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LIFE CYCLE ANALYSIS ISSUES IN THE USE OF FRP COMPOSITES IN CIVIL INFRASTRUCTURE

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ABSTRACT

A review of fiber reinforced polymer (FRP) composites is presented with discussion focusing on issues in life cycle analysis (LCA) of civil infrastructure. The review includes the advantages and disadvantages of FRP composites, findings of a few previous LCA efforts, materials and methods used to manufacture FRP composites, and recommendations for further research.

Keywords: FRP, LCA, materials, manufacturing.

1 INTRODUCTION

Composite materials consisting of strong, continuous, fibers bound together by a continuous matrix of polymer resin are increasingly being used in civil infrastructure applications such as reinforcement and prestressing for new concrete structures, strengthening for existing concrete and steel structures, bridge decks, structural shapes, and various hybrid structures [1-4]. Figure 1 shows a photomicrograph of a polished cross-section of an FRP composite with fibers all oriented perpendicular to the section. In this image, the fibers are the light colored circles and the matrix is the dark material surrounding the fibers. The fiber volume fraction in this example is close to 70%, whereas in many infrastructure applications the fiber volume fraction can range as low as 40%, depending on the degree of material compaction applied during fabrication.

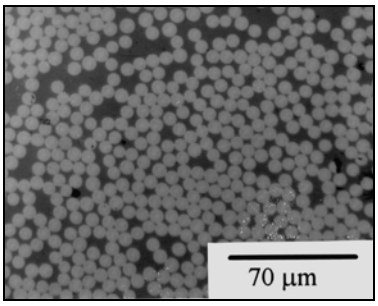

Figure 1: Photomicrograph of a unidirectionally reinforced composite, showing individual fibers.

In the civil infrastructure application area, some of the commonly quoted advantages of FRP composites leading to their use in place of traditional materials such as steel and concrete are:

- high strength in along the fiber direction, which is useful for the replacement of steel in structural elements and concrete reinforcement;
- low susceptibility to chloride-rich environments, which is useful for infrastructure located in or near salt-water or subjected to de-icing agents;
- low magnetic susceptibility and electrical conductivity, which is useful for structures requiring electromagnetic transparency;
- low cost of installation, which results largely from high specific strength (strength per unit density).
- low repair cost

Some of the commonly quoted disadvantages weighing against the use of FRP composites are:

- high first cost of the materials;
- low strength perpendicular to the fiber direction, which often necessitates the use of multidirectional reinforcement;
- lack of long-term service experience in the types of infrastructure applications under consideration and resulting doubts about maintainability and durability;
- difference in stress-strain behavior versus steel—eg., higher elastic strain limit, lower elastic modulus, and absence of plastic deformation capacity;
- limited resistance to elevated temperature;
- lack of standard materials and test methods, specifications and codes
- unfamiliarity in the work force;
- difficult to inspect.

Many of the disadvantages of composites are being addressed with heightened research, a steady accumulation of field experience [5-7] the development of guides, codes, and specifications [8-12], and the incorporation of FRP materials in civil engineering education curricula [13]. One disadvantage that is not likely to change appreciably in the foreseeable future is the high first cost of the constituent materials. The manufacturing processes for these materials are considered "mature" based on many decades of utilization of FRP composites in marine, automotive, and aeronautical transportation industries.

FRP composites provide a unique opportunity for flexibility and innovation in the design of civil structures on account of the wide array of materials and properties they embody along with the many ways that they can be manufactured in factories or at a construction site. These characteristics can be manipulated for improving the life cycle cost (LCC), as well. A LCC analysis typically incorporates the costs of building, maintaining, and disposing of a structure, as outlined for buildings in ASTM E917 [14]. The steps involved in a LCC analysis, according to ASTM E917 are:

- identify objectives, alternatives, and constraints;
- establish basic assumptions for the analysis;
- compile cost data;
- compute the LCC for each alternative;
- compare LCCs of each alternative to determine the one with the minimum LCC;
- make final decision, based on LCC results as well as consideration of risk and uncertainty, unquantifiable effects, and funding constraints (if any).

