USE OF FIBER REINFORCED POLYMER COMPOSITE IN BRIDGE STRUCTURES

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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.

In the past 10 years, experiments have been conducted to investigate the applicability of FRP composite in bridge structures, including the applications of FRP composite girder and bridge deck, column and beam strengthening, etc. This document will first present the basic information of FRP composite, including its mechanical behaviors and manufacturing processes relevant to civil engineering applications. Then the application of FRP composite in bridge engineering will be investigated, through three case studies. Four main issues contributing to the slow acceptance of the material into construction industry as a whole, despite its success in aerospace and automobile industries, are discussed at the end.

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1. Introduction

The construction industry is revolutionizing in two major ways. One way is the development of construction techniques, such as using automated tools in construction. The other is the advancement in high-performance construction materials, such as the introduction of high strength concrete. Among these high-performance materials is composites made from fiber reinforced polymer (FRP), which is gradually gaining acceptance from civil engineers. In recent years, research and development of fibers and matrix materials and fabrication process related to construction industry have grown rapidly. Their advantages over other traditional construction materials are their 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. Their application in construction includes both upgrading existing structures and building new ones, which can apply to various types of structure, for example, off-shore platforms, buildings, and bridges.

Bridge engineering is among the fields in civil engineering benefiting from the introduction of FRP composite. In the past 10 years, experiments have been conducted to investigate the applicability of FRP composite in bridge structures, including the applications of FRP composite girder and bridge deck, column and beam strengthening, etc. This document will first present the basic information of FRP composite, including its mechanical behaviors and manufacturing processes relevant to civil engineering applications. Then the application of FRP composite in bridge engineering will be investigated, through three case studies. Four main issues contributing to the slow acceptance of the material into construction industry as a whole, despite its success in aerospace and automobile industries, are discussed at the end.

2. What Is Fiber Reinforced Polymer Composite?

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 [7]. 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 as shown in Figure 2-1. 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.

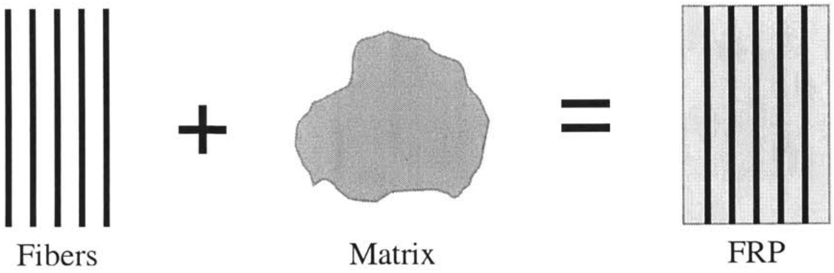

Figure 2-1: Formation of Fiber Reinforced Polymer Composite

2.1 Fibers

A fiber is a material made into a long filament with a diameter generally in the order of 10 μm [2]. The aspect ratio of length and diameter can be ranging from thousand to infinity in continuous fibers. The main functions of the fibers are to carry the load and provide stiffness, strength, thermal stability, and other structural properties in the FRP. To perform these desirable functions, the fibers in FRP composite must have:

i) high modulus of elasticity for use as reinforcement;
ii) high ultimate strength;
iii) low variation of strength among fibers;
iv) high stability of their strength during handling; and
v) high uniformity of diameter and surface dimension among fibers.

There are three types of fiber dominating in civil engineering industry—glass, carbon, and aramid fibers, each of which has its own advantages and disadvantages.

Material	**Density (g/cm^3)**	**Tensile Modulus (E) (GPa)**	**Tensile Strength (σ) (GPa)**	**Specific Modulus (E/σ)**	**Specific Strength**	**Relative Cost**
E-glass	2.54	70	3.45	27	1.35	Low
S-glass	2.50	86	4.50	34.5	1.8	Moderate
Graphite, high modulus	1.9	400	1.8	200	0.9	High
Graphite, high strength	1.7	240	2.6	140	1.5	High
Boron	2.6	400	3.5	155	1.3	High
Kevlar 29	1.45	80	2.8	55.5	1.9	Moderate
Kevlar 49	1.45	130	2.8	89.5	1.9	Moderate

Table 2.1-1: Properties of Fibers [7]

Glass fibers are processed form of glass, which is composed of a number of oxides, such as silica oxide from silica sand, together with other raw materials, such as limestone, fluorspar, boric acid, and clay. They are manufactured by drawing those melt oxides into very fine filaments, ranging from 3 to 24 μm [2]. Five forms of glass fiber strands, used in reinforcing the matrix material, are chopped fibers, chopped strands, chopped strand mats, woven fabrics, and surface tissue. The glass fiber strands and woven fabrics are the forms most commonly used in civil engineering application. Glass fibers have high strength, considering theirs relatively low cost. E-glass is the most commonly used glass fibers available in the construction industry.

Aramid or aromatic polyamide fiber is one of the two high-performance fibers used civil engineering application. It is manufactured by extruding a solution of aromatic polyamide at a temperature between -50 °c and -80 °c into a hot cylinder at 200 °c. Fibers left from evaporation are then stretched and drawn to increase their strength and stiffness. During this process, aramid molecules become highly oriented in the longitudinal direction. Aramid fibers possess higher strength and toughness among reinforcing fibers. They have high static, dynamic fatigue, and impact strengths. One drawback of aramid fibers is that they are difficult for cutting and machining.

Carbon fiber is another type of high-performance fiber available for civil engineering application. They are manufactured by controlled pyrolysis and crystallization of organic precursors at temperatures above 2000 °c. In this process, carbon crystallites are produced and orientated along the fiber length. There are three choices of precursor used in manufacturing process of carbon fibers—rayon precursors, polyacrylonitrile (PAN) precursors, and pitch precursor. PAN precursors are the major precursors for commercial carbon fibers. It yields about 50% of original fiber mass. Pitch precursors also have high carbon yield at lower cost. However, they have less uniformity of manufactured carbon fibers. Carbon fibers have high elastic modulus and fatigue strength than those of glass fibers. Considering service life, studies suggests that carbon fiber reinforced polymers have more potential than aramid and glass fibers [12].

2.2 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; and

vi) provide finish color and surface finish for connections.

Type of matrix material and its compatibility with the fibers also significantly affect the failure mode of the structure. There are various types of matrix materials, which can be used in civil engineering construction. Categorized by manufacturing method and properties, two major types of polymers are thermoplastic and thermosetting polymers. Thermoplastic polymers are ductile in nature and tougher than thermoset polymers. However, they have lower stiffness and strength. They can be reformed and reshaped by simply heating and cooling. Since the molecules do not cross-link, thermoplastics are flexible and reformable. Thermoplastic have poor creep resistance at high temperature and more susceptible to solvent than thermosets. Commonly used thermoplastics are nylon, polyetheretherketine (PEEK), polypropylene (PP), and polyphenylene sulfide (PPS).

Thermosetting polymers are usually made from liquid or semi-solid precursors. These precursors harden in a series of chemical reactions called polycondensation, polymerization, or curing. At the end of manufacturing process, they are converted into hard solid, producing a tightly bound three-dimensional network of polymer chain. Unlike thermoplastic polymers, once thermosetting polymers are cured, they cannot be remelted or reformed. Thermosets are usually brittle in nature. They offer high rigidity, thermal and dimensional stability, higher electrical, chemical, and solvent resistance. Most common thermosets are epoxy, polyester, vinylester, phenolics, cyanate esters, bismaleimides, and polyimides.

Resin Material	**Density (g/cm^3)**	**Tensile Modulus GPa (10^6 psi)**	**Tensile Strength MPa (10^3 psi)**
Epoxy	1.2-1.4	2.5-5.0 (0.36-0.72)	50-110 (7.2-16)
Phenolic	1.2-1.4	2.7-4.1 (0.4-0.6)	35-60 (5-9)
Polyester	1.1-1.4	1.6-4.1 (0.23-0.6)	35-95 (5.0-13.8)
Nylon	1.1	1.3-3.5 (0.2-0.5)	55-90 (8-13)
PEEK	1.3-1.35	3.5-4.4 (0.5-0.6)	100 (14.5)
PPS	1.3-1.4	3.4 (0.49)	80 (11.6)
Polyester	1.3-1.4	2.1-2.8 (0.3-0.4)	55-60 (8-8.7)
Polycarbonate	1.2	2.1-3.5 (0.3-0.5)	55-70 (8-10)
Acetal	1.4	3.5 (0.5)	70 (10)
Polyethylene	0.9-1.0	0.7-1.4 (0.1-0.2)	20-35 (2.9-5)
Teflon	2.1-2.3	-	10-35 (1.5-5.0)

Table 2.2-1: Properties of Typical Unfilled Matrix Material [7]

2.3 Interface

Interface is where the fibers and matrix material are chemically and physically bonded together. Material anisotropic properties gradation is exhibited in this region. To ensure that FRP composite performs satisfactorily, this region has to provide adequate bonding stability. In analysis of composite materials, it is generally assumed that the bond between the fibers and matrix material is perfect and therefore no strain discontinuity occurs across the interface.

