EFFECTS OF CELL ANATOMY ON THE PLASTIC AND ELASTIC BEHAVIOUR OF DIFFERENT WOOD SPECIES LOADED PERPENDICULAR TO GRAIN

by

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SUMMARY

In radial compression, the shape of the stress-deformation curve varies for different wood species, particularly at the transition from elastic to plastic deformation and along the stress plateau. Due to differences in anatomy and cell wall microstructure, different responses to perpendicular loads were observed in spruce (ductile plastic deformation), oak (brittle failure), and beech (elastomeric yielding). Beginning plastic deformation was examined by SEM after the application of different compression levels and by dynamic observations during the loading process of small samples under a light microscope. It was demonstrated that radial compression of spruce is limited by the critical Euler buckling load of only a few cells closely behind the ring border. The compression behaviour of oak is determined by the buckling of the earlywood vessels and vasicentric tissue, whereas beech is characterised by the densification of the vessels at high plastic deformations.

Key words: Radial compressive behaviour, wood anatomy, cell wall buckling, Fagus sylvatica, Picea abies, Quercus spp.

INTRODUCTION

Wood can be considered as a highly anisotropic material at any structural level. According to Thomas (1991) the term gross morphological features describes the internal structure of a tree trunk down to the scale of the growth rings, the anatomy within a growth ring is the wood microstructure, and the arrangement and type of chemical constituents of a single cell wall is the cell wall structure. For many wood species the microstructure in the radial direction can be regarded as a sandwich construction consisting of alternating layers with different mechanical properties.

In structural applications of wood, in production of wood composites, in drying, and in pulping, compressive stresses perpendicular to the grain play an important role. Being a cellular solid, the schematic deformation curve of wood tissue loaded in radial compression is divided into three regions. Initial linear elastic deformation is followed by a plateau which persists up to fairly large deformations. At even larger deformations, the stress increases again rapidly (Bodig 1965; Gibson & Ashby 1988; Courtney 2000; Tabarsa & Chui 2000, 2001). Thus, the compressive behaviour of wood perpendicular to grain is characterised by the absence of a clear failure of the material (Gaber 1940;
Kollmann 1959, 1982; Schneeweiss 1963). At deformations exceeding the elastic range in radial compression, the low-density earlywood of each annual ring collapses one after the other in softwoods and ring-porous hardwoods, leading to an alternating stress strain curve in the plateau region (Bodig 1965). In diffuse-porous hardwoods the elastic phase gradually merges into a plateau zone. When densification of the latewood begins, the stress deformation curve increases again (Bodig 1965; Tabarsa & Chui 2001).

Tabarsa & Chui (2001) pointed out that wood behaviour in transverse compression is strongly dependent on its anatomical features. In contrast, Beery et al. (1983) reported that elastic behaviour is more dependent on density than on anatomical characteristics. Kennedy (1968) confirmed the influence of density, and also found a relationship between the mechanical behaviour and the proportion of latewood and differences of density between earlywood and latewood.

The high variation of wood structure at different levels is generally not considered in material testing of macro-scale samples. Due to the lack of a clear failure of wood loaded perpendicular to grain, different European standards have introduced the yield point as an easily quantifiable strength value (DIN 52192, EN 408). To increase understanding of the failure mechanism, structural alterations on the microstructural and on the cell wall level during radial compression were investigated. In order to study beginning and advanced plastic deformation with respect to cellular structure, strictly radially oriented samples of different wood species were examined.

MATERIAL AND METHODS

The compressive behaviour of a cellular solid like wood is governed by cell-wall thickness, cell shape, lumen diameter, density distribution, and the mechanical properties of the cell-wall substance itself (Courtney 2000). The species investigated in this study were selected on the basis of their anatomical characteristics. Oak (Quercus spp.) is a ring-porous hardwood, beech (Fagus sylvatica L.) is a diffuse-porous hardwood, and spruce (Picea abies [L.] Karst.) is a softwood.

In order to illustrate the structural differences between the investigated wood species, cross sections were prepared for X-ray density measurements by means of a double bladed circular saw. The strictly axially oriented cross section slices (thickness 1.25 mm) were put on a X-ray sensitive film and exposed to radiation from an X-ray tube (10 kV, 24 mA, 25 min). The radiographs were digitised in a scanning densitometer and the distribution of density was calculated by comparing the grey levels of the wood radiographs to a cellulose acetate reference wedge (Fig. 1). A detailed description of X-ray densitometry is given by Schweingruber (1983).

