J Wood Sci (2003) 49:298–304
DOI 10.1007/s10086-002-0503-9

ORIGINAL ARTICLE

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# Effect of temperature and compression on the mechanical behavior of steam-treated wood

Received: April 5, 2002 / Accepted: September 26, 2002

**Abstract** The mechanical behavior of steamed spruce wood changes dramatically with compression along the grain, the change being much more moderate perpendicular to the grain. The stiffness decrement due to increased temperature is greatest in the tangential material direction. The stiffness decrement due to compression is greatest along the grain. Compression to 80% compressive strain at 131°C inverts the order of the material directions regarding stiffness, the stiffness being the least along the grain. Plastic strain due to compression is greater at higher temperatures. The compression-induced decrement of stiffness along the grain is greater at higher temperatures, but the off-axis decrement of stiffness is less at higher temperatures.

**Key words** *Picea abies* · Anisotropy · Cellulose microfibrils · Compressive loading · Stiffness modulus

## Introduction

Wood is a rather complex composite of polymeric constituents. Cellulose, hemicelluloses, and lignins display significantly different properties. In an abundance of water, hemicelluloses tend to soften below room temperature, whereas lignins and cellulose remain stiff.[1–5] A widely accepted hypothesis is that the softening of lignins largely dominates the effect of temperature and moisture on the time-dependent mechanical behavior of wood, at least in the range of moisture and temperature applicable to industrial steaming operations.[4,6]

Wood is a highly anisotropic composite. A tree bole is, in coarse terms, cylindrical and displays rotational symmetry with respect to the central axis. The cellulose microfibrils are mainly oriented in the longitudinal direction. Mechanical stiffness is much higher in the direction of the cellulose microfibrils than in the transverse direction. The cellulose is less susceptible to thermal- and moisture-induced softening than the surrounding matrix of hemicellulose and lignin, so increasing the temperature and moisture in general increases mechanical anisotropy.[1–3,7–9]

The stress-strain behavior of cellular materials in general is nonlinear.[10,11] In particular, *radial* and *tangential* compression of wood first displays an apparently linear elastic range, after which strain can be increased without any major increment of stress.[12–17] This “plateau region” is likely due to buckling of cell walls into the cell lumens.[12,13,15,18–21] Once the strain becomes so large that the space in the lumens available for cell wall buckling becomes limited, the compressive stress again starts to increase significantly as a function of increasing compressive strain.[13–17] The short-term mechanical behavior of wood may depend significantly on the degree of hydraulic filling of the lumens.[10,15]

A peculiar effect of repeated radial loading of increasing magnitude has been reported.[14–16] During repeated radial straining, the stress at a specified strain is less than the stress at that strain in a specimen strained for the first time. However, when any strain range is approached for the first time, the stress at any strain is on the same level as for a previously unstrained specimen.

The stress-strain compression behavior of wood in the longitudinal direction has been observed to differ significantly from the stress-strain behavior in transverse direction, with the longitudinal direction showing instability at strain of a few percent. It manifests as a decrease in stress as a function of increasing strain[13] (Kärenlampi et al., unpublished data).

Consisting of amorphous polymers, wood displays time-dependent mechanical behavior under ambient conditions as well as when treated with steam. At least up to 100°C, 50% compressive engineering strain in the radial direction, and straining time of a few seconds, true irrecoverable (plastic) deformation has been found to be small.[15,16] Thus, at least with radial compression, wood appears to behave

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viscoelastically. There is no definite reason to assume that the mechanical response would still be viscoelastic in other material directions or with longer straining times.[22]

Much of the research in wood has so far been technically oriented, and knowledge of the basic mechanical behavior thus is rather inadequate. This study intended to clarify the basic mechanical behavior of steam-treated wood at constant temperature and humidity. Wood was strained uniaxially in any of the three principal material directions: radial, tangential, and longitudinal directions of a trunk. Also off-axis loading between the tangential and longitudinal material directions was attempted. First, the overall stress-strain behavior was investigated in a strain range up to 80% of the logarithmic compressive strain (55% compressive engineering strain). Then, the effect of the loading direction, prior compression, and applied temperature on tangential stiffness was clarified. The magnitude of plastic strain was investigated as well. The relation between plastic strain and the stiffness decrease due to compression are clarified. Finally, the relation between tangential stiffness and dynamic stiffness was addressed.