3. Mechanical Properties of FRP Composite

Mechanical properties of FRP composite are dependent upon the ratio of fiber and matrix material, the method of manufacture, the mechanical properties of the constituent materials, and the fiber orientation in the matrix. Mechanical properties of composites made from combination of various reinforcements and epoxy rasin are shown in table below.

Material	Specific weight	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
E-glass	1.9	760-1030	41.0	1448	41.0
S-2 glass	1.8	1690.0	52.0	-	-
Aramid 58	1.45	1150-1380	70-107	-	-
Carbon (PAN)	1.6	1930-2689	130-172	1593	110.0
Carbon (Pitch)	1.8	1380-1480	331-440	-	-

Table 3.1-1: Typical mechanical properties of long directionally aligned fiber reinforced composites manufactured by an automated process (epoxy rasin) [2]

Mechanical properties also depend on reinforcement forms—continuous, aligned fibers; woven fabric; and aligned or randomly distributed discontinuous fibers. In unidirectional fiber composites, fibers are straight and parallel. They are considered orthotropic materials because they have two orthogonal planes of symmetry. To estimate extensional Young's modulus for unidirectional fiber composites, the following relationship between moduli of matrix and fiber can be used:

$$E_l = v_f E_f + v_m E_m$$

where v_f and v_m denote volume fractions of fiber and matrix, respectively [17]. Modulus in transverse direction and shear moduli in the 1-2 and 1-3 planes (1-, 2-, and 3-directions denote longitudinal, width, and thickness, respectively) are strongly dependent of the fiber distribution.

The stress-strain behavior of FRP composites has almost linear relationship; and they do not yield plastically. However, non-linearity can also be observed due to formulation of small crack in resin; fiber buckling in compression; fiber debonding; viscoelastic deformation of matrix, fibers, or both. Therefore, yield point in composite materials denotes the departing from linearity in stress-strain relationship. The axial tensile and compressive strengths are dominated by fiber properties because they carry most of the axial load. Their stiffness is higher than that of matrix. The other strength values, which are often lumped into transverse strength properties, are influenced primarily by matrix strength characteristics, fiber-matrix interfacial bond strength, and the internal stress concentration due to voids and proximity of fibers. When fiber breaks under tensile load, the matrix resists the displacement by shear stress on lateral surface of the fibers. In compression, matrix helps stabilize the fibers, preventing them from compressive buckling at low stress level.

In discontinuous fiber composites, the orientation of fibers depends on relative sizes of fibers and part, resulting in 2- or 3-dimensional fiber orientations. In addition to factors affecting the properties of unidirectional composite, fiber length and diameter often affect the properties of discontinuous composite. Variability is apparent in discontinuous composites because fiber orientation and volume fraction are difficult to control in manufacturing process. In general, fiber volume fraction for discontinuous fiber composites tends to be lower than that for continuous and fabric composite, hence lower mechanical properties. The following equations can be used to estimate the Young's modulus of discontinuous fiber composite.

For parallel discontinuous, $$E_c = \phi_e v_f E_f + (1 - v_f) E_m$$

$$\phi_e = 1 - \frac{\tanh(p)}{p}$$

$$p = \frac{2l}{d}\left(\frac{G_m}{E_f}\right)^{1/2}\left(\frac{-1}{\ln(v_f)}\right)^{1/2}$$

where d and l are bulk diameter and length of fibers, respectively [17].

For 3-and 2-dimensional random discontinuous fiber, there are 1/3 and 1/6 coefficients in front of the fiber contribution term.

Region with significant amount of fiber curvature is likely to be the source of part failure because of their low strength properties. However, strength of discontinuous fiber composites is difficult to predict than that of continuous composites due to complexity of fiber orientation. There are three potential causes of failure of FRP composite. First, failure can be caused by error in the design process of FRP composite material or structure built from FRP composite. Second, error during fabrication and processing of FRP composite can cause failure. Third, failure can be caused by fracture, which depends on type and orientation of fiber reinforcement.

4. Major Application Areas in Bridge Engineering

4.1 Repair and Retrofitting of Existing Bridge Structures

Strengthening and retrofitting of existing structures using externally bonded FRP composites are one of the first applications of FRP introduced in civil engineering. The technique is simple, rapid, and effective. For example, FRP can be used, instead of conventional steel plate, to strengthen approximately 5% of deteriorated bridges in Europe. It is expected that this strengthening method can save some €6 billion annually [1]. Another example is the Kattenbusch Bridge in Germany, in which one construction joint was strengthened by 20 glass fiber reinforced laminates. A series of loading tests showed that crack width was reduced by 50%, while stress due to fatigue was reduced by 36% [1].

FRP used for strengthening and retrofitting can be in the forms of FRP sheet or strip, depending on their application. Externally bonded FRP composites have been used for increasing both flexural and shear capacity of concrete elements, including girders, beams, and slabs. Three methods are used for application of external FRP reinforcement—adhesive bonding, hand lay-up or wet lay-up, and resin infusion. Summery of these methods are shown in Table 4.1-1.

Extensive research have been conducted in the past years on bond performance, creep effects, ductility, fatigue performance, force transfer, peel stresses, fire resistance, and ultimate strength of FRP strengthening [5]. The American Concrete Institute (ACI) has incorporated the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures in its 2002 Code. The new Canadian Highway Bridge Design Code (2001) also provides some detail on FRP composite. FRP composite have proved to be effective way of improving strength and stiffness of existing structural elements.

Procedure	Description	Features
Adhesive bonding	Composite element is prefabricated, then bonded onto the concrete substrate using an adhesive under pressure.	Rapid application; good quality control of incoming material; dependent in adhesive integrity; temperature effects the adhesive
Hand lay-up	Resin is applied to the concrete substrate, then layers of fabric are impregnated using roller. The composite and bond are formed at the same time.	Slower and need more equipment; ambient cure effects; waviness and wrinkling of fiber; non-uniform wetting and/or compaction
Resin infusion	Reinforcing fabric is placed over the area under consideration and the entire area is encapsulated in a vacuum. Alternatively, the outer layer if fabric is partially cured prior to placement to obtain a good surface.	Far slower with need for significant equipment; ambient cure effect; dry spots

Table 4.1-1: Methods of Application of FRP Strengthening [11]

4.2 FRP Composite Reinforcement

Although the steel reinforcements in concrete structure are physically protected by concrete, aggressive environmental condition can stimulate the carbonation of concrete and the formation of hydrated ferrous oxide in steel, resulting in spalling of concrete cover. The primary cause of deterioration of concrete bridge is the corrosion of steel reinforcement. Since FRP composite is corrosion resistance, it can be used to replace steel reinforcement in the forms of rebar for flexural and shear reinforcements, and tendon for prestressing or post-tensioning. FRP rebar and tendon can take the form of one dimensional or multidimensional shape, depending on type of application. There have even been some attempts to incorporate wireless sensing into infrastructure using FRP reinforcement. However, there are several challenges in using FRP rebar and tendon. One issue is the linear elastic behavior of FRP rebar when loaded to failure. This means that concrete element reinforced using FRP rebar may not have the same ductile failure of steel-reinforced element. Its lower modulus of elasticity also leads to serviceability problems, such as larger deflection and larger crack widths. Therefore, more experiments need to be conducted before its application is accepted.

4.3 Seismic Retrofit

FRP composites can be used in seismic retrofitting of reinforced concrete bridges in the form of wrapped column. Conventional methods used for seismic retrofit of reinforced concrete columns include the use of steel shells or casings, the use of steel cables wound helically around the column, and the use of external reinforced concrete section. However, these methods introduce additional stiffness, due to the isotropic nature of the retrofitting material, to the structural system and, therefore, higher seismic force can be transferred to adjacent elements. In addition to this, traffic disruption is a major problem during retrofitting operation. With the use of FRP composite, on the other hand, the FRP confinement provides only hoop stress, hence no additional stiffness. It also causes no or little traffic disruption. The largest commercial seismic retrofit in the U.S. was conducted on the Yolo causeway west of Sacramento, CA, in which over 3000 columns were wrapped with E-glass fibers and polyester matrix [11].

4.4 FRP Composite Bridge Decks and Superstructures

Bridge deck is among the most deteriorated elements in bridge structure. There may be a need to increase load rating, traffic lanes, or to conform to a new code. Therefore, FRP composite bridge deck has been introduced as a new solution into bridge engineering community. It offers easy installation, lightweight, and potential resistance against environmental and chemical damages. The design of FRP bridge deck depends more on stiffness, rather than strength. Therefore, it is prone to have over-strength design, which can be as small as 10-15% of the ultimate strength of FRP [11]. One of the barriers is still; however, the cost of prefabricated FRP bridge deck is a lot higher than that of conventional material.

