The Fourth International Conference on Woodfiber-Plastic Composites

Engineering Design and Materials Selection: Principles and Applications for Woodfiber-Polymer Composites

Mark T. Kortschot

Abstract

The choice of material for decking will be used to illustrate the formal methods of materials selection developed by M.F. Ashby (1). A stiffness requirement will be formulated, and the best material will be chosen using a graphical method. Wood is an extremely efficient structural material in this application, because it is both porous and anisotropic. The prospects for replacing wood with a wood-filled thermoplastic will be discussed.

Introduction

The selection of materials for structural applications has traditionally been based on the experience of the designer combined with data obtained from handbooks and suppliers. Over the last 10 years, however, materials databases have been computerized, and designers can now easily choose from a wide range of materials according to the requirements of their particular application. For example, it is possible to search a database to produce a list of all materials with a specific gravity of <3 and a modulus of >50 GPa. A designer must still specify these numbers. This paper reviews the methods of materials selection developed by Professor M.F. Ashby, Cambridge University, United Kingdom. The principles are fully described in Professor Ashby's excellent text on the subject (1).

Kortschot:
Dept. of Chemical Engineering and Applied Chemistry, Univ. of Toronto, Toronto, Ontario, Canada

Materials selection methodology

The goal of materials selection is to maximize the performance of a component. There are many potential measures of performance, but the underlying measure is profit. In some cases, it is desirable to minimize the cost of the materials and manufacturing of an object in order to maximize profit— manufacturers of inexpensive steel bicycles attempt to do this. In other cases, however, the manufacturer knows that a premium selling price can be obtained by enhancing the product in some way, perhaps requiring the use of more expensive materials. Thus bicycle frames built with aluminum alloys and carbon fiber-reinforced epoxies can also be profitable. It is up to the designer to choose an attribute, such as cost or mass,

that must be optimized by the materials selection and design. The process of materials selection involves a series of steps (1):

1. Determine functional and geometric requirements.
2. Identify primary constraints.
3. Choose an attribute to be optimized.
4. Identify the free variable.
5. Express the attribute in terms of the functional requirements, geometry, and material properties, thus eliminating the free variable.
6. Choose the material that optimizes the attribute, thereby maximizing performance.

Case study

The objective was to produce a 6-inch-wide deck-board of minimum mass that will span a 16-inch gap and will deflect no more than 1/8 inch when loaded by a central load of 50 kg.

Determine functional and geometric requirements. These are given in the objective statement.

Identify primary constraints. These are the "nonnegotiable" requirements (1). The material must be serviceable in the range 0° and 110°F and be resistant to fresh water.

Choose an attribute to be optimized. The cost of a single board should be minimized:

$$Cost = PwLt\rho \qquad [1]$$

where:

P = price
w = width
L = joist spacing
t = thickness
ρ = density.

Identify the free variable. We don't care about the thickness of the board. This is a "free" variable. In practice, there may be thickness limitations imposed by consumer perception—very thin or very thick boards might be aesthetically unacceptable—but this is a problem for the marketing department.

Express the attribute in terms of the functional requirements, geometry and material properties, eliminating the free variable.

$$\delta = \frac{FL^3}{48EI} \qquad [2]$$

where:

F = central load
δ = deflection
E = modulus
I = moment of inertia of the board's cross-section ($= wd^3/12$).

$$d = \sqrt[3]{\frac{FL^3}{4Ew\delta}} \qquad [3]$$

Hence the thickness of the board depends on modulus: $d \propto E^{-1/3}$. Stiffer materials can produce the desired bending stiffness with a smaller thickness. Note that this is only true when the board's thickness is the free variable. If the thickness were fixed and the width were varied to achieve the desired stiffness, we would find that $d \propto E^{-1}$.

Substituting d into Equation [1] and rearranging results in:

$$Cost = \left(\frac{L^2 w^{2/3}}{4^{1/3}}\right)\left(\frac{F}{\delta}\right)^{1/3}\left(\frac{P\rho}{E^{1/3}}\right) \qquad [4]$$

We have thus derived the exact relationship between the cost and the material properties. To minimize cost, we must maximize $\left(\frac{E^{1/3}}{P\rho}\right)$. The term $M = \left(\frac{E^{1/3}}{P\rho}\right)$ is denoted the "performance criterion." Note that this term and thus the choice of material is independent of the specific values of F, δ, w, and L. The mass of the board is the cost ($) divided by the price ($/kg), and so mass is proportional to $\frac{\rho}{E^{1/3}}$.

Choose the material that optimizes the attribute, thereby maximizing performance. In the past, this would have been a tedious job, however, modern computer databases such as the Cambridge Materials Selector (2) can simply be queried to yield the material with the best value of the performance criterion, M. It is also convenient to represent the data graphically, so we can get a quick feel for the performance of various materials. To do this in a compact form, a graph of log E versus log $P\rho$ is plotted. When this is done, materials falling on a line of slope 3 will have equivalent values of M, since:

$$\log E = 3 \log P\rho + 3 \log M \qquad [5]$$

One additional complication is that the price information can change so quickly, it is convenient to plot only the relative price data. In Figure 1, log E is plotted against log $C_r\rho$, where C_r is the price of each material relative to that of mild steel rod. (Note that even the relative price information in Figure 1 should be treated with caution since the data were produced in 1992.)

