Composite Materials: Advantages and Cost Factors

Clifford Lester and Dr. Steven Nutt*

March 21, 2018

I INTRODUCTION

Fiber reinforced composites have been in use for over fifty years, but only recently have they become common in consumer applications. Carbon fiber reinforced plastics (CFRPs), commonly referred to as "carbon fiber," are now used in supercars and performance sports equipment, as well as a wide range of defense applications. In addition to aesthetic value, carbon fiber composites can be used to make lighter weight parts and stiffen structures for superior performance. In this paper we review the benefits of carbon fiber reinforced plastics, and the reason for their relatively high costs.

II COMPARISON

CFRPs are a type of composite in which a thermosetting resin, often epoxy, is strengthened and stiffened by the addition of carbon fibers. The resin in a CFRP is referred to as the *matrix.* The fibers are stronger and stiffer than the polymer matrix, resulting in a product which is exceptionally stiff for its weight. In Figure 1, the specific strength and modulus (strength and stiffness per weight) of woven carbon fiber is compared to that of aluminum, wood (oak), steel, and plastic (high-density polyethylene). For its weight, the carbon fiber is nearly four times as strong as aluminum, and almost an order of magnitude stronger than the hardwood and steel. Nevertheless, it is important to remember that each material has its place.

A. Aluminum

Carbon fiber is used in place of aluminum when weight savings are important. Additionally, because carbon fiber has a higher modulus, or stiffness, than aluminum, parts can often be made with less material. Thus, high-performance bike frames are almost entirely carbon fiber; it is less dense, and the frame can be made thinner. The resulting performance gains are two-fold. Moreover, the stiffness can be tailored for individual components of the frame. Finally, carbon fiber adds aesthetic value to most applications, exhibiting a distinctive weave pattern on surfaces.

B. Wood

Oak is only 10% as strong as carbon fiber per unit weight, but wood is used in applications where cost is an important consideration. In fact, wood is very similar to a natural fibrous composite, and like composites, showns properties that are different in different direction (thus, plywood is laminated cross-ply). Wood is renewable, biodegradable, and floats. However, CFRPs are more durable than wood, and have superior tolerance to moisture and moderate thermal cycling.

C. Steel

Steel is much cheaper as a raw material, offers ease of manufacture, joining, repair, and recycle, and can be alloyed and heat-treated to produce a wide range of material properties. However, low carbon steel is approximately five times as dense as carbon fiber, and only 8% the specific strength. Thus, the applications of the two materials rarely overlap.

*PhD, Materials Science

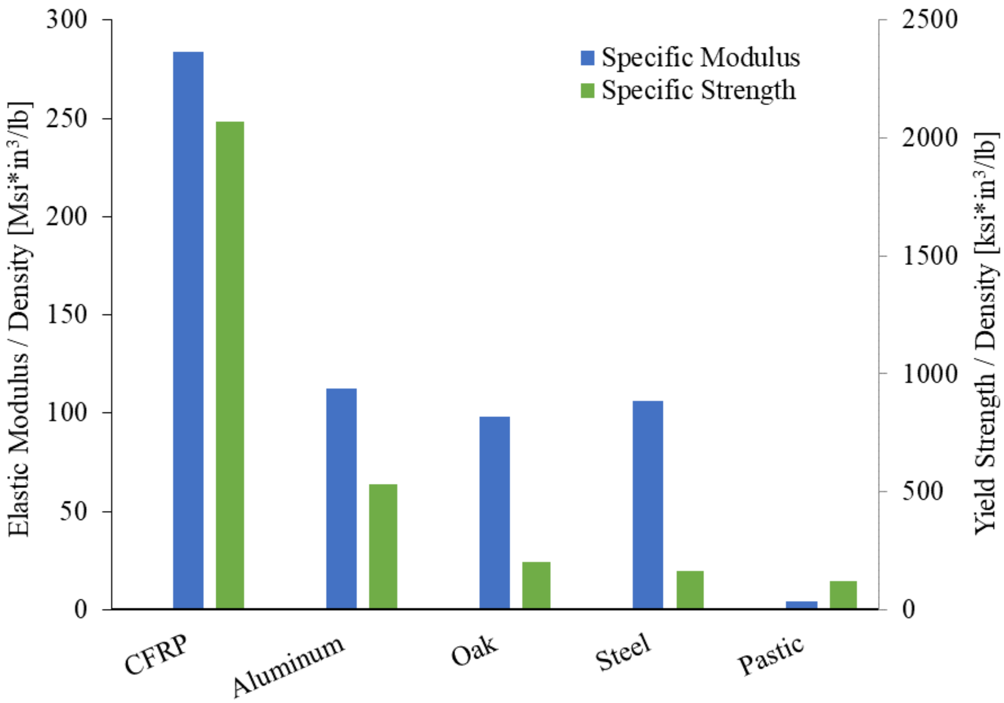

Figure 1: Specific modulus and strength of woven carbon fiber reinforced laminates compared to 6000-series aluminum, oak (along the grain), low carbon steel, and high-density polyethylene. [1].

