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Tailored material properties using textile composites

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Abstract: Lightweighting is essential for the reduction of energy consumption in transportation. The most common approach is through the application of high specific strength and stiffness materials, such as composites and high performance aluminum alloys. One of the challenges associated with the use of advanced materials is the high cost. This paper explores the opportunities of using hybrid composites (glass and carbon, for example) with selective fiber placement to optimize the weight subject to price constraints for given components.

Considering the example of a hat-section for hood reinforcement, different material configurations were modeled and developed. The required thickness of the hat section to meet the same bending stiffness as an all carbon composite beam was calculated. It was shown that selective placement of fiber around the highest moments results in a weight savings of around 14% compared to a uniformly blended hybrid with the same total material configuration. From this it is possible to estimate the materials cost of the configurations as well as the weight of the component. To determine which is best it is necessary to find an exchange constant that converts weight into cost – the penalty of carrying the extra weight. The value of this exchange constant will depend on the particular application.

1. Introduction

Most structural parts are over-designed with the entire material volume able to withstand the highest stress levels in the part. However, the actual parts rarely experience uniform stress - some areas are much more stressed than others.

An optimized part would be one where all of the material approaches the design limit stress in at least one design condition while never exceeding that limit in any design condition. This can be achieved either through geometrical design, or material property design, or a combination of both. The focus of this research is on material property design, allowing the mechanical properties to vary throughout the volume of the part.

The use of a high precision, selective fibre placement techniques can result in appropriately designed, minimal weight components. In an optimal configuration, it is possible to incorporate lower cost materials in areas where benefits of a higher cost material such as carbon fibre do not justify the cost premium, resulting in a reduced overall cost of production while fully satisfying all performance requirements. ***Figure 1*** provides a schematic illustration of how stress in a component varies with different materials placed throughout.

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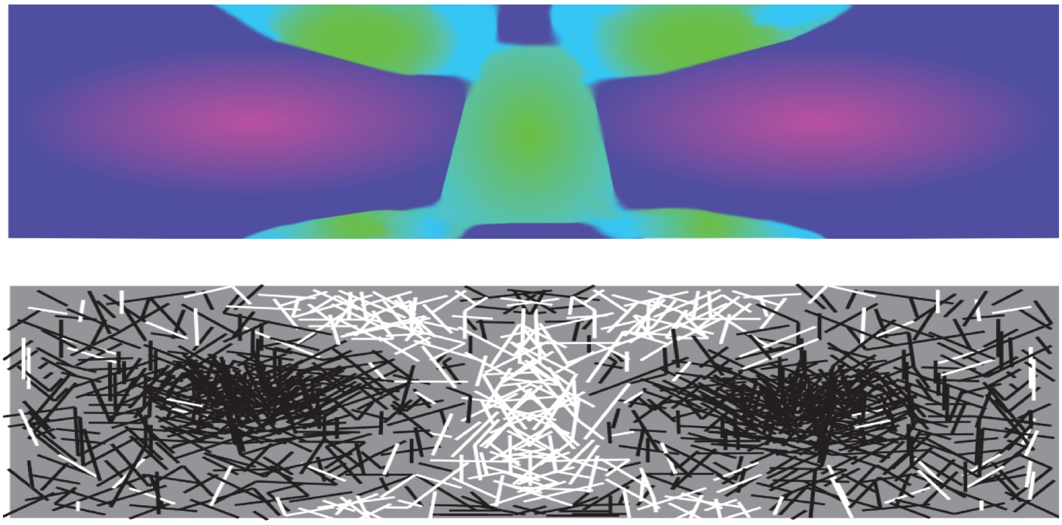

Figure 1. Schematic of stress analysis of structural component (top) with corresponding fiber placement solution (bottom) (black = carbon; white = glass)

Tailoring material properties is important where weight is crucial to performance. Lightweighting is essential for the reduction of energy consumption in transportation. The most common approach is through the use of high specific strength and stiffness materials, such as composites. One of the challenges associated with the use of advanced materials is the high cost. This research explores the opportunities of using hybrid composites (glass and carbon) with selective fiber placement to optimize the weight subject to price constraints for given components.

