ELSEVIER

International Journal of Fatigue 24 (2002) 1235–1242

International Journal of Fatigue

www.elsevier.com/locate/ijfatigue

Off-axis fatigue loading of steamed wood

Petri P. Kärenlampi *, Pekka Tynjälä, Pasi Ström

University of Joensuu, Faculty of Forestry, P.O. Box 111, FIN-80101 Joensuu, Finland

Received 29 November 2001; received in revised form 9 April 2002; accepted 11 April 2002

Abstract

Cyclical off-axis compression was applied to steamed Spruce wood in uniaxial strain under stress control. The strain level is a step function of stress level and test duration. Energy dissipation is negligible when the stress amplitude in relation to the greatest compressive stress is small, regardless of the applied stress level. There is a significant energy dissipation when the stress amplitude in relation to greatest applied compressive stress is large, regardless of stress level. Dynamic stiffness appearing during the dynamic loading strongly depends on applied stress and stress amplitude. Small-strain stiffness deteriorated during any dynamic loading experiment, apparently depending on the greatest compressive strain appearing during loading. Also plastic strain appears to depend on the strain appearing during loading. Thus stiffness decrement and plastic strain do not appear to reflect the variety of material reactions to fatigue treatments.

Keywords: Strain accumulation; Energy dissipation; Dynamic compliance; Damage; *Picea abies*

1. Introduction

Wood is an anisotropic composite of polymeric constituents. It is widely available, and used for a variety of purposes, including constructions, joinery, pulp and paper, as well as for dissolving to chemicals. A variety of such industries apply steam treatment during processing, as for example, in the moisture and temperature softening of joinery components, and the steaming of wood in the context of mechanical and chemical pulping. The mechanical properties of steam-treated wood are of interest in all those industries which combine steam treatment with mechanical action. Mechanical pulping processes consist essentially of fatigue treatments, intending to loosen the internal structure of steam-treated wood.

In the course of dynamic loading of a time-dependent material, a part of the applied energy becomes dissipated, instead of stored as recoverable strain energy. In the case of strains and stresses of regular shape forms, the dissipating energy percentage may be characterized in terms of a mechanical shift factor, or 'loss coefficient'. In the case of amorphous polymers, the energy dissipation reaches its maximum in the vicinity of a 'glass transition region'. Such a transition region in general is defined in time–temperature space, shifting in the time domain as a function temperature, and vice versa [1–5]. Short time (or high loading frequency) corresponds to low temperature, and low frequency corresponds to high temperature.

Wood is a rather complex composite of polymeric constituents. The different constituents, cellulose, hemicelluloses and lignins, display significantly different properties. At high moisture contents, hemicelluloses tend to soften below room temperature, where lignins and cellulose remain stiff [6–8,5,9]. A widely accepted hypothesis is that the softening of lignins largely dominates the effect of temperature and moisture on time-dependent mechanical behaviour of wood, at least in the range of moisture and temperature applicable in industrial steaming operations [5,10].

In the case of cyclic loading of wood, using small stress amplitudes, the dissipating proportion of applied energy has been observed to decrease as the loading frequency is increased at low temperatures, and to increase with an increase in loading frequency at high temperatures [5]. Within small-amplitude loading at 10 Hz frequency, the maximum energy dissipation has been observed to occur in the vicinity of 100°C, both along

* Corresponding author. Tel.: +358-13-251-4009; fax: +358-13-251-3590..

E-mail address: petri.karenlampi@joensuu.fi (P.P. Kärenlampi).

0142-1123/02/$ - see front matter
PII: S0142-1123(02)00039-7

the grain and in the transverse direction. The transition region temperature increases with increasing loading frequency, and decreases with decreasing loading frequency [5,11,12].

Wood is a highly anisotropic composite. A tree trunk 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 directions. The cellulose is less susceptible to thermal and moisture-induced softening than the surrounding matrix of hemicellulose and lignin, and thus increasing temperature and moisture in general increase mechanical anisotropy [6–8,13,14, cf. 15].

The stress–strain behaviour of cellular materials in general is non-linear [16,17]. 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 [18–23]. This 'plateau region' is likely to be due to buckling of cell walls into the cell lumens [24, 18, 25, 19, 21, cf. 26, 27]. 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 significantly increase as a function of increasing compressive strain [19–23]. Short-time mechanical behaviour of wood may significantly depend on the degree of hydraulic filling of the lumens [16,21].

The stress–strain compression behaviour of wood in the longitudinal direction has been observed to differ significantly from the stress–strain behaviour in the transverse directions, the longitudinal direction showing instabilities at strains of a few per cent, manifested as decrement of stress as a function of increasing strain [19,28]. Longitudinal instability appears to depend not only on stress but also on loading time, as well as the number of applied loading cycles [29,30].

