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Mechanics of balsa (*Ochroma pyramidale*) wood

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ABSTRACT

Balsa wood is one of the preferred core materials in structural sandwich panels, in applications ranging from wind turbine blades to boats and aircraft. Here, we investigate the mechanical behavior of balsa as a function of density, which varies from roughly 60 to 380 kg/m^3. In axial compression, bending, and torsion, the elastic modulus and strength increase linearly with density while in radial compression, the modulus and strength vary nonlinearly. Models relating the mechanical properties to the cellular structure and to the density, based on deformation and failure mechanisms, are described. Finally, wood cell-wall properties are determined by extrapolating the mechanical data for balsa, and are compared with the reduced modulus and hardness of the cell wall measured by nanoindentation.

1. Introduction

Balsa (*Ochroma pyramidale*), a tropical hardwood native to the Americas, is one of the fastest growing wood species, reaching about 20 m in height and up to 75 cm in diameter in 5–8 years (Fletcher, 1951). Most balsa wood used commercially is harvested from plantations, particularly from Ecuador. Because of its fast growth, the wood density is very low, making balsa the lightest commercial timber available. Density values for balsa typically range between 100 and 250 kg/m^3, although they can vary as much as from 60 to 380 kg/m^3. The low density is extremely valuable in applications that require lightweight materials with good mechanical performance. Balsa wood is one of the preferred core materials in structural sandwich panels for wind turbine blades, sporting equipment, boats and aircraft.

The large density variations in balsa derive predominantly from the fibers (Borrega et al., 2015), long prismatic cells that act as the main load-bearing elements in wood. Consequently, the mechanical performance of balsa is strongly dependent on its density. The axial compressive Young's modulus and strength increase linearly with density, reaching values up to 6 GPa for modulus and 40 MPa for strength at the highest densities (Da Silva and Kyriakides, 2007). The failure mode in compression transitions from plastic buckling of fibers to kink band formation as the density increases (Vural and Ravichandran, 2003; Da Silva and Kyriakides, 2007). Kink band formation in high density balsa is facilitated by local misalignment of fibers due to the presence of rays (parenchyma cells), which leads to the development of shear stresses during compression. The shear modulus and strength in balsa vary linearly with density, reaching values up to 350 MPa for modulus and 5 MPa for strength (Da Silva and Kyriakides, 2007). In the transverse direction, compressive modulus and strength vary roughly with the cube and square of density, respectively, due to bending of the fiber cell walls (Easterling et al., 1982). Transverse compressive modulus and strength values are about an order of magnitude lower than those in the axial direction. The transverse compressive modulus and strength are higher in the radial than in the tangential direction because the rays act as reinforcement.

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The mechanical properties of balsa have been modeled, particularly in compression, by considering the wood structure to resemble a honeycomb (Easterling et al., 1982; Gibson and Ashby, 1997; Vural and Ravichandran, 2003; Da Silva and Kyriakides, 2007). Although this assumption is a simplification of the heterogeneous cellular structure in wood, the models have proven to be useful in describing its mechanical properties over a wide range of densities. As a cellular solid, the mechanical behavior of balsa (and other woods) depends on the properties of the material from which the cell walls are made. The dry density of the cell wall material is about 1469 kg/m^3 for all woods (Kellogg and Wangaard, 1969), and thus the relative density of balsa, that is, the density of balsa divided by that of the cell wall, is generally lower than 0.25. The mechanical properties of the cell walls of wood have been determined by extrapolating mechanical data for several woods of widely different densities; extrapolated values for axial cell-wall Young's modulus and strength are about 35–40 GPa and 120 MPa, respectively (Cave, 1969; Gibson and Ashby, 1997).