Weight has a cost penalty specific to the application. The high cost of composites is a barrier to their adoption in cost-sensitive (low weight penalty) energy applications. Multi-material preforming enables the production of composite components with increased structural efficiency and reduced cost. This will accelerate the deployment of high performance composites in energy applications.

Lightweight design and construction is essential for maximizing performance in many energy applications. For example, a 10% mass reduction in passenger automobiles reduces fuel demand by about 6 – 8% [1], hence routes to compliance with 2025 U.S. CAFE regulations [2] (54.5 mpg or 23.2 km/l) typically include demanding vehicle weight reduction targets. Similarly, utility scale wind turbines are growing larger with prototype blades approaching 100 m long, requiring a combination of low mass and stiffness that can only be delivered by fiber-reinforced composites, with carbon fibers being very desirable for high stiffness.

2. Beam Bending Model

For the purposes of structural analysis, a hat section beam, representative of a hood stiffener, was chosen for evaluation. Four different material models were considered for the analysis – all glass, all carbon, a 50/50 glass/carbon (“linear”) and a 67/33 glass/carbon (“quadratic”). The latter two are selective fiber placement models with carbon predominantly in the center of the beam, but with a smooth gradation from all carbon to all glass.

In order to compare equal performance components, the wall thickness necessary to achieve the same maximum deflection (structural stiffness) for each material was determined. The all carbon composite was chosen as the baseline. This means the composites containing glass will need to be thicker and the metal parts can be thinner.

The wall thickness of each material was changed, resulting in different moments of inertia, and different maximum deflections. The thickness value at which the maximum deflection was the same as the 2 mm carbon baseline was recorded as the stiffness optimized wall thickness.

Comparing the selective placement schemes to a uniform hybrid, the thicknesses required to meet the same bending stiffness as the carbon beam are shown in Figure 2. The solid line indicates a uniform hybrid, compared to the selective fiber placement. It can be seen that there is about 13-14% thickness (thus weight) savings achieved by selective placement compared to uniform blending.

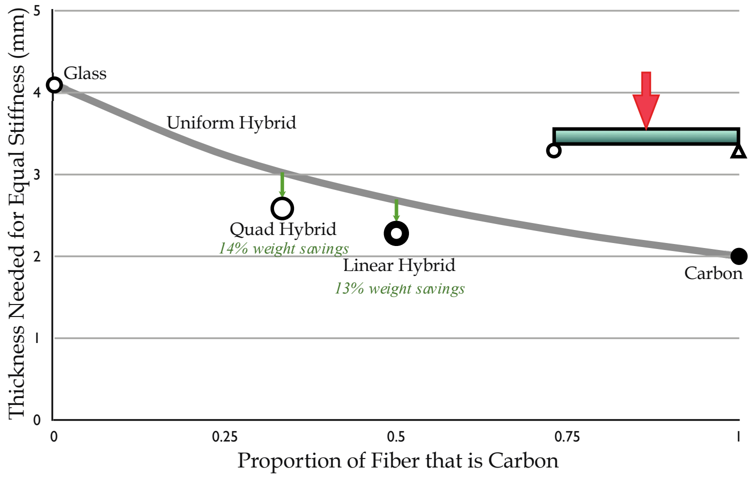

Figure 2. Thickness needed to match bending stiffness of carbon composite beam.

It is difficult to determine which product is "best." Carbon is the lightest, but steel is the least expensive. If the solution space is considered to be mass and cost, the potential material solutions can be plotted on this coordinate space, as shown in Figure 3. The optimal solution has a mass of zero and a cost of zero, which is unachievable, but gives insight into how to read this chart. The goal is to approach the origin.

