Incorporating Green Engineering in Materials Selection and Design

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INTRODUCTION

The selection of a material-of-construction for any engineering component or system will have environmental implications. Minimally, the availability of, or demand for, a particular material for an envisioned design will necessitate the expenditure of energy to convert that material from its raw material form into the specified (manufactured) form or shape. Additionally, the performance characteristics of the material will dictate the quantity or mass necessary to fulfill the functional requirements of the design; this may have additional influences with respect to the overall efficiency of the system over its lifetime in service. As such, any and all engineers engaged in the development of product or other engineering systems are positioned to make decisions in which environmentally-responsible options can be considered.

This paper illustrates a method whereby a lifetime environmental load associated with the selection of a specific material can be routinely assessed as part of the overall decision-making process used in mechanical and functional engineering design. The technique can be generically applied to any application or situation, and builds upon the approach of using mass-based material selection indices through their modification to include total energy consumption prior to, and during, service.   The specific example presented in this paper represents the subject of a project recently assigned in a senior level course entitled, "Materials Selection and Design", required of Materials Science and Engineering (MSE) majors, and offered as a technical elective to students of other engineering disciplines at Virginia Tech.

LIFETIME ENERGY CONSUMPTION

The structural materials that are inherently light, or possess low densities, tend to be both expensive and difficult to beneficiate from their native states. Prominent examples include the metallic alloys of aluminum, titanium, magnesium, and beryllium as well as the structural polymers, ceramics, and composites. While certain heavier materials, notably the ferrous alloys, are relatively inexpensive and abundant due to an existing and extensive industrial

infrastructure, they can nonetheless offer a penalty in performance when implemented in applications where mass serves to decrease efficiency. A notable example would be their use for applications in the transportation industries (automotive, aerospace, maritime) where increased vehicle mass leads to increased fuel consumption over the lifetime of the system.

Following derivations and procedures described elsewhere [1], equations which compute the mass of a particular component for an anticipated set of imposed conditions can be easily and routinely derived. For example, the required mass, m, of a beam of design-constrained length, L, capable of supporting an anticipated uniformly-distributed load, W (e.g., N/m), along its length without experiencing overload failure will be (for a fixed, 2:1 cross-sectional aspect ratio):

$$m = \left(\frac{3}{4\sqrt{2}} \cdot W \cdot L^{7/2} \right)^{2/3} \cdot \left(\frac{\rho}{\sigma_f^{2/3}} \right) \qquad \qquad \text{Eq. 1}$$

The mass computed in this fashion represents a minimum required to fulfill the functional requirements of the design (i.e., load, length, and a constrained cross-sectional shape), given the properties of the material used, ρ and σ_f. Note that for a given set of design requirements (i.e., for W and L fixed as requirements of the design), mass will vary depending on the particular material ultimately selected and the associated values of its density and failure strength. Minimization of the material-dependent bracketed term thus identifies the material option capable of fulfilling the design requirements at the least mass. The term captures the full dependency of the material on an otherwise fixed design, and thus can be used in isolation as an index to numerically rank candidate material options. Similar equations can be derived for any loading scenario or situation that is describable using a constitutive equation containing intensive (scale-normalized) material properties in addition to the extensive (functional) variables of the design. A relatively large tabulation of such indices for a variety of situations and constraints is provided in [1].

For the same application, one can additionally make an assessment of the initial environmental load implicated by the choice of material utilized in the design. For this, one requires an additional material property, that is, the material's energy content. For most engineering materials, the energy content represents a per-mass accounting of the energy (e.g., Joules/kg) expended to convert a material from its raw form into a form ready for subsequent processing or manufacture (e.g., as ingot or billet). Indeed, the energy content value for most engineering materials is often computed utilizing life-cycle-analysis (LCA) techniques as applied to the beneficiation processes used to refine or create the material.

For our example beam introduced above, the total energy expenditure, Q (e.g., Joules) required to assure its availability to the design can thus be obtained by multiplying the derived mass (e.g., in units of kg) by the energy content, q (e.g., Joules/kg), i.e.,

$$Q = \left(\frac{3}{4\sqrt{2}} \cdot W \cdot L^{7/2} \right)^{2/3} \cdot \left(\frac{\rho \cdot q}{\sigma_f^{2/3}} \right) \qquad \text{Eq. 2}$$

Analogous to Eq. 1, the bracketed term represents the properties introduced upon selection of the material, and can similarly be used as a quantitative index to assess the required energy expenditure implicated by the selection of material.

Example material properties and their incorporation into the indices as described above are provided in Table I for several example structural materials. These indices indicate that steel would represent the heaviest option, whereas the epoxy-Kevlar composite the lightest. Further, the data indicate that a component fabricated from steel would require the least initial (pre-service) energy expenditure, and titanium the most.

