panels were recovered in good condition and were easily re-installed.

Upon inspection in 2013, the panels showed some minimal wear and tear, but were holding up well with only periodic pressure washing required for maintenance. (Application Profile - Strongwell)



*Figure 8.35 STRONGDEK™ installed at Perdido Beach Resort in Orange Beach, Alabama*



### 8.29 Glass Fiber Reinforcement by ComBAR®

The composite ComBAR® was conceptualized as internal reinforcement in concrete members. The mechanical properties and bond properties are comparable to those of steel rebar. The material properties were determined for predominantly static loads in central European and North American climates. They are certified for a design service life of 100 years.

ComBAR® bars are linearly elastic up to failure. For all bar diameters it occurs at stresses well above 1,000 MPa. As a result of the comparatively low modulus of elasticity of ComBAR® ( $\geq 60$  GPa), the failure of ComBAR® reinforced concrete members is preceded by large deflections. When the load is removed the deflection returns to near zero. ComBAR® bars with end heads can be installed where geometric constraints require reduced development lengths. Double headed bars are ideally suited as shear and punching shear reinforcement in beams and slabs. ComBAR® bars cannot be permanently deformed or bent. If a straight bar is bent it returns to its original shape as soon as the applied force is removed. Bars with small diameters can be bent elastically (circular tunnel cross-sections). Customised bent bars and stirrups are prefabricated at the shop. ComBAR® bent bars have been durability-tested for a service life up to 100 years. Material characteristics include high corrosion resistance, high chemical resistance, electrically non-conductive, non-magnetic, ease of machining and very low thermal conductivity

Applications of the glass fiber reinforcement include industrial facilities, parking structures and garages, bridge decks, barrier walls, approach slabs, sidewalks, wing walls, curbs, railways, marine structures, thin pre-cast elements and facade panels, research facilities, transformer and reactor / inductor stations and civil engineering and infrastructure.



*Figure 8.36 Glass Fiber Reinforcement by ComBAR (Fiberline Composite)*

### 8.30 Sheet Piling

FRP composites in the form of panels, pipes, and posts, in addition to pultruded standard shapes can find broad applications in every type of sea-waterfront facilities. These applications include: decking, walkways, platforms, ship to shore bridges, fenders, docking systems, retaining walls, crosswalks, moorings, cables, piles, piers, underwater pipes, railings, ladders, handrails, and many others, as representatively shown in Figure 8.37. Several composite sheet piles made by Creative

Pultrusion Inc. was tested as an application to protect soil erosion near sea-front homes (Hota and Skidmore, 2012). These FRP products can survive under constant exposure to saltwater and salt air, and won't corrode, rust, or create sparks.



*Figure 8.37 FRP Handrail, Ladder, Platform and Walkway for Sea Waterfront Facilities (courtesy of Bedford Reinforced Plastics Inc.)*

### **8.31 Pont y Ddraig (Bridge of the Dragon) Foryd Harbour**

Project was built in 2012-2013. Both bridge spans were designed and built in FRP with localized CFRP reinforcement on the bridge deck and Soffit, this enabled the loads to directly transferred from the caisson hinges to the central lifting cable. Bridge weight was an important consideration due to the number of times per day the bridge would be lifted to allow marine traffic pass into the harbor. Weight reduction was also a key factor in the speed of lift and energy used in the bridge lifting operations.

The double bascule lifting design required a slender lightweight structure consisting of two 10 meters wide bridge decks each spanning 36 meters to a central caisson in the middle of the harbor incorporating the lifting mast for both bridge spans. The main body of the Bridge was built using Ampreg Epoxy resin system and layers multiaxial glass reinforcement with structural Corecell M foam and directionally orientated carbon fiber reinforcement, supplied by Gurit UK. Bridge was supplied with 100-year design life and minimum through life maintenance.





*Figure 8.38 Cycle/Footbridge across the River Clwyd at Rhyl Harbour, North Wales*

### **8.32 Large-scale Composite Bumper system for bridge pier protection against ship collision**

An innovative Large-scale Composite Bumper System (LCBS) for bridge piers against ship collision was recently proposed at Nanjing Tech University. The modular segment of LCBS is made of Glass Fiber-Reinforced Polymer (GFRP) skins, GFRP lattice webs, Polyurethane (PU) foam cores and ceramic particles in which Vacuum Assisted Resin Infusion Process (VARIP) is adopted in the manufacturing process. This novel bumper system offers several remarkable advantages, such as: self-buoyancy in water, modular fabrication of segments, efficiency for on-site installation, excellent corrosion resistance, as well as ease in replacing damaged segments. (2016, Hai Fang)

LCBS was applied in the RunYang Yangtze River Bridge in 2012. Since 2010, there are more than 10 bridge protection projects using LCBS in China now, which were all designed by the authors' research group.

The typical projects include Huanggang railway Yangtze River Bridge with 3.5m-diameter LCBS against 5000 DWT ship (Figure 8.39a), Langqi Min River Bridge with 4.0m-diameter LCBS against 10,000 DWT ship (Figure 8.39b), Chongqi Yangtze River Bridge with 3.5m-diameter LCBS against 3000 DWT ship (Figure 8.39c), Guangshen Highway Bridge with 2.0m-diameter LCBS against 1000 DWT ship (Figure 8.39d), Maanshan Yangtze River Bridge with 4.0m-diameter LCBS against 10,000 DWT ship (Figure 8.39e), Xiangtan Xiang River Bridge with 2.5 m-diameter LCBS combined with independent steel post column against 2000 DWT ship (Figure 8.39f).



*Figure 8.39 Applications of LCBS on bridge protection projects in China*

### **8.33 Reinforced Plastic Inspection walkway**

The Blennerhassett Island Bridge is located in Wood County (District 3) at Latitude, Longitude 39.27573, -81.64673 and was originally built in 2008. The twelve span bridge has an overall length of 4009 feet with a maximum span length of 878.5 feet with no skew. The bridge 16300 vehicles per day across 6 lanes on the Appalachian Corridor H highway. An inspection walkway, safety ladders and security shaft and conduit under the bridge are all GFRP.

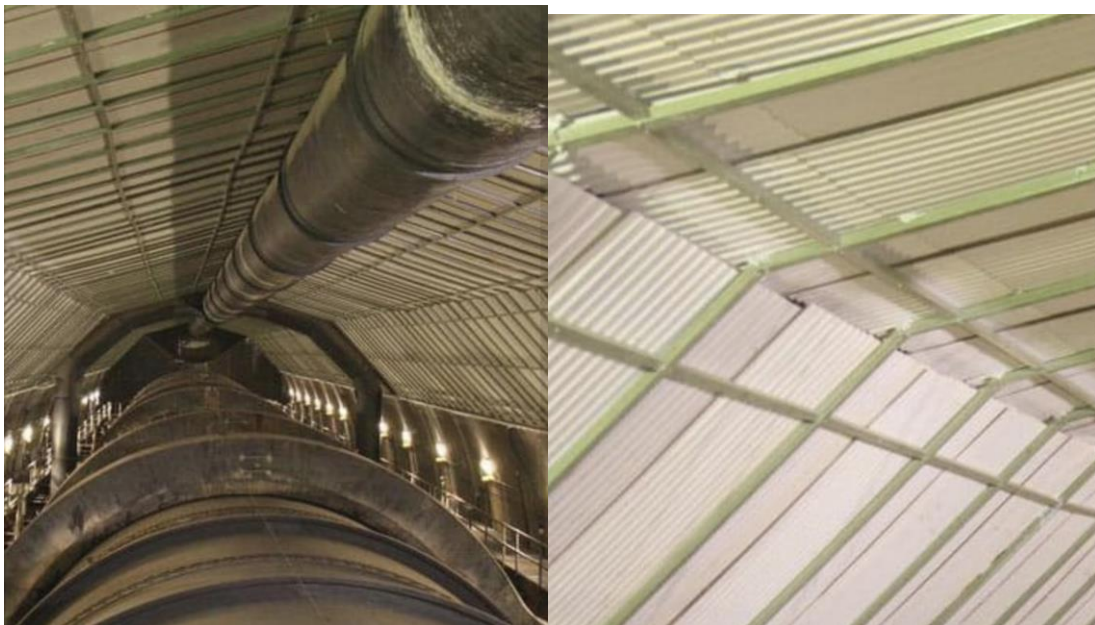
The inspection walkway is holding up well, though it is not as stiff or rigid as steel, so it has some bounce to it, comparatively. The safety ladders are fine. The security shafts surrounding the ladders are much flimsier than steel. This is considered a good thing, as it makes trespassers think about climbing down them. The security shafts are showing some UV damage, as some of the fibers are visibly coming through. The conduits and large junction boxes are also FRP, and along with the cat walk, are not subjected to UV rays, and are all fine. (FRP Composite Bridges in WV)



*Figure 8.40 Blennerhassett Island Bridge*

### **8.34 Hoover Dam Penstock Tunnels**

At the Hoover Dam, steel piles (penstocks) carry water from the intake towers in the reservoir to the power plant and canyon wall outlets. Over the years, the penstock tunnel ceilings leaked water the steel pipes, which was causing them to corrode. Because of the size and amount of pipe involved, replacement would not be an option. The Bedford supplied PROForms structural shapes made of FRP (fiberglass reinforced polymer or fiberglass reinforced plastic) were the solution to protect the Dam. The FRP profiles, such as square bar and I-beam, provided the supporting framework for canopies of corrugated fiberglass over the pipes. The canopies have been in place for nearly a decade and they are still sheltering the penstocks from further damage and corrosion. (Bedford)



*Figure 8.41 PROForms structural fiberglass shapes*



### 8.35 Drop Protection for Subsea Applications

A major supplier of manifolds and blowout preventers needed a corrosion-resistant, lightweight solution to prevent foreign materials from damaging important components that rest on ocean floor.

