Relationships between longitudinal growth strain and some wood properties in *Eucalyptus nitens*

Shakti S. Chauhan[1,2] and John Walker[1]

[1]School of Forestry, University of Canterbury, Christchurch, New Zealand
[2]Email: shakti@iwst.res.in

Revised manuscript received 4 August 2004

Summary

The relationships between longitudinal growth strain and wood properties of *Eucalyptus nitens* were investigated. Sixty-three 10-y-old trees were selected for this study. Longitudinal growth strain, green density, green moisture content, basic density, radial shrinkage, outerwood and corewood densities, volumetric shrinkage and dynamic modulus of elasticity (MOE) at 12% moisture content and length-weighted fibre length were determined. Amongst all the studied wood properties, only shrinkage-related properties were found to have some association with the mean growth strain in trees. The mean growth strain was moderately but significantly related to the volumetric shrinkage of the outerwood, but not to the shrinkage of the corewood. However, the volumetric shrinkage differential (difference between outerwood and corewood shrinkage) was strongly related to the growth strain ($r = 0.70$), suggesting that the growth stress gradient might be related to variations in shrinkage properties within the stem. The wood of trees with the lowest growth strains had statistically significantly lower volumetric shrinkage, lower outerwood MOE and less collapse than wood of trees with the highest growth strains. The results suggest that *E. nitens* trees with low strains could exhibit a lower degree of drying defects such as collapse and checking during processing.

Keywords: forest plantations; wood properties; growth stress; strain; wood density; modulus of elasticity; fibre quality; drying; shrinkage; wood defects; *Eucalyptus nitens*

Introduction

The presence of growth stresses in trees and their influence on tree growth and development was reported as long ago as the 1930s. Since then there has been extensive research on the presence and distribution of growth stresses in various species, the mechanism of growth stress generation, means of measuring growth strains in trees/logs and their influence on processing of timber. This work has been reviewed by authors such as Chafe (1979a), Kubler (1987) and Yang and Waugh (2001). In practice, growth strain is measured and then presumed to be linearly related to growth stress because the stresses are thought to reside in the elastic region of the stress–strain diagram; consequently the two terms are often used interchangeably. It is well recognized that large growth stresses in wood, especially in hardwood species, result in severe processing problems. Many eucalypt species are notorious for having very high growth stresses.

An important stimulus to research on growth stress has been the development of tools to measure growth strain in standing trees and felled logs. Several destructive and semi-destructive ways of measuring growth strain have been proposed. In most techniques, growth stress is released either by drilling holes in the stem wood or by cutting out a rectangular piece of wood and measuring the changes in the longitudinal and transverse directions gauged by reference to two fixed points, or by using wire strain gauges (Nicholson 1971; Saurat and Gueneau 1976; Okuyama *et al.* 1994; Aggarwal *et al.* 1998, 2002; Yoshida and Okuyama 2002). Several researchers have sought some meaningful relationship between growth stress/strain and physical, chemical, mechanical and anatomical characteristics of wood (Nicholson *et al.* 1972, 1975; Chafe 1979b, 1990; Muneri *et al.* 1999; Muneri and Leggate 2000) to get an indirect indicator of the level of growth stress in trees. Many studies associating growth stress or strain with other wood properties have been on leaning stems. On leaning or reoriented stems extremely large strains are generated and usually those are associated with reaction wood (tension wood in angiosperms and compression wood in gymnosperms). The anatomical characteristics of reaction wood are significantly different to those of normal wood, and changes in the cell wall structure and properties cause changes in growth stresses (Yoshida and Okuyama 2002). Since many physical properties are associated with fibre structure, significant relationships have been established between properties such as volumetric shrinkage, basic density or modulus of elasticity and the growth stress in leaning stems of various eucalypts (Nicholson *et al.* 1972, 1975; Chafe 1979b, 1981, 1990; Boyd 1980).

