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Source: *Proceedings: Mathematical and Physical Sciences*, Vol. 450, No. 1938 (Jul. 8, 1995), pp. 123-140
Published by: Royal Society
Stable URL: https://www.jstor.org/stable/52662
Accessed: 16-04-2019 06:53 UTC

The mechanical properties of natural materials. I. Material property charts

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The mechanical properties of natural materials as diverse as wood, muscle, shell and bone are plotted on material–property charts which show the relationships between properties. Performance indices are used to identify the load-bearing applications in which each performs particularly well. By these criteria, many natural materials are superior to the man-made materials of engineering. A companion paper examines some of the origins of this superiority; an explanation is sought in an analysis of the way structure influences properties.

1. Introduction

Many natural materials have exceptional mechanical properties. Woods have a strength per unit weight comparable with that of the strongest steels; shell, bone, and antler have toughnesses an order of magnitude greater than engineering ceramics; and mature bamboo stalks have slenderness ratios which are remarkable even by the standards of modern engineering (see, for instance, Wainwright *et al.* 1976; Vogel 1988; or Vincent 1990).

Natural materials are made from a relatively small number of polymeric and ceramic components or building blocks, some of which are themselves composites. The solid part of most plants is made up of cellulose, lignin and hemicellulose, while animal tissue is largely collagen, keratin, chitin and minerals such as calcite, hydroxyapatite and aragonite. From these, nature fabricates a remarkable range of structured composites. Wood consists of cellulose fibres in a lignin/hemicellulose matrix, shaped to hollow prismatic cells. Skin, tendon and cartilage are all largely collagenous composites: in skin, the collagen is sandwiched between a basement membrane and an overlying keratinized epidermis; in tendon, the collagen fibres are aligned to form rope-like structures which make up about 70–80% of the volume while the remainder is a combination of fibroblasts, non-collagenous protein, polysaccharides and inorganic salts; and in cartilage, the collagen fibres are in a proteoglycan matrix with a small volume fraction of elastin fibres. Hair, nail, horn, wool, reptilian scales and hooves are made of keratin while insect cuticle is largely chitin. Bone, shell and antler are composites of calcite, hydroxyapatite or aragonite platelets dispersed in a helical matrix of collagen.

Proc. R. Soc. Lond. A (1995) **450**, 123–140
Printed in Great Britain

TEX Paper

There is nothing very special about the individual building blocks. Cellulose fibres, for instance, have Young's moduli of elasticity which are nearly the same as those of drawn polyethylene; the lignin-hemicellulose matrix of the wood cells has a modulus within 20% of that of epoxy; the fracture toughness of hydroxyapatite is much the same as that of man-made ceramics. It is not so much the material properties of the components as their arrangement within the natural composites which give rise to the exceptional properties.

In this paper we compare the properties of natural and engineering materials using material property charts. Performance indices are listed and plotted on the charts, identifying the application in which each material performs particularly well. Natural materials were first compared in this way by Wainwright *et al.* (1976) who, by plotting strength, σ_f, against Young's modulus, E, evaluated the energy absorption capacity $U = \sigma_f^2/2E$ of a variety of natural and engineering materials. The bending stiffness performance of a variety of rigid natural materials was also compared by tabulating values of the performance index $E^{1/2}/\rho$ (Wainwright *et al.* 1976). Here we provide more comprehensive data for a wider range of material property charts and performance indices. Models for the mechanical behaviour of several natural composites, developed in a companion paper (Gibson *et al.* 1994), explain, at least in part, how their exceptional properties arise and suggest novel microstructures for efficient engineering materials.

2. The method: material property charts and performance indices

The method, outlined below, has two ingredients. The first is the idea of *material property charts* (Ashby 1989, 1992) which plot one material property – Young's modulus, E, for instance – against another – density ρ, perhaps. If the ranges of the axes are chosen appropriately, all natural materials can be shown on the plot. The second is the concept of a *performance index* (Ashby 1989, 1991, 1992): a combination of properties – such as E/ρ – which, if maximized, optimizes some aspect of the performance of the material in a given application. The performance indices can be plotted onto material property charts, allowing the efficiency of a material in a given application to be evaluated.

Figure 1 illustrates, schematically, the idea of a material property chart for engineering materials. The axes are Young's modulus, E, and density ρ. They are logarithmic, allowing wide ranges: materials as diverse as cork, lead, steel and diamond can all be plotted on the same chart. Materials of a given class – metals for instance – cluster together in the shaded balloon labelled 'engineering alloys'; individual metals can be shown as smaller bubbles within it. The other classes of engineering materials – polymers, ceramics, composites, and so on – are shown in a similar way. Other charts relate other mechanical and thermal properties (Ashby 1989, 1992). In this paper we are concerned with only five such properties, listed in table 1.

The charts become more useful when combined with performance indices. One has been mentioned already: the performance of materials as light, stiff ties (tensile members) is measured by the index E/ρ – the larger the value of E/ρ, the lighter is the tie for the same stiffness. The way in which performance indices are derived is illustrated in the appendix. The form of the index depends on the mode of loading: axial loading, bending and twisting lead to different indices. As an example, the performance of a light, stiff, beam (a component loaded in