## Materials and methods

Spruce heartwood specimens with dimensions of 33 × 33 × 9mm and a dry mass of 4.0g (±5%), frozen fresh and then melted in water overnight, were treated with saturated water steam at 101°C or 131°C, held lightly between steel compression platens during steaming. After steaming for 30min experiments were conducted by compressing the specimens in the direction of 9mm thickness, which in turn was prepared to correspond either to the radial, tangential, or longitudinal direction of the trunk. Off-axis specimens also were tested, the loading direction being in between the tangential and the longitudinal material directions.

The stress-strain behavior of the specimens was studied by uniaxial compression at a strain rate of 5%/s following the stress response during the straining. After reaching 80% compressive strain, the strain was recovered under strain control to 10% compressive strain at a rate of 5%/s, after which a tiny load of 50N was applied. Plastic strain was clarified by allowing the strain to recover until no further recovery took place. The effect of 80% compression on the stress-strain behavior of the material was investigated by compressing the specimen another time after strain recovery of 25min.

Young's modulus refers to the change of stress with respect to change of strain under the circumstance of uniaxial stress. The concept "stiffness" is used here to refer to the change of stress with respect to change of strain under the circumstance of uniaxial strain.[23] Tangential stiffness was determined as the ratio of the change of stress to the change of strain within that 0.5% strain interval of any stress-strain curve where the tangential stiffness was greatest but limiting the scanning of stiffness to compressive strains less than 40%. Thus, tangential stiffness refers to the tangent of the stress-strain curve and not to the tangential material direction. A relative stiffness decrement was calculated with the difference in tangential or dynamic modulus after the compression, related to the modulus measured during the first compression. In a few specimens, dynamic stiffness was determined as the ratio of stress amplitude to strain amplitude with a double strain amplitude of 0.5%, applied at 10Hz.

Generally, wood displays a large variation in properties. The present material was produced from battens sawn from a narrow region of a single tree, so there was only a small amount of variation, and the consequences of any particular thermal or mechanical treatment appeared to be repeatable. Some exceptions from this repeatability did appear, and these exceptions are discussed in detail below.

### Overall stress-strain behavior

Engineering stress as a function of logarithmic strain ("true strain") under monotonically increased compressive strain at a rate of 5%/s is shown in Fig. 1. After reaching 80% compressive strain, the strain was released under strain control using the same strain rate. We find that the stress-strain behavior is highly nonlinear in the radial and tangential material directions; there is a wide range of strain where the compressive stress increases only slightly as a function of increasing compressive strain. It is known that stress changes only slightly during elastic buckling, so it appears that this range of strain corresponds to buckling of cell walls. The radial and tangential material directions do not distinguish themselves dramatically from each other; however, at a specified strain the radial material direction displays greater compressive stress at small strains. The compressive strains exceed 5%, and the tangential compressive stress is greater.

With the increase in temperature from 101°C to 131°C, the compressive stress at any particular strain is reduced by approximately 40% (Fig. 1). Otherwise the stress-strain loops appear geometrically independent of temperature, although the transition from the initial linear part to the stress plateau appears to be less clearly pronounced at the higher temperature (Fig. 1).

Figure 2 shows the stress-strain loops of specimens compressed once previously. We find that the greatest compressive stresses achieved at 80% compressive strain are at the same level as they were during the first compression. At smaller compressive strains, the stress at any particular strain is somewhat less than during the first compression cycle; there is one exception in Fig. 2b, where the compressive stress at around 50% compressive strain is greater during the second cycle.