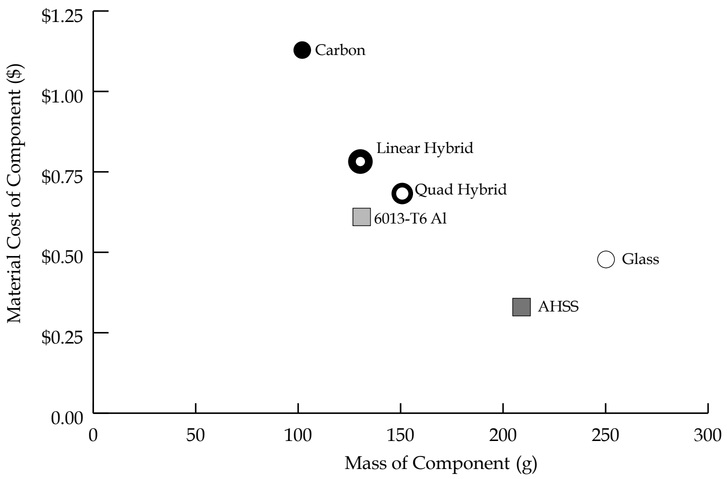

Figure 3.Plot of mass and material cost for parts optimized to meet both stiffness and strength criteria.

There is a trade-off between weight and cost, and the value of that trade-off, called the "exchange constant", depends on the particular application and market demands. When a solution space such as that shown in Figure 3 does not show a clear optimal solution, it makes sense to look at a penalty function that calculates the “effective cost” of the component.

In Figure 4 the effective cost is calculated for a range of exchange constants comparing the 4 composite solutions. The material with the lowest cost at some exchange constant would be a locally optimal solution for this space.

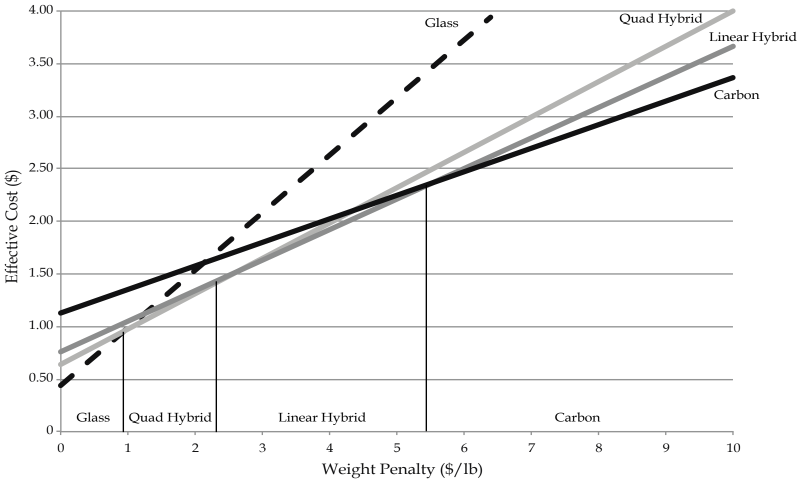

Figure 4. Effective Cost of 4 Composite Material Solutions as a Function of Exchange Constant

In Figure 4, it can be seen that for very low exchange constants (less than $0.99/lb) glass is the best choice. After that, Quad Hybrid is best, followed by Linear Hybrid and finally carbon at high exchange rates. When the metal choices are added to the analysis, steel becomes the low cost optimal choice. Steel is best for an exchange constant less than $1.62/lb, aluminum next between $1.62 and $8.02/lb and carbon the best for high value applications.

The limiting factor here is the cost of carbon, a topic of much research. As the cost of carbon decreases, assuming no property losses, the composites become more cost competitive with aluminum, and even potentially AHSS steel. The maximum cost of carbon fiber required to make the parts cost the same as 6013-T6 aluminum is shown in Figure 5.