Following Ehlen's approach [15], costs can be considered at three levels according to the following characteristics:

1. the individuals or entities incurring the costs
2. the point in time of the life cycle in which the cost occurs
3. the component or element of the project generating the cost

Members incurring costs at Level 1, quoting Ehlen [15], are:

> "Agency (such as a state DOT), user (such as drivers on and under the bridge), and third-party (those who incur costs due to bridge activity but are not direct users of the bridge). Examples of third-party costs are lost business revenues for establishments whose customers are blocked by project activity and environmental damage and costs that result from toxic runoff."

The time at which the costs are incurred could be during construction, during operation, maintenance, and repair, and during disposal. Sources of the costs could be elemental (a particular element of a bridge such as a deck, pier, superstructure, etc.), non-elemental (profit or overhead), or those due to new material introduction (laboratory testing, nondestructive evaluation, continuous monitoring, etc.).

Examples of various LCC analyses can be found in the literature (eg., Refs. [15-17]). Comparisons with conventional reinforced concrete decks reveal that FRP composite decks are relatively expensive unless the economic impact of traffic congestion caused by bridge construction is factored into the analysis. Significant societal cost savings—i.e. due to less delay of the driver and vehicle in traffic and reduced incidence of accidents—are realized when FRP decks having rapid installation and end-of-life removal characteristics are utilized [15,16]. The results of these cost analyses also support the predominant use of lower cost, but denser and more compliant glass fibers in FRP decks rather than more expensive but less dense, stiffer, carbon fibers. The minimization of traffic interruption is likewise a well-known motivation for the wide-spread use of externally bonded FRP strengthening for bridge structures [18]. An analysis of glass FRP reinforcement cages meant to replace steel cages in reinforced concrete beams demonstrated cost savings mainly due to reduced cage construction time and reduced maintenance of the beams in corrosive environments [19].

While the life cycle cost analyses discussed above include an impressive scope of material, transportation, installation, maintenance, disposal, and certain user costs, recent elevated interest in broader environmental and societal factors motivates the need for more extensive life cycle analysis tools. The balance of this paper introduces FRP composite materials and manufacturing methods with a slant towards their relative merits on broader environmental and societal factors. The discussion is aimed at experts in life cycle cost analysis (LCA) who have an introductory level knowledge of structural engineering (such as stress-strain behavior) and materials science, but who seek more in-depth information on FRP for civil infrastructure.

2 MATERIALS

The FRP material selection process may occur at any of three levels:

- the fiber/matrix level;
- the composite element level (eg., beams and plates);

- the highly integrated system level (eg., a bridge deck composed of FRP beams and plates, a wearing surface, and guide rails).

There are sequentially less degrees of freedom in material selection (and even geometry) as the level of integration increases. At the same time, the amount of knowledge required of a design engineer on composite manufacturing science, such as fiber wet-out, fiber/matrix bond, filler-viscosity relationships, polymer cure kinetics, exothermic temperatures, etc., decreases with higher levels of integration. A pedestrian example of this comparison would be the tradeoff in purchasing particular types of metals, glasses, polymers, and fabrics to construct an "ideal" automobile from scratch, versus purchasing a commercially available automobile containing materials deemed by the manufacturer to be fit for use and likely to be sold at a certain price in quantities that will produce a profit. There are indeed numerous examples where engineers involved in certain implementations of FRP composites in civil infrastructure, such as externally bonded strengthening for steel and concrete structures, need to select a specific fiber and a specific matrix material, where the matrix consists of proprietary mixture of polymer, viscosity modifiers, curing accelerants, and fillers. Thus, fiber, filler, and matrix materials are discussed separately next.