Regarding the longitudinal material direction, we find from Fig. 3 that at the increase in temperature from 101°C to 131°C the compressive stress at any particular strain is decreased by approximately 40%, roughly the same magnitude as in the case of transverse (radial and tangential) loading. However, in the longitudinal material direction, one-time compression dramatically changes further me-

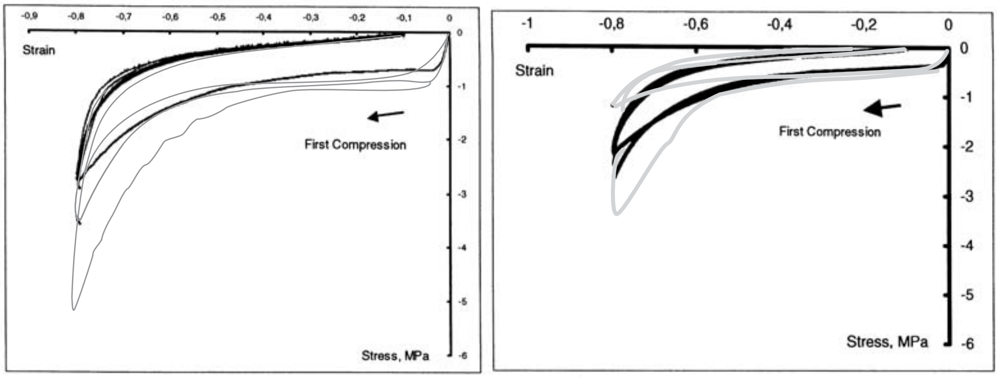

**Fig. 1.** Overall stress-strain behavior of radial (*black lines*) and tangential (*gray lines*) specimens during first-time compression. **a** Temperature 101°C. **b** Temperature 131°C

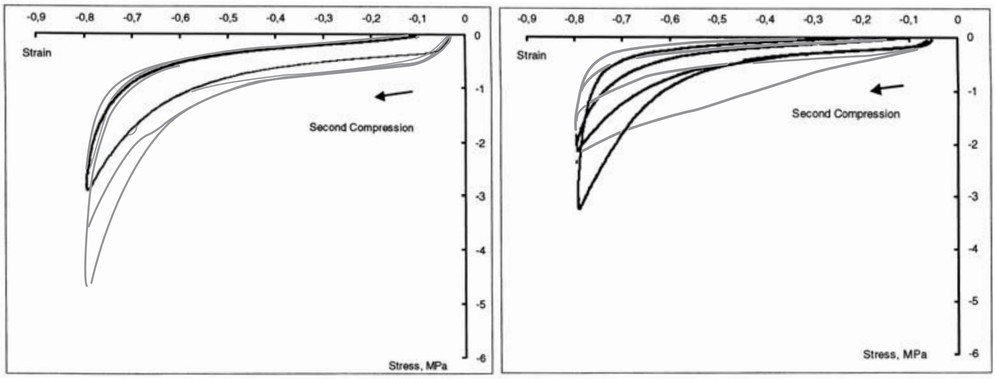

**Fig. 2.** Overall stress-strain behavior of radial (*black lines*) and tangential (*gray lines*) specimens during a second compression. **a** Temperature 101°C. **b** Temperature 131°C

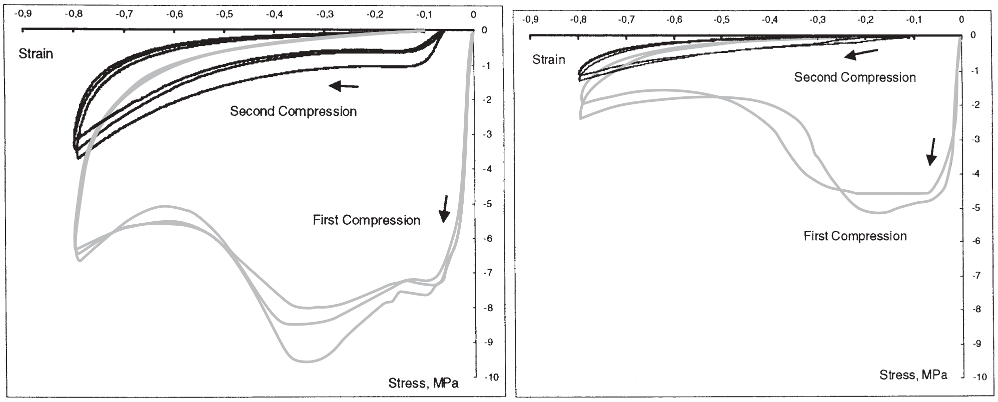

**Fig. 3.** Overall stress-strain behavior of longitudinal specimens during a first and a second compression. **a** Temperature 101°C. **b** Temperature 131°C

chanical behavior, the stress response to any particular strain during the second compression cycle being a small fraction of the stress that appeared during the first cycle (Fig. 3).