As wood consist of amorphous polymers, it displays time-dependent mechanical behaviour. However, at least up to 100°C, after a 50% compressive engineering strain in the radial direction, and a straining time of a few seconds, the true irrecoverable (plastic) deformation in wood has been found to be small [21,22]. Thus, at least in radial compression, wood appears to behave viscoelastically. However, there is no definite reason to assume that the mechanical response would still be viscoelastic in other material directions and with longer straining times [cf. 31, 28, 32].

In this paper, we will investigate the dynamic mechanical behaviour of Spruce wood, steam-treated at 101°C. In particular, the specimens will be subjected to compressive off-axis fatigue loading in unidirectional strain. Firstly, we will describe the experimental arrangements, and then secondly, we will report the evolution of compressive strain, the course of cyclical compressive loading, and address the energy dissipation during such loading. The evolution of strain amplitude and dynamic stiffness will be reported, the stress amplitude being held constant within any test. Finally, the effect of process variables on the irrecoverable strain and stiffness decrement will be reported.

2. Materials and methods

Spruce heartwood specimens of dimensions 33 mm×33 mm×9 mm and of dry mass 4.0 g (±5%), frozen as fresh and then melted in water overnight, were treated with saturated water steam at 101°C. After steaming for 30 min, experiments were conducted by compressing the specimens in uniaxial strain in the 9 mm thickness direction, which in turn was prepared in order to correspond to half way between the tangential and longitudinal material directions. Dynamic stiffness was determined before and after any experiment as the ratio of stress amplitude to strain amplitude, measured from dynamic straining of 0.5% double amplitude, applied at 10 Hz cycle frequency.

A previous investigation [33] has shown the stress–strain behaviour shown in Fig. 1, for specimens similar to those used in this investigation. Along with monotonic straining at rate of 5%/s, two distinct instabilities have been found, such instabilities roughly corresponding to 5 and 65% of compressive strain. Compressing once to 80% compressive strain has significantly changed the mechanical behaviour as shown in Fig. 1.

All dynamic test were carried out by applying a sinusoidal stress of constant set point and amplitude. Use was made of the information in Fig. 1 in the selection of the applied stress scale. Half of the tests were conducted with a largest compressive stress of 1.7 MPa, which is somewhat less than the stress inducing the first instability in Fig. 1. The other half of the tests were conduc-

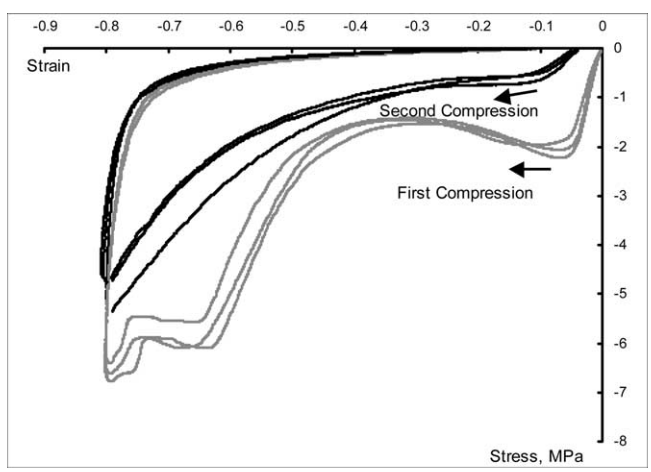


Fig. 1. Stress–strain behaviour of off-axis specimens in first-time and second-time compression.

ted using a compressive stress maximum of 5.0 MPa, i.e. three times the stress used in the first half of the experiments.

Two levels of relative stress amplitude were used. The stress amplitude in relation to the greatest applied compressive stress was taken as either 15 or 45%. Thus the double stress amplitude was either 30 or 90%. In other words, either 30 or 90% of the applied compressive stress was released within any loading cycle. Considering the applied compressive peak stresses of 1.7 and 5.0 MPa, the double stress amplitudes were thus 0.5, 1.5 or 4.5 MPa.

The dynamic testing program is shown in Table 1. Table 1 also reports the amount of mechanical work applied to any specimen, as well as the amount of energy dissipated within any test; energy which did not recover within release of compressive strain was considered as dissipated.

3. Evolution of strain

The evolution of strain level within any test is shown in Figs. 2a and b. These figures display the greatest compressive (logarithmic) strain detected within any loading cycle. We find that the strain level in general is a function of stress level. Compressive strain levels induced by loading up to 5 MPa of compressive stress (Fig. 2b) are greater than strain levels induced by compressive stresses up to 1.7 MPa (Fig. 2a).

Stresses up to 1.7 MPa applied at 10 Hz loading frequency do not induce compressive strains $>20\%$, not even in a test with 553 J energy application (Fig. 2a). Loading at 1 Hz frequency induces an instability of strain: the compressive strain ramps abruptly from 20 to 50%. In the case of 90% relative double strain amplitude, the instability takes place in the vicinity of 100 J energy application. In the case of 30% relative double stress amplitude, the instability takes place at energy application of 10–65 J.