2.1 Fibers

The most commonly used fibers in FRP composites for construction are glass (E-glass), carbon, and aramid. Typical costs, mass densities, and tensile properties for these fibers are listed in Table 1. Glass fibers are made by melting silica and various other oxides of metals in a furnace, drawing the molten glass through a die, stretching and cooling the fiber, applying highly proprietary "sizings" to facilitate handling and enhance bonding with specific matrix materials, drawing several thousand fibers into "yarn" or "tow," and then spooling the tow for further processing off-site. Carbon fibers are usually made using a polymer precursor fiber known as polyacrylonitrile, which is tensioned at a high temperature in an inert atmosphere to be transformed into a highly graphitic fiber. Graphitized fibers are cooled, sizing is applied, fibers are collected into tows, and tows are spooled for shipment. Aramid fibers are made with a different type of polymer precursor than that used for making carbon fibers. Aramid is essentially a highly oriented crystalline polymer created using certain heat treatments and tensioning operations. Like the other fibers, aramid fibers are sized, assembled into tows, and spooled for shipping. Glass and aramid fibers are considered electrical and thermal insulators, whereas carbon is the opposite. Further descriptions of these and other fibers, including manufacturing methods, are given in Ref. [20].

As with steel, the manufacture of all three of the primary fibers used in FRP composites involves the use of significant amounts of energy. Costs of the attendant environmental issues associated with the generation of that energy are an issue to contend with in LCA.

Table 1: Typical characteristics of fibers and steel.

Fiber	Cost US$/kg	Density g/cm^3	Modulus GPa	Strength MPa
Glass	2	2.5	72	3450
Carbon	25-30	1.8	230	3650
Aramid	42	1.5	130	3600
Steel	1	7.8	208	420

Stress-strain behaviors of the three primary fibers are shown along with a simplified steel stress-strain curve in Fig. 2. Notice the significantly increased ultimate strength and decreased ductility in the fibers in comparison to steel. Also, the fibers behave in a linear elastic manner—unlike steel, which can be idealized (as shown) as a bilinear, elastic-perfectly-plastic material. Although the fibers have a strain-to-failure about 10 times higher than the yield strain of steel (about 0.002 m/m), the lack of a plastic plateau is not an ideal characteristic in structural applications where large energy dissipation is desired, such as in areas of high seismic activity.

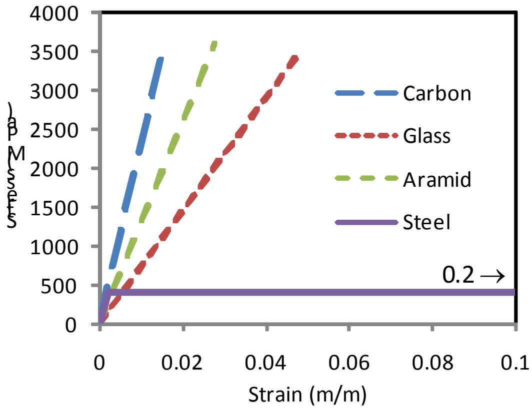

Figure 2: Stress-strain behavior to failure of common fibers and steel. The 0.2 label indicates the approximate failure strain of steel.

Plant based fibers such as jute, bamboo, banana, hemp, kenaf, sisal, etc. are under investigation as eco-friendly reinforcements for FRP composites [21]. The advantages of these fibers relate to their renewable nature, local sourcing in some instances, and usefulness in scrap form as feedstock for thermal energy production. According to one source [22], one fourth the energy is required to produce a unit mass of kenaf fiber versus glass fiber. However, inconsistencies in tensile and bond properties of plant based fibers and susceptibility to moisture-induced degradation remain problematic [23-25]. In benign environmental conditions, natural fibers can offer tensile strengths and moduli of up to 40% and 90% of the respective values of glass fiber, as shown in Fig. 3. As a replacement for glass fiber, additional natural fiber content is required on a volume percentage basis, which has the potentially beneficial effect of displacing the usage of polymer matrix materials that may be considered more environmentally costly. In addition, the mass density of natural fibers is about 1.5 g/cm^3—about 60% of that of glass which they would normally replace and nearly the same as carbon and aramid. The cost of natural fiber varies by type and place of utilization, although it can be expected to be less than that of glass fiber [21].

