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NOTE

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Elastic strain at semi-isostatic compression of Scots pine (*Pinus sylvestris*)

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Abstract Quarter-sawn and plain-sawn specimens of Scots pine were semi-isostatically compressed at 5, 15, 50, and 140 MPa in a Quintus press. Elastic strain was measured using a telescope device that was pushed together when wood was compressed and remained in this position at release of pressure. Delayed elastic and plastic strains were assessed through repeated callipering during 5 years after densification. At 140 MPa, wood reached an almost compact structure ($\rho \approx 1450\,kg/m^3$) but as a result of elastic springback the density decreased to just below $1000\,kg/m^3$. At 140 MPa, the elastic and delayed elastic strains were 14.6% and 1.8%, respectively, in quarter-sawn specimens, and were 13.1% and 0.8%, respectively, in plain-sawn specimens. The higher elastic strains in quarter-sawn specimens can be attributed to elastic springback in the tangentially deformed latewood bands.

Key words Elastic strain · Semi-isostatic compression · Quintus press · Density

Introduction

By compressing wood in a Quintus press, density is increased and strength properties are improved without inducing major checking. The pressure is mediated through a flexible oil-filled rubber diaphragm, which makes harder structures less compressed than softer structures. This gives compressed wood irregular shape but homogenous density. The pressure rises successively up to 140 MPa and is then immediately lowered to atmospheric pressure; the process will take about 3 min. No heating is needed. The moisture content of the wood is important and should be in the range of 4%–18%. Wood that is too dry will be severely affected by checking and wood that is too wet will have a low degree of compression. At the beginning of the compression process, the pressure is unidirectional perpendicular to the press table. As the pressure increases by filling the rubber diaphragm with oil, the diaphragm closes around all wood faces except the face placed on the rigid press table and the pressure becomes isostatic. Because of the gradual shift from unidirectional to isostatic pressure and the differences in friction forces between wood and rubber and between wood and steel, the process is defined as semi-isostatic compression.[1]

Because wood is a viscoelastic material, the deformation at compression comprises three major components: elastic strain, delayed elastic strain, and plastic strain.[2] The general mechanisms of unidirectional compression of wood and relaxation are well documented.[3,4] Although isostatically compressed wood has been studied by others, e.g., by Trenard[5] and Bucur et al.,[6] no reports have discussed the elastic springback that occurs at the release of pressure.

The higher the plastic proportion of the strain at compression, the higher the final density. Knowledge about the elastic springback indicates the potential for further increase in density by making strain more plastic. The amount of delayed elastic springback when wood is stored in a relatively constant indoor climate is important when semi-isostatic wood is used indoors. Further springback occurs when untreated compressed wood is exposed to water or high air humidity, but this is not studied here. Because quarter-sawn wood and plain-sawn wood are shaped very differently after applying semi-isostatic compression,[1] both types of specimens were analyzed. It is expected that quarter-sawn specimens that are more compressed in the tangential direction should have larger elastic and delayed elastic springback compared with plain-sawn specimens that are compressed mostly in the radial direction, because this is the case when wood is compressed unidirectionally.[7]

The objective of this study was to quantify how the plastic and elastic strain components vary when wood is

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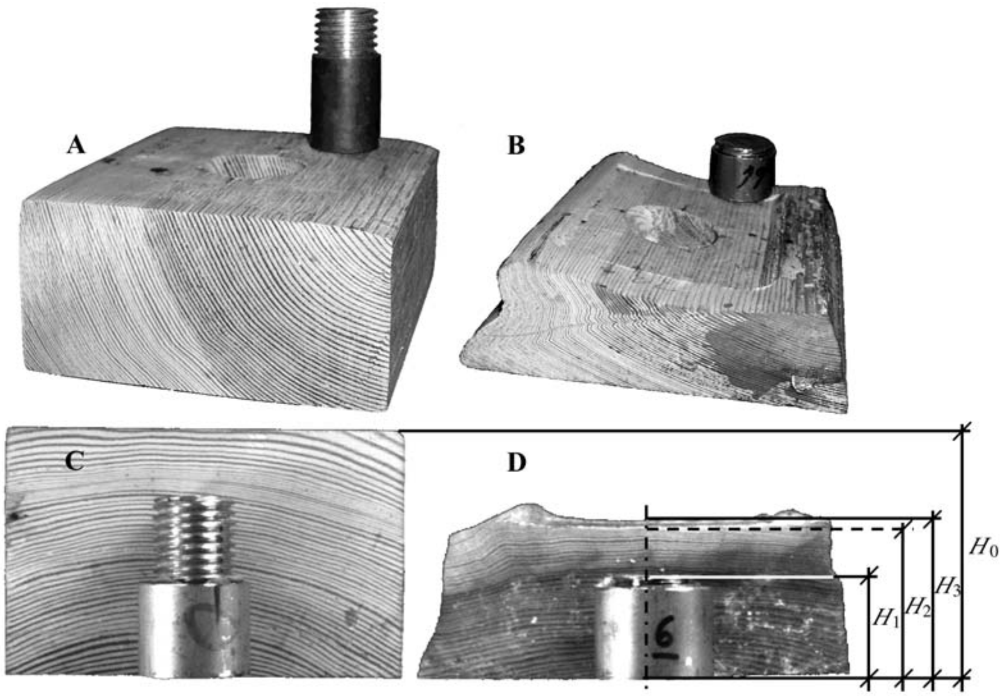