Bedford was asked to design a protection system ranging from 5kj to 20kj (kilojoules) of impact. PROForms fiberglass structural shapes and PROGrid fiberglass molded grating panels were used for this project. Unlike steel, FRP is non-corrosive and is also lightweight enough for an ROV (remotely operated underwater vehicle) to remove the covers occasionally to access valves deep within the manifolds. The project was completed after a year of testing and the results have been outstanding with no issues. (Bedford)



*Figure 8.42 PROForms fiberglass structural shapes and PROGrid fiberglass molded grating panels*

### 8.36 Bellagio Hotel and Casino Fountains

The Bellagio Hotel and Casino in Las Vegas is known for the famous choreographed fountain show. The fountain's underwater structure is made of PROForms FRP structural fiberglass shapes. During the planning process, the structural material was expected to be submerged under water most of the time without rusting, corroding or rotting and also be lightweight enough for bladders filled with air to lift the structure during the show. The FRP was the best solution for these requirements. The composite components have been part of the fountain structure since the Bellagio opened in 1998, and they continue to perform today. (Bedford)



*Figure 8.43 Bellagio Hotel and Casino fountain*



## 9 DESIGN OF COMPOSITE HYDRAULIC STRUCTURES

Construction industry relies on design codes, specifications and standards for any material to be used in construction. FRP design codes and standards are needed not only to provide credibility to FRP products and penetrate into market against existing materials, but also to do business with the government. A good example would be Underwriters Laboratories (UL) 1316 (1966) “Non-Metallic Tanks for Petroleum Products Only” for single wall FRP tank. This standard as a Performance Specification was revised for double wall FRP tank in 1984 under the same code number UL 1316: “Glass-Fiber-Reinforced Plastic Underground Storage Tanks for Petroleum Products, Alcohols, and Alcohol-Gasoline Mixtures”. This standard is the only nationally recognized standard governing the design, manufacturing, installation and inspection of FRP tanks.

The research advances made through various sponsored programs have directly resulted in the development of FRP rebar design codes and specifications. Among others, Bank et al (1998) studied the behavior of pultruded shapes and full-sized structural frames under both the short and long term loadings. Nanni et al (1997) researched on the use of FRP rebars in concrete decks and externally bonded FRP composite wraps of RC structures. Through NSF award, Vijay and Hota (1999) systemically investigated the durability responses of reinforced concrete members with FRP rebar. Based on accelerated aging test results calibrated with respect to naturally aged composites, the study concluded that the service life of the FRP rebar with durable low viscosity urethane modified vinyl ester resin is about 60 years as a minimum with 20% sustained stress on the bar. Concrete cover protection to the FRP bars would enhance the service life up to about 90 years. All the above studies have found their way in the design and construction specifications for composite rebars for concrete structural elements and composite wraps to strengthen infrastructural systems (ACI 440.1R.03 and AASHTO LRFD Bridge Design Guide).

### 9.1 Pre-standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures

Recently, a new draft design code entitled, “Pre-standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures” is being developed through American Composites Manufacturers Association (ACMA) and the American Society of Civil Engineers (ASCE). This code will allow architects and structural engineers to incorporate FRP composite materials to build stronger, safer and better buildings. Advent of these codes will help FRP composites to compete on a level playing field with other construction materials such as concrete, steel, wood and aluminum. Performance criteria for design, specification and installation will mean a higher degree of confidence for professional engineers and contractors to design and construct with FRP composites, in addition to instilling confidence in owners to field implement the advanced FRPs.

For example, the released draft LRFD design code states that during analysis and design of pultruded FRP structural components and systems, the nominal strength will be determined by multiplying the reference strength by the adjustment factors for end-use conditions, as represented in the following formula:

$$R_n = R_0 C_1 C_2 C_3 \dots C_n$$

where  $R_0$  is the reference strength and  $C_i$  represents the applicable adjustment factors for sustained end-use conditions that differ from the reference conditions. More specifically, the reference strength or stiffness is obtained from tests under short term loading at ambient temperature of  $73 \pm 3$  °F and relative humidity of  $50 \pm 10\%$ . The above mentioned draft LRFD code specifies  $C_M$  (moisture condition factor) and  $C_T$  (temperature factor) as set forth in Table 3 to account for sustained in-service moisture and temperature, respectively. Here  $C_T$  is valid for in-service temperatures higher than 90 °F but less than  $T_g$  minus 40 °F. For sustained temperatures in excess of 140 °F,  $C_T$  shall be determined from tests.

*Table 9.1 Adjustment Factors for End-use Conditions (extract from Draft LRFD code, 1)*

Reference Property	Moisture $C_M$	Temperature $C_T$ for (90 °F < T ≤ 140 °F)
Vinyl ester material		
Strength	0.85	$1.7 - 0.008T$
Elastic modulus	0.95	$1.5 - 0.006T$
Polyester material		
Strength	0.80	$1.9 - 0.010T$
Elastic modulus	0.90	$1.7 - 0.008T$

For chemical environmental factor  $C_{CH}$  in high alkalinity or acidity, the adjustment factor shall be determined from extrapolation of the results of ASTM C581 tests performed on the laminate exposed to the exposure chemical environment for a period of 1,000 hours. Also, the reference strength in the equation above shall be obtained for single members or connections without load sharing or composite action. There are adjustment factors for member strength or stiffness in structural assemblies to account for the increase in strength of the assembly over the strength of an individual member or for the increase in assembly stiffness when the members are constrained to act in a composite fashion. In addition, fatigue shall be considered in the design of members and connections subjected to repeated loading.

## 9.2 Design of FRP Recess Panel

Hydraulic structures are exposed to severe corrosion and abrasion. As steel, concrete and timber are traditionally used in majority of our waterway infrastructure, they undergo corrosion, deterioration and decaying within few years of service life requiring costly maintenance and replacement in a regular basis. FRP composites provide excellent corrosion and wear resistance while also providing superior thermo-mechanical properties. In this example, full size FRP composite shapes (recess protection panels and wicket gates) have been designed, tested, analyzed and developed to replace the current waterway infrastructure members built with steel and timber.

Recess panels are typically located in the upper lock approach in many navigational structures. They protect the recess areas in the lock wall during a time when miter gates are inoperable and an emergency gates are raised.

Primary forces on recess panels are hydraulic forces and barge impact forces. FRP composite recess filler panel was designed using off-the-shelf FRP composite components to withstand hydraulic and a barge impact loads which require over 135.6 kN-m (100 kip-ft) section with a shear capacity of ~311 kN (70 kip). The FRP recess panel was designed as shown below. The mechanical properties are also provided below.



*Figure 9.1 FRP hexagonal super-deck*

*Table 9.2 Mechanical properties of FRP hexagonal super-deck without top coating*

Properties	Values
Longitudinal compressive strength	241 MPa (35,000 psi)
In-plane shear strength	62 MPa (9,000 psi)
Moment capacity	106 kN-m (78.634 kip-ft) @ 2.4 m (8 ft.) span
Moment of inertia	10947 cm <sup>4</sup> (263 in <sup>4</sup> )
Modulus of elasticity	24 GPa (3.50 msi)
Weight	112 kg per square meter (23 psf)

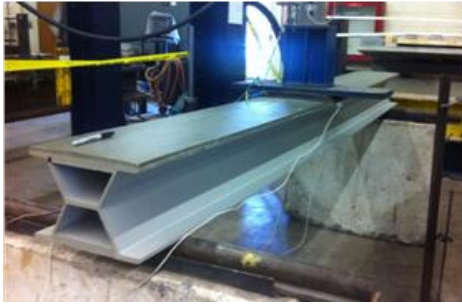


Figure 9.2 FRP super-deck under 3-point loading

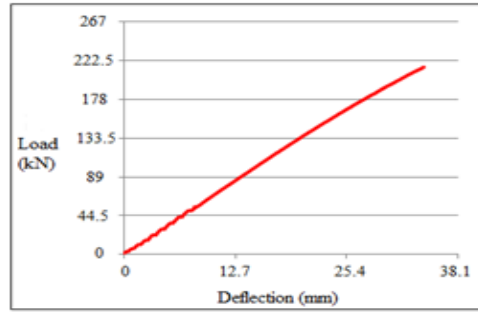


Figure 9.3 Deflection plot

### 9.3 Design of FRP Wicket Gate

A wicket gate is a movable dam that can be raised in times of low water and lowered when the water pool level is adequate for navigation. Wicket gates when composed of a large number form a dam with each wicket gate hinged individually at the river bottom.

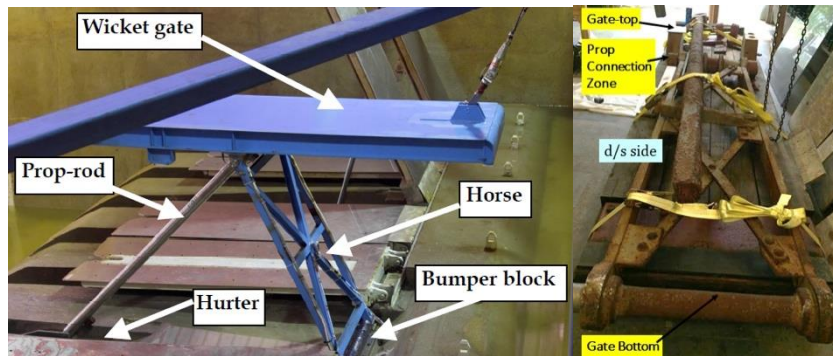


Figure 9.4 Horse-type wicket gate configuration (left), timber wicket gate (right)

Prop is connected to the middle portion (prop connection zone) of the gate as shown in Figure 9.4. The location of top hinge from the bottom of the gate is 2.44 m (8 ft.) along the gate length.

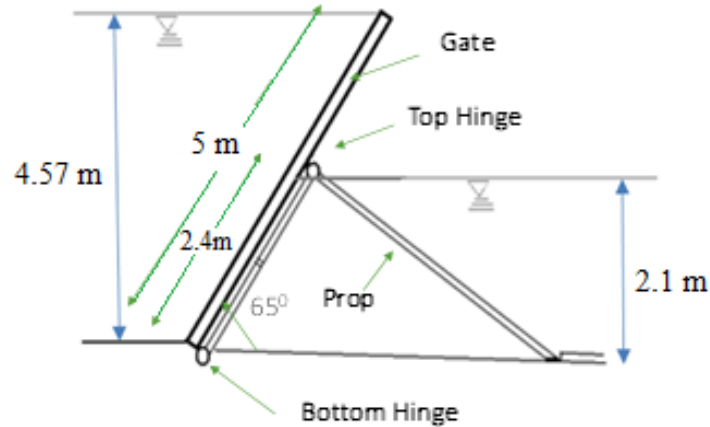


Figure 9.5 Wicket gate in operating position

The gate was analyzed in three positions: i) resting, ii) operating, and iii) lifting. Maximum bending moment and shear were noted to be in lifting position. During lifting, a winch cable is tied to either top or bottom bail (Figure 9.5). In order to achieve higher safety factor and design for the worst possible scenario, the gate is assumed to act like a simply supported beam with two ends hinged and the height of water above the gate be 4.6 m (15 ft.) just when the lifting is started from the rest position. It is also assumed to have no pressure being exerted from water below the gate (hypothetical scenario). As per the analysis, maximum shear force and corresponding maximum bending moment are 132 kN (29.6 kip) and 165.4 kN-m (122 kip-ft), respectively. During operation, the force in the is 93 kN (20.9 kip) when there is tail water and 102.3 kN (23 kip) when there is no tail water. This force is transferred to a shaft which is further connected to the gate with two steel plates of sizes 330 mm x 432 mm (13" x 17").