D. Plastic

As the name "carbon fiber reinforced plastic" indicates, polymer matrix composites are plastics reinforced with fibers that carry most of the load. As shown in Figure 1, the specific modulus of CFRP is over 60 times greater than high-density polyethylene and the specific strength is nearly twenty times greater. Most CFRPs are made with *thermosets*, or polymers which undergo an irreversible chemical change when cured. HDPE is a thermoplastic, which melts at high temperatures, but returns to its original state when cooled. Thermoplastics are much cheaper to manufacture, especially for high volumes, and easier to form, join, and recycle. However, the mechanical properties of thermoplastics are generally inferior to epoxies and other thermosets.

III WORKABILITY CONS AND PRICE

Manufacturing composite parts presents several challenges. Carbon fiber strands are approximately a tenth the diameter of a human hair, and typically thousands of fibers are bundled together to form *tows* that are then woven, spread into tape, or simply wound into spools. Producers may receive rolls of tow, or woven fabric sheets of carbon fiber. In the case of aerospace grade carbon fiber, resin is applied to the tow fabrics (or tapes) to make *prepreg* sheets. However many applications begin with dry carbon fiber, and resin must be applied manually through a process known as wet layup, or by similar liquid molding techniques. Layers of woven carbon fiber are stacked to form a laminate. An engineer typically specifies the orientation of fibers to achieve the desired the properties of the finished part, and minimize the weight. High temperature and intermediate modulus resins, such as those used in aerospace applications, are cured in an oven. The layers are either compressed by negative pressure (vacuum), as shown in Figure 2, or using heated compression molding. For industrial applications, composite parts may also be cured in an autoclave, which is a pressurized oven. These are used primarily in the aerospace industry, which requires the highest performance, but are generally avoided in other sectors of industry due to the high capital and operational costs.

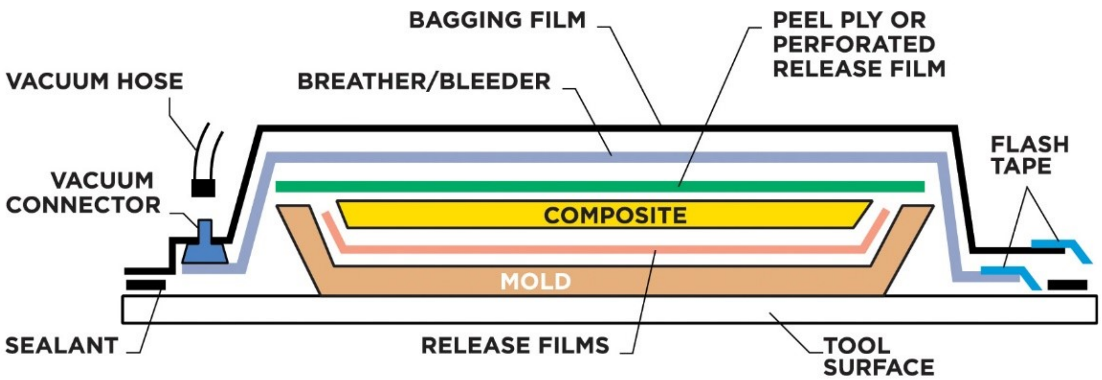

Figure 2: Vacuum bags are used to remove residual air and achieve compaction of layers of carbon fiber and resin during the cure process. This decreases porosity in the final part by removing air and volatiles (primarily moisture). A cross section of a generic vacuum bag is shown here.

During the layup process, the part is often *debulked* intermittently (many parts require a debulk for every 3-5 plies). To debulk a part, a vacuum bag is assembled as shown in Figure 2, and vacuum pressure is applied for $\sim$ 15 minutes, in order to compress plies and eliminate voids. In Fig. 3, an airplane fuselage is being sealing in a vacuum bag for debulking.

Figure 3: An airplane fuselage is manufactured with prepreg carbon fiber. Here, it is being sealing in a vacuum bag for a debulk or the final cure [6].

Because layers must be hand-placed and bagged, complex parts are labor intensive and quickly become more expensive. Moreover, parts thicker than two inches are difficult to cure, limiting the use of composites in some applications. Finally, post-machining is difficult because basic cutting tools wear rapidly and must be replaced frequently or delamination between layers may occur, compromising the parts structural integrity.

In the case of flat sheets, the raw material makes up the majority of the cost. Figure 4 presents the cost breakdown for 0.1 m^2 and 2.5 m^2 panels manufactured using vacuum-bag compaction. For a 2.5 m^2 panel, over 95% percent of the cost is the raw material and consumables. The largest cost in terms of human activity is the debulking step. In their paper on manufacturing cost relationships for composite parts manufactured with a vacuum bag, Centea and Nutt identify the cost of "raw" prepreg as the most important driver of both absolute and specific manufacturing costs [3]. In this model, a 0.1 m^2 panel costs over \$150. A 6" by 24" (0.09 m^2) panel of aluminum 6061 costs approximately \$30.