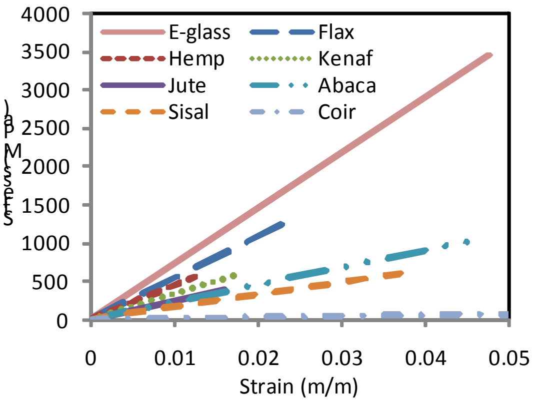

Figure 3: Stress-strain behavior to failure of natural fibers and glass fiber. Adopted from [Symington 2009].

Another type of natural fiber under current investigation for lightly loaded structures is keratin from bird feathers [26,27]. These fibers have a low mass density of 0.8 g/cm^3 on account of their hollow structure, a modulus between 1 and 10 GPa, and a tensile strength of 41-130 MPa. As with plant based fibers, bird-based fiber properties are moisture sensitive, and composite processing temperatures are limited to less than approximately 150-200°C to minimize degradation of the fibers.

Efforts are currently underway to utilize scrap fiber produced during the manufacture of fiber and FRP composites and also after recovery from post-use composites [28]. It is practically impossible to recover continuous fiber from either a production line or a retired FRP structure. Thus, *primary* recycling (i.e., use of recovered fiber for the same purpose for which it was originally used) does not seem to be a viable pursuit. Recovered fiber can be readily chopped to shorter lengths and used to randomly reinforce polymers used in lightly-loaded or nonstructural applications (eg., automobile interiors, molded plastic parts, architectural facades, etc.). Figure 4 shows examples of continuous fiber on spools and chopped fibers.

Figure 4: Spooled continuous carbon fiber (left) and short chopped carbon fiber (right) [29].

When recovering fiber from FRP materials, care must be taken to either remove the matrix material or ensure that the residual matrix material will not degrade the properties of the subsequently manufactured composite. Extracted matrix material can be combusted to recover energy. Non-structural material properties such as high damping and high/low electrical and thermal conductivity (depending on the type of fiber) are relatively easy to maintain with recovered fibers. Thus, at least in the context of structures, *secondary* recycling (the use of recovered fiber for a different purpose than it was originally used) seems to be viable. Better integration of the fiber scrap generators and the fiber supply chain is needed to improve the prospects for fiber recycling.

Depending on the direction of fiber reinforcement required in an FRP structure, fibers may be used in unidirectional or multidirectional arrangements. When multi-directional reinforcement is called for by the design process, unidirectional plies may be stacked at the various orientations, mat with two-dimensional-random fiber orientation may be used, or tows may be woven or braided into textile-like fabrics (Fig. 5).

The lamination procedure, wherein plies of two-dimensionally reinforced material are stacked to achieve required strength and stiffness in various directions, is illustrated in Fig. 6 for the case of unidirectionally reinforced plies.

Figure 5: Unidirectional carbon fiber ply and random mat (top); woven carbon fabrics (middle); and braided hybrid fibers (bottom) [29].

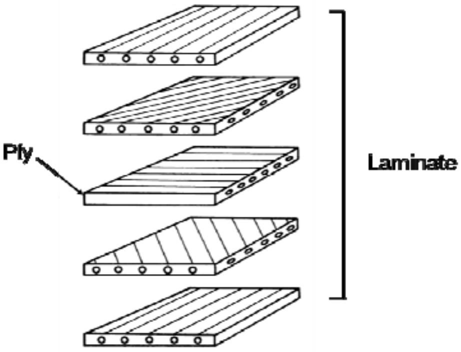

Figure 6: Illustration of a laminate comprised of 5 unidirectionally reinforced plies [after Ref. 30].