Figure 9.6 Top bail (left) and bottom bail (right)

The cross-section of the designed FRP composite wicket gate is shown in Figure 9.7. FRP composite wicket gate section with depth of 216 mm (8.5") has been selected for the analysis. There are 14 webs across the 1.17 m (46") wide section wicket gate with flange thickness of 13.3 mm (0.523") and web thickness of 10.16 mm (0.4"). Moment of inertia of a selected FRP module is 39,250.6 cm<sup>4</sup> (943 in<sup>4</sup>). In addition to the FRP section, additional existing steel attachments of timber wicket gate will be added on top and bottom of the gate as shown in Figure 9.6 along with edge steel angles.



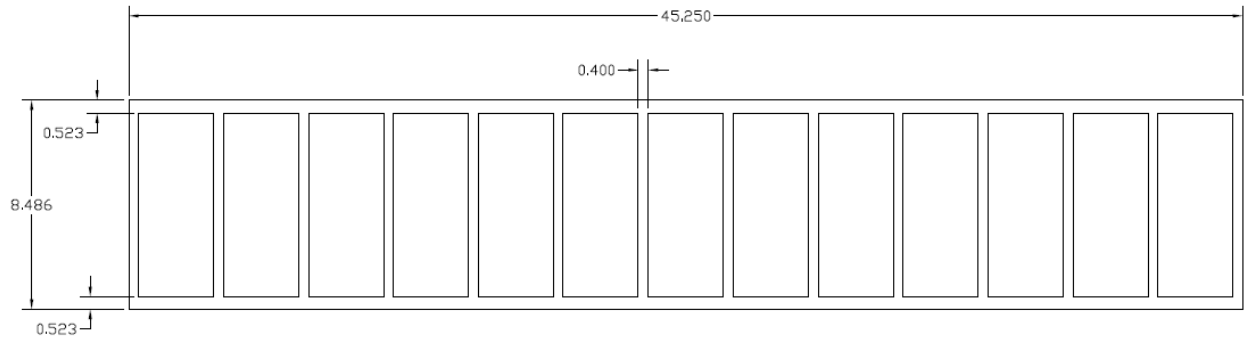


Figure 9.7 Cross-section of the FRP wicket gate (dimensions are in inches, 1 inch=25.4 mm)

The maximum bending stress of 45.5 MPa (6.6 ksi) for the gate section. The failure bending stress of the FRP panel without any steel attachment is 182 MPa (26.4 ksi). Based on this stress, total resisting bending moment of the selected FRP wicket gate is 662 kN-m (488.1 kip-ft.) giving the factor of safety for bending failure is 4 (182/45.5). After adding the load factor of 1.6, factor of safety is still 2.5.

The shear stress of 7.31 MPa (1.06 ksi) that can be present along the gate section. The failure in-plane strength of the FRP panel without any steel attachment is 103.5 MPa (15 ksi). Based on this stress, factor of safety achieved for shear failure is 14.2 (103.5/7.31).

Total prop force of 102.3 kN (23 kip) is distributed to gate through two plates of size 330 mm x 432 mm (13" x 17"). In each of this area, there are 4 webs of 10.16 mm (0.4") thickness. Conservatively, considering total prop force coming to only one steel plate, then each web gets ~26.7 kN (6 kip). For an inch width of the web, moment of inertia about minor axis is 2,218.5 mm<sup>4</sup> (0.00533 in<sup>4</sup>). The modulus of elasticity for this computation is taken as one of the conventional values of 24131.66 MPa (3.5 msi). The buckling load for 25.4 mm (an inch) length of the web is 14.79 kN (3.33 kip). The buckling load value will be higher than 14.79 kN (3.33 kip) since the length of the web will be half of 189 mm (7.44") due to fixity on top and bottom flanges. Total buckling load of the single web in the prop connection zone is 251 kN (56 kip) giving the factor of safety of 9.4 (251/26.7).

In the tensile test on FRP coupon specimens of wicket gate, samples measuring 10.9 mm x 50.8 mm x 1067 mm (0.43"x2"x42") were tested in tension which provided an average tensile stress of 491 MPa (71.2 ksi) and stiffness of 30 GPa (4.35 msi).

In four-point bending test on FRP wicket gate, four-point bending loads were applied at L/3 distance from both ends of the gate (Figure 9.8 Four-point bending test on FRP wicket gate). At different locations, 5 shear strain gages and 15 axial strain gages were bonded, and LVDTs were used for deflection measurements. Load of 266.9 kN (60 kip) each was applied with two MTS hydraulic actuators having capacities of 489 kN (110 kip) each at L/3 distance.



*Figure 9.8 Four-point bending test on FRP wicket gate*

Table 9.3 Four-point bending test results of FRP wicket gate shows the results of the testing. Maximum strains obtained at L/2 (center) and L/3 distances were 3352 micro-strain and 2001 micro-strain, respectively. The maximum shear-strain monitored was 2230 micro-strains at ‘d’ distance from left support.

*Table 9.3 Four-point bending test results of FRP wicket gate*

Items	Values
Test span, mm (ft.)	4572 (15)
Load distance from supports, mm (ft.)	1524 (5)
Total load, kN (kip)	534 (120)
Maximum moment, kN-m (k-ft)	406.7 (300)
Maximum bending strain (micro-strain)	3352
Maximum shear strain (micro-strain)	2230
Maximum deflection, mm (inches)	58.75 (2.313)

In the shear/pull test of wicket gate end bails, FRP wicket gate was placed horizontally on two end supports with top of the gate fixed against horizontal movement. Top bail was pulled horizontally with 84.07 kN (18.9 kip) of load (Figure 9.9). A longitudinal strain gage bonded at the mid-depth region just below the top bail showed a overall maximum strain of 104 micro-strains.



Figure 9.9 Pulling of the FRP gate with the chain attached to the top bale

During the operating position of the wicket gate, the gate was hinged at bottom (N1) and at N2 as shown in Figure 9.10. The flexural rigidity of the FRP gate system was found to be  $1.54 \times 10^{10} \text{ kN}\cdot\text{mm}^2$ . Maximum operating deflection of 3.91 mm (0.154") obtained from analysis of the wicket gate corresponds to a ratio of span (L)/660.

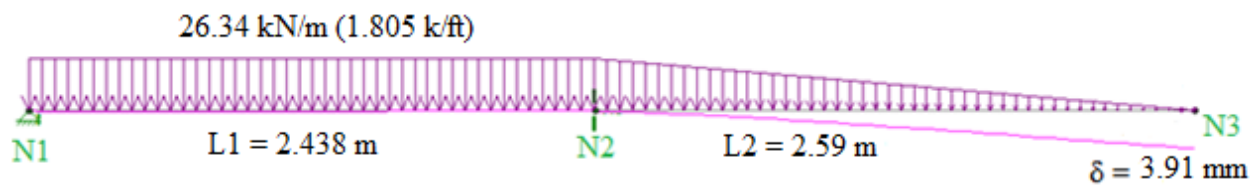


Figure 9.10 Operating position of the gate

Based on the non-destructive testing, FRP gate resisted an applied bending moment of 406.7 kN-m (300 k-ft.) with a maximum bending strain of 3352 micro-strains and a shear strain of 2230 micro-strains. Strains during bending failure in shapes was noted to be in the range of 10,000 to 15,000 micro-strains and shear strains in the range of 8000 to 10,000 micro-strains during shear failure. However, failure strains can vary based on the fiber-fabric architecture, L/d ratio, and local failure modes. Factors of safety varied from 4 to 14, based on bending, shear, and buckling considerations. Maximum deflection during the operating position of the FRP wicket gate was 3.91 mm (0.154") and corresponded to L/660. These gates were implemented in the field during Fall 2015.

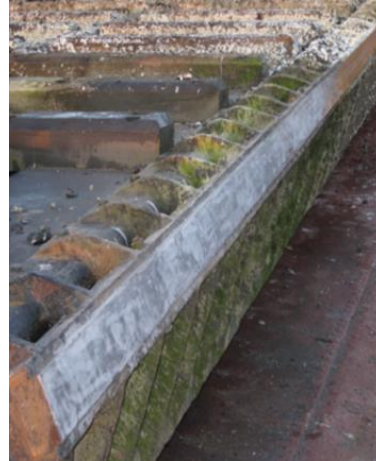
#### 9.4 Design of FRP Blocks for Miter Gates

Figure 9.11 used in hydraulic gates create a vertical line of contact between two closed miter gate leaves. Miter blocks may be exposed to harsh service conditions including wet-dry cycles, corrosive elements, hydrodynamic forces, mitering forces, and freeze-thaw effects. In this research, feasibility of FRP block for miter gates was examined by utilizing off-the-shelf FRP products. The miter block was designed for a USACE recommended compressive stress of 1400 psi that is induced by both hydrostatic and hydrodynamic forces. The miter block has to withstand 12,000+ cycles of opening and closing operations a year, and has an expected service life of 30 years. Compressive forces across mitering surfaces are the dominant forces that the FRP miter blocks

will have to withstand under service conditions. Typical dimensions of the miter block are 4"x2.5" with 13/16" holes drilled at every 18" along its length.



*Figure 9.11 Miter gate*



*Figure 9.12 Miter block*


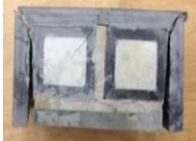


Miter blocks were manufactured in the laboratory at coupon level using currently available FRP structural shapes, flat sheets, and standard Macrocore sections (Engineered Syntactic Systems). FRP solid block specimen for miter block was produced by FiberTech, Inc. as a single block of FRP. Hetron FR 992 (Ashland Chemicals) resin was used for both fabric lamination and edge treatment. FRP laminates consisted of 2 layers of 10mil surface veil and a total of 96 layers of 24 oz. woven ravings (PPG Boron free glass woven by ValuTex). The average fiber volume fraction was found to be ~45% as per the ASTM D-3171-11 burn-off test conducted at 1050 °F (565 °C).