The specimens for macro-scale strength testing (n = 40 per species) were obtained from centre boards with strict orientation of the rays parallel to the loading direction. A reduced mid-section (12 × 12 mm) was shaped with a cutter before the specimens were sawn off the board. The sample dimensions were as follows: height = 100 mm, width = 30 mm and thickness = 12 mm (Fig. 2). The specimens were stored in a climate chamber at 20 °C and 65% rel. humidity. The equilibrium moisture content of the specimens as determined by oven drying was 10.5% for spruce, 10% for oak and 11.2% for beech, respectively.
All strength tests were performed on a mechanical testing machine (Zwick/Roell Z100/SW5A). Compression tests were performed with a constant displacement rate of 2 mm/min. The deformation was measured by a dedicated mechanical extensiometer (Macrosens Zwick/Roell). The distance between the two sensing devices of the extensiometer was 25 mm, which corresponds to the length of the reduced mid-section. The Young’s modulus was determined between 10 and 40% of the maximum load of each sample. To investigate the different stages of plastic deformation the load was stopped between 50 and 1200 µm absolute deformation of the mid-section.

After the compression tests the cross-sectional surfaces of some selected specimens were planed with a razor blade and observed with a light microscope. Growth rings with apparent compressive deformation were dissected for scanning electron microscopy (SEM). In this way 10 SEM samples per species with different stages of plastic deformation were prepared. The SEM samples were gold sputter coated at 1 kV and 20 mA and images were acquired in the SEM (Philips, XL30ESEM) at 10 and 15 kV.

Fig. 1. Density profiles of radiographs across the reduced mid-section (horizontal axis [mm]) of the specimens. – A: Spruce. – B: Oak. – C: Beech. The vertical axis of the profiles shows the absolute density [g/cm³].

Fig. 2. Specimens for compression tests with strict orientation of the rays parallel to the loading direction. Sample size: height × width × thickness = 100 × 30 × 12 mm; length of the reduced mid-section 25 mm; cross-sectional area 12 × 12 mm.
To investigate the deformation and the dynamic process of deformation within a growth ring, small spruce samples (tangential/radial/axial = 2.70/2.41/3.50 mm) consisting of only one growth ring were compressed and simultaneously observed by an incident light microscope (Olympus, ×140 magnification). The surface of the specimens was planed with a razor blade. Before applying compression load, no deformation of earlywood cells due to sample preparation was visible. The specimens were compressed by a micrometer screw and the force was acquired by a computer two times per second. A movie sequence (two micrographs per second) was recorded by means of a video camera attached to the microscope.

To calculate the critical buckling load of a single cell wall, a micro-section of the same growth ring as used for the compression tests under the light microscope was cut on a Reichert sledge microtome. The section was observed in a transmitted light microscope (magnification ×1200) (Fig. 3) and the radial lumen diameter and cell wall thickness was measured across the growth ring using image analysis software (Fig. 4).

Fig. 3. Microsection of the same growth ring as used for the compression tests under the light microscope. The section was used to determine cell dimensions across the growth ring. Thin-walled cells with largest radial lumen diameter were found in the third cell row behind the ring border (arrows), which corresponds to the observation of initial cell wall buckling in the compression tests (not shown).

Fig. 4. Mean lumen diameter (black line) and thickness of the double cell wall (grey line) across the growth ring shown in Figure 3.
RESULTS

Figure 1 shows radiographs of the three wood species investigated. Differences of the distribution of density across growth rings are clearly visible by the distribution of grey levels. While the distribution of density is fairly even in beech, heterogeneity increases in oak and is highest in spruce, where latewood, with a density of 1.2 g/cm³, is four times as dense as earlywood. In spruce, the lowest density values were primarily found in a

Fig. 5. SEM micrographs of spruce (loading direction top down) at different stages of yielding. – A: Beginning buckling of radial cell walls (arrow) corresponding to an absolute plastic deformation of 60 µm. – B: Arrows mark the first bending fracture of the cell walls near the cell corners at an absolute plastic deformation of 100 µm. – C: Beginning densification of 5–10 earlywood cell rows near the ring border in only one annual ring at an absolute deformation of about 150 µm. – D: At higher plastic deformation, the weakest cell rows of the next annual ring fail (not shown in the picture) without further densification of the initially failed growth ring.
few cell rows behind the growth ring border (Fig. 1A). The density profile of oak showed low density values in the earlywood. A strong relationship between density and the distribution of fibres and parenchyma cells was found within oak latewood (Fig. 1B). The radiograph of beech showed that density distribution depends on the stochastic distribution of vessels; peak density values were only found near the ring boundary (Fig. 1C).