Energy application per loading cycle is smaller at lower stress amplitudes. Thus at 1 Hz loading frequency, the duration of any test at a specified energy application level is longer the smaller the stress amplitude. Specimens loaded with 30% double stress amplitude experienced the instability of strain at test durations of 30–470 s, which corresponded to the same number of loading cycles (Fig. 2a). Specimens loaded with 90% double stress amplitude experienced the instability of strain at test durations of 80–170 s, which also corresponded to the same number of loading cycles (Fig. 2a). The latter range of durations is slightly more than the total duration of tests run with 90% relative stress amplitude at 10 Hz (Table 1).

Specimens loaded up to 5 MPa of compressive stress experience compressive strains already exceeding the unstable range during the first loading cycle (Fig. 2b).

4. Energy dissipation

The proportion of applied energy not recovered within three consecutive loading cycles is shown in Fig. 3. We find that instability of strain induces a peak in the energy dissipation data (Fig. 3a). However, there is no dramatic difference in the energy dissipation rate before and after the instability of strain.

In the case of loading up to 5 MPa of compressive

Table 1
The dynamic loading program

Greatest applied compressive stress (MPa)	Double stress amplitude (MPa)	Loading frequency (Hz)	Number of cycles	Applied energy(J)	Dissipated energy (J)
1.7	0.5	1	600	103	10
1.7	0.5	1	1000	164	13
1.7	0.5	1	1800	277	22
1.7	1.5	1	200	364	192
1.7	1.5	1	750	1000	463
1.7	1.5	10	600	195	76
1.7	1.5	10	820	553	246
1.7	1.5	10	1000	299	106
5.0	1.5	1	500	142	23
5.0	1.5	1	1000	273	23
5.0	1.5	1	1100	289	25
5.0	1.5	10	1000	278	25
5.0	4.5	1	130	203	90
5.0	4.5	1	150	322	129
5.0	4.5	10	250	386	165
5.0	4.5	10	350	396	161

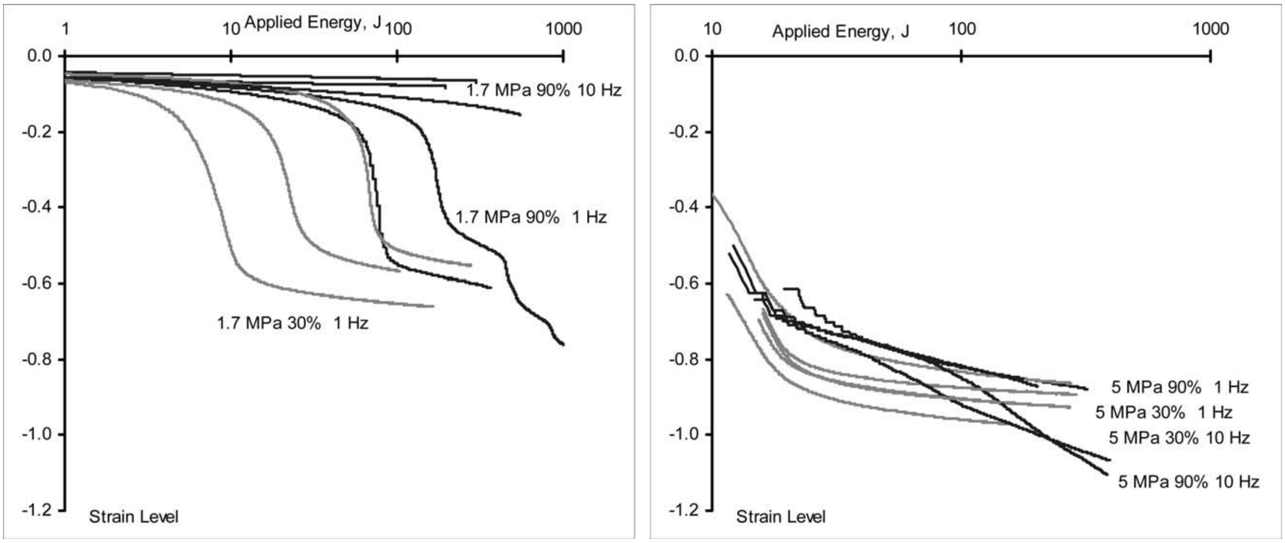


Fig. 2. Strain level as a function of applied energy in dynamic loading up to 1.7 MPa compressive stress (a, left) and up to 5 MPa compressive stress (b, right). Curves are labelled according to greatest applied compressive stress level, relative double stress amplitude, and loading frequency.