FRP can also be used in cable-stayed bridges, suspension bridges, and post-tensioning. In this case, cables are comprised of bundled pultruded CFRP wire. One example of the application is the Stork Bridge, a 124-m-span, two-lane bridge across 14 tracks at Winterthur railway station in Switzerland. Two 12 MN FRP cables were installed and being monitored along with conventional steel cables. So far, the cables have been performing as expected [12]. Although the production cost of CFRP cables are still high, it is likely that this cost will decrease in the near future.

4.5 Hybrid FRP/Concrete Section

In reinforced concrete beam, the function of concrete below neutral axis is mainly to position reinforcing steels and to protect them from corrosion. However, concrete has little tensile strength compared to steel. So concrete hairline cracking is common in reinforced members, resulting in environmental attack of the reinforcing steels. So there have been studies on a composite system that has concrete in the compressive portion of beam and FRP sheet below the neutral axis.

A project has been conducted on the use of duplex long-span beam. In this context, the term "duplex" means the combination of concrete and FRP that forms structural elements, which provide optimum properties derived from the individual characteristic of each material. The purpose of this project was to overcome economic issue, which is one of the major barriers of the use of FRP in civil engineering. Several possible advantages of duplex system are identified as:

i) Potential reduction of transport costs for finished members, and the flexibility to install the element in remote area.

ii) Cost of manufacture can be comparable to conventional material for a large number of elements.

iii) Lightweight and high strength.

iv) Cost can be paid off after several years in service.

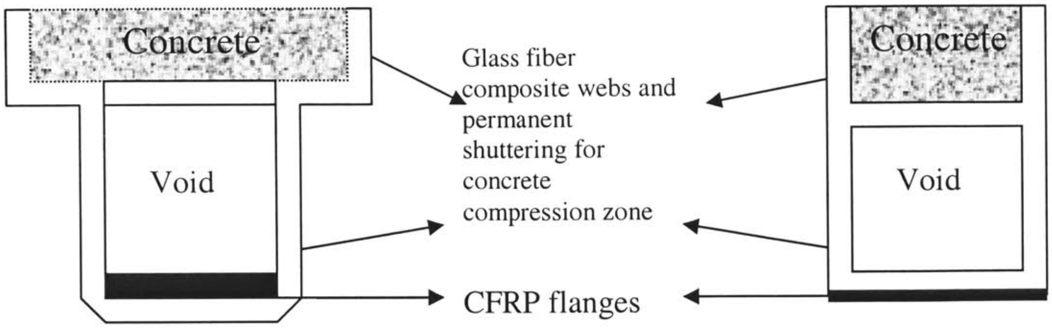

Figure 4.5-1: FRP composite and Concrete Hybrid Beam

According to the full-scale tests conducted at the University of Surrey, UK, the assumption of plane sections remaining plane in the region of predominantly bending was shown to be valid. This implies that the principles of flexural design for conventional beams can be used for this duplex section.

Another possible hybrid configuration is a circular cross-section, in which concrete core is wrapped by FRP. This system is called hybrid tube system. Although the concrete core does not provide much of flexural stiffness and strength, other than compressive strength, to the cross-section, it functions as the formwork for the FRP so that its strength is fully utilized. It also makes the FRP tube more stable, preventing premature local buckling failure, and allows connector anchorage. The purpose of this concept is two folds. Firstly, it can be used as non-corrosive compression member in off-shore structure. Secondly, it can be used as high-ductility column and pier in seismic zones. This concept is used in the first all-FRP cable-stayed bridge in the U.S., the I-5/Gilman Advanced Technology Bridge, in La Jolla, CA.

5. Major Manufacturing Process Related to Civil Engineering

5.1 Manual Process

Manual processes include methods, such as hand lay-up and spray-up. Hand lay-up or wet lay-up process is one of the oldest composite manufacturing technologies. It is labor intensive method, in which liquid resin is applied to the mold and fiber reinforcement is placed manually on top. Metal laminating roller is used to impregnate the fiber with resin and remove any trapped air. Several steps are repeated until a suitable thickness is reached. This method is usually used in strengthening and retrofit of structures. Several limitations of hand lay-up include inconsistency in quality of produced parts, low fiber volume fraction, and environmental and health concern of styrene emission.

Spray-up process is similar to hand lay-up process, but much faster and less expensive. In this process, a spray gun is used to apply resin and chopped reinforcements to the mold. Glass fibers chopped to a length of 10 to 40 mm are usually used as reinforcement. It is more suitable for manufacturing non-structural parts that do not require high strength. However, it is very difficult to control the fiber volume fraction and thickness; and it is very dependent on highly skilled operator. Therefore, this process is not appropriate for parts that require dimensional accuracy.

5.2 Semi-automated Process

One of the semi-automated processes is Resin Infusion under Flexible Tooling (RIFT) process. This method is mainly used to retrofit CFRP to steel, cast iron, and concrete bridges. In this method, fibers are preformed in a mold and transported to site. The preform is then attached to structure being retrofitted and enveloped by vacuum bagging system, together with a resin supply. Resin is then injected into the preform, forming both composite material and adhesive bond between the composite and the structure. This process yields high fiber volume fraction as high as 55%.

5.3 Fully-automated Process

Pultrusion process is a low-cost, high-volume, fully-automated manufacturing process, offering good performance-to-price ratio as well as easy processing. In this process, raw material is pulled through a heated die at constant speed, creating parts of constant cross-section and continuous length. It gives smooth finished parts that require no post-processing. E-glass, S-glass, carbon, and aramid are used as reinforcement, with polyester being the most common resin material. Pultrusion is used to manufacture solid and hollow structure with constant cross-section. It is commonly used to fabricate beams, channels, walkways, etc, with unidirectional fibers. However, pultrusion has several limitations. It cannot fabricate tapered and complex shapes, thin-walled parts, or structures that has complex loading because of typical longitudinal alignment.

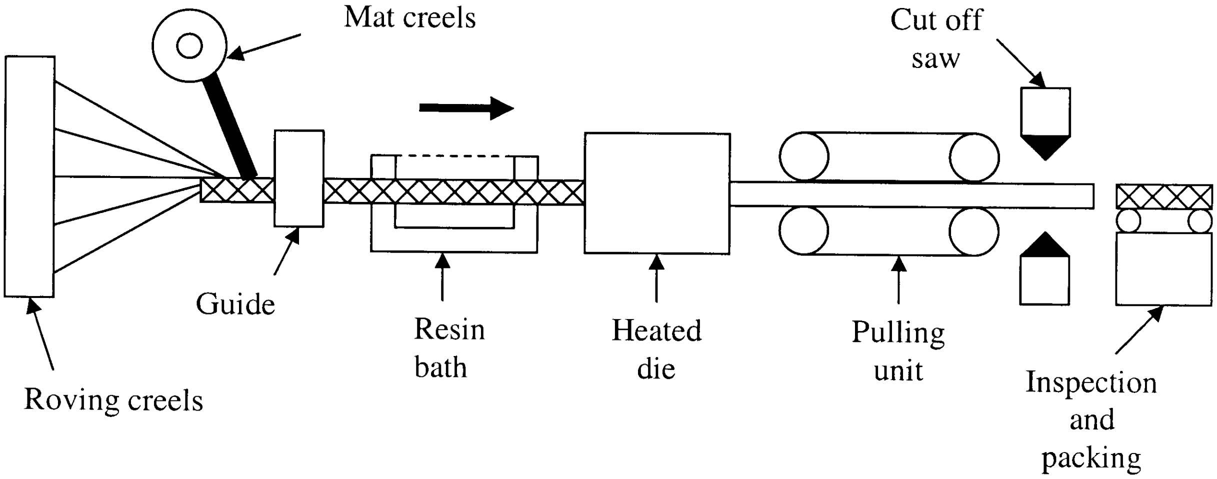

Figure 5.3-1: Pultrusion Process (Reproduced from [7])

"Filament winding is a process, in which resin-impregnated fibers are wound over a rotating mandrel at the desired angle [7]." Therefore, starting materials for this process are continuous fibers, which commonly are glass, carbon, and Kevlar fibers. Liquid thermoset resins used in this process are epoxy, polyester, and vinylester. The composite unit is then removed from the mandrel and cured by being placed in an oven enclosure at 60° for 8 hours. This manufacturing process is commonly used to fabricate tubular structures and pipes. It is a low-cost process because low-cost materials and tooling are used. This method, however, has several disadvantages. It is limited to producing closed and convex structures. It also gives comparatively low maximum fiber volume fraction.

Resin Transfer Molding process (RTM) is a process in which a preform is placed in a mold cavity, which consists of two halves clamped together. Then a pressurized mixture of thermoset resin, a catalyst, color, filler, etc., is pumped into the mold using dispensing equipment to form structural parts. This method is "suitable for manufacturing small- to large-sized structures in small-to medium-volume qualities."[7] RTM can produce complex parts at intermediate volumes rate, allowing limited production to run in a cost-effective way. The produced parts have good finish on both sides. Fiber volume fractions, as high as 65%, can be achieved by this method. RTM has a number of limitations. These include the fact that tooling and equipment costs are higher and complex than for hand lay-up and spray-up process.

