Microstructural aspects and modeling of failure in naturally occurring porous composites

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This paper is dedicated to Professor Sia Nemat-Nasser on the occasion of celebration of his 65th birthday for his pioneering contributions in the area of micromechanics of heterogeneous solids.

Abstract

Results from an experimental investigation on the compression behavior of balsa wood are presented. Specimens with varying densities, ranging from 55 to 380 kg/m³, are loaded in the grain (fiber, cell) direction using a screw-driven material testing system at a strain rate of 10⁻³ s⁻¹. The results indicate that compressive strength of balsa wood increases with increasing density. Post-test scanning electron microscopy is used to identify the failure modes. The failure of low-density specimens is governed by elastic and/or plastic buckling, while kink band formation and end-cap collapse dominate in higher density balsa specimens. Based on the experimental results and observations, several analytical models are proposed to predict the compressive failure strength of balsa wood under uniaxial loading conditions.

Keywords: Balsa wood, plastic buckling, kink band, failure mode transition, compressive strength, sandwich core materials

1. Introduction

Sandwich structures are used as energy absorbing/limiting materials in critical applications. In designing such structures, the most important properties to consider are the peak strength and the capacity for energy absorption. The former must not be too high, to limit damage to the container and its contents, and the latter must be as large as possible while minimizing the volume and weight. One of the best core materials to use in these applications is a naturally occurring porous solid such as balsa wood (Butler, 1994), which has a good combination of several properties such as high specific stiffness, strength and particularly energy absorption capacity (Knoell, 1966).

Balsa (Ochroma) has a cellular microstructure, with cells very similar to honeycomb in shape, and can be found with density varying over a wide range between 40 and 380 kg/m³, depending on the average size and the wall thickness of cells. Balsa wood has three orthogonal axes in the longitudinal (L, along the grain), radial (R, across the grain and along the rays) and tangential (T, across the grain and transverse to rays) directions forming a heterogeneous porous composite.

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This composite is highly anisotropic with a high ratio of longitudinal to transverse properties, the latter have also difference in itself due to so-called ray cells oriented in radial direction. The ratio of axial to tangential Young’s modulus, for instance, is roughly in the range 70-100 while the same ratio for compressive failure stress lies in the range 10-20. However, even though there is sufficient number of data showing that the degree of anisotropy for wood decreases with increasing density, there is not a well-established anisotropy-density relation for balsa wood. Of particular interest for balsa wood are the mechanical properties in longitudinal direction such as its peak strength, plateau stress and corresponding failure mechanisms under uniaxial compressive loading conditions. Therefore, investigation of the deformation behavior of balsa wood is needed in order to develop reliable models for their behavior over a wide range of densities.

Soden and McLeish (1976) and Easterling et al. (1982) carried out tests to determine the mechanical properties of balsa wood in longitudinal and transverse directions for the densities between approximately 80 and 200 kg/m³. Soden and McLeish carried out extensive tests and mainly concentrated on the variation of tensile strength with fiber alignment. They also reported compressive strength data. On the other hand, Easterling et al. paid particular attention to the micromechanics of deformation in their limited number of experiments. During the tests they performed in-situ SEM observations and defined the end-cap collapse of grains as the dominant compressive failure mechanism in longitudinal direction.

In the present investigation, the compression behavior of balsa wood for various densities covering almost its entire density range (from 55 to 380 kg/m³) is studied, with a particular emphasis on the identification of failure modes when loaded along its longitudinal axis. Deformation and failure response of the balsa wood and its variation with density are presented and discussed. Scanning electron microscope (SEM) examination of the failure surfaces of the recovered specimens loaded to pre-determined inelastic strains revealed that the failure mode of the balsa wood under uniaxial compression may be elastic/plastic buckling, plastic collapse of the pointed ends of hexagonal cells (end-cap collapse) or kink band formation, depending mainly on the density of balsa wood. Motivated by these experimental observations, simple analytical models are used to study the strength of balsa wood over a wide range of densities. Experimental results and model predictions of the failure strength of balsa are compared and show reasonable agreement.