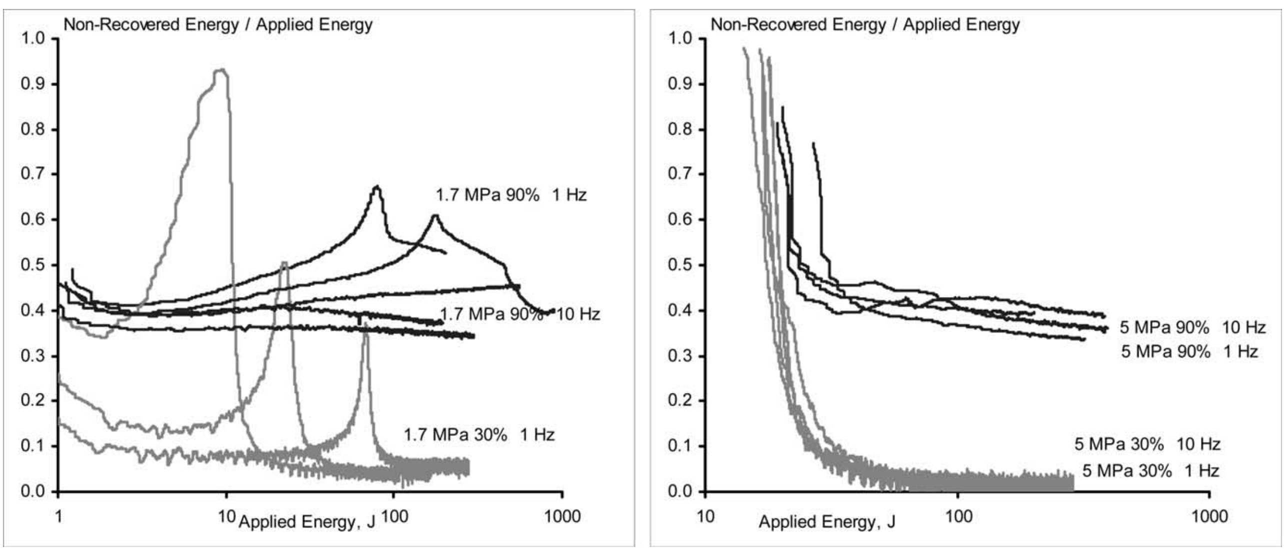


Fig. 3. Proportion of dissipated energy as a function of applied energy in dynamic loading up to 1.7 MPa compressive stress (a, left) and up to 5 MPa compressive stress (b, right). Curves are labelled according to greatest applied compressive stress level, relative double amplitude of stress, and loading frequency.

stress, a large proportion of the applied energy does not recover during the first loading cycles while the compressive strain level significantly changes (Fig. 3b). Then the strain level stabilizes (Fig. 2b), and the energy dissipation level stabilizes as well (Fig. 3b).

We find that the energy dissipation significantly depends on the applied relative stress amplitude. At 90% relative double stress amplitude, 40–50% of the applied energy dissipates, whereas at 30% relative double stress amplitude the proportion of dissipating energy is rather small (Figs. 3a and b). Surprisingly, the energy dissipation level appears independent of the applied stress level, depending only on the applied relative stress amplitude. Neither does the energy dissipation depend on the applied loading frequency.

5. Strain amplitude

At a specified loading frequency, the strain rate becomes mostly determined by strain amplitude. In the present experiments, under stress control, the strain amplitude depends on stress level, stress amplitude, loading frequency, and material properties.

We find from Fig. 4a that at compressive stress levels up to 1.7 MPa, the strain amplitude decreases along with

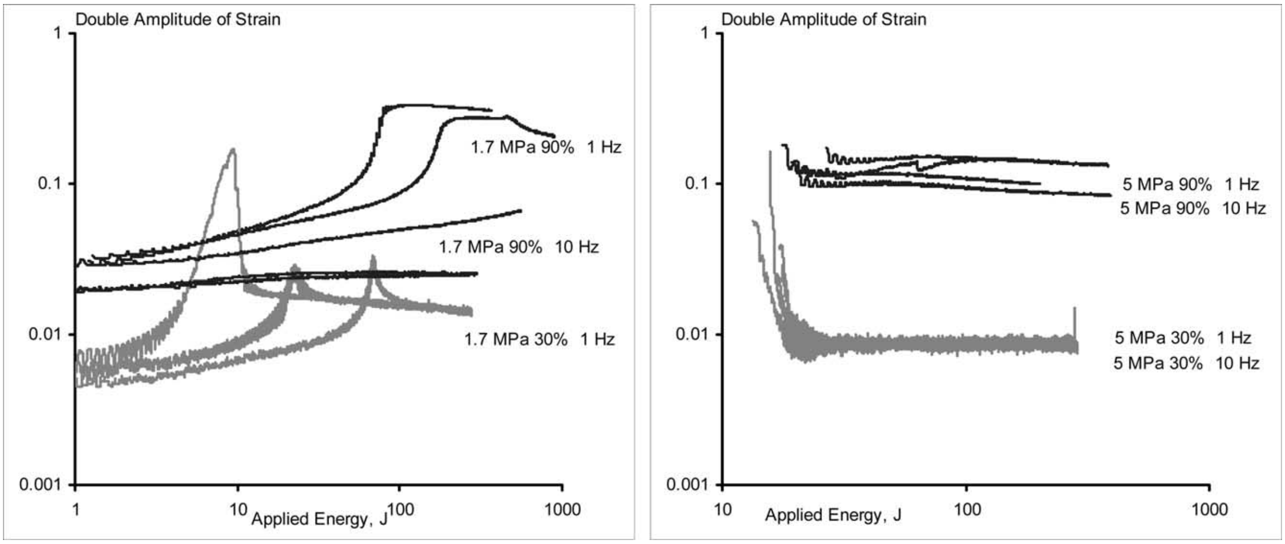


Fig. 4. Double strain amplitude as a function of applied energy in dynamic loading up to 1.7 MPa compressive stress (a, left) and up to 5 MPa compressive stress (b, right). Curves are labelled according to greatest applied compressive stress level, relative double amplitude of stress, and loading frequency.