Four different variations of FRP miter blocks were manufactured and evaluated. Off-the-shelf FRP composite components were selected to fabricate lab-scale miter gate blocks and tested in lengths of 2" to be within the load capacity of the Instron machine. These blocks were configured to meet and exceed the design criteria of 1400 psi compressive stress on mitering surfaces. Various design configurations were evaluated within each group under the following four main groups.

- i. Group I consisting of FRP components and foam core
- ii. Group II (modification to Group I) by substituting FRP square tube core
- iii. Group III consisting of stacked FRP sheets
- iv. Group IV consisting of single block of FRP (modification to Group III)

Compression tests were performed on miter block specimens using the Instron Universal Testing Machine HDX 1000. The miter blocks were placed in a fabricated steel test frame and tested to failure. Strain gages were placed on the miter block in the compressive direction of the mitering surface. Data Acquisition was used to record the strains, loads, and deflections of the miter block. The miter blocks were all tested at a load rate of ~ 30 kips per minute with a max deflection limit of 0.23" (slightly less than the 0.25" available for deflection of the platen without touching the steel frame housing) similar to the field miter block system. The load rate was initially established so that the FRP composite would fail between 2-5 minutes of loading.

*Table 9.4 Different variations of miter block manufactured*




Group	Specimen	Foam core	Hole	Max. load (kips)	Notes
I		Yes	No	83.9	Specimen showed excellent improvements that led to use of small square tubes
		No	No	41.2	
II		No	Yes	104.1	After Fatigue, specimen failed at 105.4 kips.
III		No	Yes	>191.8	No sign of cracks and did not fail. Test stopped at preset deflection limit of 0.23"
IV		No	Yes	>224	No sign of cracks and did not fail. Test stopped at max. capacity of Instron machine.

Compressive load carrying capacity results as a guide; fatigue tests were designed and then conducted on miter block specimens. The fatigue testing was set to 2 hertz on a sinusoidal curve from a range of 2 – 11.2 kips corresponding to a maximum compressive stress of 1400 psi. The fatigue test was run up to ~ 1,350,000 cycles, which correlated to ~112 years based on the 12,000+ cycles a year. Once the samples were fatigued, they were statically tested to failure to determine the remaining strength under fatigue.

Initial miter block design consisted of achieving a minimum factor of safety of 3, which with a 1400 psi compressive stress over a contact area of 8 square inches (4" x 2" of loading surface) resulted in an ultimate load of 33.6 kips. Based on the 33.6 kips compressive force, different groups of miter blocks were tested and refined over the preceding group. The compressive strength of each group is given in Table 9.4 Different variations of miter block manufactured. Groups I and II miter blocks satisfied the maximum loading criteria, however initial cracks were seen before the design load was met and those configurations were not selected. Group III specimens consisting of bonded FRP plates performed well under compressive and fatigue loads. It was manufactured as a single thick block and is referred to as Group IV specimen. Failure stresses in all 3 directions of Group IV specimen under static loading using Instron 1000HDX are shown in Table 9.5 Group IV miter block stresses in 3-directions. Compressive stress of 51 ksi far exceeds the required value of 1.4 ksi and no cracking was found after fatigue load in excess of 500,000 cycles. These FRP miter blocks will be field installed in Washington Lake Lock and Dam system during spring 2015. To prevent moisture ingress into the miter block, field drilled bolt holes may be sealed with waterproof sealants.

*Table 9.5 Group IV miter block stresses in 3-directions*



Load direction	Failed specimen	Failure stress (ksi)
Perpendicular to mitering surface (across two gates)		~51
Perpendicular to steel channel edge surfaces		~22
Along the length (height direction in the gate)		~29

Note: 1.4 ksi is required on the mitering surface vs. ~51 ksi available. Samples were tested in 0.75” and 1” lengths.

Solid FRP miter block met and even exceeded the operational requirements defined by USACE under both static and fatigue loads, carrying an average failure stress of 51 ksi (vs. required 1.4 ksi).

### 9.5 Repair of Corroded Steel Piles with FRP

East Lynn Lake Bridge is located on Cove Creek, which is a tributary of the East Fork of Twelve Pole Creek, West Virginia. It was designed in 1969 and constructed in early 1970s. It consists of 5 spans, and is a two lane, continuous reinforced concrete slab structure designed for H-15-44 loading. Each of the two end spans are 20’-3” in length and the 3 intermediate spans are 27’-6” each. The bridge is supported by four piers and two abutments. The piers and abutments consist of a five pile bent with a reinforced concrete cap with all of the piles founded on rock. The existing steel piles are exposed to year round water stream level fluctuations and are susceptible to continued oxidation, rusting, and scouring (Figure 9.13 East Lynn Lake Bridge with severely corroded steel structural members, Cove Creek, West Virginia Figure 9.14 Close-up of corroded steel pile). Under this work, steel H-piles with advanced deterioration and section loss verified to be up to 60% were rehabilitated with FRP jackets and self-consolidating concrete (SCC). This allowed the bridge to return to full load rating.



*Figure 9.13 East Lynn Lake Bridge with severely corroded steel structural members, Cove Creek, West Virginia*



*Figure 9.14 Close-up of corroded steel pile*

The objective of this work consisted of reducing/preventing corrosion of H-piles including improvement in their load rating through FRP wrapping. Steel piles with section loss and deterioration were cleaned of loose debris and corrosion by-products through pressure washing using a 5000 psi pump. Necessary corrosion treatment/monitoring schemes were implemented prior to rehabilitation. The lake was drawn to allow for the wrapping to extend to a depth of up to a minimum of half feet or beyond the corrosion zone.

Circular FRP shells of ¼" thick x 20" diameter with tongue and groove joints were placed around the H-piles up to required heights. Additional fastening/bonding schemes were used to hold the shell in place around the piles and two layers of circumferential GFRP wrapping was used over the shell. The bottom part of the FRP shell was grouted with up to 9" height of epoxy grout. The rest of the shell was filled with self-consolidating concrete pumped through the top port on the

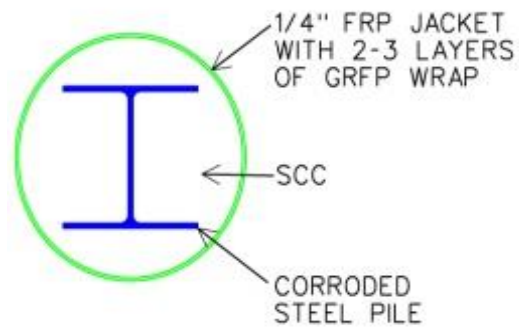
FRP shell. The design provides 3 layers of protection against further corrosion and provides pile strength over 2 times the original pile bending strength. Construction efforts were completed by WVU and East Lynn Lake personnel.

Following field installation, field monitoring is being carried out in terms of calibrated truck load and Non-Destructive Testing for bond integrity evaluations. In addition, corrosion rate evaluation, thermal strains, deformations under loading, humidity levels, and others were monitored. Calibrated truck loads were used for load tests prior to and after rehabilitation. The final view of the bridge after rehabilitation is shown in Figure 9.18.

The repair of the bridge was a “win/win” project with a successful partnership between USACE Huntington District, USACE ERDC, the National Science Foundation (NSF) and WVU. The advantages of the composite construction were: short 6 week construction duration, actual construction cost savings of approximately 35% of conventional repair (estimate \$115k vs. \$350k; total cost of project, including R&D effort –\$375k), longer life – composites expected to protect bent piles for the life of the bridge, low maintenance – no need for repainting, and relatively easy construction. The conventional fix for such corroded steel piles is by welding of additional steel plates on the existing structure, which is labor intensive and lasts only for 10 to 15 years, while the composite wrap is a long-term fix and allowed the bridge to return to its full load rating.



*Figure 9.15 Close-up of shell placed around corroded steel pile*



*Figure 9.16 Diagram of the repairs that will encapsulate and protect the piles from future corrosion*



*Figure 9.17 Columns with shells in placed and wrapped with GFRP wrap*



*Figure 9.18 View of the bridge after rehabilitation, Photo by Dale Smith.*

## 9.6 Systematic Design of fiber reinforced polymer slides in the Eastern Scheldt storm surge barrier

### 9.6.1 Introduction

The Eastern Scheldt storm surge barrier is a closeable barrier in Southwest Netherlands, which protects the Southwestern Delta from flooding from the North Sea. The barrier is constructed with lifting steel slides, which corrode rapidly in the salty environment. The service life of the coating, is too short to maintain all the slides before maintenance is necessary. Therefore, the slides can deteriorate such that maintenance costs exceed the costs of replacement of the slides. (Roeland van Straten, 2013)

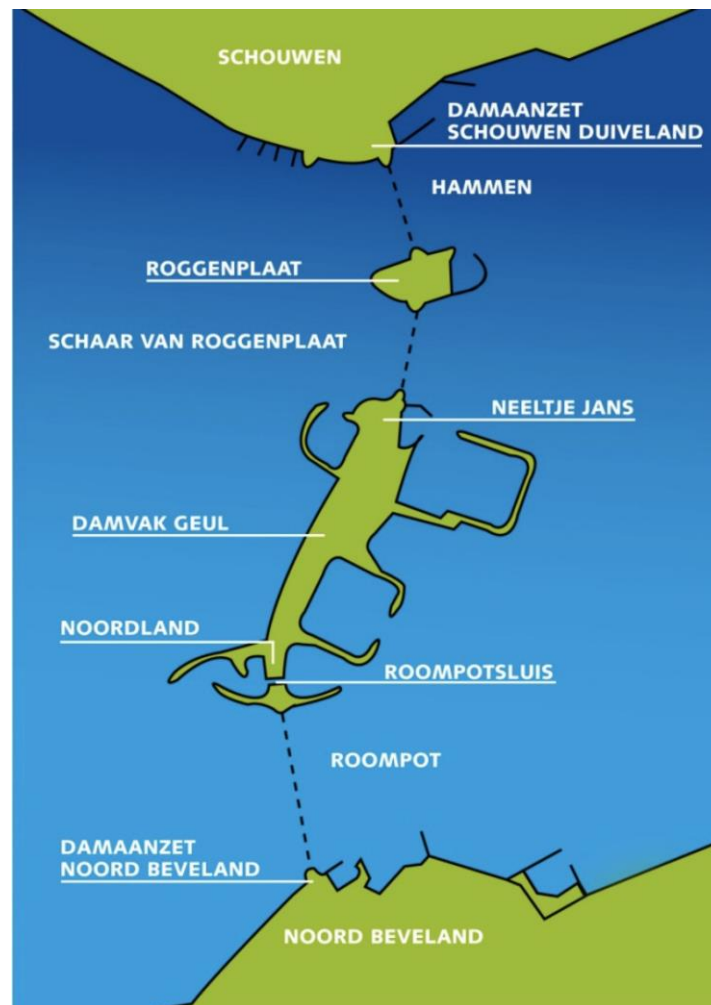


Figure 9.19 Overview of the openings (Hammen, Schaar van Roggenplaat and Roompot) and the artificial islands (Roggenplaat, Neeltje Jans and Noordland)