2. Experimental

2.1. Specimens

Experiments were performed on balsa wood specimens over a wide range of densities between 55 and 380 kg/m³. Cylindrical specimens were machined from big blocks of balsa wood at five different nominal densities provided by BALTEK Corporation (Northvale, NJ) and polished using 320 grit sand papers. Densities were measured in a consistent way, paying considerable attention particularly to the moisture content since it has significant effect on both density and properties (Dinwoodie, 1975). Hence, density of each specimen was calculated with an accuracy of ~1.5 % prior to testing by measuring its weight (within 2 milligram) and using its nominal dimensions given below. Due to the variation of density within each block of a certain nominal
density, specimens were prepared with densities varying continuously between the range specified above. In order to find moisture contents of balsa specimens a series of specimens with different densities were heat-treated in furnace at 110 °C and intermittent weight measurements were performed until they reached a constant weight. Measured moisture content ranged from 8 to 11 %, which is the typical value for well-seasoned dry woods. Since the determination of moisture content for each specimen prior to mechanical testing is inapplicable due to the irreversible nature of process, they are assumed to have moisture content within this range.

The specimens were typically 19.05 ± 0.12 mm in diameter and 25.4 ± 0.12 mm in length, corresponding to a length to diameter ratio of ~1.33. Since the diameter of these specimens is smaller than those specified in ASTM C 365-00 (Standard Test Method for Flatwise Compressive Properties of Sandwich Cores; see ASTM, 2001), another set of specimens were prepared in accordance with the specification for comparison purposes, which will thereafter be denoted as ASTM specimens. Dimensions of ASTM specimens were 31.75 ± 0.12 mm in diameter and 25.4 ± 0.12 mm in length, giving a length to diameter ratio of 0.8. Any further attempt to address the effect of specimen aspect ratio is not pursued in the present study.

2.2. Compression Fixture

Figure 1 shows the compression fixture used in the quasi-static compression tests with and without confining sleeve. It ensured that two loading rods were perfectly aligned with each other so that any unwanted shear forces on the specimen are minimized. The specimen was sandwiched in between the loading rods and the compression was applied by a screw-driven materials testing system (Instron, model 4204) at a constant displacement rate of 2 mm/min. The quasi-static compression tests in longitudinal direction (along the grain) were performed with and without lateral confining sleeve to investigate the behavior of balsa wood under compression with proportional confinement and uniaxial compression, respectively. The loading rods are made of high strength maraging steel (C-350, Rockwell hardness, $R_C = 60$) and the confinement sleeve and end caps are machined from aluminum alloy (Al 2024-T3, Rockwell hardness, $R_B = 75$). The use of bonded resistance strain gages on highly compliant balsa specimens was not considered satisfactory because the reinforcing effect of bonding these gages with adhesive might lead to large errors in measurement of strains. Therefore, deformation data of both confined and unconfined specimens was obtained from the displacement transducer, which was calibrated to eliminate the machine and fixture compliance.

The confining sleeve shown in Fig. 1b is a hollow cylinder, which resists the lateral expansion of the specimen during the axial compression. Thus, lateral confinement, which is proportional to axial compression, is applied on the specimen. The experimental setup for the confined tests consists of a cylindrical specimen placed in a hollow cylinder with a sliding fit and the specimen is axially compressed using loading sleeves (Oguni et al., 2000). Since the strength and elastic modulus of the confining sleeve is greater by two orders of magnitude than that of the balsa specimens in lateral direction, the stresses within confining sleeve remain elastic at all times during the tests. Moreover, elastic analysis of the confined configuration for balsa wood as the specimen shows that radial expansion of the specimen-sleeve interface remains practically zero. Therefore, the boundary condition at the lateral surface of the specimen can be considered as zero displacement, i.e., rigid wall confinement.
3. Microstructural Features of Balsa

Balsa is unique among commercial woods in that its density is exceptionally low and varies over a wide range (from 40 to 380 kg/m³) depending on the age and habitat of the tree. Wood, in general, has complex microstructural features: it is a porous cellular solid and heterogeneous at nano-, micro- and meso-scales. Its heterogeneity at nano-scale comes from the existence of highly crystalline cellulose microfibrils within the cell walls, which makes balsa a remarkable nano-composite tailored by nature. Its cellular structure and the existence of ray cells and sap channels are the sources of heterogeneity at micro-scale. Finally, the periodic distribution of well-known growth rings, which is much less pronounced in balsa wood compared to other species, makes the wood heterogeneous at meso-scale.