Fewer studies have suggested a relationship between some wood properties and growth stress in normal wood as well, for example a significant relationship between volumetric shrinkage and the magnitude of growth strain has been reported in normal wood (Nicholson *et al.* 1975; Aggarwal *et al.* 2002). Growth strain was reported to have a positive relationship with basic density in normal vertical stems of 36-y-old *E. regnans* (Chafe 1990) and 10-y-old *E. globulus* (Yang *et al.* 2002) but the relationship was absent in 8-y-old *E. nitens* (Chafe 1990), 10-y-old *E. cloeziana* (Muneri *et al.* 1999) and 4-y-old *E. pilularis* (Muneri and Leggate 2000). Some studies have explored relationship of modulus of elasticity (MOE), modulus of rupture (MOR) and maximum crushing strength with growth strains (Boyd 1980; Chafe 1981, 1985a, 1990; Aggarwal *et al.* 1998, 2002; Muneri *et al.* 1999; Muneri and Leggate 2000); but there was no conclusive evidence of any generalized relationship between growth strain and these properties. Overall, the association of wood properties with growth stress/strain in vertical-straight stems is not well understood.

Understanding the relationships between growth stress/strain and wood properties in vertical straight stems could have a significant bearing on the breeding and silvicultural management of eucalypts. One needs to be aware of possible influences on other wood properties while selecting trees with low strain level. This paper explores the relationships between average tree growth strain and various physical and mechanical properties measured at about breast height in *E. nitens* wood.

Material and methods

Sampling

Sixty-three trees from a 10-y-old *E. nitens* plantation were selected for the study. The plantation is located on the Port Hills near Gebbies Pass, some 30 km from the University of Canterbury. The plantation is on a north-easterly sloping site and generally exposed to strong winds. The trees were grown from seedlings of uncertain genetic origin. The uphill side of the trees was marked using spray paint. The selected trees were felled with a stump height of about 10 cm. Total tree height, and diameter at intervals of 1 m up the stem, were recorded. The mean tree height and diameter over bark at breast height of the sampled trees were 11.5 m (SD ±0.9 m) and 17.4 cm (SD ±1.4 cm) respectively. Most of these trees had an essentially clear bole up to a height of about 5 m. From each tree, a butt log section (from ground to 1.3 m height), a second or upper log section (from 1.6 m to 3.6 m) and a short billet (300 mm in length, at breast height) were extracted. The billets were stored in polythene covers immediately after extraction to avoid any moisture loss. All logs and billets were transported to the laboratory on the day the trees were felled.

Growth strain measurements

The two logs from each tree were used for growth strain and green dynamic MOE measurements. Longitudinal growth strains were measured at approximately mid-length on two opposite sides (uphill and downhill side) of each log, using the strain gauge method and KYOWA 120 ohm strain gauges with a gauge factor of 2.05. The average of four strain measurements was taken to be the mean growth strain for that tree. A portion of the bark was removed carefully, with a hand chisel, to avoid damaging the cambium. The cambial surface was scraped with the edge of a chisel to remove the differentiating xylem and to smooth the wood surface, which was wiped with cotton to remove excess moisture and cleaned with ethyl alcohol. The strain gauge was glued onto the clean surface using a cyanoacryalate-based glue, and after the glue had fully cured the centre-line of the gauge and points were marked, 17.5 mm above and below the centre point. The lead wires of the strain gauge were connected to the strain meter in the half-bridge configuration, the bridge circuit was balanced to 0 and the initial strain value recorded. Wood fibres were cut above and below the gauge by two series of intersecting holes, 8 mm in diameter, made with a battery-powered hand drill. The horizontal centre lines of the series passed through the two positions previously marked. The resulting slots were about 20 mm long and 20 mm deep. The distance between the opposed edges of two slots was 27 mm. This distance was less than 1.5 times the width of the slots, necessary to obtain the strain value of about 90% of the actual value as suggested by Saurat and Gueneau (1976). Immediately after cutting, the released strain was recorded.