Given the initial energy expenditures required for each of the material options as in Table I, one can now consider how the selection of material affects energy consumption over the course of its lifetime in service. This requires the determination or estimation of a proportionality, or exchange, constant that quantifies the value of mass in terms of lifetime energy consumption. The value will rely on the magnitude of the desired lifetime, as well as the origins of how mass affects energy consumption. Figure 1 illustrates how an estimated value of the exchange constant might vary with desired vehicle lifetime on a total mileage basis.[*]

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[*] In this example, the energy value of mass (e.g., Joules/kg) can be estimated using a simple approximation. Gasoline has a raw (upper) energy value of approximately 126 MJ/gal [3]. In (hypothetical) qualifying tests, it was determined that a 3,000 kg version of a vehicle could travel 14 miles per gallon of fuel, whereas a 1,800 kg version was capable of 19 miles per gallon. Assuming that everything but the vehicles' masses are essentially the same:

For the 3,000 kg vehicle and a 50,000 mile lifetime:

$$\frac{50,000 \text{ miles}}{\text{lifetime}} \text{ x } \frac{\text{gal. fuel}}{14 \text{ miles}} \text{ x } \frac{126 \text{ MJ}}{\text{gal.}} = 450,000 \frac{\text{MJ}}{\text{lifetime}}$$

For the 1,800 kg vehicle and the 50,000 mile lifetime:

$$\frac{50,000 \text{ miles}}{\text{lifetime}} \text{ x } \frac{\text{gal. fuel}}{19 \text{ miles}} \text{ x } \frac{126 \text{ MJ}}{\text{gal.}} = 331,580 \frac{\text{MJ}}{\text{lifetime}}$$

The energy value of mass over a 50,000 mile lifetime will thus be

$$C_E \approx \frac{\Delta \text{MJ}}{\Delta \text{m}} = \frac{(450,000 - 331,580) \text{ MJ}}{(3,000 - 1,800) \text{ kg}} = 99 \frac{\text{MJ}}{\text{kg}}$$

TABLE I.

Representative material data and its implementation into mass and energy selection indices.
Data from [2] (midpoint of data ranges).

Material Option	Density	Failure Strength	Energy Content	Mass Index $\dfrac{\rho}{\sigma_f^{2/3}}$	Energy Index $\dfrac{\rho \cdot q}{\sigma_f^{2/3}}$
	(kg/m^3)	(MPa)	(MJ / kg)	$\left(\dfrac{kg}{m^3 \cdot MPa^{2/3}}\right)$	$\left(\dfrac{MJ}{m^3 \cdot MPa^{2/3}}\right)$
1015 Steel	7,850	328	66	165	10,893
6061-T6 aluminum	2,700	270	285	65	18,420
Titanium alloy	4,480	845	1,000	50	50,143
Epoxy-Kevlar Composite	1,325	460	500	22	11,118

Lifetime energy consumption (LEC) can thus be summed using the two components described above, and incorporating the exchange constant to maintain unit compatibility:

LEC = Initial Energy Content + Energy Consumed over Lifetime of Vehicle   Eq. 3

Simplifying Eq. 3 by considering only the indices of the individual components leads to a LEC index, LEC′:

$$LEC' = \frac{\rho \cdot q}{\sigma^{2/3}} + C_E \cdot \frac{\rho}{\sigma^{2/3}} \qquad \text{Eq. 4}$$
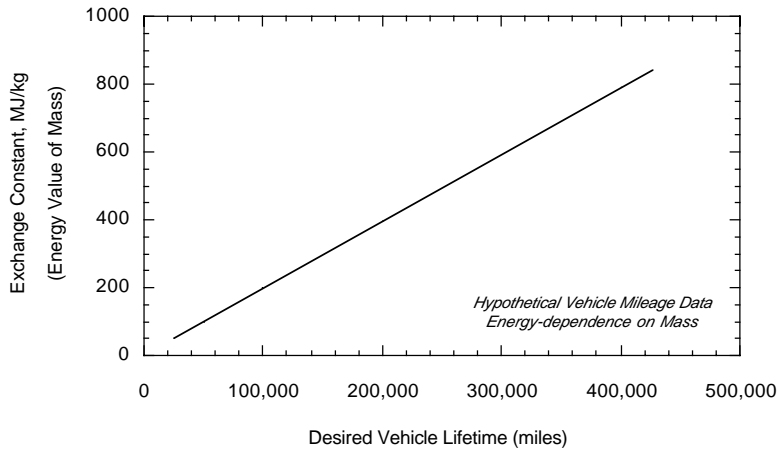

Figure 1.   Approximated relationship between vehicle mass and lifetime energy consumption, computed as a function of vehicle lifetime in miles.