Balsa, as a diffuse-porous hardwood, has a uniform distribution in type and size of cells throughout the grain cross section (see Fig. 2a,b). Cells of nearly hexagonal shape (grains) have diameters ranging from 30 to 70 µm, with an average of 45 µm. These long, hexagonal-prismatic cells are pointed at the ends (Fig. 2c,d) and have an average length of 650 µm, giving the cell an aspect ratio of about 16:1, as also reported by Easterling et al. (1982). Blocks of these large cells are separated by narrower rays in which the cells are smaller and of a different shape. Large sap channels running parallel to the axis of the tree penetrate the entire structure. Average diameter of sap channels is around 350 µm.

It must be noted that even though the grains in balsa wood are highly oriented in longitudinal direction this alignment is far from being perfect, as would be expected in a natural material. Upon careful examination, one can see from Fig. 2c,d that grains are not perfectly aligned to the longitudinal axis of balsa wood. Figure 3 shows a typical misalignment caused by the existence of ray cells penetrating the complete structure in radial direction. Experimental observations reveal that rays are the major source of grain misalignment in LT plane. Even though there exist longitudinal misalignments in LR plane as well, they are both smaller in magnitude and not considered as important as LT misalignments in terms of their effect on the failure mode/strength of balsa wood. This issue will be revisited in detail and its relevance to kink band formation will be given in the discussion of failure models.

4. Results and discussion

4.1. Stress-strain response

Monotonic compression tests were carried out on balsa wood specimens under displacement (crosshead velocity) control by using a screw-driven materials testing system (Instron, model 4204). The corresponding nominal strain rate was \( \dot{\varepsilon} = 0.0013 / s \) in all of the experiments. The stress states used in these tests are uniaxial compression (unconfined specimens) and multiaxial compression with proportional lateral confinement (confined specimens). In all experiments, specimens were loaded in longitudinal (L) direction (i.e., along the grain) and the load-displacement response of the specimens was measured.
Typical engineering stress-strain curves obtained from experiments for both unconfined and confined balsa specimens of different densities are shown in Fig. 4. For both cases the stress-strain curve is almost linear up to the maximum stress (hereafter referred to as failure strength, $\sigma_f$) beyond which, as the deformation is increased, the stress level either remains nearly constant or experience a sudden drop depending mainly on the density of specimen. After this sudden drop, if there is, the specimen continues to deform at a lower level of stress (hereafter referred to as plateau stress, $\sigma_p$). Eventually, at high strains, the cells collapse sufficiently so that opposing cell walls touch (or their broken fragments pack together) and further deformation compresses the cell wall material itself. This gives the final, steeply rising portion of the stress-strain curve called densification regime. Figure 4 clearly shows that, as the compressive deformation in plateau region is fairly smooth and occurs almost at a constant stress level for low-density balsa specimens, it is significantly irregular and of a fluctuating nature for high-density specimens. These two different characters of stress-strain response reflect the fact that there occurs a transition both in failure mode and in progressive deformation mechanism as the specimen density increases, which will be discussed in the context of the following section.

Figure 5 shows the variation of compressive failure strength for balsa wood over the entire range of its densities. There is a strong correlation between density and strength so that the latter increases as much as 15 times from $\sim 3$ MPa to $\sim 45$ MPa as the density increases from the low end to the high end of spectrum. As also mentioned above, the great majority of specimens used in this study have a diameter smaller than those specified in ASTM standard. The reason to do so was the restriction set by the diameter of the loading rods in compression fixture. In order to keep the consistency in confined and unconfined compression tests a smaller diameter was adopted for specimens. However, a series of tests was performed also with ASTM specimens for comparison purpose and the data in Fig. 5 justifies the use of these specimens for balsa wood. As opposed to many other materials, compressive strength of balsa wood in longitudinal direction is insensitive to lateral confinement as evidenced by experimental data in Fig. 5. This is attributed to the combined effect of high porosity, nature of cellular microstructure and high compliance of cell walls in lateral (across the grain) directions, which altogether give the material flexibility of accommodating the would-be-induced lateral strains within the initial lateral dimensions without exposing itself to significant lateral stresses.