2.2 Veils and Fillers

Veils and fillers are used in FRP composites mainly for non-structural reasons. Veils are thin, sparse mats of randomly oriented glass or polymer fibers positioned on the surface layer of a composite to absorb a high amount of resin and provide a smooth surface that is both visually appealing and relatively impermeable to moisture diffusion in comparison to bulk fiber-reinforced composite material [20]. Fillers are generally low-cost, sub-micron-sized particles added to the matrix primarily to reduce cost but also to provide one or more of the following desired characteristics to the polymer: reduced chemical shrinkage, reduced coefficient of thermal expansion, increased thermal conductivity, increased electrical conductivity, ultra-violet radiation resistance, and flame resistance. Fillers may be derived from natural minerals (eg., calcium carbonate, clay, alumina trihydrate), manufactured products (eg., metal powders, glass beads, phenolic polymer), or plant sources (eg., wood flour, ground rice hulls and peanut shells). These and additional fillers are described in Ref. [31].

The use of filler and veil materials enhances the price and performance of FRP composites, but adds additional challenges to consider in the sustainability/recyclability of composites and LCA efforts in general. Currently, fillers are not designed to play any role in end-of-life treatment of composites. However, perhaps future research will lead to the discovery of sustainable fillers that not only perform the usual functions but additionally facilitate the separation and recovery high value constituents of discarded composites.

2.3 Matrices

When reinforcing fibers are highly aligned and continuous, they provide considerable strength, stiffness, and creep (time dependent deformation) resistance to a composite material. However, the polymer matrix plays an important role by carrying loads that bundles of dry, aligned fibers would be unable to bear by themselves, such as shear load transmission between the fibers, loads perpendicular to the fibers, and compressive loads parallel to the fibers. Clearly, in multidirectionally reinforced composites, matrix is essential to hold the fibers together under any type of loading.

The polymer matrix should be soft and ductile enough to absorb a limited amount of individual fiber damage without transmitting excessive stresses to nearby fibers, so that failure of a single weak fiber does not immediately cascade into a complete structural failure. The polymer and fiber (including the sizing or surface treatment) must be formulated to bond well to each other in all service environments, or else the radial and shear strength at the interface will be poor. The matrix may also need to protect the fibers from potentially aggressive environmental agents such as ultraviolet radiation and high or low pH liquids.

Most polymers used in FRP composites are *thermosets*, meaning that once chemically cured they cannot be melted by heating. This can be considered a detriment to their recyclability. (Note: *thermoplastic* polymers can be repeatedly melted and solidified, but currently have not been widely applied in infrastructure-grade composites on account of high cost, poor processing characteristics, or poor performance). The primary matrix materials used in FRP composites for civil infrastructure are vinylester, polyester, and epoxy—all of which are thermosets. A non-exhaustive list of cost, density, and mechanical properties of these resins is given in Table 2. The physical and mechanical properties of the three resins are quite similar to each other, although epoxy tends to have the best adhesion and least chemical shrinkage upon curing, both of which are necessary for realizing the maximum strength of a fiber reinforced ply in shear and perpendicular to the fiber direction. Polyester is generally inferior to vinylester and epoxy in terms of resistance to water and alkaline environments, such as inside concrete. Detailed descriptions of these and additional matrix materials are given in Ref. [20].

Table 2: Typical characteristics of matrix materials.

Matrix	Cost US$/kg	Density g/cm^3	Modulus GPa	Strength MPa
Vinyl-ester	2	1.2	3-3.4	86-93
Poly-ester	2	1.2	1-11	10-120
Epoxy	4-20	1.2	2-5	35-80

A consideration for LCA models is the petroleum source of typical polymers used as matrix materials, and what ultimately is done with waste matrix material when the FRP structure is scrapped. In light of such considerations, plant based resins are being investigated for their suitability to partially or completely displace petroleum based resins. Soy and linseed based epoxy resins have been shown to have modulus and strength values generally less than those of petroleum based epoxies [32,33]. However, by blending plant based epoxy resins with conventional epoxies and/or adding plate-shaped nano-fillers, the mechanical properties can approach those of petroleum based epoxies.