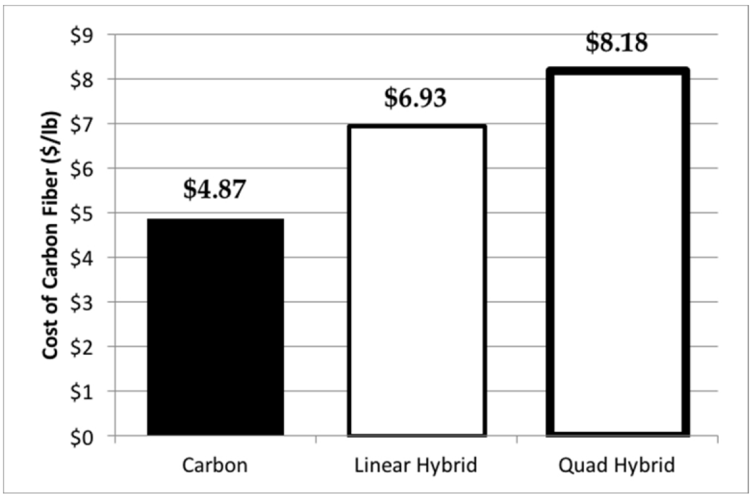

Figure 5. Cost of Carbon Fiber Needed to Make Optimized Composite Hat Section Component with Same Cost as Aluminum with Equivalent Stiffness and Strength

IOP Conf. Series: Materials Science and Engineering **254** (2017) 042023 doi:10.1088/1757-899X/254/4/042023

In order to make the composites cost effective with AHSS steel, the cost of carbon needs to be extremely low – approximately $2.50 per pound. If exchange rates are included, depending on the particular cost of weight, the needed cost of carbon fiber will vary with the specific exchange rate. Figure 6 shows the minimum carbon fiber cost needed to achieve equivalency with 6013-T6 aluminum as a function of exchange rate. For the carbon composite, as the exchange rate increases, it is acceptable to pay more for the carbon fiber. The Linear Hybrid has a slight increase in minimum fiber cost, but is generally flat due to the 50% glass content. For the Quad Hybrid, because of the greater amount of glass and thus higher overall mass, increasing the exchange constant makes it less attractive, and requires less expensive carbon fiber to be competitive.

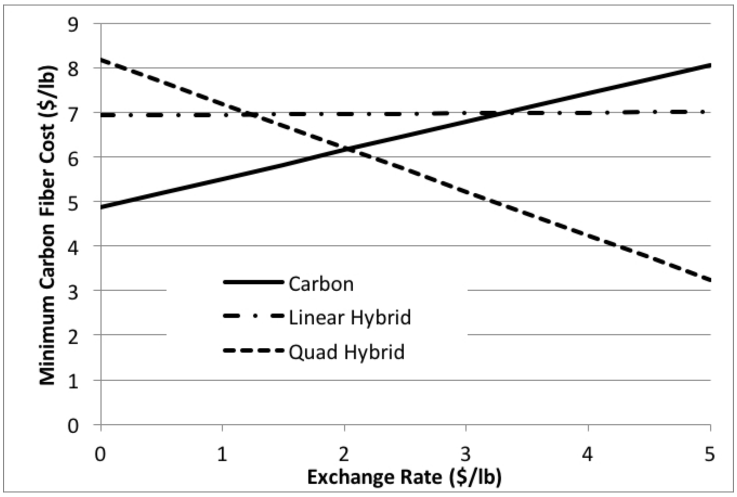

Figure 6. Minimum Carbon Fiber Cost needed to Make Optimized Composite Hat Section Component with Same Cost as Aluminum with Equivalent Stiffness and Strength as a Function of the Exchange Rate

3. Citations

[1] Cheah L. 2010, *Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.,* Massachusetts Institute of Technology Ph.D. Thesis, Sept 2010

[2] NHTSA 2011 *CAFÉ 2011-2016 Final Rule*, National Highway Transportation Safety Administration.