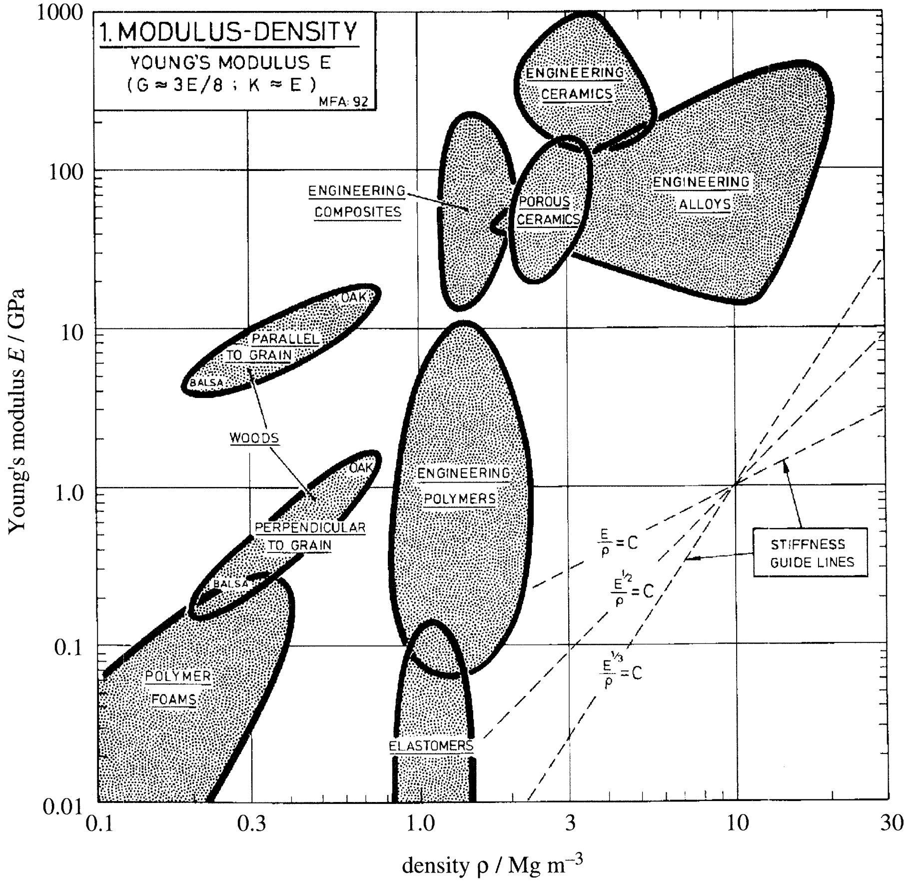

Figure 1. An example of a material property chart for engineering materials showing Young's modulus plotted against density. Guidelines show the slopes of three performance indices. Their use is explained in the text.

Table 1. *The properties plotted on the charts of this paper*

property	units
density, ρ	$\mathrm{Mg\ m^{-3}}$
modulus, E	GPa
strength, σ_f	MPa
toughness, J_c	$\mathrm{kJ\ m^{-2}}$
fracture toughness, K_{Ic}	$\mathrm{MPa\ m^{1/2}}$

bending) is measured not by E/ρ but by the index $E^{1/2}/\rho$. That for flat plates in bending is $E^{1/3}/\rho$. The logarithmic scales allow all three to be plotted on figure 1; each appears as a set of straight, parallel lines. One member of each set is shown on the figure, labelled 'stiffness guide lines'; the required set can be constructed from these. One class of natural material – woods – appears on this chart. The guide lines show that the value of E/ρ for woods is the same as that for steel or aluminium, but that the values of $E^{1/2}/\rho$ and $E^{1/3}/\rho$ for woods are larger than

Table 2. *Performance indices*

(ρ is the density (Mg m^{-3}), E is Young's modulus (GPa), G is the shear modulus (GPa), σ_f is the failure strength (MPa), $K_{IC} = (EJ_c)^{1/2}$ is the fracture toughness (MPa m$^{1/2}$), J_c is the toughness (kJ m^{-2}).)

(*a*) *Minimum weight design*

component (cross-sectional shape given)	loading	maximize M = stiffness	maximize M = strength
tie (tensile strut)	load, stiffness, length specified	E/ρ	σ_f/ρ
torsion bar or tube	torque, stiffness, length specified	$G^{1/2}/\rho$	$\sigma_f^{2/3}/\rho$
beam	loaded externally or by self-weight in bending; stiffness, length specified	$E^{1/2}/\rho$	$\sigma_f^{2/3}/\rho$
column (compression strut)	failure by elastic buckling or plastic compression; collapse load and length specified	$E^{1/2}/\rho$	σ_f/ρ
plate	loaded externally or by self-weight in bending; stiffness, length, width specified	$E^{1/3}/\rho$	$\sigma_f^{1/2}/\rho$
plate	loaded in-plane; failure by elastic buckling or plastic compression; collapse load, length and width specified	$E^{1/3}/\rho$	σ_f/ρ

(*b*) *Elastic design*

component	design goal	maximize M =
springs	energy storage specified, volume to be minimized	σ_f^2/E
springs	energy storage specified, mass to be minimized	σ_f^2/E_ρ
elastic hinges	radius of bend to be minimized	σ_f/E

(*c*) *Plastic and fracture-safe design*

tensile member	load controlled design	K_{IC} and σ_f
tensile member	displacement controlled design	K_{IC}/E and σ_f/E
tensile member	energy controlled design	K_{IC}^2/E

those for the other two materials, that is, it is more efficient (lighter, for the same stiffness) than either aluminum or steel when used as light, stiff beams or plates.

There are many performance indices, each measuring some aspect of efficiency in a given mode of loading. The subset of interest to us here is listed in table 2. All appear on one or another of the charts which follow, identified by the words 'Guide lines'. Section shape (solid, tubular, I-section, box section, etc.) can be included in the indices in the way illustrated in the appendix.

When natural materials are judged by these criteria, they are often found to perform exceptionally well. The value of $E^{1/2}/\rho$ for wood is high – around 10 in units of GPa$^{1/2}$ (Mg m^{-3})$^{-1}$, compared with 3.1 for aluminium alloys. The capacity to store elastic energy at minimum weight is measured by the index

$\sigma_f^2/E\rho$ where σ_f is the strength of the material; by this criterion silk performs better than the best spring steel. The resistance to fracture is measured by the index $(EJ_c)^{1/2}$, where J_c is the toughness (the fracture energy per unit area) of the material; by this criterion, shell and enamel perform better than any man-made ceramic. These and similar observations have led us to plot charts for natural materials in an attempt to identify those which perform well by each criterion, and to seek explanations of how this efficiency arises. The charts, shown in figures 2–6, are described in detail in the next section. They were constructed with data derived from the references listed in each figure caption; values are tabulated by Ashby *et al.* (1992).

3. Material property charts for natural materials

Like engineering materials, natural materials can be grouped into classes. *Natural ceramic and ceramic composites* include bone, shell, coral, antler, enamel and dentine. All are made up of ceramic particles such as hydroxyapatite, calcite or aragonite in a matrix of collagen; all have densities between 1.8 and 3.0 $\mathrm{Mg\,m^{-3}}$. Their moduli are lower than those of engineering ceramics but their tensile strengths are roughly the same and their toughnesses are greater, by a factor of 10 or so.

Natural polymers and polymer composites include cellulose, chitin, silk, cuticle, collagen, keratin and tendon. All have densities of around 1.2 $\mathrm{Mg\,m^{-3}}$. Their moduli and tensile strengths are larger than those of engineering polymers: cellulose fibrils, for instance, have moduli of about 50–130 GPa and a strength of 1 GPa, and silks have moduli of 2–20 GPa and strengths of 0.3–2.0 GPa. Of man-made polymers only Kevlar fibre has a higher stiffness (200 GPa) and strength (up to 4 GPa) which it achieves, as do natural fibres, through its highly oriented molecular structure.