Fig. 1. Specimens and the telescope device before (**A**, **C**) and after (**B**, **D**) compression. In the middle of the specimen a hole was drilled and a telescope device, which consists of a screwed pin that is partly pressed into a tube, was placed into the hole before compression. The quarter-sawn specimens (**A**, **B**) were compressed with their outside faces toward the press table. Plain-sawn specimens (**C**, **D**) were compressed with their inside faces toward the press table. **C** and **D** show the measured heights of the telescope device and the wood used for calculating the strain components

semi-isostatically compressed at different pressure levels and also how the delayed elastic strain component develops over time.

Measuring of elastic strains demands knowledge of the dimensions at maximum pressure inside the press. Because strain gauges or extensometers cannot be used due to high pressure and large deformations, a new method was developed.

Materials and methods

Plain-sawn and quarter-sawn specimens of Scots pine (*Pinus sylvestris*) with a mean moisture content of 8.9% (standard deviation 0.9%) and with dimensions of 100 × 100 × 50 mm (width × length × thickness) were compressed at 5, 15, 50, and 140 MPa. One specimen of each type was compressed at the lower pressures, and three specimens of each type were compressed at 140 MPa. The density of the plain-sawn specimens was 503 (±72) kg/m^3 and that of the quarter-sawn specimens was 508 (±26) kg/m^3. Before compression a hole with diameter 30 mm was drilled in the middle of the specimens in a vertical direction relative to the press table. A telescope device was made with a screwed pin that was partly pressed into a short steel tube and was placed in the drilled hole. A steel plate, covering the hole, was placed on top of the specimen to distribute the pressure in a vertical direction and to prevent the rubber diaphragm from filling the hole. At compression the pin was pushed further into the tube as much as the surrounding wood was compressed perpendicular to the press table. At release of the pressure, the telescope device remains at this position, whereas the wood sprung back (Fig. 1).

The plain-sawn specimens were placed with their inside faces (pith sides) against the press table which oriented the telescope devices in the radial direction (Fig. 1C, D). Quarter-sawn specimens were placed with their outside faces (bark sides) against the press table and the telescope measured the deformation of wood with the annual ring angle between 45° and 90° relative to the press table (Fig. 1A, B).

Specimen thickness (H_0) was measured before compression. Immediately after the release of pressure, the height of the telescope device (H_1), as well as the specimen thickness (H_2), was measured. Specimen thickness was also measured after 5 years (H_3) of indoor storage (Fig. 1D). Moisture content of the wood varied annually between 5% and 9%. Plastic strain (ε_P), elastic strain (ε_E), and the delayed elastic strain (ε_{DE}) were calculated as:

$$\varepsilon_p = \frac{H_0 - H_3}{H_0} \cdot 100\,[\%] \tag{1}$$

$$\varepsilon_E = \frac{H_2 - H_1}{H_0} \cdot 100\,[\%] \tag{2}$$

$$\varepsilon_{DE} = \frac{H_3 - H_2}{H_0} \cdot 100\,[\%] \tag{3}$$

For the measurements a digital calliper was used with an accuracy of 0.03 mm and repeatability of 0.01 mm.

Because the plastic and delayed elastic strain in the axial (longitudinal) direction was negligible, the volume strain at each stage of deformation (n), ε_{Vn}, was calculated as:

$$\varepsilon_{Vn} = \frac{A_0 - A_n}{A_0}\left(n = 1,\ 2,\ 3\right) \tag{4}$$

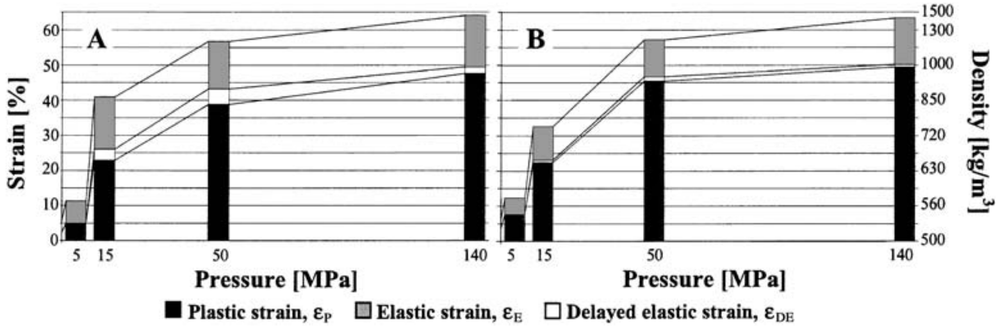

Fig. 2. Components of strain perpendicular to the press table at different pressures for quarter-sawn specimens (**A**) and plain-sawn specimens (**B**). The density that corresponds to the strain is shown to the right