The current closable storm surge barrier was built in the openings Hammen, Schaar van Roggenplaat and Roompot, see Figure 9.19. The barrier was finished in 1985 and cost up to 3 billion gulden. The design of the current storm surge barrier is shown in Figure 9.20. The barrier consists of 65 concrete piers and 62 steel slides. (Roeland van Straten, 2013)



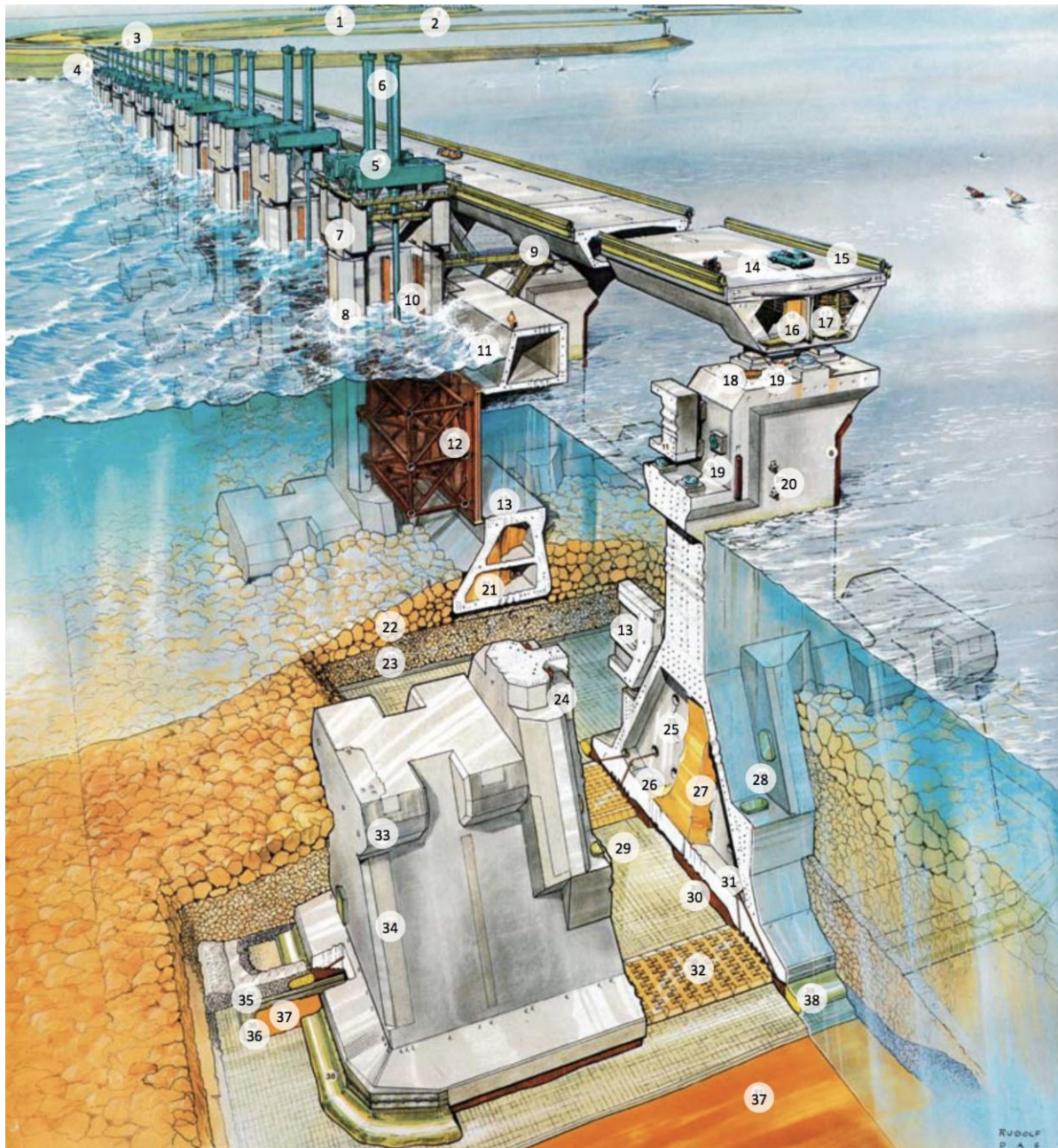


Figure 9.20 Overview of the construction of the storm surge barrier

- |  |   |  |   |
|--|---|--|---|
| 1 opening Hammen                       | 11 upper beam                               | 21 sand filling sill beam                | 31 grout pipes                          |
| 2 opening Schaar van Roggenplaat       | 12 slide                                    | 22 top layer threshold                   | 32 foundation mat                       |
| 3 sluice Roompot                       | 13 sill beam                                | 23 core layer threshold                  | 33 lifting lugs                         |
| 4 rubble as land abutment              | 14 traffic road                             | 24 bearing top slide                     | 34 protective layer against bulk stones |
| 5 cardan girder carries cylinders      | 15 guardrail                                | 25 partition holes for filling with sand | 35 extending of gravel bag              |
| 6 lift cylinders                       | 16 devices gallery                          | 26 piers bottom                          | 36 lower mat                            |
| 7 extending part of pier               | 17 cable and pipes duct                     | 27 sand filling                          | 37 consolidated soil Eastern Scheldt    |
| 8 wood fender                          | 18 access pier                              | 28 bearings sill beam                    | 38 gravel bag                           |
| 9 platforms and stairs for maintenance | 19 bearings                                 | 29 upper mat                             |   |
| 10 conduction of slide                 | 20 anchor points for maintenance sill beams | 30 grout                                 |   |

### 9.6.1 Design Requirements and Assumptions

The fiber reinforced polymers could be used in the replacement of the existing slides due to their high strength properties, low self-weight and low maintenance. The requirements of the new FRP slides are based on the requirements of the current slides, including the geometric boundary conditions and loads on the slides. The geometric boundary conditions focuses on the dimension of the slides, fatigue time and the range of temperature that the slides can be movable. The design process is shown in Figure 9.21.

The loads discussed for the FRP slides are vertical wave loads, dead load, torsion, longitudinal loads, ice loads, wind loads, water flows, collision and terrorist attack condition. The horizontal wave impact loads are neglected because they are much lower than the others. Water pressure loads are discussed by both positive drop and negative drop conditions, modeled as a distributed load of  $100\text{kN}/\text{m}^2$  and  $35\text{kN}/\text{m}^2$ , respectively. Wind loads are much smaller than the water pressure loads, with only  $0.72\text{kN}/\text{m}^2$ . Vertical wave impact loads on horizontal elements near the water level can reach pressures up to  $240\text{ kN}/\text{m}^2$  for truss beams and  $440\text{ kN}/\text{m}^2$  for horizontal plates. (2016, R.W. van Straten)

Based on the situation of the current slide and surrounding environments, several assumptions are made for the FRP slides design: 1, No hydraulic research will be carried out on the new slide design. 2, The slides should function with the current movement works. 3, The design of the highest slide is considered to be decisive. 4, Due to sea level rise the slides height could be increased with 0.6 m, also the upper beam could be lifted with 0.6 m in that case. 5, only the water pressure difference load including the static wave pressure are considered. 6, The upper beam and sill beam are positioned directly beside the rabbet (at the Eastern Scheldt side). (2016, R.W. van Straten)

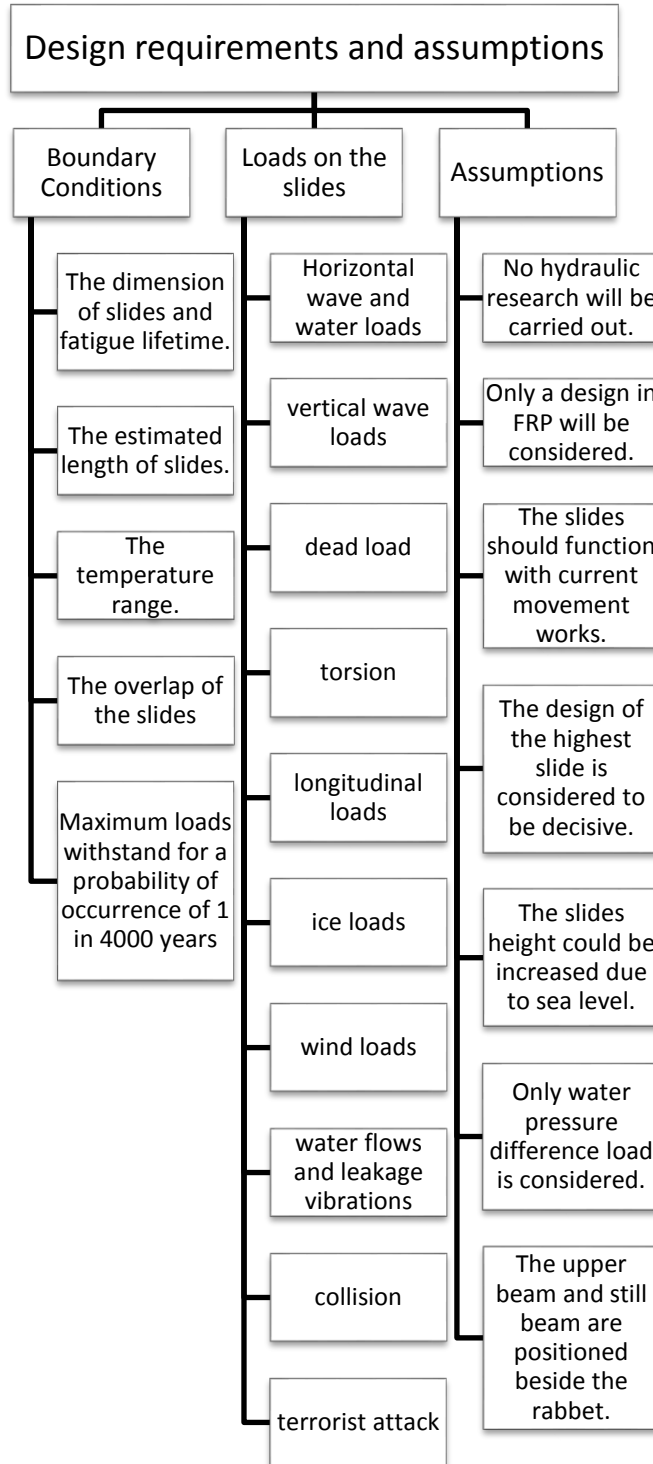


Figure 9.21 Design requirements and assumptions

### 9.6.2 Material Selection

This selection of materials is based on the properties of FRP and manufacturing process of FRP. The suitable manufacturing processes is selected after selecting suitable reinforcement and resin. Then, the lamina properties of the selection are calculated and the material safety factors and design values are determined. The material selection process is shown in Figure 9.22