increasing loading frequency. At compressive stresses up to 5 MPa the strain amplitude is rather insensitive to loading frequency. Within any level of the greatest applied compressive stress, the strain amplitude increases with increasing stress amplitude. However, at 5 MPa applied compressive stress level, the strain amplitude induced by 30% relative double stress amplitude is not greater than the strain amplitude induced by 30% of 1.7 MPa. Within the 5 MPa stress experiments, the strain amplitude induced by 90% relative double stress amplitude is an order of magnitude greater than the strain amplitude induced by 30% double stress amplitude.

Fig. 4a shows a peak in strain amplitude by the occurrence of a instability of strain. Fig. 4b shows initial decrement of strain amplitude at the 30% double stress amplitude while the strain level evolves (cf. Fig. 2b).

We find from Fig. 4a, that along with energy application, the strain amplitude increases while instability is approached. This obviously corresponds to deterioration of stiffness. After the occurrence of instability, the strain amplitude decreases along with energy application, corresponding to increasing stiffness. Fig. 4b does not show any significant systematic evolution of strain amplitude, despite the initial decrement at 30% relative double stress amplitude.

It is worth noting that the strain level is greater in the case of experiments with 5 MPa compressive stress, in comparison to experiments with 1.7 MPa compressive stress (Fig. 2). Thus a specified strain amplitude in Fig. 4b corresponds to a somewhat smaller displacement amplitude than in Fig. 4a.

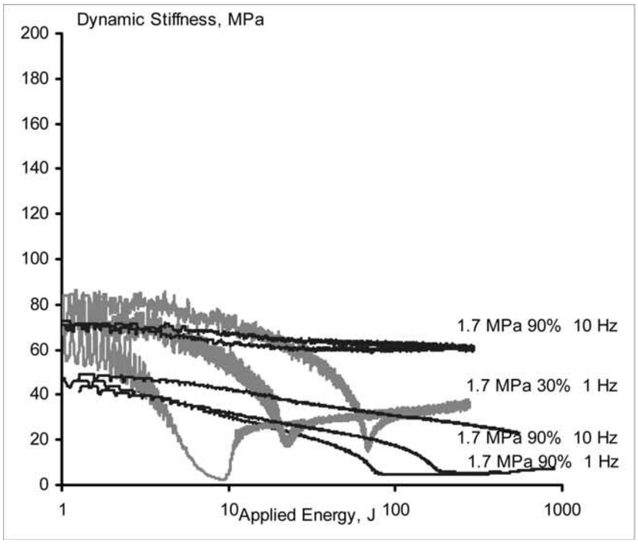
6. Dynamic stiffness

For an applied compressive stress of 1.7 MPa, the dynamic stiffness decreases along with energy application while instability is approached (Fig. 5a). After instability, the stiffness increases with further energy application. The changes in stiffness along with energy application are more pronounced with 30% relative double stress amplitude. At 1 Hz loading frequency, the stiffness of a virgin specimen is greater at 30% double stress amplitude than at 90% amplitude. At 90% double stress amplitude, the stiffness is the higher the greater the loading frequency. However, one of the specimens loaded at 10 Hz is almost as compliant as the specimens loaded at 1 Hz.

At an applied compressive stress of 5 MPa (Fig. 5b), the dynamic stiffness strongly depends on stress amplitude, being with 30% relative double stress amplitude about five times the stiffness which appears with 90% double stress amplitude, which in turn approximately equals the range of stiffnesses appearing in Fig. 5a. The stiffnesses with a 5 MPa stress level do not strongly depend on loading frequency (Fig. 5b). With 90% amplitude, the stiffness slightly increases along with energy application.