Natural elastomers such as skin, muscle, cartilage, artery, abductin, resilin and elastin all have densities of about 1.15 $\mathrm{Mg\,m^{-3}}$. Their moduli and densities are similar to those of engineering elastomers. Muscle is unique in combining low modulus (of the order of an elastomer) with high strength (of the order of steel).

Natural cellular materials such as wood, cancellous bone, palm and cork all have low densities ($\rho = 0.1\text{–}1.0\ \mathrm{Mg\,m^{-3}}$) because of the high volume fractions of voids they contain. They are almost always anisotropic because of the shape and orientation of the cells and of the fibres they contain; the prismatic cells of wood, for instance, give a much greater stiffness and strength along the grain than across it.

A word of caution is needed here: natural materials show a large variability in properties. The value of a property varies within one organism, between organisms and between species. Some of the properties plotted on the charts appear to show less variability than others, but this may simply be due to the lack of data; additional tests are likely to reveal a wider range.

We next describe the charts themselves. There are four basic charts: modulus–density, strength–density, modulus–strength and toughness–modulus. They (or modifications of them) allow the performance of natural materials to be assessed by four classes of criteria: stiffness per unit weight, strength per unit weight, elastic energy storage per unit volume or weight, and resistance to fracture, in various modes of loading.

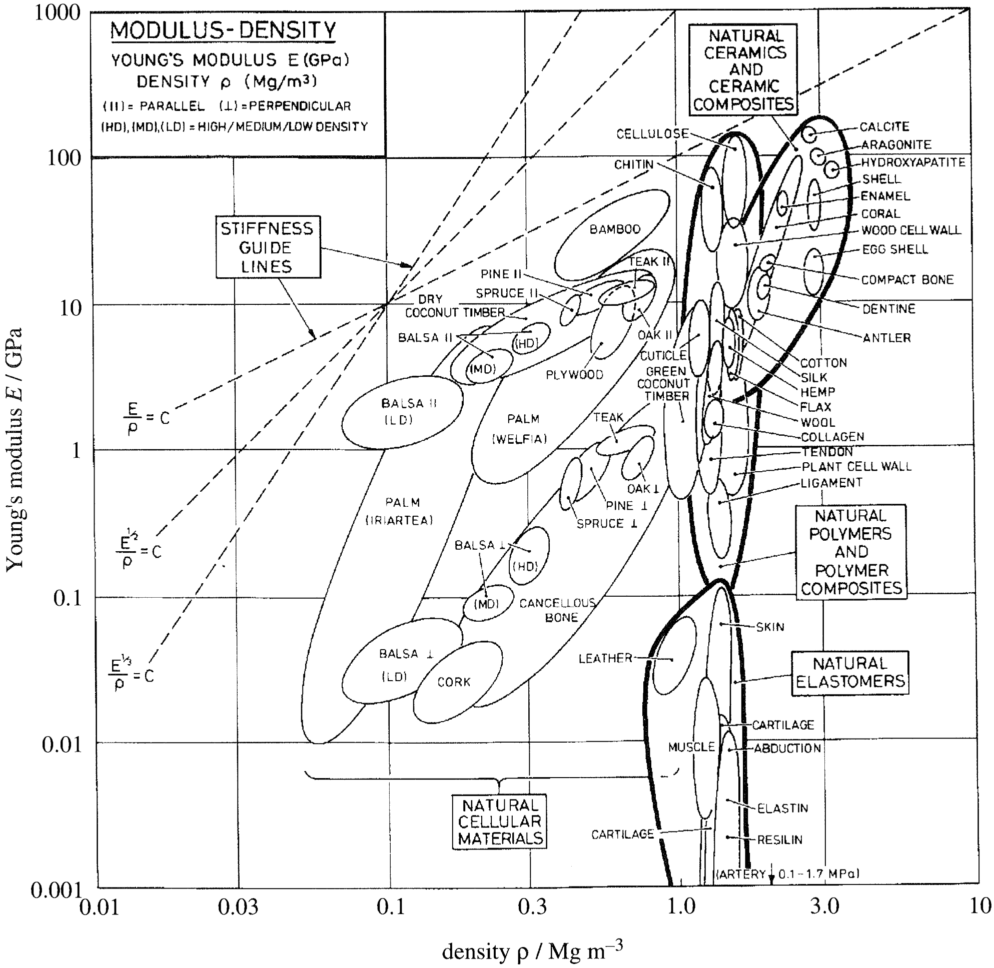

Figure 2. A material property chart for natural materials, plotting Young's modulus against density. Guidelines identify structurally efficient materials which are light and stiff. Data are taken from references [1, 7–20, 22, 23, 26–32, 34–44, 46–48, 51–53, 55–72].

(a) *The Young's modulus–density chart: figure 2*

The elastic moduli measure the resistance of a material to elastic deformation. Data for the Young's modulus E and density ρ of many natural materials are shown on figure 2 (the shear modulus G and bulk moduli K are roughly proportional to E). Data for each class are enclosed by a heavy balloon while data for class members are shown as smaller bubbles within it. Where necessary, the longitudinal and transverse moduli are plotted separately. Three guidelines are shown, each representing the performance index for a particular mode of loading. They are:

$$
\begin{array}{rrcll}
 & M_1 & = & E/\rho & \text{(tie, in tension)} \\
 & M_2 & = & E^{1/2}/\rho & \text{(beam in flexure; column buckling} \\
 & & \text{or} & G^{1/2}/\rho & \text{shafts in torsion)} \\
\text{and} & M_3 & = & E^{1/3}/\rho & \text{(plate in flexure).}
\end{array} \qquad (1)
$$

Table 3. *Modulus–density performance indices*

(Values in brackets reflect the longitudinal Young's modulus; they are not representative of the efficiency of a stiff plate in bending which requires isotropic moduli. The properties of natural materials show a range of values; those listed here are in the middle of the range.)