In Figure 1, the "best" materials—the ones with the lowest cost—can be found in the upper left hand corner. We can neglect the porous ceramics, since these are not good in tension. Not surprisingly, wood turns out to be the best material in this application. In fact, even when the design objective is minimum mass, wood is superior to metals and even advanced fiber composites!

The effect of shape

Wood is efficient because it has a complex internal structure. Cellulose, which is a relatively stiff polymer, is distributed in an expanded structure which produces an elevated moment of inertia and hence higher bending stiffness. In unfoamed wood fiber-reinforced thermoplastic composites, however, the matrix is not porous, and the fibers may be collapsed, thereby increasing density.

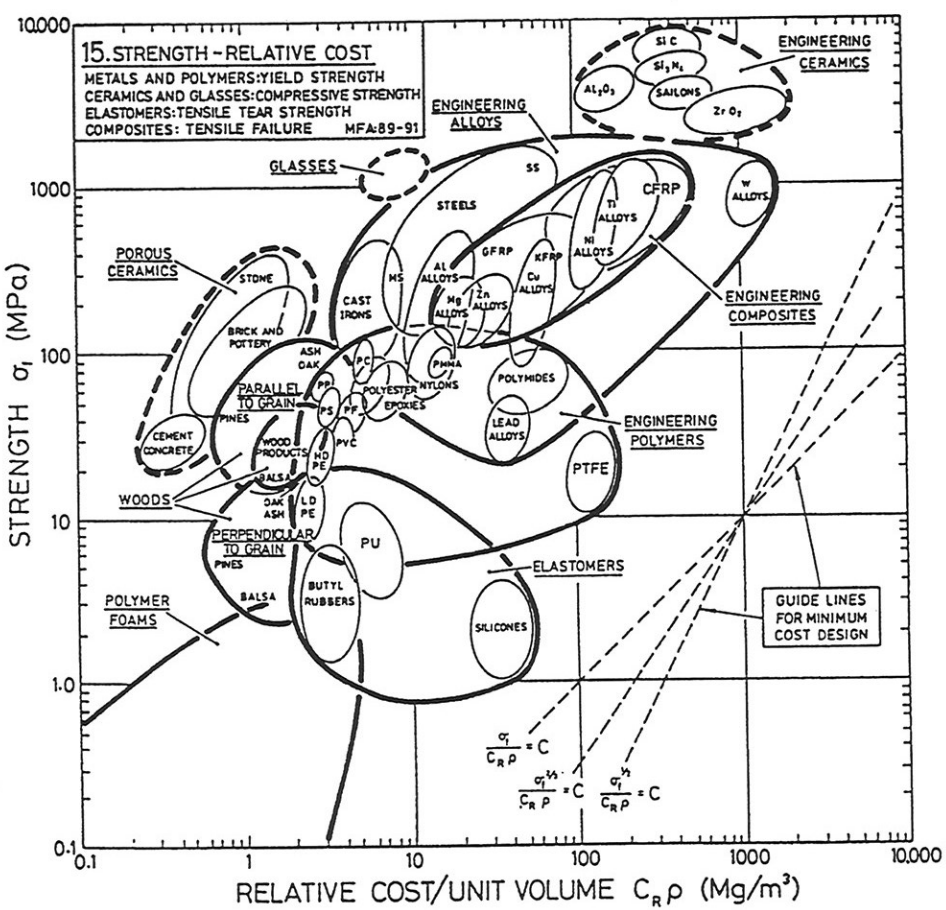

FIGURE 1.—Young's modulus versus the product of relative price (C_r) and density (ρ). All materials lying on a line with a slope of 3 have the same value of $\left(\frac{E^{1/3}}{P\rho}\right)$ and hence the same cost in a bending application where the thickness is the free variable. Reprinted from Ashby (1) with permission.

Figure 1 shows that metals and fiber composites cannot compete with wood in bending applications. Why has structural steel found such wide application? The answer is that steel and composites intended to support moments are rarely used in solid rectangular blocks. More often they shaped into I-beams or tubes. The moment of inertia is elevated by the macroscopic shape in much the same way that the moment of inertia of wood is elevated by the microscopic shape. The result is that a properly shaped mild steel I-beam is far cheaper than a solid steel beam of the same bending stiffness, since much less mass is required.

The data of Figure 1 is therefore a bit misleading, since some of the materials can be conveniently shaped into thin-walled tubes, I-beams, or box beams, while others are cannot. There is a rigorous method for dealing with this discrepancy, but it is beyond the scope of this brief review.

Conclusions

Computerized materials databases allow the designer to choose from a wider range of materials than would otherwise be possible. By using the formal methods of formulating a problem originally developed by Ashby (1) and reviewed briefly in this paper, the designer can find the right combination of material properties that can determine the exact relationship between material properties and the performance of the design. In many cases, it is possible to find the best material without knowing all of the details of loading and geometry. Since the choice of material determines, to some extent, the form of the final product, the process of materials selection should be carried out early in the design process.

Wood is an extremely efficient material in bending and buckling applications because of its porous structure and the resulting elevation of the moment of inertia. To compete with wood in such applications, wood fiber-reinforced thermoplastic composites should be "shaped" to obtain the best performance/mass ratio.

Literature cited

1. Ashby, M.F. 1992. Materials selection in mechanical design. Pergamon Press, Oxford, U.K.
2. Cambridge Materials Selector V.2.02. Granta Design Ltd., Cambridge, U.K.