7. Deterioration of small-strain stiffness

Dynamic small-strain stiffness deteriorated due to the compressive loading. Fig. 6 shows the relative decrement of stiffness as a function of the greatest applied



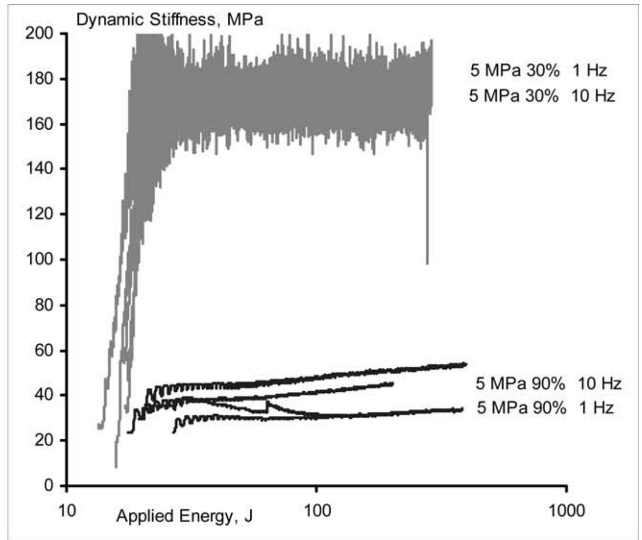


Fig. 5. Dynamic stiffness as a function of applied energy in dynamic loading up to 1.7 MPa compressive stress (a, left) and up to 5 MPa compressive stress (b, right). Curves are labelled according to greatest applied compressive stress level, relative double amplitude of stress, and loading frequency.

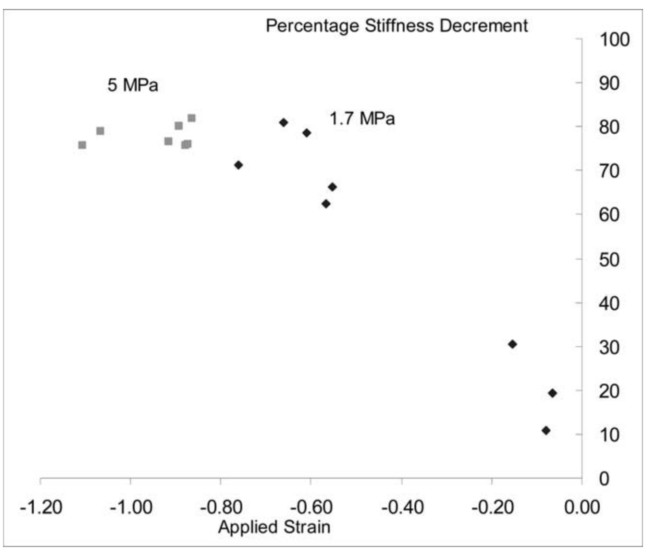


Fig. 6. Decrement of dynamic stiffness as a function of greatest applied compressive strain.

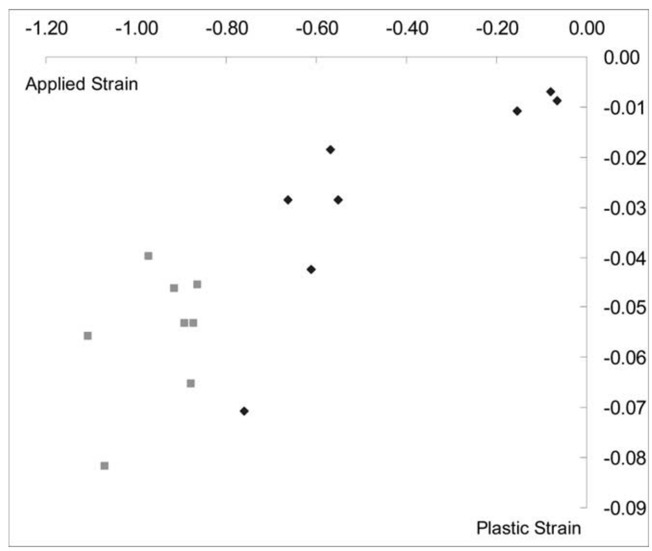


Fig. 7. Plastic strain as a function of greatest applied compressive strain.

compressive strain. We find that the relative stiffness decrement ranks according to the greatest applied compressive strain. However, the stiffness decrement is in the order of 80% in all the cases where the compressive strain has reached 80%. As a consequence, the stiffness decrement is in the vicinity of 80% in all the cases where compressive stresses up to 5 MPa have been applied (Figs. 2 and 6).

8. Plastic strain

Plastic strain accumulated due to the compressive loading. Fig. 7 shows the plastic strain as a function of the greatest applied compressive strain. The amount of compressive plastic strain appears to increase with increasing applied compressive strain. As a consequence, the compressive plastic strain in general is the greatest where compressive stresses up to 5 MPa have been applied (Figs. 2 and 7).

Since both the plastic strain and the stiffness deterioration appear to depend on the applied strain level, there is likely to be a relationship between plastic strain and stiffness decrement. Fig. 8 shows that this is the case. In all the cases where compressive plastic strain exceeds 4%, the decrement of small-strain stiffness is in the order of 80%.