material	E [a]	ρ [b]	$M_1 = E/\rho$ [c]	$M_2 = E^{1/2}/\rho$ [d]	$M_3 = E^{1/3}/\rho$ [e]
single cellulose fibre	100.0	1.5	67	6.7	(3.1)
wood cell wall	35.0	1.5	23	3.9	(2.2)
balsa (HD)	5.5	0.3	18	7.8	(5.9)
balsa (MD)	4.0	0.2	20	10.0	(7.9)
balsa (LD)	2.0	0.1	20	14.1	(2.9)
oak	11.5	0.7	16	4.8	(3.2)
pine	11.0	0.5	21	6.3	(4.2)
spruce	9.0	0.4	21	7.1	(5.0)
teak	12.0	0.65	18	5.3	(3.5)
bamboo (bulk material)	22.5	0.75	30	6.3	(3.8)
palm (*Iriartea*)	3.5	0.15	23	12.5	(10.1)
palm (*Welfia*)	11.0	0.55	20	6.0	(4.0)
coconut timber	7.0	0.5	14	5.3	(3.8)
plywood	8.0	0.6	13	4.7	3.3
single carbon fibre	390.0	2.0	195	9.9	(3.6)
CFRP unidirectional	200.0	1.5	133	9.4	(3.9)
CFRP laminate	50.0	1.5	33	4.7	2.5
mild steel	210.0	7.9	27	1.8	(0.8)

Units: [a]GPa, [b]Mg m^{-3}, [c]GPa $(\text{Mg m}^{-3})^{-1}$, [d]$\text{GPa}^{1/2}$ $(\text{Mg m}^{-3})^{-1}$, [e]$\text{GPa}^{1/3}$ $(\text{Mg m}^{-3})^{-1}$.

Materials with the largest value of the appropriate index have the lowest weight for a given stiffness in the loading modes indicated (see table 2 for details). Values of the three performance indices for natural and engineering materials are compared in table 3.

The natural polymer material with the highest value of E/ρ, measuring efficiency in tension, is cellulose: it is higher than that of steel by a factor of about 2.5. The high value arises from the highly oriented state of the semi-crystalline chains. The best engineering materials have higher values of E/ρ than this; note, however, that woods and palms have values comparable to mild steel. It is in bending that palm and wood really excel: they have the highest values of $E^{1/2}/\rho$ when the bending stresses act along the grain (that is, the longitudinal axis of the beam is parallel to the grain); the value for balsa, for instance, is 5 times greater than that of steel. The values of $E^{1/2}/\rho$ increase as the density of the wood decreases; the value for balsa is roughly double that for oak. The principal loads acting on a tree are bending (of the trunk under wind loads or the branches under their own weight) and uniaxial compression leading to buckling (of the trunk under its own weight). The height of a tree is, in fact, limited by its resistance to buckling (McMahon 1973). Wood, with its high value of $E^{1/2}/\rho$, is well suited to resist both bending deflection and elastic buckling. Palm, with a more primitive structure, is slightly less efficient than wood in resisting bending deflections and

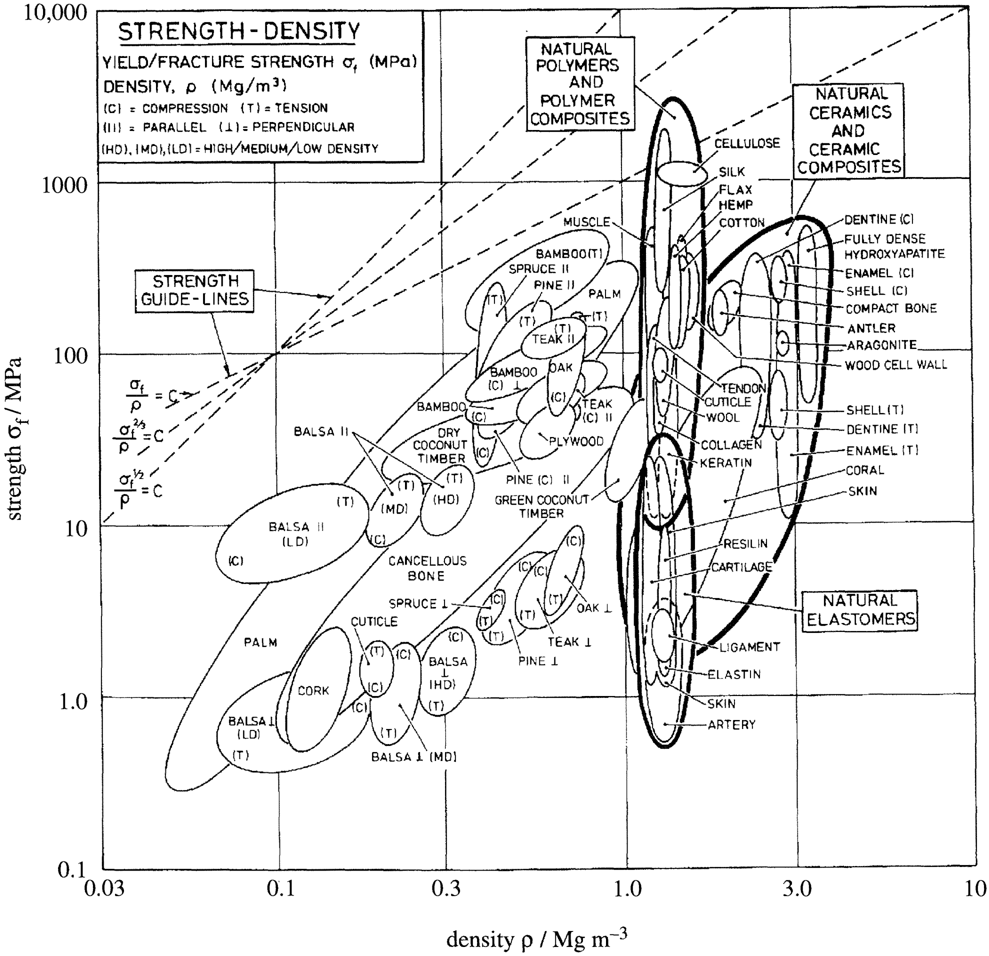

Figure 3. Material property chart for natural materials, plotting strength against density. Guidelines identify structurally efficient materials which are light and strong. Data are taken from references [7–18, 21, 22, 24–26, 30, 31, 34, 36, 37, 39–41, 43, 44, 48, 50, 52, 54–60, 62–66, 68–72].

buckling but it is still better than most engineering materials. Bamboo, which combines the features of wood with a macroscopic tubular shape, is better than both.