At 101°C, specimens compressed the second time in the longitudinal direction (Fig. 3a) have a stress-strain curve that resembles the stress-strain curve of specimens loaded in the transverse (radial and tangential) material direction (Figs. 1a, 2a): After an initial increase in compressive stress as a function of increased compressive strain, a plateau region appears where stress changes only slightly along with strain, the change of stress again accelerating at compressive strains exceeding 40%.

At 131°C, specimens compressed the second time in the longitudinal direction display another kind of behavior (Fig. 3b). The stress response to strain is apparently linear, lacking instability as well as plateau regions, and is rather small. Somewhat surprisingly, specimens compressed in the longitudinal direction for the second time (Fig. 3b) display compressive stresses that are less than the compressive stresses within specimens compressed for the second time in the transverse direction (Fig. 2b).

In the case of off-axis straining applied between the longitudinal and tangential material directions, we find from Fig. 4 that with the increase in temperature from 101°C to 131°C the compressive stress at any particular strain de-

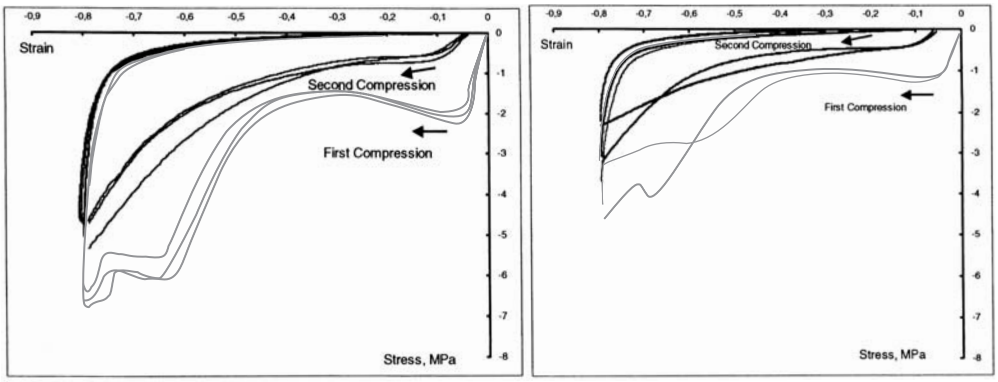

**Fig. 4.** Overall stress-strain behavior of off-axis specimens during a first and second compression. **a** Temperature 101°C. **b** Temperature 131°C

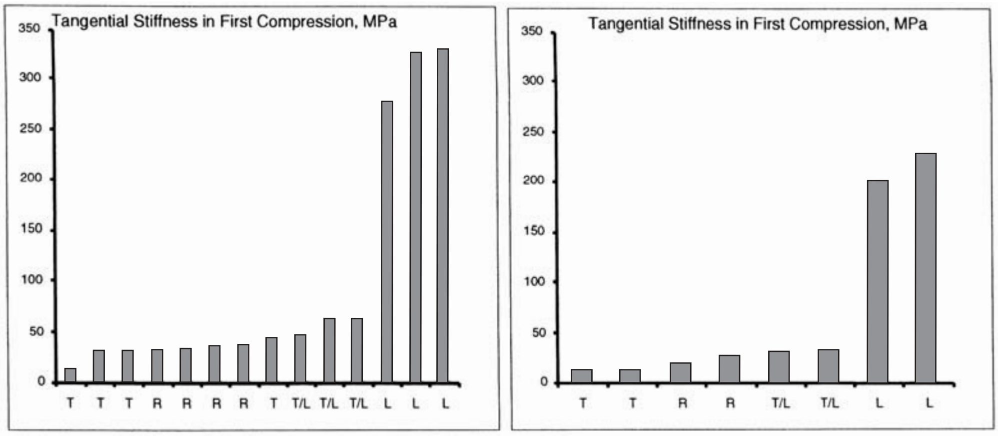

**Fig. 5.** Tangential stiffness during a first compression. **a** Temperature 101°C. **b** Temperature 131°C. *T*, tangential direction; *R*, radial direction; *T/L*, off-axis specimens; *L*, longitudinal direction

creases approximately 40%, roughly the same magnitude as in the case of transverse (radial and tangential) and longitudinal loading. At 101°C, two distinct instabilities are seen along with first-time compression, taking place in the vicinity of 5% and 65% compressive strain. The instabilities are visible also at 131°C, even though the material here appears somewhat less brittle. One-time off-axis compression (Fig. 4) changes further mechanical behavior clearly more than transverse compression (Figs. 1, 2) but significantly less than longitudinal compression (Fig. 3).