A plastic compressive deformation of about 60 to 70 µm corresponds to the initial buckling of the radial spruce cell walls of one or two cell rows (Fig. 5A, B). At the highest compression level, a few (5–10) cell rows of two or three annual rings had collapsed completely (Fig. 5C, D). In most cases, initial cell wall buckling was observed approx. 3–10 cell rows behind the annual ring border. Figure 6A & B show the initial

Fig. 6. SEM micrographs of the progress of plastic deformation in oak earlywood vessels (loading direction top down). – A: The arrows mark the initial bending of vessels and the surrounding parenchyma tissue at plastic deformations of 60 µm. – B: 70 µm and C: 80 µm. – D: At higher deformation levels of 100 µm and E: 150 µm the surrounding tissue breaks into the vessel cavities. – F: At 200 µm absolute plastic deformation all vessels of only one annual ring completely collapsed. At this stage no deformation is visible in other annual rings.
deformation of vessels and the vasicentric tracheids in oak. At higher absolute plastic strain, strong vessel deformation and beginning fracture of cell walls were visible (Fig. 6C, D). Yielding at the final level corresponded with the complete collapse of vessels in only one annual ring (Fig. 6E, F). The SEM micrographs taken from beech samples with low plastic deformation between 60 and 150 µm did not show any obvious structural alterations. At higher compression levels beginning densification was observed (Fig. 7A–C). In comparison with spruce and oak, however, structural deformations at medium plastic strain (> 150 µm) were observed in more than one annual ring (not shown in the picture).

Figure 8 shows typical stress-strain curves of the examined wood species determined in radial compression. Spruce, with the lowest Young’s modulus, showed a cyclic up and down curve in the plateau zone, agreeing with
the consecutive failure of earlywood cells within the growth rings in the reduced mid-section of the test specimen. Oak is characterised by a higher Young’s modulus and by an abrupt change to the plateau zone. After a peak force (in most cases) the stress-strain curves oscillated around a slightly decreased stress level. In comparison with spruce and oak, beech compressed in radial direction showed a ‘smooth’ change from elastic to plastic deformation. The Young’s modulus was in the same range as for the oak samples. Table 1 presents the average Young’s modulus and the arithmetic mean for the proportional limit (defined as the stress at 1% plastic deformation) and their coefficients of variation (COV) for the three wood species.

Figure 9 shows the force deformation curve of a micro-scale spruce sample. After an initial linear elastic deformation the curve reaches a peak force of 32 N. At this deformation level, first cell wall buckling could be observed in the incident light microscope movie. After diminishing slightly, the force increased again, which corresponded to the collapse of the weak earlywood cells near the ring border. At higher deformation (> 50 µm) a steep force increase was noticed, which matched with the densification of the transition wood.

![Force deformation curve of a micro-scale spruce sample.](image)

**DISCUSSION**

Corresponding to their specific gravity, cell-wall mechanical properties, and especially due to the cell dimensions and different cellular structure, spruce, oak, and beech exhibited different behaviour in radial compression testing (Fig. 8). Because the transition from the zone of elastic deformation to the stress plateau and the plateau itself depends on the mechanical properties of the cell wall substance (Gibson & Ashby 1988; Courtney 2000). Alexiou (1994) found no correlation between strain at proportional limit and density. He concluded that strain at proportional limit must be mostly dependent on the anatomy of the wood and the ultrastructure of the cell wall, which is confirmed by the results of the present study.

The angle between cellulose microfibrils and the longitudinal cell axis is called microfibril angle (MFA). MFA is the most important parameter for mechanical properties.
of the cell wall, determining strength and elasticity (Cave 1969; Salmén & de Ruvo 1985; Reiterer et al. 1999). The MFA-orientation in the cell walls of the investigated wood species is variable: in spruce earlywood, the MFA is low with small scattering; in oak vessels the MFA is randomly oriented and in beech vessels the MFA is about 30°, with considerable scattering (Lichtenegger et al. 1999). Courtney (2000) described a different cell wall behaviour under load. If the cell wall material is ductile, the failure stress corresponds to plastic yielding of the wall hinges as observed with spruce (Fig. 5A, B). Following initiation of plastic collapse in a plastic cellular solid, the stress often decreases slightly, and stress serrations cycling about the average plateau stress occur (Courtney 2000) (Fig. 8). Since the MFA in spruce tracheids is relatively low, varying from 0–15–30°, depending on the method of measurement (Meylan 1967; Sahlberg et al. 1997; Reiterer et al. 1998), the mechanical behaviour in transverse direction is also influenced significantly by the more ductile lignin-hemicellulose matrix (Bergander & Salmén 2000a). When the cell wall material is brittle, ‘failure’ corresponds to the fracture of cell walls (Courtney 2000). The behaviour and morphology of the investigated oak samples corresponded closely to such a model brittle cell wall (Fig. 6D–F) because of the following: serrations in the plateau zone corresponding to the fracture of individual cell walls were evident (Fig. 8). The average plateau stress lies below the fracture initiation stress (Fig. 8). This behaviour of oak earlywood vessels may be explained by their random MFA orientation, corresponding to tubes reinforced by randomly oriented filaments. In elastomeric cellular solids, failure is caused by the plastic deformation of the cell walls (Courtney 2000), as could be demonstrated for the beech samples in Figure 7A. Compressive stress-strain curves for elastomeric cellular solids are ‘smooth’ (Fig. 8). The plateau persists up to a strain at which densification begins, then the curve gradually slopes upwards until the densification strain is attained (Courtney 2000).