Woods and palms also have the highest values of $E^{1/3}/\rho$, suggesting that they are efficient materials for resisting plate bending. But here we have overlooked their anisotropy. The high values of $E^{1/3}/\rho$ apply only for loading along the grain. In plate bending we need to consider both in-plane moduli: $E^{1/3}/\rho$ for loading across the grain is much smaller, reducing the efficiency in plate bending. The effect of anisotropy can be reduced by making a quasi-isotropic plate, with the grain in the laminae oriented at 0°, ±45° and 90°; plywoods have laminae oriented at 0° and 90°, reducing, but not eliminating, the effect of anisotropy. Values for plywood and carbon fibre reinforced polymer (CFRP) laminates are listed in table 3; laminating a material with a high unidirectional stiffness reduces the value of $E^{1/3}/\rho$ by a factor of only about $1/2^{1/3}$ or 0.8, so plywoods, too, have high values of this index.

Table 4. *Strength–density performance indices*

(Values in brackets reflect the longitudinal strength; they are not representative of the efficiency of a strong plate in bending which requires isotropic strengths.)

material	σ_f [a]	ρ [b]	$M_4 = \sigma_f/\rho$ [c]	$M_5 = \sigma_f^{2/3}/\rho$ [d]	$M_6 = \sigma_f^{1/2}/\rho$ [e]
single cellulose fibre	1000	1.5	667	66.7	(21.1)
single cotton fibre	350	1.5	233	33.1	(12.5)
single flax fibre	250	1.5	167	26.5	(10.5)
single hemp fibre	400	1.5	267	36.2	(13.3)
single silk fibre	2000	1.3	1500	120.0	(35.0)
single wool fibre	100	1.3	77	16.6	(7.7)
balsa (HD)	24	0.3	80	27.7	(16.3)
balsa (MD)	20	0.2	100	36.8	(22.4)
balsa (LD)	16	0.1	160	63.5	(40.0)
pine	160	0.7	229	42.1	(18.1)
oak	180	0.53	340	60.2	(25.3)
spruce	240	0.42	571	92.0	(36.9)
teak	150	0.65	231	43.4	(18.8)
bamboo (bulk material)	400	0.75	533	72.4	(26.7)
coconut timber	45	0.5	90	25.3	(13.4)
palm	100	0.42	240	50.0	(24.0)
plywood	35	0.6	58	17.8	9.9
single carbon fibre	2200	2.0	1100	84.6	(23.5)
CFRP unidirectional	1200	1.5	800	75.3	(23.1)
CFRP laminate	600	1.5	400	47.4	16.3
mild steel	400	7.9	51	6.9	2.5

Units: [a]MPa, [b]Mg m^{-3}, [c]MPa (Mg $\mathrm{m}^{-3})^{-1}$, [d]$\mathrm{MPa}^{2/3}$ (Mg $\mathrm{m}^{-3})^{-1}$, [e]$\mathrm{MPa}^{1/2}$ (Mg m^{-3}).

(*b*) *The strength–density chart: figure 3*

The strength of a material is its resistance to permanent deformation or to fracture, whichever occurs first. Data for the strength σ_f and density ρ of natural materials are shown in figure 3. For natural ceramics, the compressive strength is the crushing strength while the tensile strength is the modulus of rupture in beam bending. For natural polymers and elastomers, the strengths are tensile strengths. And for natural cellular materials, the compressive strength is the stress plateau while the tensile strength is either the stress plateau or the modulus of rupture, depending on the nature of the material (see, for example, Gibson & Ashby 1988). Where relevant, strengths parallel and perpendicular to the material orientation have been plotted separately. Guidelines are shown for the performance indices

$$
\begin{aligned}
M_4 &= \sigma_f/\rho && \text{(a tie under uniaxial load)} \\
M_5 &= \sigma_f^{2/3}/\rho && \text{(a beam in flexure or shaft in torsion)} \\
\text{and} \quad M_6 &= \sigma_f^{1/2}/\rho && \text{(a plate in flexure)} \qquad (2)
\end{aligned}
$$

(see table 2 for details). Values of these three performance indices for natural and

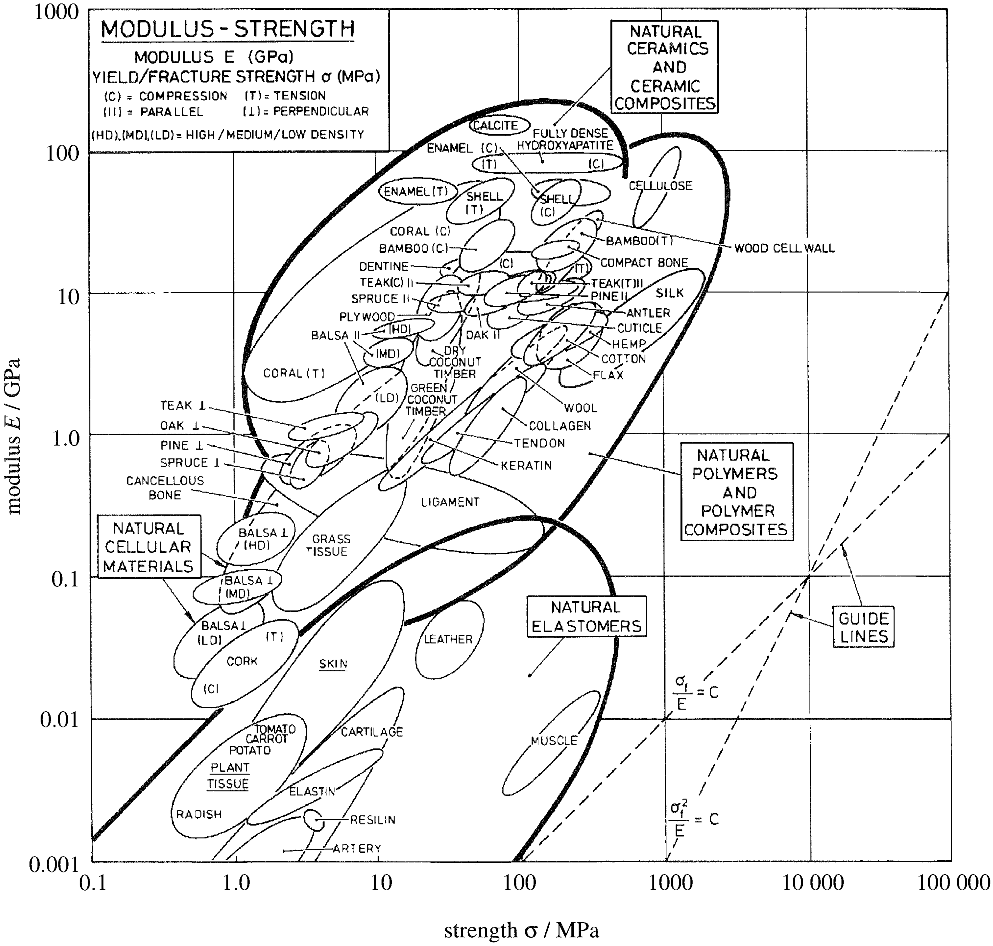

Figure 4. Material property chart for natural materials, plotting Young's modulus against strength. Guidelines identify materials which store the most elastic energy per unit volume, and which make good elastic hinges. Data are taken from references [1, 5, 7–32, 34–48, 50–58, 60–72].