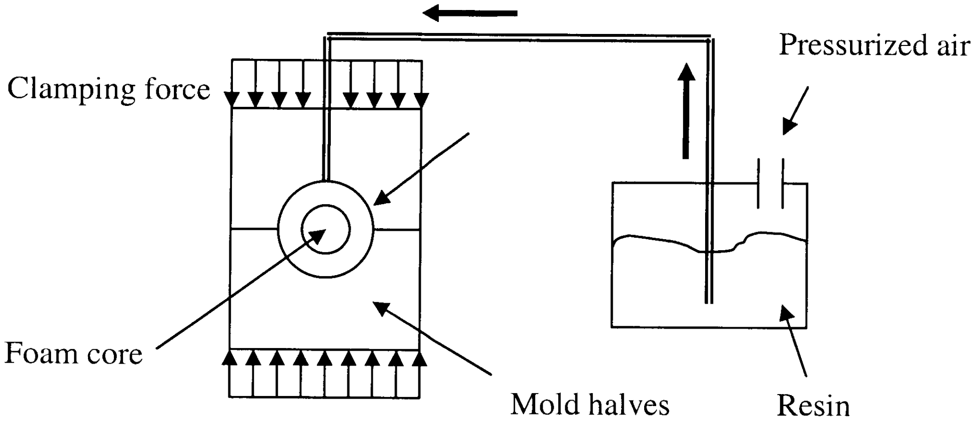

Figure 5.3-2: Resin Transfer Molding Process

Method	Tensile Strength (MPa)	Tensile Modulus (GPa)	Flexural Strength (MPa)	Flexural Modulus (GPa)
Hand Lay-up	62-344	4-31	110-550	6-28
Spray-up	124-335	6-12	83-190	5-9
RTM	138-193	3-10	207-310	8-15
Filament winding	550-1380	30-50	690-1725	34-48
Pultrusion	275-1240	21-41	517-1448	21-41

Table 5.3-1: Typical mechanical properties of glass fiber composites manufactured by different fabrication methods

5.4 Joining Methods for Composites

Several parts or components are joined together to transfer load or to create relative motion between two members. In general, joints are avoided because there can be stress concentration in the area around them and, therefore, can cause structural failure. Two types of joints are commonly used in composite—adhesive bonding and mechanical joint.

Adhesive Bonding

In adhesive bonding, two parts or substrates are joined by some kind of adhesive. Several bonding configurations are shown in Figure 5.4-1. In general, loads are transferred from one substrate to another by shear stress. However, since in most cases loads are not applied concentrically with the joint, moment can create normal stress in joint, resulting in lower strength. This problem can be eliminated by using double lap joint, which transfer force only by shear stress. In general, adhesive bonding can fail in four modes—adhesive failure, cohesive failure, substrate failure, or combination of the first two.

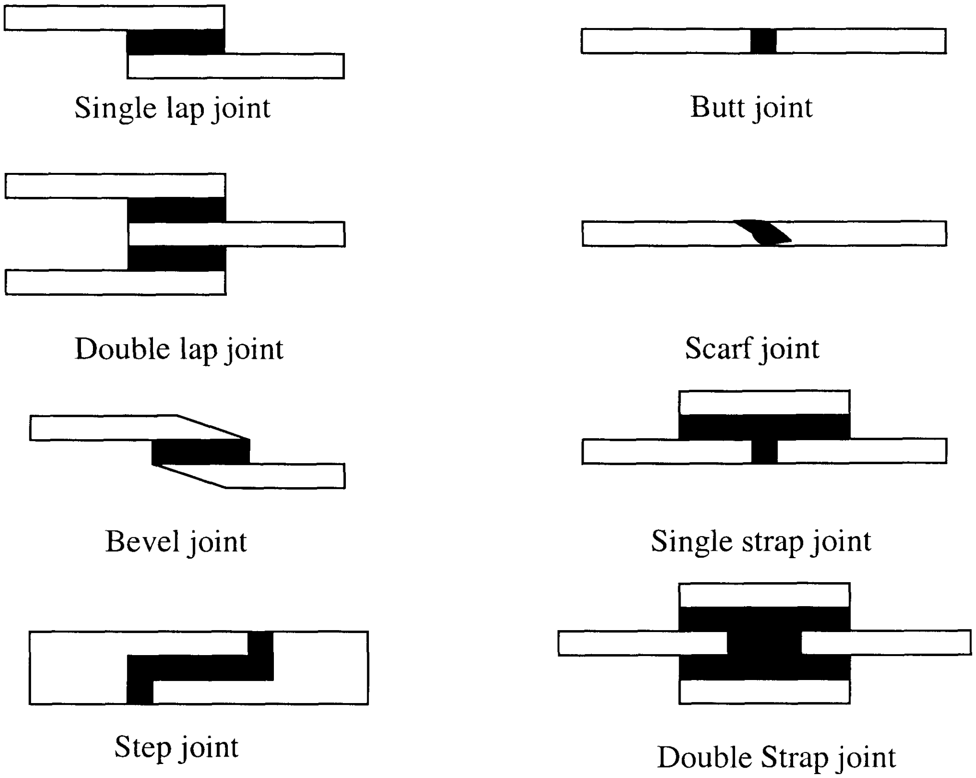

Figure 5.4-1: Types of adhesive bonding [7]

Adhesive bonding has many advantages over mechanical joints. First, since the load is distributed over an area of adhesive bonding, this results in a more uniform distribution of stresses and higher resistance to flexural, fatigue, and vibrational stresses. Second, it is more applicable to join irregular surfaces than mechanical joints. Third, it is less expensive and faster than mechanical joints. However, some disadvantages associated with adhesive bonding are requirements for surface preparation, longer cure time, more training and strict process control. Inspection is also difficult after bonding is complete.

Mechanical Joint

Mechanical joints for composites are similar to those for metal construction. For most mechanical joints, two members are overlapped and a hole is created for bolts and rivets. If screws are used, metal inserts are required because threads in composites do not have enough strength in shear. Mechanical joints have several advantages. They require little or no surface preparation. In case of repairing and maintenance, reassembly and disassembly can be done without damaging the materials. Inspection is also easier than the case adhesive bonding. However, mechanical joint can cause stress concentration. This is quite crucial for composites because they do not have stress redistribution by yielding. Furthermore, if not properly protected, fiber discontinuity caused by hole can be exposed to environments and chemicals.

6. Case Studies

6.1 Case Study 1: Long-span Pedestrian Bridge

Opened in 1992, the Aberfeldy Bridge is a long-span symmetrical cable-stay footbridge crossing the River Tay in Scotland. It is the world's longest span all-composite bridge, connecting two halves of Aberfeldy golf course. Its innovative composite technologies include pultruded GFRP system and aramid cables. Since the ratio of live load to dead load in high-performance composite bridge is high, one of design issues is the dynamic behavior. In the case of the Aberfeldy Bridge, the design live load is 5.6 kN/m, while the dead weight is only 2.0 kN/m. Therefore, concrete ballast was installed in the cells of the central deck panel to prevent uplift under wind and to improve transverse mass distribution. To maximize the critical wind speed for aerodynamic flutter, the first torsional and vertical natural frequencies are separated.

Structural Components

The deck and tower of the Aberfeldy Bridge was prefabricated from the Advanced Composite Construction System (ACCS), which was comprised of a number of modular components pultruded from GFRP (E-glass fiber and isophthalic polyester resin) [4]. The use of this prefabricated system helped reduce complication in construction. Several GFRP sections were combined to form main structural units, a 600 mm x 80 mm plank with an area of 80 mm^2. Each leg of the towers was constructed from four planks and four connectors, with total cross-sectional area of 760 mm^2 [9]. To build up the deck, three planks are used with two connectors. These components were joined edge-to-edge using a combination of bonding and H-shaped toggle type mechanical connectors. The bridge was stiffened longitudinally by edge beams and laterally by crossbeams, which are also constructed from ACCS. Each edge beam was consisted of five connectors, while only one connector was used for each secondary crossbeam. The bridge decks were then supported by lightweight cables, which are manufactured from a core of parallel Kevlar-49 fibers with polyethylene as matrix material. These cables were connected to ten primary crossbeams, which were consisted of four connectors, resulting in 160 mm^2

cross-sectional area. At the top of the towers, cables were inserted through the tower via 200 mm diameter steel tubes, and anchored to a galvanized steel plate on both sides.

Construction

Most of the elements were pre-assembled in factory due to dimensional accuracy requirement. Towers were delivered as two legs and a primary crossbeam. The decks, on the other hand, were delivered to site in pieces, each of which was 6 m long. Edge beams were also pre-assembled on site before construction of the deck. It was crucial that all components were kept dry before and during bonding process, so that the adhesive properly cured. Because of its lightness, the method of erection used for the towers was quite unique. After the assembly was complete on ground, the towers, which were hinged to their concrete footings, were lifted to vertical simply by hand winches and guy ropes. The cables and primary crossbeams were then installed. Cable net and crossbeams were used as framework, over which the decks were pulled into position. In total, the prefabrication and erection were carried out in 8 weeks by a small team.