At both testing temperatures, off-axis specimens compressed the second time (Fig. 4) have a stress-strain curve that resembles the stress-strain curve of specimens loaded in the transverse direction (Figs. 1, 2): After an initial increment of compressive stress as a function of increased compressive strain, a plateau region appears where stress changes only slightly along with strain, the change of stress again accelerating at compressive strains exceeding 40%. It is worth noting that at 131°C the stress response to any given strain is greater in once-compressed off-axis specimens (Fig. 4b) than in once-compressed longitudinal specimens (Fig. 3b).

## Tangential stiffness

The tangential stiffness is shown in Fig. 5, with the specimens tested at any temperature. They are arranged in the order of increasing stiffness. We find that at both testing temperatures the order of stiffness between the material directions is the same: The tangential material direction is least stiff followed by the radial and longitudinal material directions. The off-axis specimens were stiffer than the transverse specimens but much less stiff than the longitudinal specimens. The relative decrement of stiffness due to the temperature increase from 101°C to 131°C varies between 30% and 50%, being greatest in the tangential material direction.

The tangent modulus of specimens compressed for the second time is shown in Fig. 6. We find from Fig. 6a that compression at 101°C significantly reduces mechanical anisotropy. In most cases (but not all) the longitudinal specimens are still stiffer than the specimens loaded in the transverse direction. However, the difference in stiffness is much less than during the first compression.

At 131°C, the order of the principal material directions regarding stiffness becomes inverted as a consequence of compression to 80% of compressive strain. The longitudinal material direction, which is stiffest during the first compression (Fig. 5b), is the least stiff during the second compression (Fig. 6b). The tangential material direction, which is the least stiff during the first compression (Fig. 5b) is the stiffest principal material direction during the second compression (Fig. 6b), where, however, off-axis specimens are stiffer than any of the specimens tested in the principal material directions.