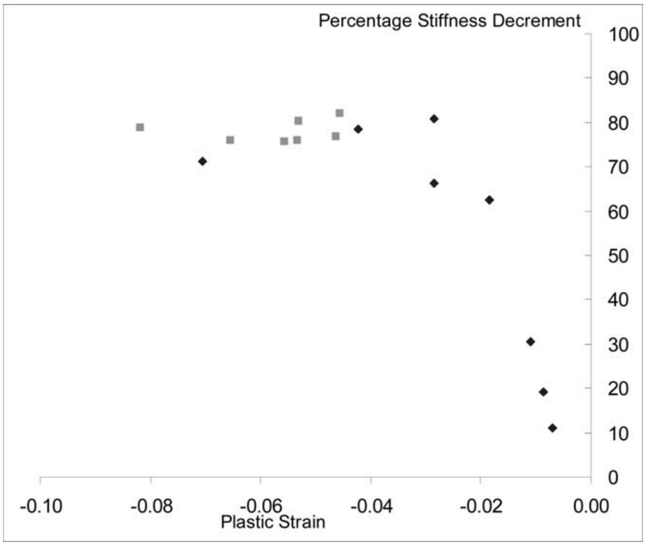


Fig. 8. Decrement of dynamic stiffness as a function of plastic strain.

9. Discussion

Cyclical off-axis compression was applied to steamed Spruce wood in uniaxial strain under stress control. The strain level was a step function of stress level and test duration. Energy dissipation was negligible when the stress amplitude, in relation to the greatest compressive strain, is small, regardless of the applied stress level. There was a significant energy dissipation when the stress amplitude in relation to greatest applied compressive stress is large, regardless of stress level. Dynamic stiffness appearing during the dynamic loading was strongly dependent on applied stress and stress amplitude. Small-strain stiffness deteriorated during any dynamic loading experiment, apparently depending on the greatest compressive strain appearing during loading. Also plastic strain appears to depend on the strain appearing during loading.

Previously, instabilities have been observed in the longitudinal compression of wood, at strain levels of a few per cent [19,28]. Such instabilities are assumed to be a consequence of re-arrangement of fibrillar alignment due to the applied load. Recently, compressive strain levels exceeding 10–20%, but being $<$100%, have been found to be unstable in the longitudinal loading of steam-treated wood [34]. Fig. 2a demonstrates an instability of off-axis compressive strains between 20 and 50%. These instabilities, observed in different kinds of experiments, may be related. However, off-axis loading may induce a more uniform sliding shear deformation than longitudinal loading.

Energy dissipation is negligible when the stress amplitude in relation to the greatest compressive strain is small, regardless of the applied stress level (Fig. 3). There is a significant energy dissipation when the stress amplitude in relation to greatest applied compressive stress is large, regardless of stress level. The authors do not have any straightforward explanation for these observations. The smaller relative stress amplitudes correspond to smaller strain amplitudes (Fig. 4). It is hypothesized that such small strain amplitudes cover an almost linear section of the stress–strain curve, and thus the behaviour is nearly elastic.

Dynamic stiffness appearing during the dynamic loading strongly depends on applied stress and stress amplitude. In particular, the dynamic stiffness during low-amplitude loading at high compressive stress level is much greater than dynamic stiffness in less compressed loading situations (Fig. 5). Such an observation is in accordance with the free volume theory [35–37,3,2]. However, the mechanism dominating this behaviour does not need to appear at the molecular size scale, but it may be due to closure of much larger pores like cell lumens.

Even though the mechanical behaviour in terms of energy dissipation, strain amplitude and dynamic stiffness is rather sensitive to stress level and stress amplitude (Figs. 3–5), the decrement of small-strain stiffness appears to be an almost unique function of the level of greatest compressive strain which has appeared during loading (Fig. 6). The stiffness decrement also is closely related to plastic strain (Fig. 8). Thus these measures do not appear to reflect the variety of material reactions to fatigue treatments.

Acknowledgements

The authors are obliged to Tomas Björkqvist for commenting on the manuscript, as well as to the National Technology Agency of Finland for financing.

References

[1] Williams ML, Landel RF, Ferry JD. Temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquids. J Am Chem Soc 1955;77:3701–7.
[2] Ferry JD. Viscoelastic properties of polymers. New York (NY): Wiley, 1961.
[3] Smith TLS. Stress–strain–time–temperature relationship for polymers. In: ASTM Materials Sci. Series 3, STP-325. New York (NY): American Society of Testing and Materials; 1962. p. 60–89.
[4] Halpin J. Introduction to viscoelasticity. In: Tsai SW, Halpin JC, Pagano NJ, editors. Composite Materials Workshop. Stamford (CT): Technomic; 1968. p. 87–152.
[5] Salmén L. Viscoelastic properties of in situ lignin under water-saturated conditions. J Mater Sci 1984;19(9):3090–6.
[6] Kersavage PC. Moisture content effect on tensile properties of individual Douglas-fir latewood tracheids. Wood Fiber 1973;5(2):105–17.
[7] Cousins WJ. Elasticity of isolated lignin: Young's modulus by a continuous indentation method. New Zealand J Forestry Sci 1977;7(1):107–12.