In-Service Performance

In 1995 and 2000, two experimental investigations into the dynamic behavior under footfall live load were conducted on the bridge. According to the studies, the damping ratio of the bridge is comparable to that of the isolated deck. The aramid cables provide much less energy dissipation than conventional steel cables do.

Mode*	Frequency (Hz)		Damping ratio for empty structure (%)	
	1995	2000	1995	2000
H1	1.00	0.98	-	1.0
V1	1.56	1.52	0.84	0.4
V2	1.92	1.86	0.94	0.7
V3	2.59	2.49	1.20	0.7
H2	2.81	2.73	-	1.2
V4	3.14	3.01	-	0.8
T1	3.44	3.48	-	5.5
V5	3.63	3.50	-	0.6
V6	4.00	3.91	-	0.9
T2	4.31	4.29	-	3.2
V7	4.60	4.40	-	0.8
V8	5.10	4.93	-	1.8

* H = horizontal, V = vertical, T = torsional

Table 6.1-1: Dynamic Response of Aberfeldy Bridge, from Studies in 1995, and 2000 [4].

In the 1995 experiment, peak acceleration was 0.22g when a person deliberately walked on the bridge at the fundamental natural frequency [4]. This acceleration is higher than the maximum allowed in BD37/88. However, after being strengthened by externally bonded GFRP pultruded plate in 1997, the measured natural frequencies in 2000 were marginally lower due to the increases in mass and stiffness. In conclusion, the world's first all FRP pedestrian bridge has been performing quite well. Although there was initially a dynamic problem, this was solved by adding more mass to the bridge. Some continuing problem is delamination of FRP wearing surface, which requires constant maintenance as the bridge is still in service.

6.2 Case Study 2: FRP Bridge Deck

A number of projects have been done by the collaboration of composite material companies and state agencies to verify and showcase the use FRP decks in bridge structures. However, in order to further develop design, testing, and manufacturing standards, there is still a great need for significant amount of database of FRP composite in civil engineering application. Therefore, an all-FRP bridge deck was built at Lemay Center for Composites Technology at St. Louis, Missouri. It was installed on the campus of University of Missouri at Rolla in July, 2000. In order to verify the strength, maximum deflection, and durability of the composite cross section, a test program was conducted on a specimen similar to a quarter of the bridge deck.

The deck was designed to comply with American Association of State Highway and Transportation Officials (AASHTO) specification. The deflection was limited to less than 1/800 of the span length to ensure serviceability. The load distribution requirement was based on one AASHTO H-20 truckload, which was calculated to be 32,000 lbs with 16,000 lbs on each back axle [14]. The bridge deck was fabricated from pultruded carbon and glass fibers with vinylester matrix in the shape of rectangular hollow sections. Each section is a square of 3 inches and a thickness of 0.25 inches [4]. Several tests were conducted on tube configurations and three different epoxy adhesives. Finally an I-beam configuration was chosen as main structural system (see Figure 6.2.1). Tubes were laid in both longitudinal and transverse directions to provide stiffness in both directions. Beam was divided into eight layers as shown in Figure 6.2-1. The second and the eighth layers from top were consisted of CFRP tubes, while the other layers were consisted of GFRP tubes. They were connected to each other using an epoxy adhesive and mechanical connection. Bridge deck was composed of four I-beams with total length of 30 ft and width of 9 ft [14]. A roughly 0.25 inch thin polymer concrete was used as wearing surface because of its high tensile elongation.

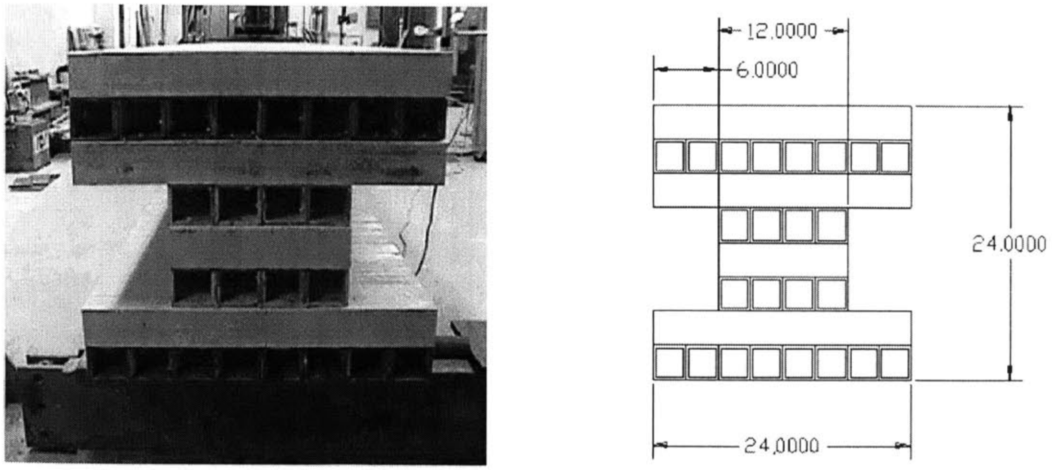

Figure 6.2-1: I-beam configuration [14]

For fatigue and ultimate load tests, a sample was built to the same configuration of an I-beam section, which is equivalent to a quarter of the bridge deck. The objectives of testing the section were to verify the proposed design configuration of the bridge deck, to investigate the stress and strain at points of loading and supports, and to obtain information required for extrapolating the analysis to the full-size bridge deck. Three types of test were performed, namely design load test; fatigue or cyclic load test; and ultimate load test.

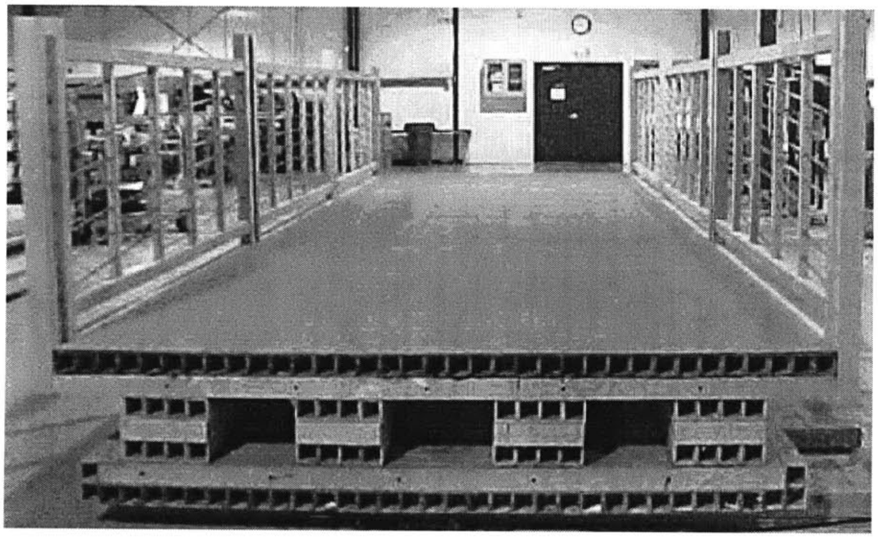

Figure 6.2-2: Cross-section of full-size bridge deck [14]

The design load and ultimate load tests were conducted using four point bending test configuration. The load was applied by a 200,000 lb hydraulic jack. In case of fatigue test, a 50,000 lb actuator was used, with load range, frequency, and number of cycles being controlled. The specimen was subject to 2 millions cycles of load, with the minimum load of 500 lb and the maximum load of 11,000 lb at a frequency of 4 Hz. A test for static load of 20,000 lb was performed after every 400,000 cycles during the fatigue load test to check lose of stiffness. Three LVDTs (Linear variable differential transformers) were installed at the mid-span and the supports to measure deflection of the deck. Several strain gages were installed at important locations on the deck to obtain strains. Load, deflection, and strain were recorded and interpreted for the behavior of bridge deck. After running design load test, the first GFRP layer was removed because it was deemed to be unnecessary. The final height of the bridge deck was 21 inches.