Radial shrinkage measurements

A disc 50 mm thick was cut from each 300-mm billet taken at breast height. To determine radial shrinkage, one strip was cut from each of the discs across the radial direction from pith to cambium. Samples 15 mm x 15 mm in cross-section and of maximum possible length in the radial direction were prepared from these strips. The radial sample length was 58–88 mm, depending on the disc diameter. For tangential shrinkage, samples 25 mm x 25 mm in cross-section and 100 mm in length in the tangential direction were prepared. From each disc one radial and one tangential specimen was taken. Some of the radial and tangential samples cracked or broke during sample preparation due to pre-existing end cracks in the discs, so these samples were rejected. In total, 50 radial shrinkage samples and 46 tangential shrinkage samples were obtained. The length of each radial and tangential sample was recorded in the green condition using a Vernier calipers with an accuracy of 0.01 mm. Subsequently these samples were dried to 12% moisture content (mc) in a controlled environmental chamber at 65% relative humidity and 20°C. The dried samples were reconditioned in steam for 90 minutes. As the steaming increased the moisture content in the samples by 3–4%, they were then returned to the air-conditioned room to re-equilibrate to 12% mc. The length of dried samples was measured. Unfortunately the dry tangential shrinkage samples exhibited severe distortion and, as it was not practical to measure their length accurately, measurement of the tangential shrinkage was abandoned. However, the severity of distortion in the tangential samples provided another index of wood quality.

The remaining billets (250 mm long) were used to determine green and basic densities. The billets were debarked and weighed to an accuracy of 0.1 g, and green volume was measured by water displacement. The billets were then oven-dried at 105°C, to constant weight. From the oven-dry weight and green volume, the basic density and green moisture content were determined.

Samples for volumetric shrinkage and MOE determination

Volumetric shrinkage and MOE of outerwood (near the cambium) and corewood (close to pith) were determined in the samples from 51 of the 63 trees in which growth strain was measured: this procedure was adopted only after the first 12 trees had been processed. A section 500 mm long was cut at the small end of each butt log to give clear wood specimens for measurements of MOE and volumetric shrinkage. Duplicate specimens, 20 mm x 20 mm cross-section, were prepared from both the outerwood and corewood regions. These specimens were trimmed to a length of 300 mm, numbered accordingly, weighed to an accuracy of 0.01 g and volume-determined to an accuracy of 0.1 mL, dried, weighed and volume-determined, reconditioned and dried to 12% mc to recover collapse, and weighed and volume-determined again.

Volumetric shrinkage from green to 12% moisture content was determined for both outerwood and corewood samples, for before and after reconditioning with steam, using the equation

$$\text{Volumetric shrinkage} = 100(V_g - V_d) / V_g ,$$

where V_g and V_d are volumes when green and air-dried respectively. The percentage difference in the volume of the sample before reconditioning (V_{BR}) and after reconditioning (V_{AR}) with respect to the volume in green condition was considered to be the amount of collapse in the samples, i.e.

$$\text{Collapse} = 100\,(V_{AR} - V_{BR}) / V_g \;.$$

MOE determination

Acoustic velocity in the air-dried and reconditioned samples was measured using the resonance based tool 'WoodSpec' described by Lindstrom *et al.* (2002). The dynamic MOE was estimated from the air-dry density of the sample and acoustic velocity using the following relationship:

$$\text{MOE}_{dyn} = \text{density} \times \text{acoustic velocity}^2 .$$

Fibre property measurements

Outerwood chips were taken on the same sides from the billet (extracted from tree breast height) as growth strain was measured in the logs. The chips were initially treated with 10% NaOH solutions for 4 hours and subsequently macerated with peracetic acid solution for 4 hours at 95°C. The fibres were analysed using the Metso FibreLab analyzer. Length-weighted fibre length, fibre width and cell wall thickness values were assessed from a minimum of 5000 fibres in each sample.

Data analysis

The data analysis investigated significant differences in the means of various wood properties between trees with high and low strain. The sample population was ranked and then divided into four distinct groups according to their strain values ($\leq$600 με: low-strain group; 600 με – 900με: medium-low group, 900 με – 1200 με: medium-high group, ≥1200 με: high-strain group). Both the low- and high-strain groups had 14 trees, while the medium-low group had 22 trees and the medium-high group had 13 trees. Average wood properties for the lowest-strain and the highest-strain group were determined and the mean values of the properties of each were compared by Fisher's Least Significant Difference (LSD) method at $\alpha = 0.05$ and 0.01, using SAS statistical software (SAS 1998).