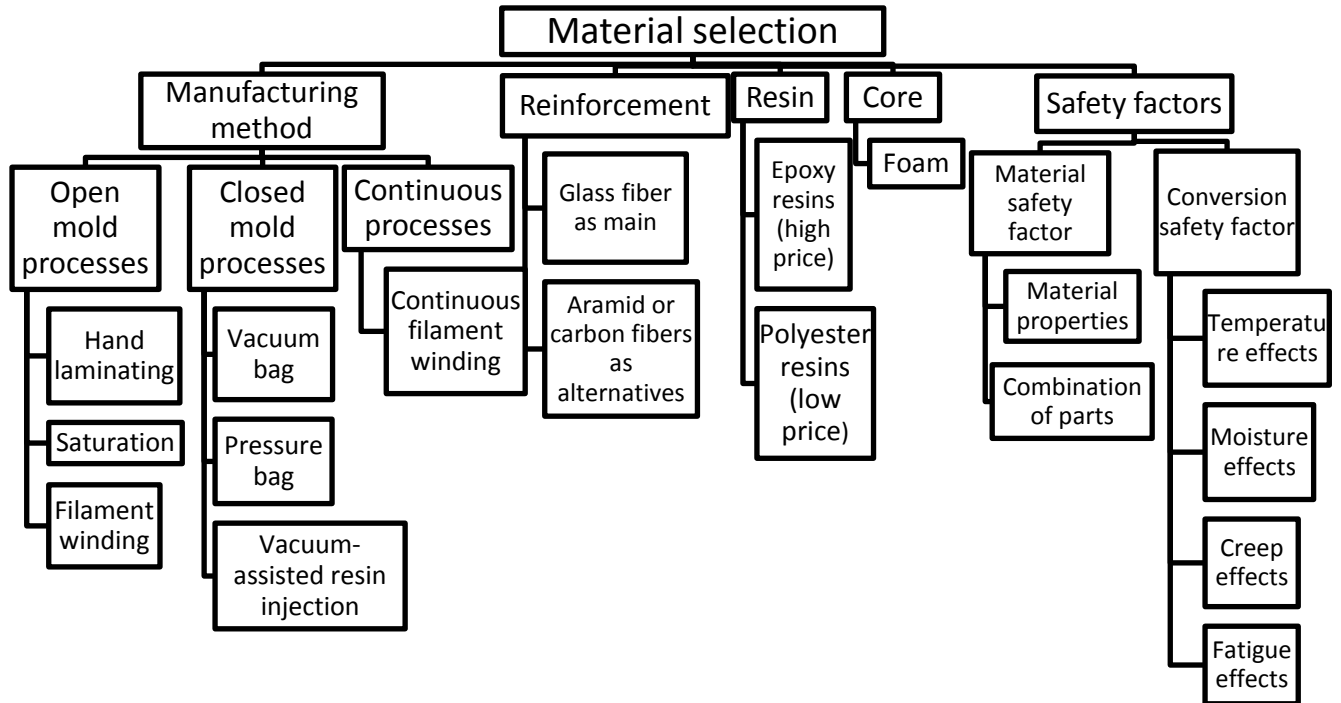


Figure 9.22 Material selections

The manufacturing methods which are suitable for composite slides in the Eastern Scheldt barrier should achieve high fiber contents, which improve the strength and stiffness of the material. The selection of manufacturing processes is shown in **Error! Reference source not found.** and the suitable manufacturing methods are shown in **Error! Reference source not found.**. The reinforcement types and the possibility to use polyester, vinyl ester and epoxy as resin are both mentioned per method. (2016, R.W. van Straten)

Table 9.6 Selection of manufacturing processes for composite slides

Manufacturing process	Suitable	Reason
<b>Open mold processes</b>		
hand laminating	Yes	
saturation	Yes	
spray-up	No	Only random reinforcement
auto spray-up	No	Only random reinforcement
filament winding	Yes	
spray winding	No	Not cost-effective for highly loaded structures
centrifugal casting	No	random reinforcement + mats of cloths and resin inner surface not especially needed
<b>Closed mold processes</b>		
vacuum bag	Yes	
pressure bag	Yes	
autoclave	No	Limited size
cold press	No	Limited press size
hot press	No	Limited press size
resin injection	No	Limited size
vacuum-assisted resin injection	Yes	
injection molding	No	Limited size
<b>Continuous processes</b>		
continuous laminating	No	low fibre volume fraction
pulltrusion	No	Only suitable for profiles
continuous filament winding	Yes	continuous form not especially needed for the slides

Table 9.7 Manufacturing methods which are suitable for the composite slides

Manufacturing process	Polyester	Vinyl ester	Epoxy	Reinforcement
<b>Open mold processes</b>				
hand laminating	X	X	X	most types
saturation	only low viscosity resins			most types
filament winding	X	X	X	only continuous rovings
<b>Closed mold processes</b>				
vacuum bag	as far as know: all			most types
pressure bag	as far as know: all			most types
vacuum-assisted resin injection	as far as know: all			all types
<b>Continuous processes</b>				
continuous filament winding	as far as know: all			only continuous rovings

For reinforcement, glass fiber is selected since they are much cheaper than aramid or carbon fibers though the stiffness relatively lower. For resin, polyester resin is selected also because of their low price. Foam is chosen as core material, since it is a widely used and isotropic. The lamella



properties are determined by the selection of reinforcement and resin. A reduction factor on these properties should be applied. For uni- directional (UD) lamella the reduction factor is 0,97. (2016, R.W. van Straten)

Both the material and conversion factor should be applied for FRP. The design value of material properties is calculated as :

$$X_d = \frac{X_k}{\gamma_m \cdot \gamma_c}$$

With:

$X_k$	Nominal value of a property
$\gamma_m$	Material safety factor
$\gamma_c$	Conversion safety factor

In the material safety factor, the uncertainties due to the combination parts should be taken into account. Also the uncertainties regarding obtaining the right material properties are taken into account.

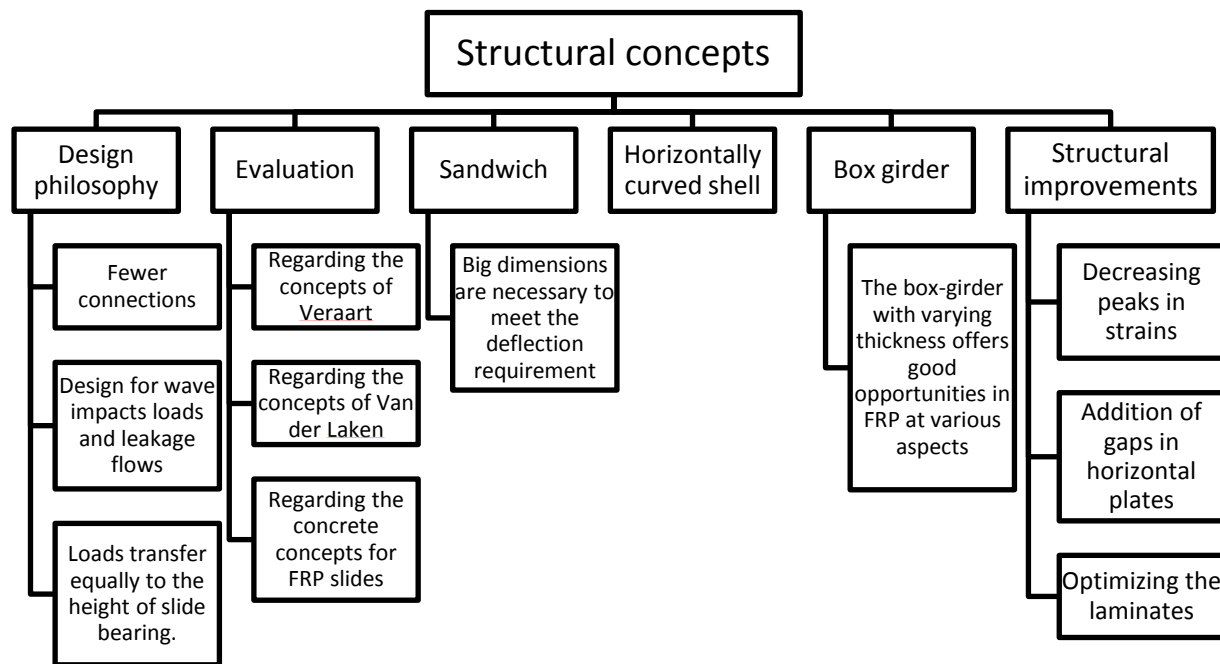
In the conversion safety factor, four effects are taken into account: temperature effects, moisture effects, creep effects and fatigue effects. Temperature factor is based on resin systems with a heat distortion temperature (HDT) of minimal 30°. Moisture factor takes account of the decrease of mechanical properties which are caused by moisture intrusion. Creep effects are caused by long duration (sustained) loads. The fatigue effects in this situation are not taken into account.

### 9.6.3 Structural Concepts

The structural concepts are followed by three important aspects or the development of variants for the slides :

- Use of limited number of connections
- Optimal esign under wave impacts loads and leakage flows
- Uniform load transfer over the entire height of the slide bearings.