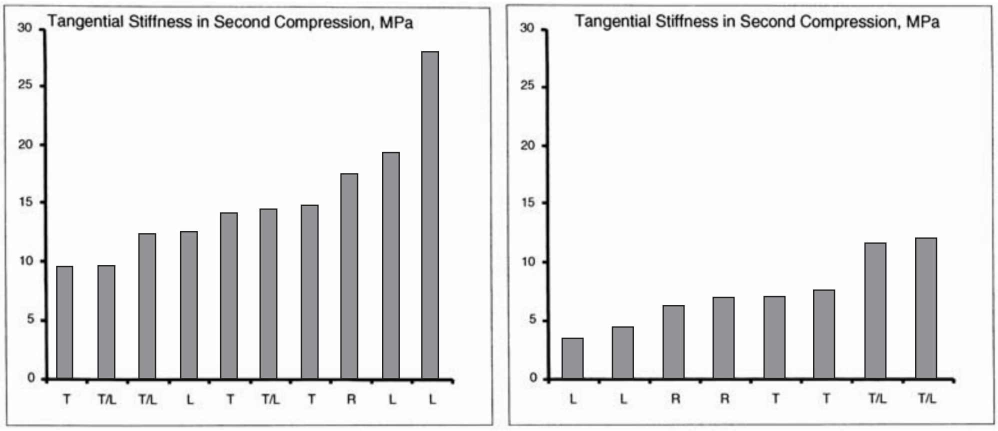

**Fig. 6.** Tangential stiffness during a second compression. **a** Temperature 101°C. **b** Temperature 131°C

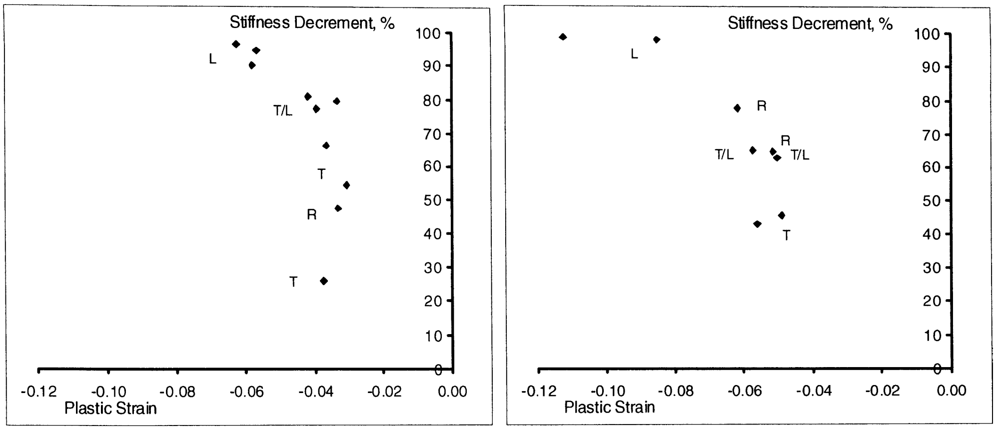

**Fig. 7.** Tangential stiffness decrement as a function of plastic strain, both being due to compression to 80% compressive strain. **a** Temperature 101°C. **b** Temperature 131°C

When comparing the stiffness of specimens compressed the second time between the two temperatures, one finds that the off-axis specimens treated at 131°C differ only negligibly in stiffness from the specimens treated at 101°C. The longitudinal specimens treated at 131°C, however, display only 20% of the stiffness of the specimens treated at 101°C. The second compression of transverse (radial and tangential) specimens treated at 131°C show stiffness that is 40%–60% of the stiffness of the specimens treated at 101°C.

## Plastic strain and stiffness decrement due to compression

The relative stiffness decrement as a function of plastic strain – both the stiffness decrement and the plastic strain being due to one compression up to 80% compressive strain – are shown in Fig. 7. We find that the compressive plastic strain is greater in the case of specimens treated at 131°C, the compressive plastic strains being 3%–6% at 101°C and 5%–11% at 131°C.

In the longitudinal material direction, both stiffness decrease and compressive plastic strain were greater at the higher temperature. At 101°C the stiffness decrease was 90%–96%, and it was 98% at 131°C. The compressive plastic strains were 6% and 9%–11%, respectively.

The off-axis specimens display somewhat greater plastic strain when compressed at 131°C, but the stiffness decrease is less at the higher temperature. The off-axis stiffness decrease was 77%–81% at 101°C and 62%–65% at 131°C.

In the transverse (radial and tangential) loading directions, the compressive plastic strain was somewhat below 4% at 101°C and about 5% at 131°C. The stiffness decrease due to transverse loading displays significant scatter in both material directions (Fig. 7).

## Dynamic stiffness

For a few specimens, not only tangential stiffness but also dynamic stiffness was determined. The relation of dynamic stiffness and tangential stiffness is shown in Fig. 8. We find that the stiffness measures agree with each other. In the case of virgin specimens (Fig. 8a) the dynamic stiffness ranks the same way as the tangential stiffness, which also was shown in Fig. 5. The peculiarity shown in Fig. 6b—the order of material directions regarding stiffness becoming inverted owing to compression at 131°C—is visible also in Fig. 8b. In the case of specimens compressed once at 131°C, the off-axis specimens are stiffer than any of the specimens treated in the principal material directions, also regarding dynamic stiffness (Fig. 8b).