engineering materials are compared in table 4. Silk and cellulose have the highest values of σ_f/ρ; that of silk is higher even than carbon fibres. Palm has a high value of $\sigma_f^{2/3}/\rho$, giving it a high resistance to flexural failure. Silk, cellulose, palms and woods also have high values of $\sigma_f^{1/2}/\rho$. Materials for use in strong panels (selected for high values of $\sigma_f^{1/2}/\rho$) should be roughly isotropic in the plane of bending: laminates such as plywood and CFRP have values roughly a factor of $1/\sqrt{2}$, or 0.7 times that of their oriented components, wood and unidirectional CFRP.

(*c*) *The Young's modulus–strength charts: figures 4 and 5*

Young's modulus is plotted against strength in figure 4. Guidelines are shown for three performance indices:

$$M_7 = \sigma_f^2/E \qquad \text{(maximum elastic strain energy per unit volume) (elastic springs)}$$

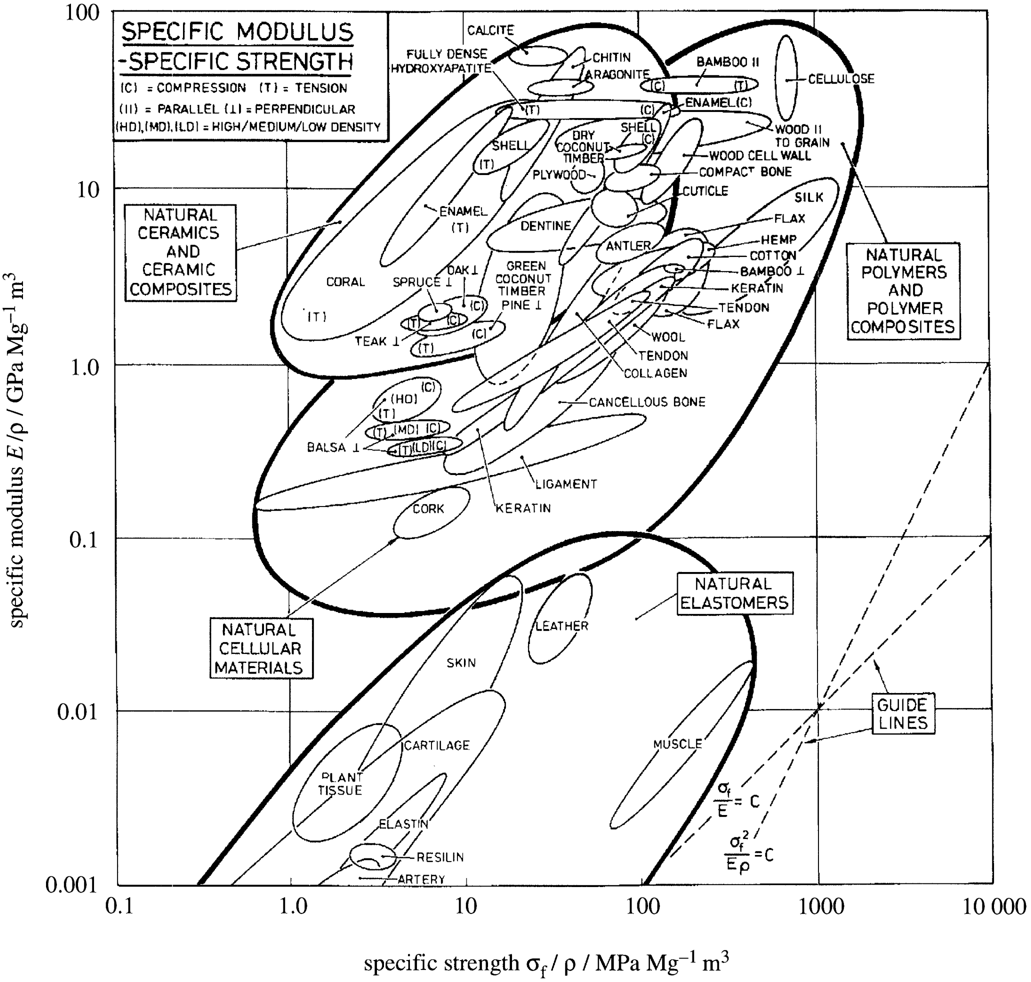

Figure 5. Material property chart for natural materials, plotting specific Young's modulus against specific strength. Guidelines identify materials which store the most elastic energy per unit weight, and which make good elastic hinges. Data are taken from references [1, 5, 7–32, 34–48, 50–72].

$$M_8 = \sigma_f/E \qquad \text{(allow large, recoverable deformations) (elastic hinges)}$$

and

$$M_9 = \sigma_f^2/E\rho \qquad \text{(maximum elastic strain energy per unit mass) (elastic springs)} \tag{3}$$

Values of these indices for natural and engineering materials are compared in table 5. One natural material stands out as exceptionally efficient at storing energy (index M_7): silk (including spider's web). In nature, it has an energy-storing role, and, as table 5 shows, it does it better than any engineering material: its values of σ_f^2/E, in the range 200–6000 MJ m^{-3}, exceed that of the best spring steel or rubber (20 MJ m^{-3}). It can be argued that energy storage per unit weight (rather than volume) is a more relevant measure of performance. It is measured by $M_9 = \sigma_f^2/E\rho$, and is plotted on the specific modulus-specific strength chart (figure 5). By this criterion, silks perform even better because their densities are low.