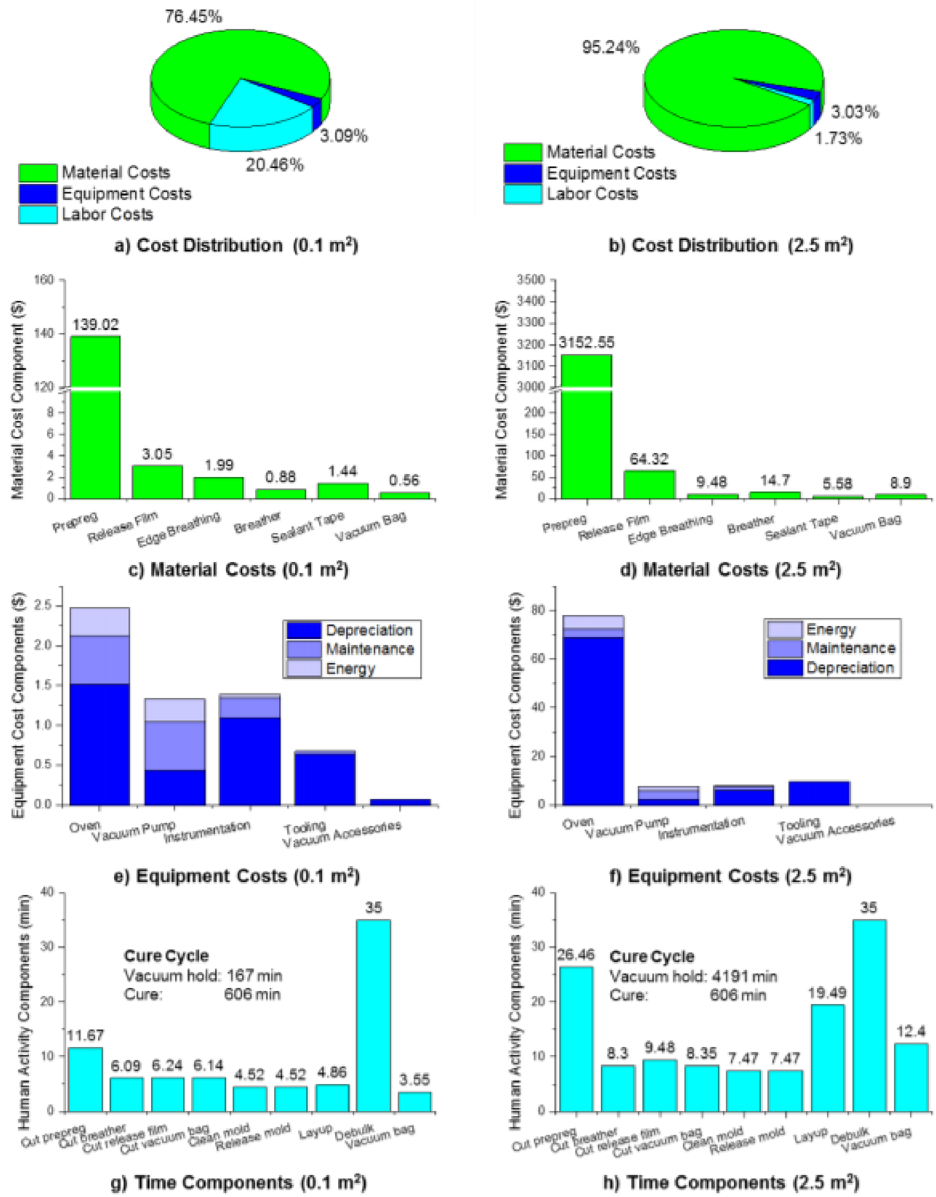

Figure 4: Cost breakdown for aerospace grade carbon fiber parts produced under baseline conditions. Cost is modeled for vacuum-bag only prepreg processing [3].

IV CONCLUSIONS

Carbon fiber is gaining traction in applications where performance gains derived from a lighter and stiffer part out-weigh the additional cost. Carbon fiber composite parts offer clear benefits over steel, aluminum, wood, and performance plastics due to the high specific strength and modulus. Nevertheless, they remain expensive due to the high costs of raw materials and labor required.

References

[1] G. Design, ”CES EduPack Software—Material Level 2,” 2015.

[2] ”Tap into the Strength and Flexibility of Engineering Composites,” Engineering 360, 18 April 2017. [Online]. Available: https://insights.globalspec.com/article/4770/tap-into-the-strength-and-flexibility-of-engineering-composites. [Accessed 26 February 2018].

[3] T. Centea and S. R. Nutt, ”Manufacturing Cost Relationships for Vacuum Bag Only,” J. Compos Mat, vol. 50, no. 17, pp. 2305-2321, 2016.

[4] ”Titanium Ti-6Al-4V (Grade 5), Annealed,” [Online]. Available: http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=mtp641.

[5] ”TC275-1 Product Data Sheet,” Tencate Advanced Composites, 2018. [Online]. Available: https://www.tencatecomposites.com. [Accessed 20 February 2018].

[6] Mouawad, C. (2018). New Challenges for the Fixers of Boeing’s 787. [online] The New York Times. Available at: http://www.nytimes.com/2013/07/30/business/boeings-787-poses-new-challenges-for-repair-teams.html [Accessed 7 Mar. 2018].