It should be kept in mind that moderate changes in the modulus of elasticity of a polymer matrix may not affect the modulus of a continuous fiber reinforced FRP composite if the behavior of the composite if fiber dominated. The rule-of-mixtures expression for the modulus of a unidirectional composite in the direction of the fibers, E_1, is

$$E_1 = V_f E_f + V_m E_m, \qquad (1)$$

where V_f and V_m are the volume fractions of fiber and matrix, respectively, and E_f and E_m are the moduli of fiber and matrix, respectively [30]. Using a glass FRP with $V_f = 0.6$ as an example, if the modulus of the resin decreases from 2 to 1 GPa, E_1 decreases only from 44.0 to 43.6 GPa. The difference in E_1 under these conditions is even less noticeable in carbon and aramid FRP on account of the higher fiber moduli. In terms of tensile strength in the fiber direction, not much difference is likely to be seen for such a change. However, a less stiff resin will have a marked reduction in compressive strength along the fiber direction, F_{1c}, as suggested by a simple formula

$$F_{1c} = G_m/(1-V_f), \qquad (2)$$

where G_m, the shear modulus of elasticity of the matrix, varies in proportion to the Young's modulus of elasticity according to the relationship

$$G_m = E_m/[2(1+ \nu_m)]. \qquad (3)$$

In Eq. (3), ν_m is the Poisson's ratio of the matrix (usually around 0.35 to 0.4 for most polymers) [30]. Likewise, perpendicular to the fibers and in shear, there will be a nearly one-to-one dependence of the modulus and strength of the FRP on the corresponding matrix properties. Thus, the disadvantage of affordable thermoplastic matrix materials (low modulus and strength) becomes apparent as well. Actually, strong, stiff, thermoplastics are currently used to manufacture FRP composites for the aerospace industry. Some of these have extraordinary high temperature behavior, as well. The problem with these resins is extraordinary cost—sometimes as high as US$200/kg.

3 FRP Manufacturing

Structural shapes and bridge decks typically contain multidirectional reinforcement akin to that shown in Fig. 6. These can be manufactured using various combinations of unidirectional fibers, woven fabrics, and braided shapes, which are first placed in the proper sequence and orientation, infused with resin, and then cured. An increasingly common method for rapidly inserting resin into a fiber preform without much release of volatile organic compounds is called *vacuum assisted resin transfer molding* (VARTM). VARTM is done with a relatively low cost, thin mold (tool plate) on only one side of the part and only a vacuum bag on the other side, as shown in Fig. 7 for a flat plate. The method is most suitable for plate-like structures and open shells. As vacuum is applied to the inside of the bag, resin is drawn into the bag and through the fiber preform. This results in a low void content in the composite due to the vacuum, as well as good consolidation of the fiber preform (i.e., high fiber volume fraction) due to the application of ambient air pressure (101 kPa). VARTM avoids the significant capital expense of an autoclave, which is a heated pressure vessel traditionally used to consolidate aerospace grade composites.

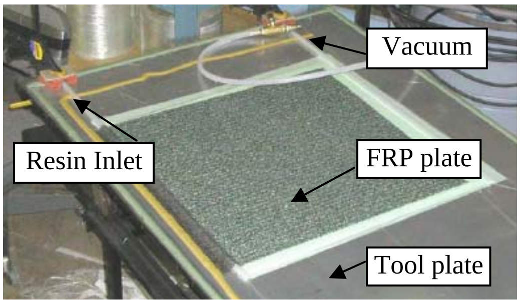

Figure 7: A flat fiber reinforced plate prepared for infusion of resin by the VARTM process.

