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Fiber Reinforced Polymer Composite

Abhishek^{#1}, Neeraj^{*2}

[#]Civil Department, GITM, Kablana (Jhajjar)

Abstract—Fiber reinforced polymer composite (FRP) is a new construction material, gradually gaining acceptance from civil engineers. Bridge engineering is among the fields in civil engineering benefiting from the introduction of FRP composite. Its advantages over traditional construction materials are its high tensile strength to weight ratio, ability to be molded into various shapes and potential resistance to environmental conditions, resulting in potentially low maintenance cost. These properties make FRP composite a good alternative for innovative construction. This paper is a review of various types of fiber reinforcements and composite fiber.

Keywords—fiber reinforced polymer, composite materials.

I. INTRODUCTION

Fiber reinforced polymer (FRP) is a composite material made by combining two or more materials to give a new combination of Properties. However, FRP is different from other composites in that its constituent materials are different at the molecular level and are mechanically separable [1]. The mechanical and physical properties of FRP are controlled by its constituent properties and by structural configurations at micro level. Therefore, the design and analysis of any FRP structural member requires a good knowledge of the material properties, which are dependent on the manufacturing process and the properties of constituent materials. FRP composite is a two phased material, hence its anisotropic properties. It is composed of fiber and matrix, which are bonded at interface. Each of these different phases has to perform its required function based on mechanical properties, so that the composite system performs satisfactorily as a whole. In this case, the reinforcing fiber provides FRP composite with strength and stiffness, while the matrix gives rigidity and environmental protection. Fiber is a material made into a long filament.

II. WHAT IS REALLY IN COMPOSITES?

As the name implies, advance fiber reinforced polymer composites is made of fiber reinforcements, resin, fillers, and additives. The fibers provide increased stiffness and tensile capacity. The resin offers high compressive strength and binds the fibers into a firm matrix. The fillers serve to reduce cost and shrinkage. The additives help to improve not only the mechanical and physical properties of the composites but also

workability. The discussions that follow immediately will explain the basic functions and behaviors of the constituents.

CHARACTERISTICS OF COMPOSITES

The mechanical properties of composites depend on many variables such as fiber types, orientations, and architecture. The fiber architecture refers to the preformed textile configurations by braiding, knitting, or weaving. Composites are anisotropic materials with their strength being different in any direction. Their stress-strain curves are linearly elastic to the point of failure by rupture. The polymeric resin in a composite material, which consists of viscous fluid and elastic solids, responds visco-elastically to applied loads. Although the viscoelastic material will creep and relax under a sustained load, it can be designed to perform satisfactorily. Composites have many excellent structural qualities and some examples are high strength, material toughness, fatigue endurance, and light weight. Other highly desirable qualities are high resistance to elevated temperature, abrasion, corrosion, and chemical attack.

Some of the advantages in the use of composite structural members include the ease of manufacturing, fabrication, handling, and erection. Project delivery time can be short. It took the Russell county engineer one day to install the deck panels in the first vehicular composite bridge. Composites can be formulated and designed for high performance, durability and extended service life. They have excellent strength-to-weight ratios. If durability can be proven to last 75 years,

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composites can be economically justified using the life-cycle cost method.

Some of the disadvantages in the use of composites in bridges are high first cost, creep, and shrinkage. The design and construction require highly trained specialists from many engineering and material science disciplines. The composites have a potential for environmental degradation, for examples, alkalis' attack and ultraviolet radiation exposure. There are very little or non-existent design guidance and/or standards. There is a lack of joining and/or fastening technology. Because of the use of thin sections, there are concerns in global and local buckling. Although the light weight feature may be an advantage in the response to earthquake loading, it could render the structure aerodynamically unstable. In manufacturing with the hand layup process, there is a concern about the consistency of the material properties.

III. FIBER REINFORCEMENTS

The fiber is an important constituent in composites. A great deal of research and development has been done with the fibers on the effects in the types, volume fraction, architecture, and orientations. The fiber generally occupies 30% - 70% of the matrix volume in the composites. The fibers can be chopped, woven, stitched, and/or braided. They are usually treated with sizings such as starch, gelatin, oil or wax to improve the bond as well as binders to improve the handling. The most common types of fibers used in advanced composites for structural applications are the fiberglass, aramid, and carbon. The fiberglass is the least expensive and carbon being the most expensive. The cost of aramid fibers is about the same as the lower grades of the carbon fiber. "Other high-strength and high-modulus fibers such as boron are at the present time considered to be economically prohibitive"[14].