Table 5. *Modulus–strength performance indices*

(The properties of natural materials show a wide range of values; those listed here are in the middle of the range.)

material	ρ [a]	σ_f [b]	E [c]	$M_7 = \sigma_f^2/E$ [d]	$M_8 = \sigma_f/E$ [e]	$M_9 = \sigma_f^2/E\rho$ [f]
single cellulose fibre	1.5	1000	100 000	10.0	0.01	6.7
single cotton fibre	1.5	350	8 000	15.3	0.04	10.2
single flax fibre	1.5	250	6 000	10.4	0.04	6.9
single hemp fibre	1.5	400	7 000	22.9	0.06	15.2
single silk fibre	1.3	2000	14 000	290.0	0.14	220.0
single wool fibre	1.3	100	5 200	1.9	0.02	1.5
cartilage	1.3	10	10	10.0	1.00	7.7
skin	1.3	10	40	2.5	0.25	1.9
leather	0.9	45	45	45.0	1.00	50.0
soft butyl rubber	1.0	14	10	19.6	1.40	19.6
spring steel	7.5	2000	210 000	19.0	0.01	2.5

Units: [a]$\mathrm{Mg\ m^{-3}}$, [b]MPa, [c]MPa, [d]$\mathrm{MJ\ m^{-3}}$, [e]no units, [f]$\mathrm{MPa\ (Mg\ m^{-3})^{-1}}$.

A third index is of interest here: σ_f/E. Materials with high values of this index allow large, recoverable deflections and, for this reason, make good elastic hinges. Nature makes much use of elastic hinges: skin and cartilage are both required to act as flexural and torsional hinges. The index is plotted on both figures 4 and 5, which show that silks, skin and cartilage all rank highly by this criterion.

(*d*) *The toughness–Young's modulus chart: figure 6*

The toughness of a material measures the resistance it offers to the propagation of a crack. The limited data available for toughness, J_c, are plotted against Young's modulus, E, in figure 6. The performance index for fracture-safe design depends on the design goal (see table 2, last section). When a component containing a crack must carry a given load without failing, the safest choice of material is that with the largest value of:

$$M_{10} = K_{Ic} = (EJ_c)^{1/2}, \tag{4}$$

where K_{Ic} is the fracture toughness. Diagonal contours, sloping down from left to right on figure 6, show values of M_{10}. When, instead, the component must absorb a given impact energy without failing, the safest choice is the material with the largest value of

$$M_{11} = J_c. \tag{5}$$

These materials lie high up on figure 6. And when the component must support a given displacement without failure, the performance is measured by

$$M_{12} = (J_c/E)^{1/2}. \tag{6}$$

This is shown as a second set of diagonal contours sloping upwards from left to right on figure 6.

Values of these three indices for natural and engineering materials are compared in table 6. The standard structural materials of engineering – steels, aluminum alloys – all have toughnesses and fracture toughnesses which are much higher than

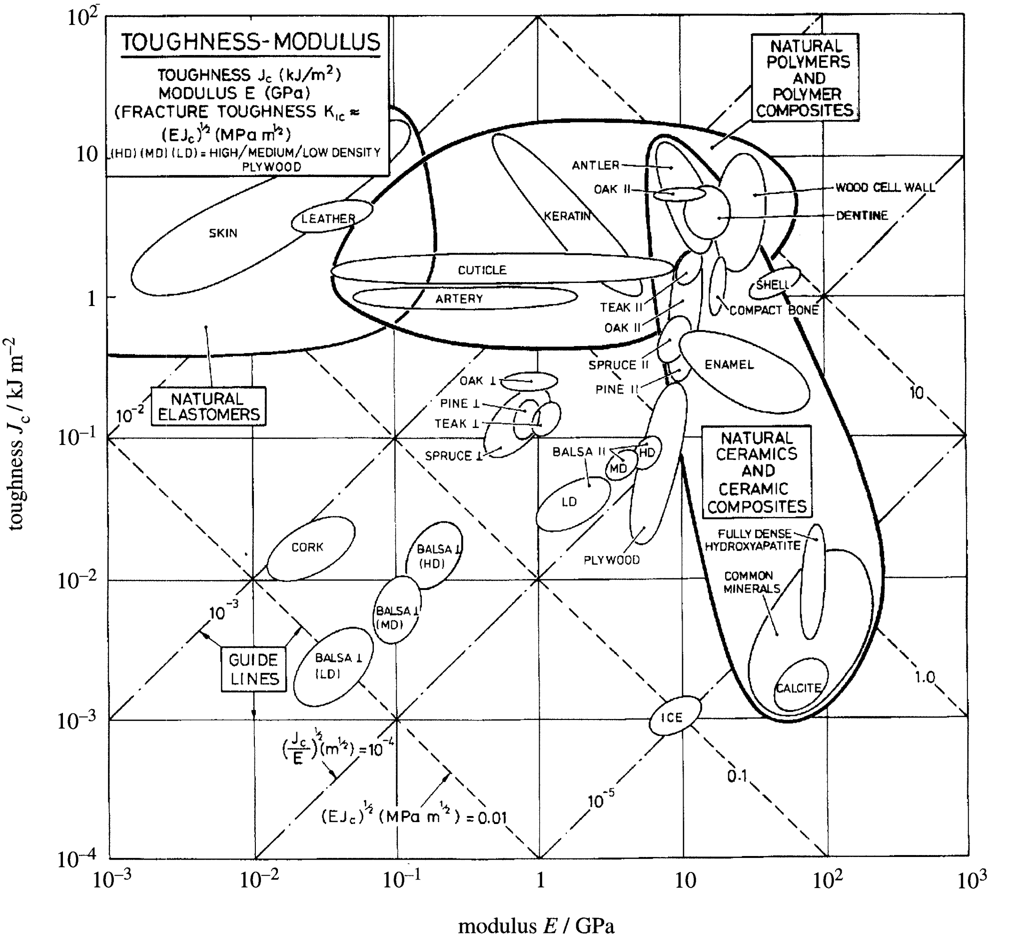

Figure 6. Material property chart for natural materials, plotting toughness against Young's modulus. Guidelines identify materials best able to resist fracture under various loading conditions. Data are taken from references [1, 5, 7–12, 14–20, 22, 23, 26–32, 34–44, 46–48, 51–53, 55–57, 60–72].

those of the best natural materials. But the toughnesses of natural ceramics like shell, dentine, bone and enamel are an order of magnitude higher than those of conventional engineering ceramics like alumina. These natural materials are really composites: particles of ceramics such as calcite, hydroxyapatite or aragonite, bonded by a small volume fraction of a polymer, usually collagen. Their toughness increases with decreasing mineral content and increasing collagen content (Currey 1984, 1988, 1990). Antler and bone have high values of M_{10} and M_{11}; skin, cuticle and keratin all have high values of M_{12}. When weight is important the indices for natural materials become even more attractive, because of their low densities.