where A_0, A_1, A_2, and A_3 are the cross-sectional areas before compression, under compression, immediately after compression, and after storage, respectively. A_3 was measured through image analysis of cross sections, and A_0 through callipering. It was assumed that all deformation was proportionately similar during the compression, i.e.,

$$A_3/(1-\varepsilon_p) = A_2/[1-(\varepsilon_P+\varepsilon_E)] = A_1/[1-(\varepsilon_P+\varepsilon_E+\varepsilon_{DE})]$$

From this relation, A_1 and A_2 can be calculated.

The density that corresponds to each strain measured perpendicular to the press table (in radial direction when plain-sawn wood is densified, Fig. 1D) is then calculated as:

$$\rho_{dn} = \frac{\rho_0}{1-\varepsilon_{Vn}}(n = 1, 2, 3) \tag{5}$$

where ρ_{dn} is the density of the densified wood and ρ_0 is the original density (rounded to $500\,kg/m^3$).

Results

Figure 2 shows the plastic, elastic, and delayed elastic strain at different pressure levels for quarter-sawn and plain-sawn specimens. The elastic and the delayed elastic strain were higher in quarter-sawn specimens compared with plain-sawn specimens at all four pressure levels. In both types of specimens, the delayed elastic strain was lower when wood was compressed at 140 MPa compared with at 50 MPa when the elastic strain had its maximum. The amount of elastic strain was about the same at the pressures of 15, 50, and 140 MPa in quarter-sawn specimens while it was increasing with pressure in plain-sawn specimens. At 140 MPa, elastic strain was 14.6% and 13.1%, delayed elastic strain was 1.8% and 0.8%, and plastic strain was 47.6% and 49.4% perpendicular to press table for quarter-sawn and plain-sawn specimens, respectively.

At 140 MPa, the wood density almost reaches $1500\,kg/m^3$, i.e., the compact density.[8] Due to the springback, the final density decreased to about $1000\,kg/m^3$. Because the plastic strain was higher in plain-sawn specimens, the density became higher than for quarter-sawn specimens.

Discussion

The method used for measuring elastic strain was simple and worked well. However, the accuracy of the method must be discussed. Elastic strain could only be measured perpendicular to the press table with the telescope device. Elastic strain in other directions was assumed to be proportional to the plastic strain. This assumption is justified by the fact that there is a positive correlation between the modulus of elasticity and some strength properties.[2,9] Callipering the heights of the specimens and the telescope devices at different times may introduce errors, although because strains were large this is of minor importance. In order to ensure that the telescope device was pushed as much as the surrounding wood, a steel plate was placed above the device. As shown by the indentation made by the plate, this tactic influenced the deformation. This could be adjusted for and it is not likely that the degree of plastic or elastic strain was influenced.

In quarter-sawn specimens, the elastic strains at 15, 50, and 140 MPa were about the same, while it increased with pressure in plain-sawn specimens. Elastic strain was also higher in quarter-sawn than in plain-sawn specimens. In quarter-sawn specimens, the elastic strain is attributed to tangentially compressed latewood bands that will act like springs because latewood cells do not readily remain buckled after unloading.[7] The contribution from the latewood to the elastic springback is more pronounced in quarter-sawn specimens than in plain-sawn specimens. In plain-sawn specimens, the latewood bands are compressed radially without buckling. The deformation of plain-sawn specimens is strongly controlled by the rays, which probably are more permanently crushed, compared with the latewood bands in quarter-sawn specimens.

The delayed elastic strain was very small, especially in plain-sawn specimens compressed at 140 MPa, and should not be a problem in long-term indoor use of compressed wood when the climate is relatively stable. The delayed elastic strain at 140 MPa, which was smaller than that at 50 MPa in both types of specimens, can be explained by a more destructed structure at the higher pressure.

It was shown that wood compressed at 140 MPa reached an almost compact structure and that springback was large at the release of pressure. This indicates that applying higher pressure would not increase the plastic strain. To increase the plastic strain component and the final density, the process must be more destructive so that the wood structure collapses and the structure is less prone to spring back elastically. Kollman and Côté[9] showed that wood became more plastic after repeated loading and unloading, probably due to fatigue and creep. Changing the moisture content of the wood at the time of compression could also easily change elastic parameters. Lowering of moisture content will increase the modulus of elasticity[2] and make the cell walls more fragile. A more destructive process may induce large checking and the strength properties may be negatively affected in spite of increased density. Alternatively, chemical modification of the wood can be made to increase density. One possibility is pretreatment of wood with heat or steam to make the hemicelluloses degrade or to change the crystallinity of the wood.[10] The structure can also be chemically cross-linked when it is fully compressed.[11,12]

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