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Research paper

Bending efficiency through property gradients in bamboo, palm, and wood-based composites

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ABSTRACT

Nature, to a greater extent than engineering, takes advantage of hierarchical structures. These allow for optimization at each structural level to achieve mechanical efficiency, meaning mechanical performance per unit mass. Palms and bamboos do this exceptionally well; both are fibre-reinforced cellular materials in which the fibres are aligned parallel to the stem or culm, respectively. The distribution of these fibres is, however, not uniform: there is a density and modulus gradient across the section. This property gradient increases the flexural rigidity of the plants per unit mass, mass being a measure of metabolic investment made into an organism's construction. An analytical model is presented with which a 'gradient shape factor' can be calculated that describes by how much a plant's bending efficiency is increased through gradient structures. Combining the 'gradient shape factor' with a 'microstructural shape factor' that captures the efficiency gained through the cellular nature of the fibre composite's matrix, and a 'macroscopical shape factor' with which the tubular shape of bamboo can be described, for example, it is possible to explore how much each of these three structural levels of the hierarchy contributes to the overall bending performance of the stem or culm. In analogy, the bending efficiency of the commonly used wood-based composite medium-density fibreboard can be analysed; its property gradient is due to its manufacture by hot pressing. A few other engineered materials exist that emulate property gradients; new manufacturing routes to prepare them are currently being explored. It appears worthwhile to pursue these further.

1. Introduction

Trees, palms, and particularly bamboos, are known to provide the most efficient materials when mechanical performance at minimum mass is sought (Ashby et al., 1995; Gibson et al., 1988; Wegst and Ashby, 2004; Wegst, 1996; Gibson et al., 2010; Rich, 1987b). All three are slender plants composed of slender components; all three have to support mechanical loads which are due to both self-weight and external forces such as wind, rain, and snow that act primarily in bending, compression, and torsion. They achieve efficiency in three ways: (i) by using efficient composite materials, (ii) by shaping the component into a tube, for example, and (iii) by distributing the composite's components efficiently, through property gradients. Here, the material aspect of the structural optimization of two slender plants, palm and bamboo, is investigated. We examine the role which the microstructure plays in their mechanical performance, concentrating on

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the elastic bending behaviour of the material and property gradients. The effect of structural optimization on the failure modes of bamboo has been described elsewhere (Wegst and Ashby, 2007). Note that similar arguments could be made for other properties, such as strength and toughness (Gibson et al., 2010). Finally, applying the same analysis to the wood-based composite medium-density fibreboard (MDF), we illustrate how much a gain in bending efficiency can be achieved in an engineered material that exhibits a property gradient because of its processing.

2. Property gradients in palm and bamboo

The slender shape of palm stems and bamboo culms as well as their performance and survival under severe weather conditions such as tropical storms are remarkable. The material they are made of allows them to elastically bend to a quarter circle without failure, which significantly reduces the wind loads in hurricanes. Palm and bamboo are fibre composites with an axisymmetric density and a distinct modulus gradient across the section. Wood, in contrast, is a comparatively homogeneous cellular material, in which much more subtle property gradients are achieved through variations in the cellulose microfibril angle in the wood cell wall (Fratzl and Weinkamer, 2007). The details of the inhomogeneity in palm and bamboo are important: it is formed by sclerenchymatous fibre cells that form the important load-bearing fibre bundles. The fibres are embedded in the parenchymatous ground tissue; the distribution of the fibre bundles is graded. Also, in contrast to wood, palm and bamboo lack a cambium through which radial growth can occur to provide support with increasing height. Instead, they largely rely on increasing the cell wall thickness and degree of lignification, and possibly a higher alignment of the cellulose fibrils with the fibre axis during cell wall thickening, thereby adding to the radial modulus gradient across the stem's section and leading to a longitudinal modulus gradient along the length of the stem (Rich, 1986, 1987a).

Summarizing the considerable literature that describes studies of the structure and properties of bamboo (see, for example, Alvin and Murphy, 1988, Amada et al., 1996, Dunkelberg, 1992, Grosser and Liese, 1971, Higuchi, 1989, Itoh and Shimajii, 1981, Janssen et al., 1991, Janssen, 1991, Liese, 1985, 1998), we further find that bamboos have a smooth, usually circular and hollow stem, termed the culm. Regular transverse diaphragms at the nodes separate the culm into sections, the internodes. A very few bamboos have a solid culm. Branches leave the culm at the nodes, mostly in the upper two thirds of its height. The fibre composite structure of the material that forms the bamboo's culm wall is shown in Fig. 1. Optical micrograph (a) depicts a transverse cross-section of a bamboo culm, and (b) shows the radial distribution of the vascular and fibre bundles across the thickness of the culm wall. The scanning electron micrographs (c)–(e) illustrate the alignment of both the fibre bundles and the parenchyma with the longitudinal axis of the culm, and show that toward the periphery of the wall the bundles are increasingly closely packed. At higher magnification, the fibres are shown to be almost fully dense, with a plywood-like structure, which is due to the internal secondary growth of the cells, which increases both density and modulus of the fibres. At this level of structure, both the cell walls of the parenchyma and those of the sclerenchyma are polylamellate fibre composites with cellulose fibrils embedded in a hemicellulose and lignin matrix in each layer.

A schematic of the cross-section of a palm stem is shown in Fig. 2. Like bamboo, it is a fibre composite whose varying volume fraction of fibres from the centre to the periphery of the stem produces a radial modulus gradient, as shown in (a). In contrast to bamboo, the stem modulus significantly varies not only across the section but also along the height of the palm tree, as shown in (b), a schematic for a young and an old stem. Another difference between palm and bamboo is that, in the palm stem, more bundles of larger diameter are concentrated at the periphery than at the centre, producing a radial density and modulus gradient (Rich, 1987b; Tomlinson, 1990), while, in bamboo, more bundles of smaller diameter are concentrated at the outside of the tube wall (Fig. 1).

Quantified below is by how much the property gradients across the section in palm and bamboo increase the flexural rigidity of these plants per unit weight.

3. Modelling

3.1. Microstructural length scale

Before modelling the materials palm and bamboo, we need to demonstrate that they can be treated as a continuum. In the case of wood (cell size: 50–100 μm) it is obvious that the microstructure of the material is of a small enough scale for it to be considered a microstructural material; it is usual to regard wood as a solid material having 'wood' properties rather than as a 'shaped' cellulose composite. However, in the case of the cellular fibre composites palm and bamboo with comparatively large fibre-bundle diameters, this situation is not quite so clear.

If the microstructural length scales (e.g., cell size, fibre diameter, and spacing) are small enough compared to the specimen size, then the flexural rigidity, EI, can be evaluated by treating the material as a continuum. In particular, if the composite structure is homogeneous across the section, then the modulus in bending, E_b, derived from EI is equal to the normal tensile modulus, E_t, of the material (Gibson et al., 1995; Wegst, 1996). This raises the question how many fibres the cross-section of a sample must contain to be classified as a microshaped material and to behave with the same apparent modulus in bending as in tension.

Gibson et al. (1995) and Wegst (1996) investigated the effect of the length scale by calculating and comparing the flexural rigidity of two model sections. The first section was built up of unit cells of solid matrix with a central square hole aligned along the axis of the beam, and the second of unit cells of solid matrix with a square central fibre, which had a modulus greater than that of the matrix by a known factor. In each case, the depth, d, and width, b, of the beam was made up of n unit cells; the size of the unit cell was thus b/n. The ratio of the flexural modulus, E_b, to the tensile modulus, E_t, was