The axial cell-wall Young's modulus has also been determined by a number of direct methods, including tensile tests of isolated fibers and bending of a fiber cell wall. Measured values for modulus are generally lower than those obtained by extrapolation. A mean axial cell-wall modulus of about 20 GPa has been obtained by tensile tests on mechanically and chemically isolated spruce fibers, but this elastic modulus was probably affected by mechanical damage and degradation of structural components during the isolation procedures (Burgert et al., 2005). Alternatively, an axial cell-wall modulus of about 28 GPa has been obtained by Orso et al. (2006) by bending of cantilever beams, which were produced with a focused ion beam (FIB) from the cell wall of spruce fibers. Typical values for the reduced modulus of the cell-wall measured by nanoindentation range from 16 to 24 GPa (Gindl et al., 2004; Wu et al., 2009). However, this technique tends to underestimate the cell-wall modulus because it reflects a combination of both axial and transverse properties, arising from the anisotropy of the wood cell wall. The axial compressive strength of the secondary cell wall in spruce, Keranji and Loblolly pine fibers, measured on micropillars machined by FIB, has been reported to be about 120–160 MPa (Adusumalli et al., 2010; Zhang et al., 2010).

The relatively high mechanical properties of balsa, for its density, make it attractive for cores in sandwich panels. To date, there are no engineered materials suitable for sandwich panel cores with a similar combination of mechanical properties and low density. With a view towards guiding the design of engineering materials inspired by balsa, we recently conducted a detailed characterization of its structure and composition (see Borrega et al., 2015). In this paper, we investigate its mechanical behavior over a wide range of densities and analyze the failure mechanisms under different loading conditions, relevant to the use of balsa wood in structural sandwich panels. The reduced modulus and hardness of the cell wall are also measured by nanoindentation. The mechanical properties are then modeled using existing models for cellular materials, microstructural data for balsa, and cell-wall properties determined by extrapolating the results from mechanical testing of macroscopic balsa specimens.

2. Structure and composition of balsa wood

The cellular structure in balsa wood consists of fibers (66–76%), rays (20–25%) and vessels (3–9%) (Borrega et al., 2015). The vessels are long tubular structures that run axially along the trunk of the tree and transport fluids from the roots to the crown. Their building blocks are known as vessel elements. The rays are brick-like parenchyma cells that run radially from the central pith to the outer part of the trunk. Their main function is to store sugars and other nutrients, although they also contribute to the radial strength of the tree (Burgert and Eckstein, 2001). The fibers are long prismatic cells, often resembling a hexagon in cross-section, that provide mechanical support to the tree. For mechanical purposes, wood is considered an orthotropic material, the three axes of symmetry being the longitudinal (L, along the fibers), radial (R, along the rays), and tangential (T, across the rays) (see Fig. 1). In balsa, the vessels are about 380 μm in length and 200–350 μm in diameter, the rays are about 30 μm in length and 20–50 μm in cross-section, and the fibers are about 700 μm in length and 20–40 μm in diameter, decreasing with density. The thickness of the double cell wall is about 4 μm in vessels, 0.9 μm in rays, and between 0.8 and 3 μm in fibers, increasing with density (Easterling et al., 1982; Da Silva and Kyriakides, 2007; Borrega et al., 2015).

The wood cell wall consists of a primary layer and three secondary layers, the S1, S2 and S3. The S2 is generally the thickest layer, making up about 80–90% of the total cell wall thickness in spruce tracheids (Fengel and Wegener, 2003). In high density balsa, the S2 layer makes up about 73% of the cell wall thickness, while in low-density balsa the S2 is of similar thickness as the S1 and S3 layers, making up about 30% of the total cell wall thickness (Borrega et al., 2015). The middle lamella is a thin layer located between primary layers of adjacent cells, bonding them together.

The cell wall layers in woods are made up of lamellae having a fiber composite structure, in which cellulose microfibrils are embedded in a matrix of hemicelluloses and lignin. In the primary layer, the cellulose microfibrils have no definite orientation. In the secondary S1 and S3 layers, the microfibrils are oriented almost at 90° from the longitudinal cell axis, while in the S2 layer they are mostly aligned with the longitudinal axis, with angles typically varying between 10° and 30° (Barnett and Bonham, 2004; Donaldson, 2008). In balsa, the mean microfibril angle (MFA) appears to be less than 2°, irrespective of density (Borrega et al., 2015). The thickness and the low mean MFA of the S2 layer largely govern the axial mechanical properties of wood, particularly the stiffness (Cave, 1969). The mechanical contribution of the S1 and S3 layers appears to be significant when wood is loaded in the transverse direction (Bergander and Salmén, 2002).