4. Conclusions

Natural materials have evolved to fill needs posed by the ways in which animals and plants function. Many of these needs are mechanical: the need to support static and dynamic loads created by the mass of the organism; the need to store and release elastic energy; the need to flex through large angles; and the need to

Table 6. *Toughness–modulus performance indices*
(Values in brackets are calculated from the relationship $K_{IC} = (EJ_c)^{1/2}$.)

material	$M_{10} = K_{IC}$ (MPa $m^{1/2}$)	$M_{11} = J_c$ (kJ m^{-2})	E (GPa)	$M_{12} = (J_c/E)^{1/2}$ ($\mu m^{1/2}$)
wood cell wall	17.0	(8.0)	35	0.5
antler	(7.07)	5.0	10.0	0.7
mollusc shell material	(9.5)	1.5	60.0	0.4
skin	(0.4)	15.0	0.01	38.7
cuticle	(0.2)	1.5	0.04	6.1
mild steel	90.0	(40.0)	210.0	0.4
aluminum alloys	30.0	13.0	70.0	0.4
alumina	4.0	(0.05)	300.0	0.01
polyethylene (LD)	2.0	(13.0)	0.3	6.6
polypropylene	3.0	(6.0)	1.5	2.0

resist fracture. Not surprisingly, evolutionary optimization has led to materials of nature which are remarkably efficient in filling these needs. Mechanical efficiency can be quantified and compared by the use of 'performance indices', twelve of which are described in this paper. They are used in conjunction with material–property charts to assess and rank natural materials, and to compare them with the materials of mechanical engineering.

Material property charts for natural materials are presented in this paper. They show the ranges of density, modulus, strength, and toughness for each of a large number of natural ceramics, elastomers, polymers and cellular solids, giving an overview of their mechanical response. All twelve of the performance indices can be plotted onto one or another of the charts, allowing comparison of the efficiencies they measure. They show, for instance, that wood is more efficient than steel for a light component that is loaded in bending; that silk stores more elastic energy per unit weight or volume than the best man-made spring materials; that leather and skin have exceptional flexural properties; and that antler and nacre resist crack propagation better than any monolithic engineering ceramic.

There is much contemporary interest in understanding and modelling the mechanical response of these naturally efficient materials, partly to increase knowledge of them, partly with the goal of emulation. A companion paper (Gibson *et al.* 1995) examines a subset of these: those which combine a cellular structure with fibres, or with a tubular shape, to give overall mechanical efficiency.

The material property charts in this paper were expertly drawn by Mrs Sheila Mason. We gratefully acknowledge the financial support of the US Department of Energy (Grant No. DE-FG02-90ER45422) (L.J.G.) and the NATO Program for International Collaborative Research which provided travel funding which made this collaborative project possible.

Appendix A. Derivation of performance indices

Consider the selection of the material which minimizes the mass of a beam of a given span and bending stiffness. The bending stiffness of the beam, S_b, is

$$S_b = P/\delta = CEI/\ell^3, \qquad \text{(A 1)}$$

where P is the load, δ is the deflection, E is Young's modulus, I is the moment of inertia of the cross section, ℓ is the length of the span and C is a constant which depends on the end constraints of the beam. The mass of the beam is given by

$$m = \rho A \ell, \tag{A 2}$$

where A is the area of the section and ρ is the density. The stiffness depends on the section shape through the second moment of area, I. It is helpful to define a dimensionless shape factor, ϕ, as $4\pi I/A^2$; the number ϕ characterizes shape independent of scale (Ashby 1992). Substituting for A in the mass equation (A 2) and then substituting for I in the stiffness equation (A 1) gives

$$m = \left[\frac{4\pi \ell^5 S_\mathrm{b}}{C}\right]^{1/2} \left(\frac{\rho^2}{\phi E}\right)^{1/2}. \tag{A 3}$$

For a given stiffness S_b and shape ϕ, the mass of the beam is minimized by selecting the material with the largest value of the 'performance index'

$$M = \frac{E^{1/2}}{\rho}. \tag{A 4}$$

The guideline with slope 2 on the materials selection chart shown in figure 1 corresponds to a constant value of this parameter; lines parallel to this one lying towards the top left of the diagram have higher values of $E^{1/2}/\rho$ than those towards the bottom right. Note the meaning of M: an increase in M by a factor of 2 decreases the mass, for a given stiffness by a factor of 2; or it increases the stiffness, for a given mass, by a factor of 4.

The selection of a material by the criterion of a high value of $E^{1/2}/\rho$ alone may conceal an associated consequence: if E and ρ are low, the cross sections of the beam will be large. The area of the beam is given by $A = m/\rho\ell$ (where ℓ is its length and m its mass); for a beam of a given stiffness, span and cross-sectional shape, the mass, m, is proportional to $\rho/E^{1/2}$. The ratio of the cross-sectional areas of beams of equal stiffness, span and cross-sectional shape is

$$\frac{A_1}{A_2} = \left(\frac{E_2}{E_1}\right)^{1/2}.$$

For instance the cross-sectional area of a balsa ($E = 5\,\mathrm{GPa}$) beam is 6.5 times greater than that of an equivalent steel ($E = 210\,\mathrm{GPa}$) one for equal stiffness, span and cross-sectional shape.

The selection of a material with a high value of $\sigma_f^{2/3}/\rho$ may also increase the cross-sectional area of the beam. The area of the beam $A = m/\rho\ell$; for a beam of a given strength, span and cross-sectional shape, the mass, m, is proportional to $\rho/\sigma_f^{2/3}$. The ratio of the cross-sectional areas of beams of equal strength, span and cross-sectional shape is

$$\frac{A_1}{A_2} = \left(\frac{\sigma_{f2}}{\sigma_{f1}}\right)^{2/3}.$$

For instance the cross-sectional area of a palm ($\sigma_f = 100\,\mathrm{MPa}$) beam is 5.2 times that of an equivalent CFRP ($\sigma_f = 1200\,\mathrm{MPa}$) beam. Performance indices for plate bending, column buckling, failure of beams, and so forth, are derived in a similar way. Full details are given by Ashby (1989, 1991, 1992).

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Received 22 July 1994; revised 1 November 1994; accepted 9 November 1994