Long structural shapes of constant cross section and containing predominantly unidirectional reinforcement along the length are most effectively made using the *pultrusion* process. In this continuous process, illustrated schematically in Fig. 8, dry fibers and cloths are pulled through a resin bath, a forming die, and a heated mold by a tractor-type puller. Vinylester and polyester resins are typically used so that curing takes place in a matter of minutes in the first half of the die. As the part hardens, a controlled amount of resin shrinkage (along with an internal mold release that migrates to the heated surface of the part) ensures a smooth release of the part from the mold. Line speeds of several feet per minute are possible, making pultrusion a highly economical process. Examples of structural shapes made by pultrusion are shown in Fig. 9.

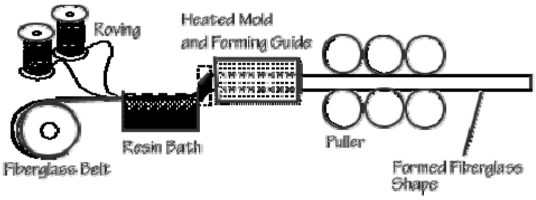

Figure 8: Schematic of the pultrusion process [34].

Figure 9: Examples of FRP structural shapes made by pultrusion [35].

Other FRP applications in civil infrastructure calling for unidirectional or nearly unidirectional reinforcement are made by pultrusion as well. Examples include reinforcement bars, prestressing tendons, and externally bonded or near-surface bonded strengthening for beams, walls, and slabs. A sampling of bars and tendons with surface treatments for enhancing bond with concrete are shown in Fig. 10. The surface treatments are made by various processes such as wrapping of filaments, sand coating, and molding.

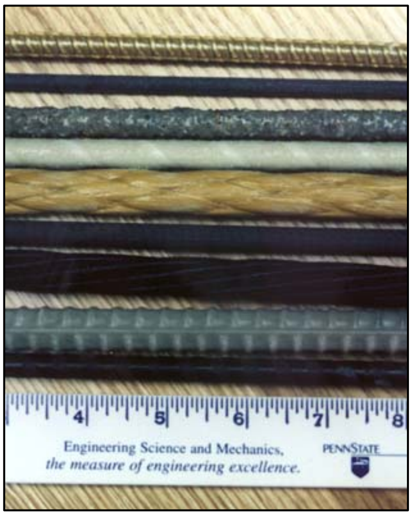

Figure 10: Examples of FRP bars and tendons. Scale is in inches (1 inch = 2.54 cm).

While the elastic properties of laminated composites can be easily tailored by changing the fiber orientations in the laminate, often there is need to obtain a certain modulus of elasticity in a unidirectionally reinforced composite such as a bar or plate. In such cases, if the appropriate fiber and fiber volume fraction cannot meet the objective according to the rule-of-mixtures expression given previously in Eq. (1), fibers of elastic moduli bracketing the target can be combined in various proportions. In such so-called *hybrid* unidirectional fiber composites, the modulus in the fiber direction is given by a similar rule-of-mixtures expression,

$$E_1 = V_{fA}E_{fA} + V_{fB}E_{fB} + V_mE_m, \tag{4}$$

where subscripts fA and fB denote fiber types A and B, respectively. Figure 11 shows the outcome of varying the volume fraction of carbon fiber in a glass FRP from zero to 0.6, holding the volume fraction of matrix constant at 0.4 and filling the remainder with glass. When there is no carbon fiber present (carbon $V_f = 0$), the composite modulus is equal to that of glass FRP. Similarly, when there is no glass fiber present (carbon $V_f = 0.6$), the composite modulus equals that of carbon FRP. Thus, the modulus in the fiber direction can be tailored from 44 to 139 GPa by simply changing the relative amount of carbon and glass fiber in the composite.

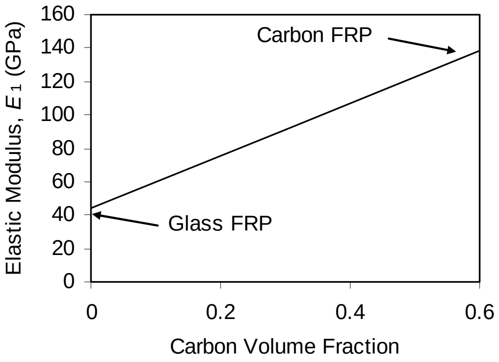

Figure 11: Fiber direction elastic modulus of a unidirectional hybrid carbon/glass FRP composite with total fiber volume fraction 0.6 and matrix volume fraction 0.4.