The variation of failure strength normalized by plateau stress ($\sigma_f/\sigma_p$) is shown in Fig. 6 whose value can be considered as a measure of deviation from the material characteristics ideal for energy absorption applications. What is required of an ideal sandwich core material, for instance, is to have capability of absorbing as much energy as possible per unit weight/volume while keeping the stress constant, which turns out to be the elastic-perfectly inelastic behavior with a ratio of $\sigma_f/\sigma_p = 1$. It is important to note here that the comparisons of this type are meaningful only for materials with the same capacity of specific energy absorption. Otherwise it does not mean that a particular material with a lower ratio, say $\sigma_f/\sigma_p = 1.1$, is always superior to another material with a higher ratio, say $\sigma_f/\sigma_p = 1.6$, for a specific application.

From a material behavior point of view, a high ratio of failure strength to plateau stress implies that the initiation of inelastic deformation mechanism requires a higher driving force (or stored elastic energy) than required for the progressive deformation mechanism. In this sense, slight increase observed in the data of Fig. 6 from the interval 1.0-1.4 for low-density balsa to the
interval 1.3-2.0 for high-density balsa indicates that even though it becomes more and more
difficult to initiate failure as the density increases, at the same instance, to keep deforming the
material has become relatively easier. Slight increase observed in the scatter of data in Fig. 6 as a
function of density is the combined effect of increased scatter in both failure and plateau stresses (see Fig. 4). The increase in both the magnitude and the scatter of $\sigma_f/\sigma_P$ data is attributed to the transition in the failure mode from elastic/plastic buckling to kink band formation, and to the resulting increased susceptibility of plateau stress to the random nature of increased perturbations in the stress field. As the length scale of the deformation geometry increases from a fraction of cell diameter in buckling mode to as much as 10-15 times the cell diameter in kink band formation mode, an increased level of perturbation is induced in the stress field. As the average magnitude of these stress perturbations experienced during the progressive deformation period is responsible for the increase of $\sigma_f/\sigma_P$ ratio, the random nature of kink band formation process, in the sense that it relies on the presence of initial microstructural imperfections, accounts for the slight increase in the scatter of data, which will be discussed in the next section.

Another aspect of stress-strain response is the significant decrease observed in densification strain ($\varepsilon_d$) with increasing density and is shown in Fig. 7. Densification strain, which is defined in this study as the strain at the last local minimum before the stress starts rising steeply, varies between 0.66 and 0.86 depending on the density (Fig. 7). As expected, the denser the balsa wood the lower is the densification strain due to its close correlation with the level of porosity. As the increase in density results in higher plateau stress and hence higher specific energy absorption capacity per unit strain, concurrent decrease in densification strain puts a limit on total specific energy absorption capacity.

4.2. Failure mode characterization

Post-test examinations on the failure surfaces of specimens sectioned by a sharp razor blade were performed using scanning electron microscopy (SEM). Both visual observations during compression tests and SEM observations on a series of deformed balsa wood specimens at various densities suggest that the failure mode undergoes transition from elastic/plastic buckling of cell walls to kink band formation as the density of the specimen tested increases. Figure 8a shows a typical SEM micrograph of the failure surface of a low-density balsa wood specimen. This micrograph was taken from a specimen compressed up to a total strain of 3.2 percent, its stress-strain history is shown in Fig. 8b. It is seen that the deformation is localized into a narrow region in the form of plastic buckling waves and that the region outside of the localized zone is characterized by small wrinkles, which would eventually grow into buckling waves if the deformation were increased further. For this particular specimen maximum stress occurs at 2.3 % strain and the subsequent stress drop is negligible as usually observed in low-density specimens (Fig. 4).

Figure 9 shows the failure surface and corresponding stress-strain curve of a high-density balsa specimen. SEM micrograph clearly shows that in this case failure occurs by kink band formation. The maximum stress occurs at 2.8 % strain and the subsequent deformation is associated with a large stress drop that is characteristic of kinking. The kink band formation represents a compressive instability in the highly anisotropic materials. The fibers that deform into the kink band geometry involve a primary axial shear deformation. The initiating mechanism is that of the
imperfections in the material, usually expressed through a fiber misalignment angle for the nominally aligned state of fibers. Balsa wood, as shown above (see Fig. 3), has favored sites for misaligned fibers, which in return trigger the observed kink band formation.