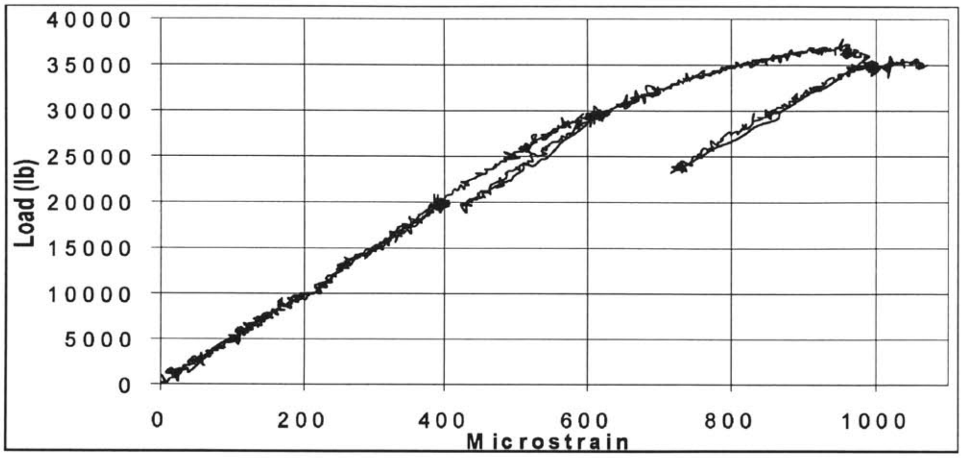

Figure 6.2-3: Load-strain curve from ultimate loading test [14]

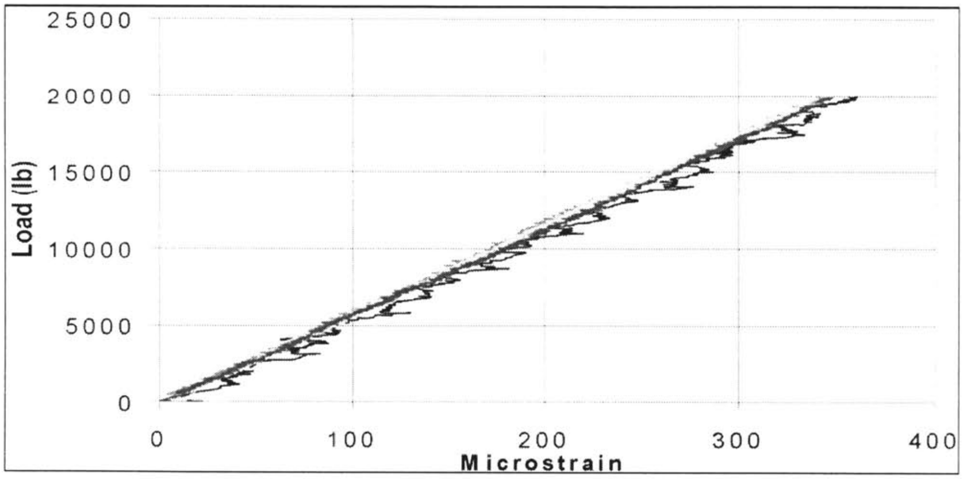

Figure 6.2-4: Load-strain for progressive increments of fatigue cycles up to 2 million cycles [14]

The mid-span deflection of the specimen at the design load were 0.26 inches and 0.31 inches before and after fatigue test, respectively. These values were within the limit value specified by AASHTO. In the fatigue test, the deflection and strain of the deck remained almost constant for all static loads applied. No apparent lose of stiffness was observed up to the maximum applied load of 20,000 lb. In addition to this, no permanent bending occurred. In the ultimate load test, the specimen demonstrates linear elastic behavior up to a load of 30,000 lb. It started losing its stiffness and the behavior became non-linear beyond this load. Ultimately, the specimen failed at approximately 35,000 lb, which is considerably larger than the design load on a quarter of the bridge deck. Ultimate failure was not catastrophic. When removing the ultimate load, the mid-span of the deck moved almost back to its original location, indicating ductility of the structure.

The bridge was installed on April, 2000. Fiber optic sensors were installed to observe the behavior of the bridge during its service life. The tests performed on the deck specimen show that FRP bridge deck is a good alternative for replacing conventional short-span bridges. No stiffness lost was observed during the test, indicating that FRP composite has sufficient fatigue strength. The proposed design also meets the requirement specified in AASHTO guideline.

6.3 Case Study 3: Pedestrian Bridge for the Boston Botanical Center Project

The Boston Botanical Center Project (BBC) is one of the projects in the Master of Engineering Program of academic year 2004-2005. The main goal of the project is to revitalize the area above Central Artery Tunnel, which was formerly occupied by removed turnpike, with green areas. It is comprised of three main structures—north side steel space frame, south side concrete frame, and supporting concrete pedestal. The structures on both sides are linked by a pedestrian bridge, which is supported by cables at its mid span, spanning over Hanover Street.

Conventional Material Alternative

Conventional materials are used for bridge deck. Steel I-beams are used as bridge girders to support concrete slab sections. The cables are then attached to a space-truss arch located on the north. Steel I-beam is chosen because it helps reduce construction time, therefore resulting in minimum traffic disruption.

Using simplified calculations together with computer analysis, the specifications of the bridge are as follows:

i) Design live load is 100 psf;

ii) Use W24x68 as girders spanning 70 ft between two halves of the garden;

iii) Girders are spaced 6 ft apart and support steel plate of 2 inches thick;

iv) 4 inches of concrete is placed on top of the steel plat to provide wearing surface;

v) Use cables of 3 inches diameter made from 60 ksi steel.

Hybrid FRP Alternative

To compare the performance and cost, another design for the pedestrian bridge using FRP composite as the main structural element is also proposed. The design uses the same live load and dimensions as required in the conventional bridge. Instead of designing as an all-FRP bridge, hybrid FRP bridge is chosen for economic and structural performance reasons.

The design process followed closely the fundamental requirements and warning of failure specified in a design code for structural polymer composites, EUROCOMP Design Code and Handbook [13]. In general, limit state design method is used. Two types of limit state under consideration were ultimate limit states and serviceability limit states.

Ultimate limit states are those associated with structural failures, which may endanger the safety of people or the continued performance of associated structures or components [13]. These include loss of equilibrium or stability of the structure or any part of it, and failure by excessive deformation or rupture. On the other hand, serviceability corresponds to effectiveness and appearance of structure. It includes deformation or deflection; buckling or wrinkling; vibration; cracking, delamination, and local damage of FRP composite.

It is necessary to consider all relevant limit states when designing any structure or component using FRP. In most case, stress-strain relationship of FRP is assumed to be linear. Beyond this point of linearity, FRP can exhibit little or no ductile behavior, which also has to be taken into account. As a result, design of FRP tends to be controlled by stiffness requirement both with respect to deflection and buckling. While this means choice of section for stiffness and stability is of concern, some strength will need to be provided to ensure that the structure fails in serviceability limit state before ultimate limit state. In designing FRP beam for flexure, stabilities of flange to resist compression and web to resist shear have to be taken into account in the form of ratio of width to thickness. Regarding serviceability, deflections due to bending and shear deformations have to be checked. In order to calculate deflections, equations for conventional, isotropic, homogenous beam can be applied.

The FRP beam was designed for service live load of 100 psf and construction live load of 20 psf. Pultruded E-glass with polyester, vinylester, and modar as matrix, were chosen for prefabricated I-beam section. Fiber volume fraction of 0.48 from pultrusion process should be sufficient for strength required in this type of application. The bridge deck will be 3 inch thick concrete slab, instead of FRP composite, for economic reason. Spaced equally every 6 ft, each beam will have to carry dead load due to bridge deck equal to 225 lb/ft, service live load of 600 lb/ft, and construction live load of 120 lb/ft. The maximum deflection is limited to 1/800 of the total span. The initial goal was to design a hybrid FRP bridge in a way that it had the same deflection as the conventional bridge. However, it turned out that stability of the flange under compressive stress governed the design. The final dimension of FRP is shown in Figure 6.3-1.

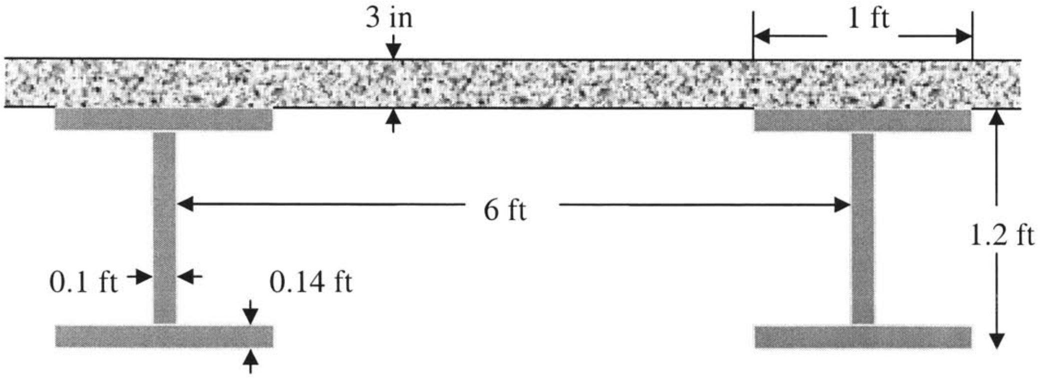

Figure 6.3-1: FRP beam and concrete deck configuration

Computer Analysis

These two design alternatives are analyzed using a computer program called SAP2000. This computer program is very versatile, capable of analyzing structure statically and dynamically. Both bridges were modeled as simply supported beams with uniformly distributed load.