Glass Fibers

The glass fibers are divided into three classes -- E-glass, S-glass and C-glass. The E-glass is designated for electrical use and the S-glass for high strength. The C-glass is for high corrosion resistance, and it is uncommon for civil engineering application. Of the three fibers, the E-glass is the most common reinforcement material used in civil structures. It is produced from lime-alumina-borosilicate which can be easily obtained from abundance of raw materials like sand. The fibers are drawn into very fine filaments with diameters ranging from 2 to 13 X 10⁻⁶ m. The glass fiber strength and modulus can degrade with increasing temperature. Although the glass material creeps under a sustained load, it can be designed to perform satisfactorily. The fiber itself is regarded

as an isotropic material and has a lower thermal expansion coefficient than that of steel.

Typical Properties	E-Glass	S-Glass
Density (g/cm ³)	2.60	2.50
Young's Modulus (GPa)	72	87
Tensile Strength (GPa)	1.72	2.53
Tensile Elongation (%)	2.4	2.9

Table 1 [5]

Aramid Fibers

These are synthetic organic fibers consisting of aromatic polyamides. The aramid fibers have excellent fatigue and creep resistance. Although there are several commercial grades of aramid fibers available, the two most common ones used in structural applications are Kevlar® 29 and Kevlar® 49. The Young's Modulus curve for Kevlar® 29 is linear to a value of 83 GPa but then becomes slightly concave upward to a value of 100 GPa at rupture; whereas, for Kevlar® 49 the curve is linear to a value of 124 GPa at rupture (see Table 2). As an anisotropic material, its transverse and shear modulus are an order of magnitude less than those in the longitudinal direction. The fibers can have difficulty achieving a chemical or mechanical bond with the resin.

Typical Properties	Kevlar 29	Kevlar 49
Density (g/cm ³)	1.44	1.44
Young's Modulus (GPa)	83/100	124
Tensile Strength (GPa)	2.27	2.27
Tensile Elongation (%)	2.8	1.8

TABLE 2 [5]

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Carbon Fibers

The graphite or carbon fiber is made from three types of polymer precursors -- polyacrylonitrile (PAN) fiber, rayon fiber, and pitch. The tensile stress-strain curve is linear to the point of rupture. Although there are many carbon fibers available on the open market, they can be arbitrarily divided into three grades as shown in Table 3. They have lower thermal expansion coefficients than both the glass and aramid fibers. The carbon fiber is an anisotropic material, and its transverse modulus are an order of magnitude less than its longitudinal modulus. The material has a very high fatigue and creep resistance.

Typical Properties	High Strength	High Modulus
Density (g/cm ³)	1.8	1.9
Young's Modulus (GPa)	230	370
Tensile Strength (GPa)	2.48	1.79
Tensile Elongation (%)	1.1	0.5

Table 3 [5]

Since its tensile strength decreases with increasing modulus, its strain at rupture will also be much lower. Because of the material brittleness at higher modulus, it becomes critical in joint and connection details, which can have high stress concentrations. As a result of this phenomenon, carbon composite laminates are more effective with adhesive bonding that eliminates mechanical fasteners.

IV. MATRIX

Matrix material is a polymer composed of molecules made from many simpler and smaller units called monomer. Without the presence of matrix material, fibers in and of themselves are of little use. The matrix must have a lower modulus and greater elongation than those of fibers, so that fibers can carry maximum load. The important functions of matrix material in FRP composite include:

- i) Bind the fibers together and transferring the load to the fibers by adhesion and/or friction.

- ii) Provide rigidity and shape to the structural member.
- iii) Isolate the fibers so that they can act separately, resulting in slow or no crack propagation.
- iv) Provide protection to the fibers against chemical and mechanical damages.
- v) Influence performance characteristics such as ductility, impact strength.
- vi) Provide finish color and surface finish for connections.

V. RESIN SYSTEM

The resin is another important constituents in composites. The two classes of resins are the thermoplastics and thermosets. A thermoplastic resin remains a solid at room temperature. It melts when heated and solidifies when cooled. The long-chain polymers do not chemically cross link. Because they do not cure permanently, they are undesirable for structural application. Conversely, a thermosetting resin will cure permanently by irreversible cross linking at elevated temperatures. This characteristic makes the thermoset resin composites very desirable for structural applications. The most common resins used in composites are the unsaturated polyesters, epoxies, and vinyl esters; the least common ones are the polyurethanes and phenolics.

Unsaturated Polyesters

The unsaturated polyester amounts to about 75% of all polyester resins used in USA. It is produced by the condensation polymerization of dicarboxylic acids and dihydric alcohols. The formulation contains an unsaturated material such as maleic anhydride or fumaric acid which is a part of the dicarboxylic acid component. The formulation affects the viscosity, reactivity, resiliency and heat deflection temperature (HDT). The viscosity controls the speed and degree of wet-out (saturation) of the fibers. The reactivity affects cure time and peak exotherm (heat generation) temperatures. High exotherm is needed for a thin section curing at room temperature and low exotherm for a thick section. Resiliency or flexible grade composites have a higher elongation, lower modulus, and HDT. The HDT is a short term thermal property which measures the thermal sensitivity and stability of the resins.