5. Failure models

Post-mortem observations on both unconfined and confined specimens reveal that elastic/plastic buckling and kink band formation are two major compressive failure mechanisms in balsa wood. Easterling et al. (1982) report in their study on the mechanics of balsa wood that compressive failure in axial direction is dominated by the plastic collapse of end-caps (pointed end of long hexagonal cell). Even though end-cap collapse is not observed as the sole mechanism for failure in the present study, pyramidal end-cap collapse and/or fracture is observed to have occurred at some portions of the hinges of the kink bands. Therefore, elastic buckling, plastic buckling, end-cap collapse and kink band formation can be considered to be potential failure mechanisms in balsa wood. It has been shown in the following that simple analytical models based on these failure mechanisms have a strong potential to explain the observed trends and the model predictions correlate well with the experimental data for a natural porous composite such as balsa wood.

5.1. Elastic buckling

The elastic buckling of a thin plate (the cell wall) which is constrained along the two edges that lie parallel to the loading direction is a standard problem in structural mechanics (see, for example, Timoshenko, 1936). The buckling load per unit length which is determined by the flexural rigidity of the wall \( D \) and by the width \( l \), not the height \( a \) of the panel (see Fig. 10 for notation), is given by:

\[
N_{\text{crit}} = k \frac{\pi^2 D}{l^2}
\]

(1)

If the vertical edges in Fig. 10 are simply supported (i.e., they are free to rotate), and the height \( a \) is large compared with \( l \) \((a > 3l)\), then \( k = 4 \). If, instead they are clamped, \( k = 6.97 \). In the honeycomb structure, the cell wall is neither completely free nor rigidly clamped, therefore, to take a value just in between them appears reasonable. However, in a natural material like wood, the deviations from perfect geometry such as imperfections in cell wall planarity and spatial variation of cell wall thickness are considered highly effective in reducing the critical load for elastic instability. Therefore, the use of a much lower value like, for example, \( k = 2 \) is proposed arbitrarily. For simple hexagonal cells, the relative density \( \rho/\rho_s \) is related to the dimensions of the cell wall by (see Gibson and Ashby, 1997),

\[
\frac{\rho}{\rho_s} = \frac{2}{\sqrt{3}} \frac{t}{l} \left(1 - \frac{t}{2\sqrt{3}l}\right) \approx \frac{2}{\sqrt{3}} \frac{t}{l}
\]

(2)

for low-density regular hexagons; where \( \rho \) is the density of entire cellular structure (balsa wood) and \( \rho_s \) is the density of wood cell substance which is generally taken to be approximately 1,500
kg/m$^3$ (Wangaard, 1950; Mark, 1967). Then, by using Eqn. (2) and hexagonal configuration of cell walls, Eqn. (1) gives the critical stress for elastic buckling ($\sigma_{eb}$) as a function of density,

$$\sigma_{eb} = k \left( \pi/4 \right)^2 \frac{E_s}{1-\nu_s} \left( \rho/\rho_s \right)^3$$

where $E_s$ and $\nu_s$ are the axial Young’s modulus (35 GPa, from Cave, 1968) and Poisson’s ratio of the cell wall (assumed to be 0.3), respectively. Zhang and Ashby (1992) used the similar approach to predict the out-of-plane compressive strength of Nomex honeycombs and showed that the failure stress for this material could be represented by elastic buckling analysis for relative densities, $\rho/\rho_s$, lower than 0.1. As will be discussed later, the comparison of Eqn. (3) with experimental strength data for balsa wood also shows that elastic buckling can be considered as one of the failure mechanisms only for very low densities.