As described in the specification section, the deck of conventional bridge is comprised of steel plate and concrete deck. The steel plate functions as formwork for pouring concrete deck. In the model, however, these two materials are lumped together using transformed cross-section principle for composite element. Using steel plate and concrete with elastic moduli of 29,000 ksi and 3,600 ksi, respectively, these result in additional 16" thickness of concrete deck. Bridge decks are then entered into the program as shells, each of which is supported by two connected I-beams. In order to simulate the behavior of expansion joint, these I-beams are simply supported in the model. Live load of 100 psf is applied on the shell.

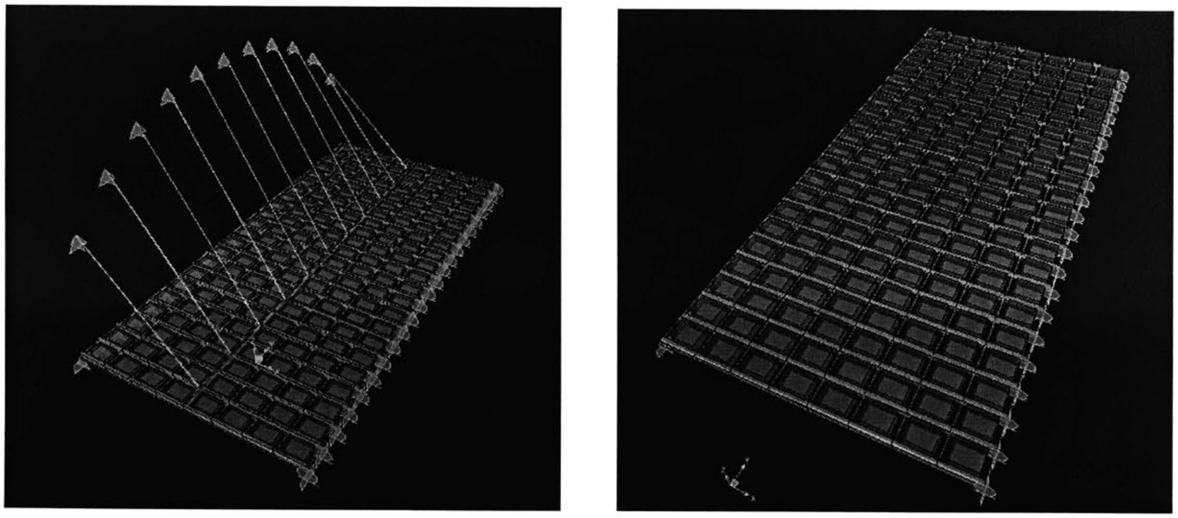

Figure 6.3-2: Conventional and hybrid bridge models

The hybrid FRP bridge was modeled in the same way as the conventional bridge. Material properties were modified to account for orthotropic properties of GFRP, which is shown in Appendix A. GFRP I-beams were simply supported and carrying concrete deck, which was modeled as shell. In order to model the behavior of adhesive joint between concrete and I-beams, each beam was subdivided into smaller eight portions. A concrete shell and a beam are then connected at four nodes. The maximum deflection and dynamic characteristics of the two alternatives are shown in Table 6.3-1.

	Conventional	Hybrid FRP
Maximum deflection (ft)	0.16	0.15
Fundamental period (sec)	0.36	3.8

Table 6.3-1: Result from static and dynamic analysis of the two alternatives

Construction

In the conventional bridge, since standard prefabricated steel section is used, construction in this case is not too complicate. However, the use of cable and arch support system adds a technical constraint to the construction sequence. Construction has essentially two phases. First, the wide flange steel beams are placed by crane across Hanover Street. This phase can be done with two night shifts, meaning that the street will be temporarily closed only during those times [15]. Then galvanized steel plate will be placed on the girders to provide formwork for concrete wearing surface. Concrete is poured to make 6 inches thick deck in total. It is worth noting that addition live load of 20 psf is also taken into account in selecting steel section to reflect construction sequence. Upon the completion of the first phase, cables are attached to cross beam at the mid-span of the deck and pretensioned. These helps increase load capacity of the bridge and reduce deflection at the mid-span.

Similar to the case of conventional bridge, the hybrid FRP bridge can be constructed very quickly due to its prefabricated parts. Lightweight also eliminates the need for mobilization of heavy machine. Concrete surface can be joined to the FRP deck using epoxy adhesive. Although it is difficult to project how much time will be required to construct the bridge, it is reasonable to assume that the construction time will be less than that required for the conventional bridge. However, this assumption will hold true only if construction crews have sufficient experience with handling and installation of FRP composite structure. The process of joining concrete slab and FRP beam with adhesive is a complicate one. For adhesive to achieve high bond strength, concrete surface needs to be prepared before applying adhesive. This process requires a lot of attention and experience, which may delay construction time.

Cost Estimate

When comparing costs of two alternatives using FRP composite and conventional material, it is important to take into account basic material cost, construction cost, and long-term cost. Material quantities and costs are provided in Appendix B. The total material and construction costs of the two alternatives are shown in Table 6.3-2.

Alternative	**Component**	**Quantity**	**Cost**
Traditional	concrete on steel deck (ft^3)	10070	$37,762.50
	steel girders (ft^3)	221.81	$163,030.35
	steel cables	800	$60,000.00
	steel truss arch (ft^3)	1430	$1,051,050.00
	concrete arch column (ft^3)	1529	$5,733.75
		total:	**$1,317,576.60**
Hybrid GFRP	concrete deck (ft^3)	2310	$8,662.50
	GFRP I-beams (kg)	34929.01	$322,045.47
	epoxy resin	n/a	n/a
		total:	**$330,707.97**

Table 6.3-2: Total material and construction costs

Taking into account only material and construction costs, the hybrid FRP bridge is much cheaper than the traditional one. However, considering the fact that a cable-arch system is added to the traditional bridge for deflection control and aesthetics, the price could have been reduced to $206,527. This makes the hybrid FRP bridge 60% more expensive than the traditional one. It is expected that the use of FRP composite will help reduce some indirect costs, such as less construction time; and the long-term cost, such as maintenance. However, since the structural systems in these two cases are quite similar, same construction procedure can be used. Saving from construction time is questionable in this case. Environmental, chemical, and mechanical resistance of FRP composite has the potential of saving some maintenance cost. However, it is quite difficult to quantify at this state of project.

7. FRP Barriers

In spite of its advantages over conventional construction materials, FRP composite is slowly accepted by bridge engineering industry. Four main issues contributing to this slow uptake are cost, structural performance, durability, and nature of FRP composite industry and code specifications.

7.1 Costs

Costs incurred in a construction project using FRP composites are categorized as short-term and long-term costs. Short term cost includes material cost, fabrication cost, and construction cost. Currently, material and fabrication costs of FRP composites for civil engineering application are still expensive compared to traditional materials. Most fabrication processes are originally used in the aircraft, marine, and car industries, in which mass production of one design specification is common [18]. Civil engineering industry, on the other hand, involves the design and construction of large-scale structures, in which design specifications are usually different from project to project. Some manufacturing techniques of FRP may not be economically suitable for civil engineering industry. However, light-weighted and modular components made from FRP can help decrease construction cost. This includes easy erection or installation, transport, and no need for mobilization of heavy equipment as indicated in Case Study 1. More saving, though difficult to quantify, can also be achieved from less construction time, less traffic disruption, or other factors commonly affected by construction project. These advantages have to be considered on case-by-case basis.

Long term cost of FRP composites is more complicated to evaluate because it involves various unpredictable costs, such as maintenance, deconstruction, and disposal costs. Some costing techniques have been developed. One of them is the "Whole of Life (WOL)" technique [20]. This technique, derived from life-cycle costing, includes initial cost, maintenance cost, operating cost, replacement and refurbishing costs, retirement and disposal costs, etc, through out the expected life-span of the project. Using this technique, FRP composite and traditional materials can be compared by calculating economic advantages for structures designed for same performance criteria. As environmental awareness increases, long-term cost of project becomes more important. Along with performance characteristics, such as stiffness and strength, sustainability has become one of the criteria in selecting construction material. FRP composites are considered a potential candidate because they allow virtually any combination of material properties.

Unlike other industries, in which FRP composites have been successfully introduced, construction industry is very cost-sensitive. It is really difficult to justify the use of FRP composite over other cheaper construction materials, when a project does not require a specific advantage of FRP composites. The claim of lower life-cycle cost is also difficult to justify because limited number of relevant projects have been built using FRP composites.

7.2 Structural Performance

In general, ductile materials are used in bridge engineering to ensure ductile failure and obvious deformation and warning to users. For example, steel is used for members and reinforcement because of its inherent linear elastic/perfectly plastic behavior. However, FRP composite, as shown in Case Study 2, exhibits almost elastic linear behavior to failure. FRP composite is also very sensitive to strength concentration. When stress concentration occurs at joint, stress is not distributed over this area due to linear elastic property of FRP composites. Therefore, if this is not taken into account, a structure built from FRP composite can fail in brittle manner.