The advantages cited in the unsaturated polyester are its dimensional stability and affordable cost. Other advantages include ease in handling, processing, and fabricating. Some of the special formulations are high corrosion resistant and fire

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retardants. This resin is probably the best value for a balance between performance and structural capabilities.

Epoxies

The epoxies used in composites are mainly the glycidyl ethers and amines. The material properties and cure rates can be formulated to meet the required performance. Epoxies are generally found in marine, automotive, electrical and appliance applications. The high viscosity in epoxy resins limits its use to certain processes such as molding, filament winding, and hand lay-up. The right curing agent should be carefully selected because it will affect the type of chemical reaction, pot life and final material properties. Although epoxies can be expensive, it may be worth the cost when high performance is required.

Vinyl Esters

The vinyl ester resins were developed to take advantage of both the workability of the epoxy resins and the fast curing of the polyesters. The vinyl ester has higher physical properties than polyesters but costs less than epoxies. The acrylic esters are dissolved in a styrene monomer to produce vinyl ester resins which are cured with organic peroxides. A composite product containing a vinyl ester resin can withstand high toughness demand and offer excellent corrosion resistance.

Polyurethanes

Polyurethanes are produced by combining polyisocyanate and polyol in a reaction injection molding process or in a reinforced reaction injection molding process. They are cured into very tough and high corrosion resistance materials which are found in many high performance paint coatings.

Phenolics

The phenolic resins are made from phenols and formaldehyde, and they are divided into resole and novolac resins. The resoles are prepared under alkaline conditions with formaldehyde/phenol (F/P) ratios greater than one. On the contrary, novolacs are prepared under acidic conditions with F/P ratios less than one. Resoles are cured by applying heat and/or by adding acids. Novolacs are cured when reacting chemically with methylene groups in the hardener. The phenolics are rated for good resistance to high temperature, good thermal stability, and low smoke generation.

VI. FILLERS

Since resins are very expensive, it will not be cost effective to fill up the voids in a composite matrix purely with resins.

Fillers are added to the resin matrix for controlling material cost and improving its mechanical and chemical properties. Some composites that are rich in resins can be subject to high shrinkage and creep and low tensile strength. Although these properties may be undesirable for structural applications, there may be a place for their use.

The three major types of fillers used in the composite industry are the calcium carbonate, kaolin, and alumina tri-hydrate. Other common fillers include mica, feldspar, wollastonite, silica, talc, and glasses. When one or more fillers are added to a properly formulated composite system, the improved performance includes fire and chemical resistance, high mechanical strength, and low shrinkage. Other improvements include toughness as well as high fatigue and creep resistance. Some fillers cause composites to have lower thermal expansion and exotherm coefficients. Wollastonite filler improves the composites' toughness for resistance to impact loading. Aluminum trihydrate improves on the fire resistance or flammability ratings. Some high strength formulations may not contain any filler because it increases the viscosity of the resin paste. High viscosity resins may have a problem wetting out completely for composite with heavy fiber reinforcement. Filler should not be used with fiber volume greater than 50% for the sheet molding composite production method.

VII. ADDITIVES

A variety of additives are used in the composites to improve the material properties, aesthetics, manufacturing process, and performance. The additives can be divided into three groups -- catalysts, promoters, and inhibitors; coloring dyes; and, releasing agents. Their roles are as simple as their names imply, and they need no further discussion here.

VIII. DESIGN CONSIDERATIONS

Professor Steenkamer and his coauthors at the University of Delaware stated it well when they wrote: "The development of a composite is a complex process that requires the simultaneous consideration of various parameters such as component geometry, production volume, reinforcement and matrix types and relative volumes, tooling requirements, process and market economics, etc. Every decision made during the product development process is intricately related to a set of three interacting decision's areas (i.e., materials, processing, and configuration)" [8].

The development of the advanced composite technology is an engineer's dream for innovative design and application. The characteristics of a composite can be tailored and designed to meet any desired specifications. Most of the information and

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design data available on composites are in the aerospace applications, but they are protected under the guise of proprietary systems and/or military classified documents. Unlike conventional isotropic materials of steel and concrete, there are no readily available design charts and guidelines to help the structural engineer. When it comes to working with composites as opposed to conventional materials, as the author has discovered, the difference can be as dramatic as night and day.

The challenge in applying composites is for one to understand the behavior of not only the constituents in the composites but also the completed end product in the way they respond to an applied load. Since a separate design specification for composites bridges is not yet available, existing bridge design guidelines may have to be used with some caution. Under the current American Association of State Highway and Transportation Officials (AASHTO) LRFD bridge design specifications, the philosophy is one of a probability-based limit state approach. The four basic limit states that is applicable in bridge design with advanced composite materials are the service, fatigue and fracture, strength, and extreme event.