5.2. Plastic buckling

The axial collapse of hexagonal honeycombs has been treated by McFarland (1963) and, more recently improved by Wierzbicki (1983). Wierzbicki identifies a compatible collapse mode which requires plastic hinges both on the cell walls and at the corners, and a limited amount of cell wall extension also at the corners. By minimizing the collapse load with respect to buckling wavelength Wierzbicki’s method, together with Eqn. (2), gives the stress for collapse by plastic buckling as

$$\sigma_{pb} = m \sigma_{ys} \left( \rho/\rho_s \right)^{5/3}$$

where $\sigma_{ys}$ is the yield stress for wood cell wall substance (350 MPa, from Cave, 1969) and $m$ is 4.4 for regular hexagons with uniform wall thickness $t$. However, due to the same reasoning discussed above regarding the imperfections in wood cell geometry, a lower arbitrary value of $m = 2$ has been chosen to show its potential to represent the experimental data. Actually, the expression originally derived by Wierzbicki (1983) is for the prediction of progressive crushing strength (plateau stress). However, the fact that that the stress ratio ($\sigma_f/\sigma_P$) is very close to 1 for low-density balsa wood justifies the use of Eqn. (4) to predict the failure strength, at least, for low density specimens.

5.3. End-cap collapse

Figure 11 shows an idealized pyramidal end-cap which represents the tapered ends of long hexagonal cells in balsa wood (see Fig. 2). When the cell is loaded axially these end-caps collapse by the stretching of the triangular faces, i.e., by the plastic extension of elements like the one shaded in Fig. 11. The collapse strength ($\sigma_{pc}$) is calculated by equating the work done by a small displacement $\delta u$ due to the load $P$ to the plastic work required to stretch a triangular face plastically:
\[
P \delta u = 6 \int_0^{r'} \frac{\sigma_y \delta u r t z}{r'^2} dz \quad \text{and} \quad r' = \sqrt{r^2 + \frac{3}{4} l^2}
\]

or

\[
\sigma_{pc} = \frac{1}{2} \sigma_y \left( \frac{R}{\rho_s} \right)
\]

where \(\sigma_y\) is the yield strength of the wood cell wall material in the direction of the length of the shaded element (assumed to be 350 MPa), and the dimensions \(r, l, z\) and \(t\) are indicated in Fig. 11. The SEM observations show that \(r/l\) ratio varies roughly in the range from 1 to 3 for balsa wood. Therefore, the minimum value of \(r/l = 1\), representing the weakest sites, is adopted for modeling the behavior of balsa wood.

5.4. Kink band formation

Kink band formation has long been recognized as a major failure mechanism limiting the compressive strength in unidirectional fiber reinforced composites. Therefore, this problem has received wide attention. Following the elastic fiber microbuckling concept originally proposed by Rosen (1965) to model the compressive instability in composites, Argon (1972) took the alternative view that long-fiber composites undergo plastic kinking and recognized that the initial fiber misalignment angle, \(\theta_o\), would have a large degrading effect on the compressive strength. Budiansky (1983) extended Argon’s formula for an elastic-perfectly plastic composite to a more general expression for stress \((\sigma_{kb})\) required for kink band formation,

\[
\sigma_{kb} = \frac{G_{13}}{1 + \theta_o / \gamma_y}
\]

where \(G_{13}\) is the axial shear modulus of the composite and \(\gamma_y = \tau_{y13}/G_{13}\) is the yield strain in longitudinal shear. The fibrous and anisotropic structure combined with the favored sites for large fiber misalignment angles (see Fig. 2) makes the kink band formation a major failure mode in balsa wood, which is also evidenced by SEM observations (Fig. 9a). Therefore, Budiansky’s formula was used to see its correlation with experimental data. Out of plane shear modulus, \(G_{13}\), in Eqn. (7) is replaced by \(G_{LT}\) for balsa wood, because the majority of fiber misalignments are observed to exist in LT plane due to the ray cells lying along the radial direction. Furthermore, the fact that ray cells act as a reinforcing phase to increase the shear modulus in LR plane is also supported by the experimental evidence that the kink band failure always occurs in the LT plane.

Based on the cellular mechanics calculations of Gibson and Ashby (1997) for out of plane shear properties of regular hexagonal honeycombs, and in conjunction with Eqn. (2), the shear modulus and shear strength in LT plane for balsa wood can be approximated by
\[ G_{LT} = \frac{1}{2} G_s \left( \frac{\rho}{\rho_s} \right) \]  

(8)

and

\[ \tau_{LT} = \tau_{ys} \left( \frac{\rho}{\rho_s} \right) \]  

(9)

where \( G_s \) and \( \tau_{ys} \) are the shear modulus and yield strength in shear of the wood cell wall material, respectively. The values \( G_s = 2.6 \) GPa and \( \tau_{ys} = 30 \) MPa will be used here, which have been determined to be the relevant values by Gibson and Ashby (1997) through the extrapolation of the experimental data for shear moduli and shear strength of a number of woods. The use of Eqns. (8) and (9) give a yield strain \( (\tau_{LT}/G_{LT}) \) of \( \gamma_y = 0.023 \) in longitudinal shear, which is independent of the relative density because of their individual dependence on density is the same (linear).