Another aspect of structural performance, about which bridge engineers are still skeptical, is the dependence of strength of FRP composites on fiber orientation and placement. Since matrix provide little resistance to load, alternative load paths are almost nonexistent in FRP composites. This situation is critical in bridge engineering because load paths are very difficult to predicted, even for a simple structure built from steel or concrete. So it is considered safer to use materials that can provide load resistance from unpredictable directions. In addition to this, the design of civil structures is generally governed by stiffness performance, such as maximum deflection criterion. Since FRP composites have low stiffness, their use can result in civil structures being significantly over-designed for strength. Although this issue can be overcome by using FRP with high stiffness, such as carbon fibers, they tend to be very expensive [18].

7.3 Durability

The proponent of FRP composites claims that environmental, chemical, and mechanical durability is one of advantages over traditional materials. A number of constituent materials have potential resistance against moisture effect, ultraviolet radiation, chemical attack, freeze thaw cycles, dynamic loading, and material aging effects. Several experiments conducted in the past show this potential, such as fatigue test in Case Study 2. However, this is not obvious in current civil engineering application of FRP composites because all of them have been in service for a short period pf time. Therefore, long-term durability data are required to strengthen such claim.

7.4 Nature of FRP Composite Industry and Code Specifications

Unlike conventional material industries, FRP composite producers do not currently have any representative organization to interact directly with the bridge engineer community, i.e. the AASHTO Subcommittee on Bridges and Structures [5]. Moreover, FRP composites are generally developed as patented proprietary items, which "traditionally do not work well in this open, competitive-bid nature of construction industry [5]." Manufacturers are hesitant to allow bridge designers and bridge owners to observe fabrication of their materials of choice. This is very different from conventional material industry, in which shop inspection of steel girder or prestressed concrete girder is common and necessary for bridge designers and bridge owners. As a result, material specification of FRP composites is not as widely available as that of conventional materials to bridge engineers.

In contrary, bridge engineers are trained to utilize appropriate material in appropriate manner. They do not need expertise in material science to design, construct, and maintain bridges of conventional material like concrete or steel. However, application of FRP composite at current state requires knowledge in material behavior and manufacturing process far more than that required for the conventional materials. One example is the prediction of failure mode of FRP composite, which requires knowledge of fiber orientation and fiber-matrix interaction. This results in difficulty for a bridge engineer to design bridge structures using FRP composite. Prescriptive nature of AASHTO specification also makes FRP composite not preferred material because bridge engineers do not want to be liable for any structural failure associated with using this new material.

8. Conclusion

FRP composite is a two-phased material made by combining two or more constituent materials. Its advantages, in term of mechanical behaviors and durability, can be predetermined during manufacturing process. A number of manufacturing processes are available for producing structural members used in civil engineering applications. According to the case studies, FRP composite is a potential construction material for bridge engineering. It has several advantages over traditional materials. These include its high strength to weight ratio; its potential resistance to environmental and chemical damages. However, its acceptance into bridge engineering industry is quite slow. Issues contributing to this are cost, structural performance, nature of FRP composite industry and code specifications, and durability. Before it is fully accepted as practical construction material, more projects involving FRP composite are still needed to verify its long-term cost-saving and in-service durability.

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Appendix A: Material Properties and Design Procedure

FRP Beam Design

Material:	GFRP
Process:	Pultusion
Reinforcement:	E-glass
Resin system:	Polyester, vinylester, modar
Volume fraction of fiber:	0.48

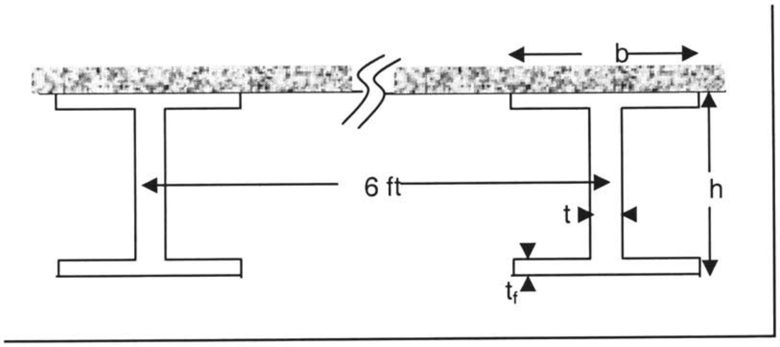
Material Properties	-			
mass/unit volume				
weight/unit volume	0.075	lb/in^3		
modulus of elasticity		tension	compression	
	dir 1	5.64E+08	5.01E+08	psf
	dir 2,3	7.31E+07	9.40E+07	psf
Poisson's ratio	plane 12	0.2		
	plane 13	0.2		
	plane 23	0.1		
Shear modulus	plane 12	8.77E+07	psf	
	plane 13	8.77E+07	psf	
	plane 23	8.77E+07	psf	
Strength				
Tensile	dir 1	8.56E+06	psf	
	dir 2,3	9.19E+05	psf	
Compressive	dir 1	5.64E+06	psf	
	dir 2,3	n/a	psf	
Shear	in-plane	3.13E+05	psf	

List of partial coefficients		**ULS**	**SLS**
Partial load coefficient, γ_f		1.5	1.5
Partial material coefficient, γ_m	strength	1.5	n/a
	stiffness	1	1

concrete deck		
thickness	0.25	ft
width	6	ft

Loads	factor	load	
Dead load (self weight)	1.5	48.2112	lb/ft
Dead load (wear surface)	1.5	225	lb/ft
Live load	1.5	600	lb/ft
Construction live load	1.5	120	lb/ft
total factored load	1152.3168	lb/ft	

Design parameters (Simply supported)		
span	70	ft
depth	1.2	ft
span to depth ratio	58.33333333	
shear deformation	**not required**	



Cross-section properties		
width, b	1	ft
depth, h	1.2	ft
flange thickness, t_f	0.14	ft
web thickness, t_w	0.1	ft
shear area	0.372	ft^2
moment of inertia, I	0.115367	ft^4

Deflections check		
limit	0.0875	ft
deflection due to bending	0.079094329	ft
deflection due to shear	0.00030899	ft
total deflection	0.079094329	ft
:	**pass**	

Strength check

-

Bending

Maximum bending moment, M_{max}	7.06E+05	lb-ft
max compressive/tensile stress, σ_{max}	3.67E+06	psf
:	**pass**	

Shear

Maximum shear	4.03E+04	lb
Shear resistance	7.77E+04	psf
:	**pass**	

Stability Check

Critical flexural stress in the web

flexural rigidity in long. Dir, D_x	47959.18	
$D_x = E_x t^2/12(1-v_{xy}v_{yx})$		
flexural rigidity in trans. Dir, D_y	6215.902	
$D_y = E_y t^2/12(1-v_{xy}v_{yx})$		
k	20	
t_w	0.1	ft
d_w	0.92	ft
Critical buckling due to flexure, $\sigma_{x,cr,b}$	1.12E+08	psf
$\sigma_{x,cr,b} = (k\pi^2 D_x)/(d_w^2 t_w)$:	**pass**	
☐		

Critical shear stress in the web

k	5.35	
Critical buckling due to shear, $\tau_{xy,cr,b}$	4.58E+07	psf
$\tau_{xy,cr,b} = k\pi^2 E(t_w/d_w)^2/12(1-v^2)$:	**pass**	
☐		

Combined shear and in-plane bending in the web

$(\tau_{xy}/\tau_{xy,cr,b})^2 + (\sigma_{b,x}/\sigma_{x,cr,b})^2$ =	0.001078	
:	**pass**	

Local buckling of compression flange

D'_{xy}	2.01E+04	
$D'_{xy} = G_{xy} t^3/12$		
local buckling compressive stress	8.50E+06	
$\sigma_{x,cr,b} = \pi^2\{(D_x(b/a)^2)+(12D'_{xy}/\pi^2)\}/t_f b^2$		
:	**pass**	
☐		

Minimum length of bearing

Strength, S_s	7.15E-02	ft
Buckling, n	7.36E+00	ft
requires	7.36E+00	ft

Appendix B: Cost Estimation

Unit costs	cost	unit
Steel	$735.00	per ft^3
Concrete	$3.75	per ft^3
Steel girders	$14.96	each
Steel cables	$75.00	per ft^3
GFRP (pultruded E-glass with vinylester)	GBP 4.87	per kg
or	$9.22	per kg
(1 GBP = 1.89 USD) **Note:** Unit costs already include labor cost		

Table B-1: Unit Cost of Material

Alternative	Component	Quantity	Cost
Traditional	concrete on steel deck (ft^3)	10070	$37,762.50
	steel girders (ft^3)	221.81	$163,030.35
	steel cables	800	$60,000.00
	steel truss arch (ft^3)	1430	$1,051,050.00
	concrete arch column (ft^3)	1529	$5,733.75
		total:	$1,317,576.60
Hybrid GFRP	concrete deck (ft^3)	2310	$8,662.50
	GFRP I-beams (kg)	34929.01	$322,045.47
	epoxy resin	n/a	n/a
		total:	$330,707.97

Table B-2: Construction Costs