A photograph of the cross section of a round pultruded composite bar hybridized with carbon and glass fibers is shown in Fig. 12. The measured elastic modulus of this bar was 52 GPa, whereas the prediction by Eq. (4) for the material properties given in Tables 1 and 2 is 56 GPa. Experimental moduli slightly less than those predicted by theory can be expected due to imperfect fiber collimation during processing.

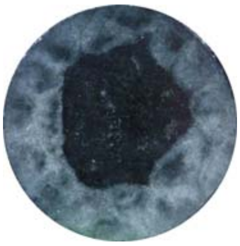

Figure 12: Photograph of the cross section of a hybrid composite bar containing 13% carbon fiber (black region in center), 35% glass fiber (gray region around periphery), and 52% matrix [36].

The strength of a hybrid fiber composite fiber composite does not follow the rule-of-mixtures expression given in Eq. (4). Rather, due to the homogeneous strain condition along the fiber direction under longitudinal applied stress, stresses in the different types of fiber vary in proportion to their respective moduli. Moreover, the fiber with the lowest ultimate strain governs failure of the bar. In the example shown in Fig. 12, the carbon fibers fail first because of their lower ultimate strain (~1.6%) versus glass (~4.8%). However, provided the glass fibers are able to take up the load shed by the broken carbon fibers, the bar may actually continue to carry load (albeit at a reduced stiffness) until the glass fibers themselves fail at still higher value of strain. This type of two-stage failure process can be utilized to warn of imminent failure if the electrical conductivity of the bar is monitored during service as part of a structural health monitoring regimen [36].

The filament winding manufacturing method is appropriate for making cylindrical structures using FRP and is used for a few applications in civil infrastructure such as stay-in-place formwork for concrete columns. A photograph of a filament winding machine and partially complete tube is shown in Fig. 13. Several tows of dry fibers are impregnated with liquid resin in a bath and are wrapped around a rotating mandrel (corresponding to the inside dimension of the tube) with some tension to effect a degree of compaction of the part. Precise placement of the tows is done with payout tooling which traverses along the length of the mandrel at a rate calculated to give the desired wrapping angle. Fibers are typically wound in combinations of helical and circumferential patterns to obtain the desired properties along the axial and hoop directions of the tube. Purely axial fibers are difficult to wind with this type of machine and are typically approximated by winding helical patterns at low angles to the longitudinal axis, such as ±2 degrees. A close-up view of a helical fiber pattern on the outer surface a carbon FRP tube is shown in Fig. 14.

Figure 13: Example of FPR tube winding with a filament winder [37].

Figure 14: Small-scale example of a helically wound carbon FRP tube with fibers at ±40-degrees relative to the longitudinal axis.

4 RECOMMENDATIONS

As a highly tailorable class of materials, FRP composites offer tremendous potential to be used as multifunctional structures in civil infrastructure. The main disadvantage of these materials in terms of their value after disposal is really the same as their main advantage—i.e., their complex, heterogeneous, anisotropic characteristics. These characteristics make re-use and recycling, in part or in whole, very challenging problems. Efforts are already underway to address these challenges, but more needs to be done to design materials with end-of-service in mind and to improve the overall eco-footprint of composites.

LCA models require robust mathematical relationships between aspects such as environmental effects, human effects, raw material feed-stocks, manufacturing methods, material design, embodied energy, transportation costs, disposal/recycling costs, etc. To the author’s knowledge, connections among all these aspects are incomplete. Making the connections will require a highly multi-disciplinary approach that is likely take significant financial resources to be done properly. Many experts need to be engaged from diverse areas such as materials science, chemical engineering, mechanics, structural engineering, manufacturing engineering, business analysis, transportation engineering, environmental engineering, law, and climatology, to name a few.

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