Kollmann (1959, 1982) stated that compressive strength perpendicular to the grain is determined by the critical stress of single cell walls. Buckling of the weakest cell wall initiates failure. Beery et al. (1983) and Bodig (1963) described failure characteristics as a function of weak zones in wood, which are created naturally by various anatomical elements. A decreasing maximum stress of wood loaded in radial direction was observed with increasing vessel area and increasing ray width (Beery et al. 1983). SEM and dynamic microscope observations performed in this study showed that spruce samples always ‘failed’ in the weakest tracheid layer (earlywood cells at the ring border or few cell rows (3–10) from the beginning of a growth ring) (Fig. 5). The zone of minimum density as determined by X-ray densitometry is located in that part of an annual ring (Fig. 1A). These observations agree with cell wall measurements of Tabarsa and Chui (2000), who pointed out that the first cell collapse of softwood species occurred in the cells with the thinnest walls.

Figure 10A shows that earlywood cell walls of spruce behave exactly like a buckling column built in at both ends. By using the equation for the critical Euler buckling load, the critical load of a single cell wall was determined (Eqn. 1). Bergander and Salmén (2000b) found the mean transverse Young’s modulus of radial earlywood cell walls in spruce to be about 2000 N/mm². This value was used for E in the calculation.
Young’s modulus exerts a minor effect on the Euler buckling load in relation to the cell wall thickness and to the radial width of the cell wall, which influence, respectively, the Euler buckling load to the third power and the second power. The cell wall thickness and lumen diameter in radial direction shown in Figure 4 were used for the calculation. Figure 10B shows the critical buckling load of a single cell wall across the chosen growth ring. The distribution of $F_{\text{crit.}}$ across the growth ring resulting from Eqn. 1 (Fig. 10B) clearly confirms that the critical Euler buckling load of radially loaded softwood is the lowest at three cell rows behind the ring border ($F_{\text{crit.}} = 0.4 \, \text{N}$), which corresponds well with the measured cell dimensions and with the results of the X-ray density measurements.

$$F_{\text{crit.}} = 4 \pi^2 \frac{E (a \, w^3/12)}{l^2}$$

(Eqn. 1)

($F_{\text{crit.}}$ = Euler buckling load, $E$ = Young’s modulus of the cell wall, $a$ = axial length, $w$ = cell wall thickness, $l$ = radial width of the cell wall between two cell corners).

A theoretical critical load for the micro-scale spruce sample of 34 N was calculated by multiplying the number of the cells in tangential direction ($n = 85$) by the $F_{\text{crit.}}$ (i.e. 0.4 N) of the 3rd cell row. The calculated buckling load of 34 N corresponds well with the peak force of 32 N observed in Figure 9, before the small force drop when cell wall buckling was observed for the first time in the recorded movie sequence.

Beech (a diffuse-porous hardwood) with a more homogeneous structure with small vessels embedded in thick-walled fibers is characterized by a continuous densification of the material during loading perpendicular to grain. Cell wall buckling of thin-walled vessels only plays a minor role. In contrast, the transition from elastic to plastic deformation of spruce (a softwood) and oak (a ring-porous hardwood) is primarily influenced by cell wall buckling and therefore by a critical load of these elements. Due to the minor effect of the Young’s modulus on the Euler buckling load it can be assumed that the compression limit of these wood species is rather a problem of the stability of the structure than a problem of the mechanical properties of the cell wall itself. Due to the different
compression behaviour perpendicular to grain of the three wood species investigated, we conclude that the compression limit is mostly dependent on the microstructure and cell anatomy, whereas the plastic deformation and the compression behaviour in the plateau zone is a function of the ultrastructure of the cell wall.

REFERENCES