Equation 4 can be easily utilized to identify and assess lifetime energy consumption for any conceivable material option, given the material's properties and a value of the exchange constant for a desired lifetime. Figure 2 illustrates a selection chart showing two lines of constant lifetime energy consumption – one computed using a 50,000 mile vehicle lifetime and the other a 200,000 lifetime, for a variety of materials. The LEC for steel was used as a basis for both.

Materials whose indices co-reside on the line represent options offering identical LEC. Materials with property indices residing to the left and/or below the lines represent options that would result in lower LEC over the indicated lifetime.

In this example, the 6061-T6 aluminum, the carbon fiber reinforced plastic (CFRP), the alumina ceramic matrix composite (CMC), the glass-fiber reinforced plastic (GFRP) and the epoxy-Kevlar composite all represent more environmentally-friendly options relative to the steel for a defined vehicle lifetime of 50,000 miles, based on a total lifetime energy consumption criterion. Note that, except for the latter two, all require higher initial energy
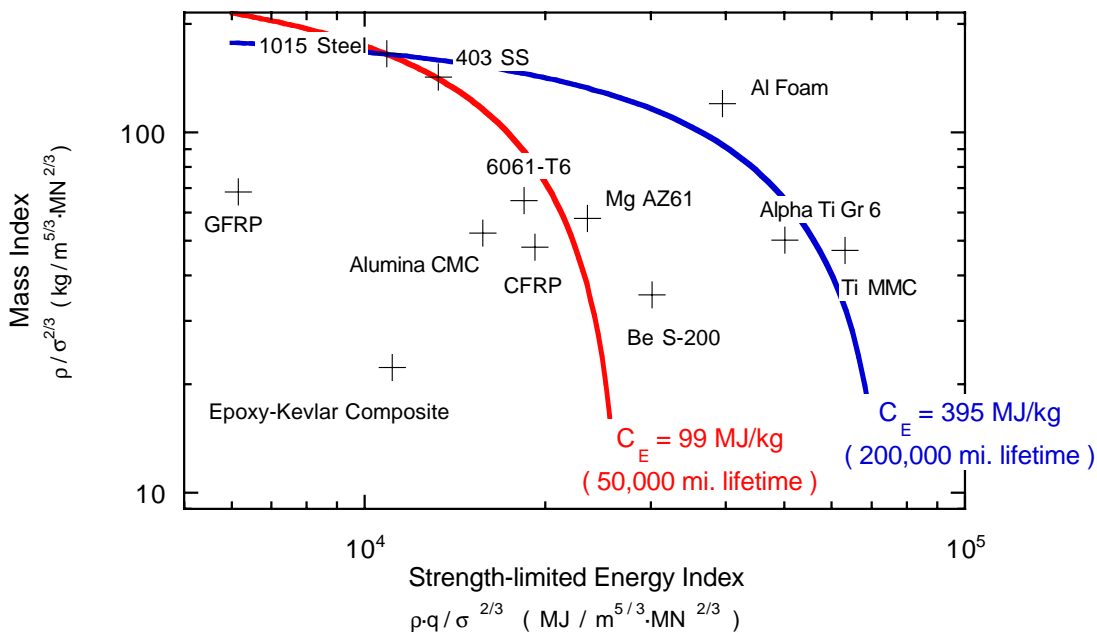

Figure 2. *The mass index plotted as a function of the energy index. The energy index is a measure of the energy expended to initially produce the material. The mass index is relevant to the energy expended during service over the desired lifetimes. The total energy expended is plotted for two desired lifetimes. Materials with indices falling to the left and/or below the plotted lines represent options leading to lower lifetime energy consumption.*

expenditures, but lower in-service energy expenditures. Extension of the defined lifetime to 200,000 miles enables materials of higher initial energy expenditure to become competitive or superior to that of the steel baseline material.

DISCUSSION

As with any material selection exercise, lifetime energy consumption and its relevance to the decision-making process in design represents just one of several criteria that must evaluated for an envisioned design. Other factors, including and notably cost, are also generally prominent within the process. However, the ability to quantify a green-based analysis provides tangible opportunity for design engineers to incorporate such issues on an ongoing and routine basis.

ACKNOWLEDGEMENTS

BIBLIOGRAPHY

1. M.F. Ashby, *Materials Selection in Mechanical Design*, Second Edition, Butterworth-Heinemann, Oxford, UK, 1999.
2. *Cambridge Engineering Selector*, Version 3.1 (CES3.1 application software), Granta Design, Inc., Cambridge, UK.
3. Myer Kutz, editor; *Mechanical Engineers Handbook*, Second Edition, John Wiley & Sons, New York, 1998, p. 1519.

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