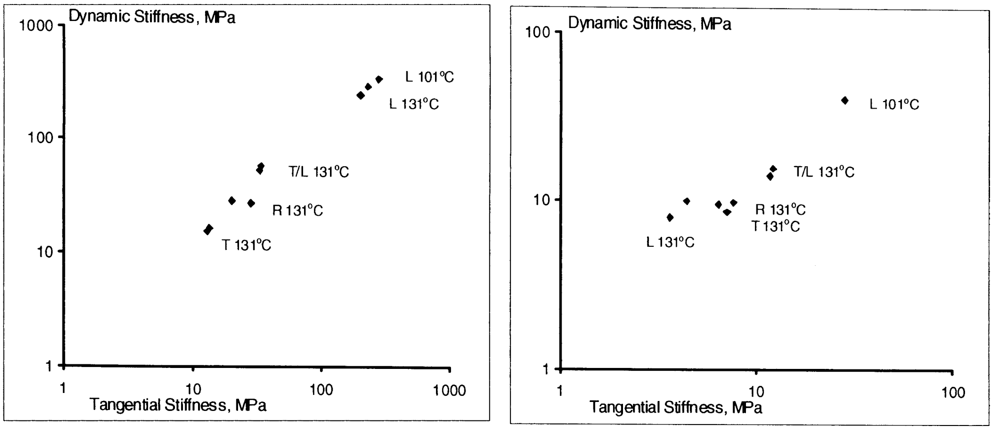

**Fig. 8.** Dynamic stiffness as a function of tangential stiffness. **a** Virgin specimens. **b** Once-compressed specimens

## Discussion

The mechanical behavior of steamed spruce wood changed dramatically when compressed along the grain, the change being much more moderate perpendicular to the grain. The decrease in virgin specimen stiffness due to increased temperature was greatest in the tangential material direction. The stiffness decrease due to compression was greatest along the grain. Compression to 80% compressive strain at 131°C inverted the order of the material directions regarding stiffness, the stiffness being least along the grain. Plastic strain due to compression is greater at the higher temperature. The decrease in stiffness along the grain was greater at the higher temperature, but the off-axis decrement of stiffness is less at the higher temperature.

The reason for the stiffness decrease due to increased temperature being greatest in the tangential material direction appears obvious. The cellulose microfibrils are mainly oriented in the longitudinal direction. The cellulose is less susceptible to thermal- and moisture-induced softening than the surrounding matrix of hemicellulose and lignin, so increasing the temperature and moisture in general increases mechanical anisotropy.[1–3,7–9] The softening due to the temperature obviously is most pronounced in the tangential material direction, as the alignment of the microfibrils deviates from the longitudinal direction more in the radial cell walls than in the tangential cell walls.[24–28] During compression in the tangential material direction, no visible damage (e.g., cracks, disintegration) was observed.

The reason for the mechanical behavior changing dramatically when wood is compressed along the grain also appears obvious. Eighty percent compressive strain resulted in major macroscopic damage to the specimens, the specimens still being in one piece but significantly disintegrated. The same 80% compressive strain applied predominantly along the microfibrils significantly changes the spatial arrangement of these load-carrying elements. It appears that such a new configuration may be even more compliant than the configuration that results from compression in the transverse direction (Figs. 6b, 8b). This result is astonishing but obviously correct, the same result being achieved with different specimens as well as with two independent methods to measure stiffness (Figs. 6b, 8b). The greater the softening of the amorphous matrix, the more pronounced is the change in the microfibrillar configuration due to longitudinal compression (Figs. 7, 8b).

The third phenomenon requiring an explanation is the peculiar behavior of off-axis specimens. The compressive off-axis plastic strain is greater at 131°C than at 101°C, but the relative decrease in stiffness due to compression is less at the higher temperature (Fig. 7). During a second compression at 131°C the off-axis specimens are the stiffest (Fig. 6b). We are unable to propose any definite explanation for these observations, but we hypothesize that the off-axis specimens deform through sliding shear deformation, without significant realignment of microfibrils. The smaller relative stiffness decrease at the higher temperature along with somewhat greater plastic strain may be associated with the decrease in the free volume at the molecular level.[29–33]

As the specimens used in the present investigation were rather uniform regarding material properties, the results of any thermal and mechanical treatment appear to be repeatable. There is one exception. The stiffness decrease due to compresson at 101°C displays significant scatter in the tangential and radial material directions (Fig. 7a). The results appear to be repeatable at 131°C, where the stiffness decrease is significantly greater in the radial material direction than in the tangential material direction (Fig. 7b). Figure 8 confirms the repeatability of stiffness measurements at 131°C, whereas the reason for the scatter at 101°C remains unknown.

**Acknowledgments** The authors are obliged to Tomas Björkqvist for commenting on the manuscript and to the National Technology Agency of Finland for financing.

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