The service limit states dictate the level of deformation and crack width under normal service conditions for a bridge to perform satisfactorily during its service life. The fatigue and fracture limit states restrict the stress range under normal service conditions within an expected number of load cycles. They are to limit crack growth under repetitive loading and to prevent fracture during the design life of a bridge. The strength limit states are to ensure that both the global and local strength and stability are provided to resist the statistically significant load combinations as experienced by a bridge during its design life. Some overstress and structural damage may be inevitable, but the overall integrity of the structure will not be compromised. The extreme event limit states ensure the structural survival of a bridge during a major earthquake or unusual collision force.

Based on some of the design data obtained from completed composite bridge structures to date, the deflection and/or local buckling govern composite design. With the inherent low section modulus of a composite structural member and critical high stress demand in structural applications, a designer should consider the following features carefully in his design:

Avoid abrupt thickness change in components

In steel or concrete design, an increase in the plate or flange thickness will usually keep the stresses under control. Although this concept also works for composites, it is

inefficient for a composite member to follow suit by increasing its overall part thickness. Because composites are viscoelastic materials, it is undesirable to create high stress risers. An understanding in the stress flow of a structural member will help a designer tailor the parts' thicknesses locally and avoid abrupt changes in its geometry.

Take advantage of geometrical shapes

In most design using composites, the stress level is very low. An optimal design in composites balances the stress, deflection, and stability with the use of flanges, ribs, stiffeners, honeycomb or box-cells, or tubes to maximize the stiffness of the section. By placing flanges farther apart at the top and bottom of a hollow core, the section modulus can be designed to span longer structures. By proportioning and orienting the cells adequately, local buckling can be eliminated and material stiffness can be increased.

Take advantage of hybrid systems

By taking advantage of the high stiffness in concrete and the high strength in composites, concrete filled carbon composite tubes for piles and main superstructure members in bridges are found to be very cost effective. Structural timber beams reinforced with composites in strategic locations have demonstrated an increase in the beam capacity. Prestressing tendons in concrete beams and decks are being studied in South Dakota and Michigan. Pultruded carbon FRP composite laminates bonded to steel beams and concrete slabs are being considered for strengthening of bridges. Composite fiberglass rods replacing reinforcing bars in concrete bridge decks are being studied in West Virginia. With any of these hybrid systems, the designer should account for the difference in the strains of each material affecting the compatibility of the total unit.

Use bonded assemblies and joints

Much work needs to be done in developing good joints to assemble the composite members. The successful use of the epoxy adhesive technology from the aerospace industry has been transferred to many recent civil structural applications. The concept of using epoxied shear transfer toggle strips has been demonstrated in two composite bridges in the United Kingdom. Plate bonding using epoxy adhesive on thin laminates to strengthen civil structures is seen as a promising application. The column wrapped with carbon tows (sheets) will be as strong as the epoxy bonded overlapping splice. The ability to advance the composite technology in civil structures will depend on the integrity and durability of these joints.

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Provide good details for connected joints

Discontinuities within a structural system can be a designer's nightmare. Special attention must be given to the local stress flow, overall load path, and joint lines that create weak links or porosity introduced during the manufacturing process. Other irregularities introduced during the cutting/drilling and fit up process must be evaluated. It is important to select proper fasteners. Certain composites with high flexural modulus are very brittle and have a tendency to granulate; they would not be suitable with screws. The ability to connect the components into a structural system will enable composites to go far in civil applications. It needs a technological breakthrough from the current thinking of using nuts and bolts to connect its members.

IX. CONCLUSION

There has been a great deal of development in the composite technology. It is an exciting time for civil engineers to be involved with composites. Both the US Government and private institutions are funding many demonstration bridge projects to show that advanced composite materials can be applied to rebuilding our highway infrastructure.

There is much to be learned about composites. Manufacturers, bridge owners, government officials, academia, researchers and contractors need to work together. Trade secrets should be honored and respected to the extent that information is provided to bridge owners to understand and evaluate the behavior of their structures. The bridge owner has been and will continue to be held responsible for the safety of the traveling public during the service life of a structure. Current laws require bridge owners to inventory and rate their bridges. The owners need to know the pertinent information and data that are used in bridge design, manufacturing, and fabricating. The AASHTO, ASTM, and American Concrete Institute have established numerous technical committees to develop design specifications, guidelines, standards, testing methods and methodologies. The Composites Institute which represents the composite industry has been coordinating the industry's effort to develop product design manuals, improve manufacturing processes, and collect test data. Numerous universities are offering research and design courses in composites. There are ample opportunities for civil engineers to participate and contribute to this growing technology.

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