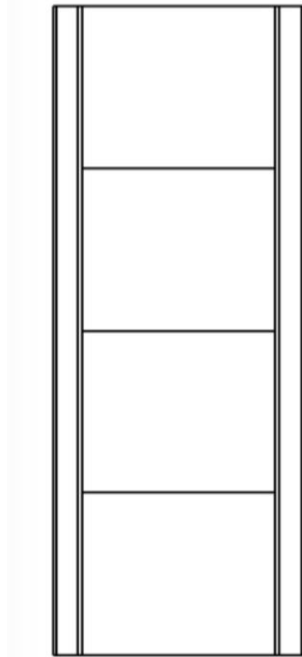
The design includes guiding principles for the structural concepts, description and calculation of different variants. Then the most suitable variant is selected. The design process is shown in **Error!**  
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*Figure 9.23 Structural concepts*

Structures of sandwich, horizontally curved shell and the box girder are compared. The sandwich variant consists of a core and two skins which are connected by some webs. Due to its dimension, it is not economical to apply for the slide. The horizontally curved shell can be easily designed as a pressure arc. But it cannot be applied directly to the Eastern Scheldt barrier because 1, the piers are not designed to carry horizontal forces; 2, The water resistance cladding should be placed in one plane along with the sill beam and the upper beam. (2016, R.W. van Straten)

The box-girder variant consists of a water defense cladding which is stiffened by some horizontal plates as shown in Figure 9.24. After conducting Finite Element analysis for all three structures, the box-girder with varying thickness offers close to optimal in FRP at various aspects. The box-girder can fulfill the strength and deflection requirements. The deflection of this variant is so big that the slide will hit the upper beam of the barrier so the thickness of the slide should be reduced to make that a realistic adjustment, which brings to the next step. (2016, R.W. van Straten)



*Figure 9.24 Two sandwiches are connected with horizontal plates*

#### **9.6.4 Deflection requirements**

The maximum deflection requirement influences the design of a composite slide since the stiffness of the composite is low. Therefore the slide is thick and such thick slide is not feasible, since the bottom of the slide should be adjusted to an oblique bottom to prevent vibrations by flow. (2016, R.W. van Straten) There are two options provided. One option called rigorous solution that requires extra adjustments on the current barrier to vanish the deflection requirement. The upper beam should be removed, the sill beam should be replaced and the rabbets should be increased. Another option requires the increase of leakage gap or application of a camber to meet and increase the stiffness of FRP slide by using carbon fibers. Extra adjustments on the current barrier are not required in this case.

The second option is not feasible by using glass fiber which is much cheaper than carbon fiber. So the first option was chosen. The advantages of the first solution on the long term are: The top of the slide has increased to cope with the sea level rise in the future; The sill beam height is halved to increase the trough-flow opening of the barrier.

Some other solutions are checked as shown in Figure 9.25 by using carbon fibers, increasing the leakage gap or apply a camber. With a combination of these options, it is probably possible to reduce the thickness of the slide. However, the slide will become more expensive, since carbon fibers should be probably used.

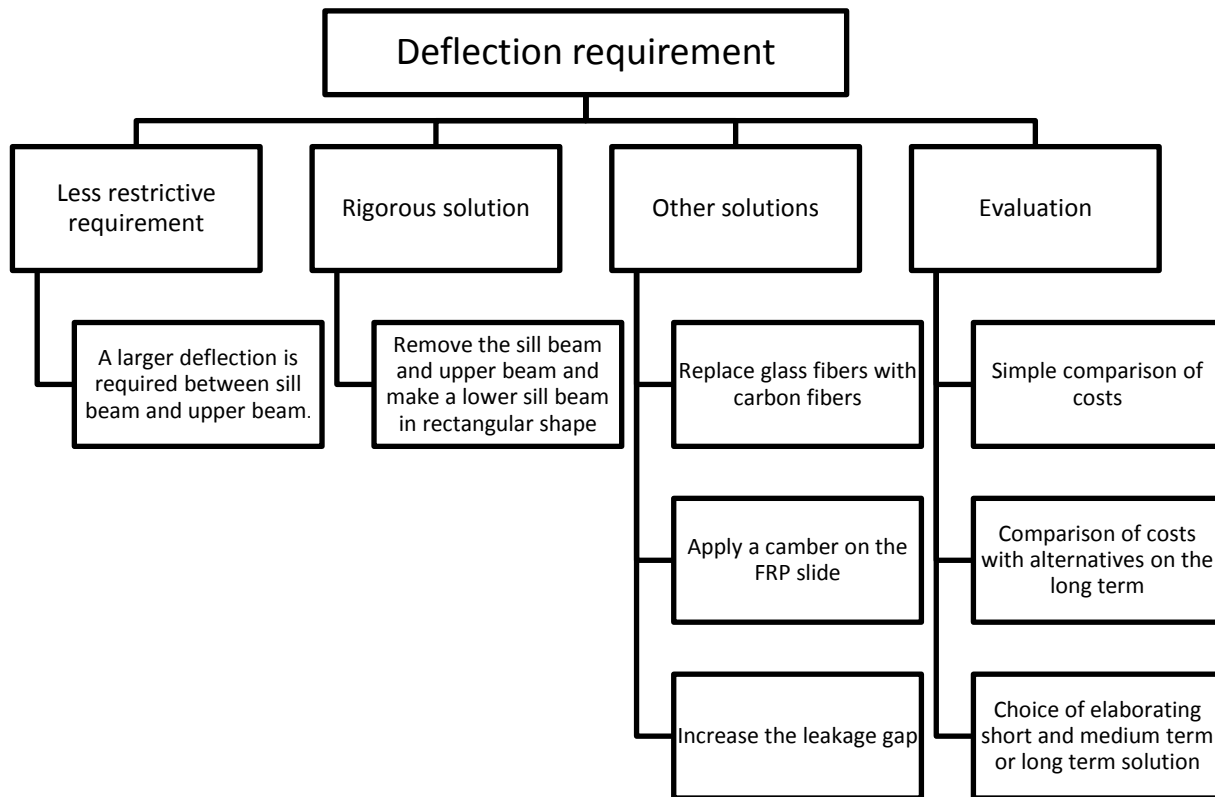


Figure 9.25 Deflection requirement

### 9.6.5 Cost comparison

The cost comparison is made among different variants which can withstand sea level rise. The process is shown in Figure 9.26. Including the previous rigorous solution, there are two more variants that can offer a solution against flooding: rising dikes and dam.

A comparison of the costs of each variant in million euros is shown in Table 9.8. The costs of dike raising and constructing a dam are converted to euro's and are updated to the present price level.

The dam variant is not very logical, since in 1976 the decision is made to build a closeable storm surge barrier, and not to build a dam. A dam would interfere with the nature in the Eastern Scheldt, which is a disadvantage in comparison with the other two variants. The costs of the dam variant are also much higher than the costs of the rigorous solution. Therefore the dam variant is not preferable. (2016, R.W. van Straten)

The two other variants, dike raising and the rigorous solution, can withstand the sea level rise and help to solve the problem with the disappearing intertidal zones and are therefore good alternatives.

The rigorous solution will probably strengthen the position of the storm surge barrier as an exemplary project for the Dutch hydraulic engineering industry, dike raising will possibly weaken this position. (2016, R.W. van Straten)

Table 9.8 Investment of investment costs (Price level 1976)

Variant	Price (million euro)
Dike raising	1340
Dam	995
Rigorously solution	225

Also a life cycle analysis is carried out to compare the investment costs of an FRP slide with the maintenance costs of the current barrier. The life cycle costs of an FRP slide are much lower over 100 years, the payback time of the FRP slides is between 40 and 50 years. Therefore, it's technically feasible and financially attractive to replace the current steel slides with larger FRP slides.

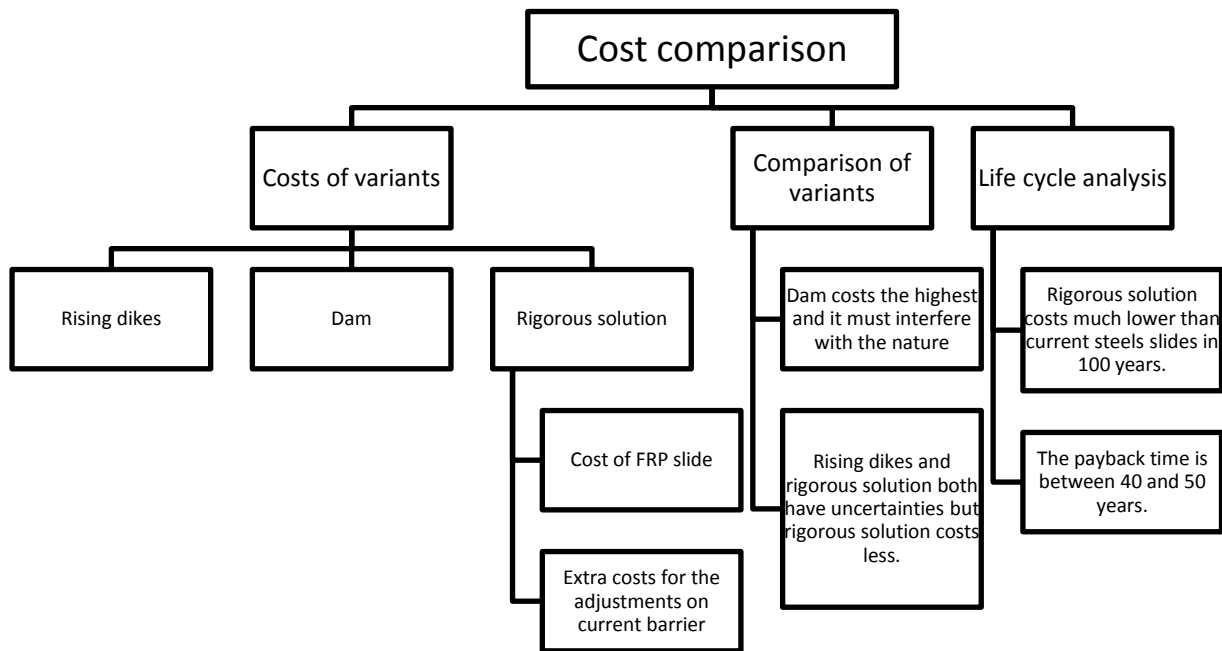


Figure 9.26 Cost comparison



## 10 INSPECTION, OPERATIONS AND MAINTENANCE

This chapter briefly describes the Nondestructive Testing (NDT) methods that are commonly used for condition assessment of FRP composite structural members, with focus on field use. Examples of field condition assessment include checking for debonding between FRP composite fabric wrap and the underlying concrete member, checking for debonding between polymer concrete overlay and the underlying concrete or composite bridge deck, or checking for delaminations within a FRP plate or flange of a FRP bridge deck. For in-situ testing, the NDT equipment has to be light-weight and portable, and should offer easy data acquisition capability. In addition, NDT systems that offer real-time data analysis capability to identify debonds and delaminations in the field are highly desirable. This chapter describes two such NDT methods, infrared thermography and digital tap testing.