The last term that remains to be determined in Eqn. (7) is the fiber misalignment angle, \( \theta_o \). The SEM examinations (e.g., Fig. 3) performed on the LT planes of balsa specimens with various densities shows that the maximum fiber misalignment angles are highly scattered in the range between \( 7^\circ \) and \( 11^\circ \). Hence, an average value of \( \theta_o = 9^\circ \) is used to predict the critical stress \( (\sigma_{kb}) \) for kink band formation.

It should be noted that the two parameters in Eqn. (7), \( G_{13} \) and \( \gamma_y \), are predicted by using Eqns. (8) and (9). Even tough these equations are tuned according to the experimental data in literature they reflect an averaging process over different species of wood, thereby introducing a certain amount of error for the balsa wood. However, the experimental determination of these values for the complete density range of balsa wood would exceed the scope of present paper. Moreover, it is considered that the large scatter observed for the third parameter of Eqn. (7), fiber misalignment angle \( \theta_o \), and the selection of an arbitrary average value for it justifies the use of this approximation.

5.5. Comparison with experiments

The predictions of the four separate models described above are plotted in Fig. 12 along with the experimental strength data for balsa wood obtained from compression tests in longitudinal direction. It is obvious that none of these models is capable of representing the entire data by itself. However, as also suggested by the experimental evidence of failure mode transition, the combination of models successfully correlates with the present experimental data. It should be noted that the plots of the first two models, namely elastic and plastic buckling models, are based on arbitrary assumptions concerning the geometric imperfections such as the spatial variations of thickness and the deviations from planarity in cell walls.

Basically, the two failure models based on plastic buckling and kink band formation mechanisms correlate well with the experimental data. The transition region predicted by these models lies between \( \rho = 170 \) kg/m\(^3\) and \( \rho = 200 \) kg/m\(^3\) and is compatible with experimental observations. At very low densities, elastic buckling seems to have the potential as a competing failure mechanism. In this region progressive failure occurs by plastic folding of cell walls into buckles.
comparable in length to the width of cell walls. However, to identify the initiation mechanism for failure is extremely difficult. One can only speculate that depending on the type and degree of geometric imperfections at micro scale failure initiates either by elastic or by plastic buckling of the cell walls. At high densities above transition region, the predictions of pyramidal end-cap collapse mechanism correlate with data, interestingly, equally well as those of kink band formation do, hence making these two mechanisms compete at high densities. Actually, geometric perturbations induced by end-cap collapse at favored sites may also trigger kink band formation. Therefore, the last two mechanisms are open to both competition and interaction.

6. Conclusions

The mechanical behavior of balsa wood over a wide range of densities has been investigated with a particular emphasis on the microstructural characterization and the analytical modeling of compressive failure mechanisms. Results from unconfined and confined experiments show that neither compressive strength nor plateau stress is significantly affected by confinement. Independence of strength from confinement is attributed to the highly porous cellular microstructure of balsa. Compressive strength and plateau stress of balsa wood increases linearly as a function of its density while the densification strain decreases. The increase in plateau stress results in an increase in the specific energy absorption capacity (per unit volume) per unit strain, $E_s$. In spite of the decrease in densification strain, total specific energy absorption capacity ($E_t = E_s \epsilon_d$) continues to increase with density. The post-mortem SEM examinations reveal that failure mode transition from elastic/plastic buckling to kink band formation occurs as the density increases. Based on the experimental results and observations, several analytical models were described and their relevance to represent the failure behavior of a natural material like balsa wood was discussed. Results show that these analytical failure models describing the elastic/plastic buckling, end-cap collapse and kink band formation mechanisms have a strong potential to predict compressive strength of balsa wood in a range of densities that differ by an order of magnitude.

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References


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