[8] Cousins WJ. Young's modulus of hemicellulose as related to moisture content. Wood Sci Tech 1978;12:161–7.
[9] Salmén L. Responses of paper properties to changes in moisture content and temperature. In: Tenth Fundamental Research Symposium, Oxford. Letherhead (UK): Pira International; 1993. p. 369–430.
[10] Irvine GM. The significance of the glass transition of lignin in thermomechanical pulping. Wood Sci Tech 1985;19:139–49.
[11] Höglund H, Sohlin U, Tistad G. Physical properties of wood in relation to chip refining. Tappi 1976;59(6):144–7.
[12] Becker H, Höglund H, Tistad G. Frequency and temperature in chip refining. Pap Puu 1977;59(3):123–30.
[13] Salmén L, Fellers C. The fundamentals of energy consumption during viscoelastic and plastic deformation of wood. 1981 International Mechanical Pulping Conference, EUCEPA, Oslo, 16–19 June, Session VI, Paper 1
[14] Björkqvist T, Liukkonen S, Lucander M, Saharinen E. Kuidutuspinnan ja puun tehokkaampi vuorovaikutus (KUPU). Loppuraportti. Tampere University of Technology, Automation and Control Institute, Report 4/1998
[15] Page DH, Schulgasser K. Evidence for a laminate model for paper. In: Mechanics of cellulosic and polymeric materials. New York: American Society of Mechanical Engineers; 1989. p. 35–9.
[16] Gibson LJ, Ashby JB. Cellular solids. Oxford: Pergamon Press, 1988.
[17] Christensen RM. Mechanics of cellular and other low-density materials. Int J Solids Structures 2000;37:133–4.
[18] Bodig J. The effect of anatomy on the initial stress–strain relationship in transverse compression. For Prod J 1965;15:197–202.
[19] Easterling KE, Harrysson R, Gibson LJ, Ashby MF. On the mechanics of Balsa and other woods. Proc R Soc Lond A 1982;A383:31–41.
[20] Gril J, Norimoto M. Compression of wood at high temperature. In: Birkinshaw C, Morlier P, Seoane I, editors. COST 508 — wood mechanics, workshop on wood: plasticity and damage. CEC; 1993. p. 135–43.
[21] Uhmeier A. Some aspects on solid and fluid mechanics of wood in relation to mechanical pulping. Dissertaition, Royal Institute of Technology, Stockholm; 1995
[22] Uhmeier A, Salmén L. Influence of radial strain rate and temperature on the radial compression behavior of wet spruce. ASME JEMT 1996;118:289–94.
[23] Uhmeier A, Salmén L. Repeated large radial compression of heated spruce. Nordic Pulp Paper Res J 1996;11(3):171–6.
[24] March HW, Smith CB. Buckling loads of flat sandwich panels in compression. Various types of edge conditions. D.S.D.A. Forest Service, Forest Prods. Lab., Madison, WI, Report 1525 (March 1945)
[25] Kunesh RH. Strength and elastic properties of wood in transverse compression. For Prod J 1967;18(1):65–72.
[26] Bienfait JL. Relation of the manner of failure to the structure of wood under compression parallel to the grain. J Agric Rec 1926;33(2):183–94.
[27] Kitahara R, Tsutsumi J, Matsumoto T. Observations on the cell wall response and mechanical behavior in wood subjected to repeated static bending load. Mokuzai Gakkaishi 1981;27(1):1–7.
[28] Kärenlampi PP, Tynjälä P, Ström P. Mechanical behavior of steam-treated spruce wood under compressive strain. Submitted for publication
[29] Bach L. Frequency-dependent fracture in wood under pulsating loading. Forest Products Research Society Annual Meeting 1975, 15 June, Portland, OR. The Technical University of Denmark, Department of Civil Engineering, Building Materials Laboratory, Technical Report 68/79; 1979
[30] Clorius CO, Pedersen MU, Hoffmeyer P, Damkilde L. Compressive fatigue in wood. Wood Sci Tech 2000;34:21–37.
[31] Keith CT. The mechanical behavior of wood in longitudinal compression. Wood Sci 1972;4(4):234–44.
[32] Kärenlampi PP. Viscoplasticity of steam-treated wood. Submitted for publication
[33] Kärenlampi PP, Tynjälä P, Ström P. The effect of temperature and compression on the mechanical behavior of steam-treated wood. Submitted for publication
[34] Kärenlampi PP, Tynjälä P, Ström P. Dynamic mechanical behavior of steam-treated wood. Mechanics of Materials, in press
[35] Doolittle AK. Studies in Newtonian flow. II. The dependence of the viscosity of liquids on free space. J Appl Phys 1951;22(12):1471–5.
[36] Doolittle AK, Doolittle DB. Studies in Newtonian flow. V. Further verification of the free-space viscosity equation. J Appl Phys 1957;28:901–5.
[37] Ferry JD, Stratton RA. The free volume interpretation of viscosities and viscoelastic relaxation times on concentration, pressure, and tensile strain. Kolloid Z 1960;171(2):107–11.