### 10.1 Infrared Camera and Heating System

Infrared Thermography is one of the widely used field testing systems for nondestructive assessment of FRP composite structural member (Halabe et al 2007, Halabe and GangaRao 2013, Halabe et al 2010, Halabe et al 2014). Figure 10.1(a) shows the picture of a portable infrared camera that can acquire “still” digital infrared images. This infrared camera is capable of capturing the surface thermal image in the temperature range between  $-10^{\circ}\text{C}$  and  $+350^{\circ}\text{C}$  with an accuracy of  $\pm 0.1^{\circ}\text{C}$  at an ambient temperature of  $30^{\circ}\text{C}$ . This low-cost (less than \$3000) hand-held camera is one of the lightest available models weighing 1.21 pounds. The captured images can be stored in radiometric JPEG format directly on a removable SD flash card housed in the camera, and can be further analyzed using the associated software if required. For most field applications, a quick analysis can be conducted in real-time in the field by simply looking at the infrared images and identifying debonded areas which correspond to the “hot spots” or brighter areas in the image. Figure 10.1(b) shows an advanced infrared camera (cost of about \$50,000) with an accuracy of  $\pm 0.06^{\circ}\text{C}$  at an ambient temperature of  $30^{\circ}\text{C}$ . This camera can capture infrared images in the “still” or “video” modes. The capture rate in the video mode can be up to 60 frames/s (even higher capture rates are now available), which enables accurate recording of the surface cooling pattern. Analysis of the cooling data can lead to estimation of the defect depth and also allows use of advanced image processing algorithms utilizing the contrast parameters and derivative analysis. Therefore, this kind of camera, which is significantly heavy and expensive, is typically used for laboratory research.

Figure 10.1(c) shows the picture of shop heater used for heating the GFRP/CFRP wrapped components prior to capturing of infrared images. It is a 1500W quartz heater with two 750W heating rods. This shop heater does not have any tilt control safety feature, which allows it to be used in any position in the field. The components under inspection should be uniformly heated by moving the heater back and forth over the surface from a distance of about 12” (0.3 m). For detecting debonds in FRP wrapped components, a heating duration of 60s (one minute) is recommended. Subsurface air-filled debonds impede the heat transfer through the thickness of the composite, which results in higher surface temperatures above debonded areas and can be seen as hot spots in an infrared image. In case of composite decks, solar heating on a hot sunny day is

adequate and use of a heater is not needed. However, heaters are needed for structural components under the bridge to heat the specimens prior to acquiring infrared image.

Recent advances in infrared test equipment has resulted in advanced systems (Figure 10.2) which include computer controlled pulsed and flash heating systems, advanced infrared camera, and advanced data processing algorithms (e.g., thermal signal reconstruction using contrast parameters, first and second derivative images). Such test systems are bulky and often difficult to carry under a bridge. Currently, such systems are being used in the laboratory environment. Other techniques such as Ground Penetrating Radar (GPR) have been found to be moderately effective for defect detection in composites [Pyakurel and Halabe, 2013; Hing and Halabe 2010].



(a)

(b)

(c)

*Figure 10.1 Infrared testing equipment - (a) low cost infrared camera (b) advanced infrared camera, and (c) shop heater*

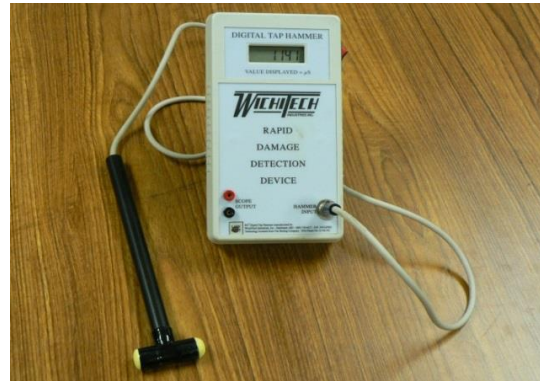


*Figure 10.2 Advanced infrared testing equipment including pulsed and flashed heating and data processing computer*

## **10.2 Digital Tap Hammer**

The digital tap hammer (Figure 10.3) is an electronic device that displays a number when a test object is tapped. As per the user manual for this device, for an area to be classified as a debond or subsurface defect, the tap number should be at least 10% higher than the number from defect-free areas. This device has been developed by Boeing for detecting delaminations in thin composites (typically up to 10 mm thickness). The device also works very well for detecting debonds between FRP composite wraps and underlying concrete member. For FRP composite bonded concrete, a tap hammer reading in the range of 1100 to 1180 represents good bond [Halabe, 2013; Halabe et

al., 2014]. For most locations with a good bond, the reading is around 1140. A reading exceeding 10% of this value, that is exceeding about 1250, represents debonded region. The device offers an easy way to cross check the infrared thermography results and can also be used independently. It should be noted that the tap hammer device offers point-by-point measurement while infrared thermography is an area scanning technique.



*Figure 10.3 Digital tap hammer*

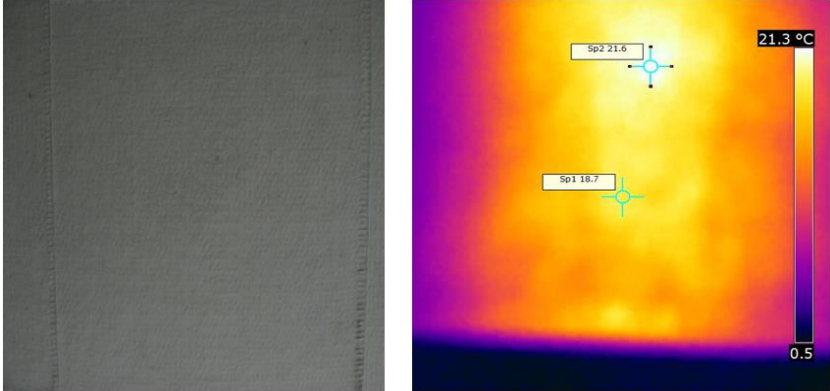
### 10.3 Sample Field Testing Results

Figure 10.4(a) shows an area on a concrete T-beam that was wrapped with CFRP fabric about a decade ago. This beam is part of the Muddy Creek Bridge in WV that was built in 1943. (b) shows the recently acquired infrared image using the infrared camera shown in Figure 10.4(a). This image was acquired after heating the area with a shop heater for about 60 seconds. Figure 10.4(b) indicates the presence of a small debond with a slightly higher temperature of 21.6<sup>0</sup>C (70.9<sup>0</sup>F) at spot Sp2 when compared to temperature at Sp1 of 18.7<sup>0</sup>C (65.7<sup>0</sup>F) representing the surrounding region. Typically, areas which are hotter by at least 2 to 3<sup>0</sup>C compared to the background (defect-free) area temperature are classified as defective (i.e., presence of subsurface debonds). The digital tap hammer reading in this area ranged from 1100 to 1180 at all the defect-free locations, but gave a higher reading of 1255 at spot Sp2 indicating a tiny defect with an approximate size of 1/4" x 1/4" (6 mm x 6 mm) [Halabe et al. 2014].

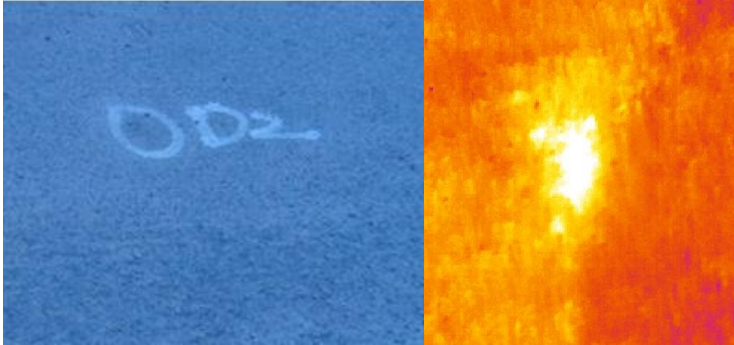
Figure 10.5 shows a digital picture and corresponding infrared image of an area on the La Chein GFRP bridge deck which was overlaid with 3/8" (9.5mm) thick polymer concrete overlay. The infrared image was acquired around mid-day after the bridge was heated by the sun. The hot (bright white) spot in the infrared image corresponds to the circular debond "D2" in the digital picture. This bridge had several debonds between the wearing surface and the underlying GFRP deck which was mapped using infrared thermography in order to determine the extent of debonding for planning the repair (overlay replacement) work.

The results presented in this chapter demonstrate the effectiveness of using portable NDT test equipment which are fairly easy to use in the field environment. Low cost infrared camera was found to be very effective in detecting debonds between the FRP fabric and the underlying concrete member, and between polymer concrete overlay and underlying bridge deck. Digital tap testing is another portable equipment that is very useful for debond detection in the field. NDT techniques should be adopted for routine field inspection of FRP composite structural components, since early

detection of subsurface defects and timely repair using FRP composite fabrics or FRP composite plates in accordance with ACI 440.2R-08 [ACI 440.2R-08, 2008] can ensure continued structural integrity and prolong the service life of FRP composite wrapped members.



(a) (b)  
*Figure 10.4 Digital picture, and (b) infrared image of the inner side of outer west beam in Muddy Creek Bridge*



*Figure 10.5 Digital picture and corresponding infrared images of various debonded areas in the La Chein GFRP bridge deck*

## **11 CONCLUSIONS, DISCUSSIONS AND RECOMMENDATIONS**

This report deals with composites for hydraulic structures. After providing introduction, characteristics and manufacturing techniques of composites along with recent advances are presented, followed by a wide range of composite applications in general markets. Focus is placed on applications of composites in waterfront, marine, navigational structures. Design of hydraulic composite structures is presented for the cases available. Intention is to provide information on composites and design methodologies that are applicable for design and maintenance of navigational structures. This report is useful for parties including government managers, consultants, designers, contractors, maintenance engineers interested in design and rehab of navigational structures with FRP structural components, rebars and wraps resulting in minimal traffic interruption while maximizing cost effectiveness. We will engage more members for their contributions to the report. We will also solicit more case studies from non-member countries.



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