Results and discussion

Wood properties

The descriptive statistics showing average values with standard deviation and range for various wood properties are presented in Table 1. The average tree growth strain and basic density at breast height were 898 με (standard deviation (SD) ±336 με) and 495 kg m^{-3} (SD ±49 kg m^{-3}), respectively, in the sampled trees. The observed growth strain was about 20% greater, and the density value was about 10% greater than that observed in 8-y-old trees measured at breast height (Chafe 1990), and at 3.3 m above ground level in 25 trees of *E. nitens*, 8.5-y-old, from five provenances in Australia (McKimm 1985). For comparisoin, Raymond and Muneri (2001) observed mean whole-tree basic densities of 444–563 kg m^{-3} in 9-y-old *E. nitens* grown at five different sites in Tasmania and Victoria (Australia).

The corewood density (heartwood) at 12% mc (Table 1) was significantly less than the outerwood (sapwood) density, in agreement with results obtained by McKimm (1985) in 8.5-y-old *E. nitens*. As with the density profile, dynamic MOE of the outerwood was significantly greater (about 56%) than the corewood MOE. The radial shrinkage measured on radial strips from green to 12% mc after reconditioning in steam was less than that reported by Lausberg *et al.* (1995) in boards taken just below the breast height (1.8% vs 2.26%). When the samples were dried from green to 12% mc, the observed shrinkage included shrinkage associated with collapse. Steaming of the dried sample for about 90 minutes was presumed to result in nearly complete recovery of collapse. After reconditioning, the volumetric shrinkage in outerwood samples was greater than the volumetric shrinkage in corewood samples. The average volumetric shrinkage and collapse was derived as the mean of outerwood and corewood volumetric shrinkage (after steaming) and collapse values (from the volume differences before and after steaming). A wide range in collapse was observed, ranging from 0.45% to 20%. Generally, collapse was greater in corewood samples.

Overall, the wood properties measured for the sample trees were in broad agreement with the properties reported by other researchers for the wood of *E. nitens* of about the same age (McKimm 1985; McKimm *et al.* 1988; Chafe 1990; Raymond and Muneri 2001).

Relationship between growth strain and other wood properties

The prime objective of the extensive wood property assessments was to search for any relationship between the average growth strain level in the tree and other wood properties measured in the samples taken from breast height area. The large variation in growth strains in the population sampled provided an opportunity to seek a relationship between growth strain and other wood properties. One of the major differences between this study and other studies relating growth strain to wood properties is the sampling procedure. In most of the earlier studies, wood properties were measured on the samples extracted either from the strain measurement positions or from its immediate vicinity and measurements were done at several locations around the periphery. In the present study, wood properties were assessed in the samples taken from breast height or near breast height, and growth strain value was the average of the four strain values per tree (two logs per tree and two positions per log). Results of a correlation analysis of the pooled data indicate the strength of association of wood properties and the level of growth strain (Table 2).

Only volumetric shrinkage of outerwood exhibited a significant positive relationship ($r = 0.56$, $P < 0.001$) with mean tree growth strain. The positive relationship of volumetric shrinkage with growth strains has been reported by other researchers (Nicholson *et al.* 1972, 1975; Aggarwal *et al.* 2002). In their studies, volumetric shrinkage was determined in the samples extracted from the vicinity of the strain measurement positions. In a recent study, Clair *et al.* (2003) found a significant positive correlation between growth strain measured using a single-hole method and tangential shrinkage in end-matched samples from normal wood, i.e. not tension wood, in two leaning trees of chestnut (*Castanea sativa* Mill.). They also reported a strong within-tree relationship

Table 1. Average values of wood properties together with standard deviation and minimum and maximum values for all the samples

Wood property	Mean	Standard deviation	Minimum	Maximum	CV (%)
Growth strain (microns)	898	336.2	430	1645	37.4
Green moisture content (%)	129	21.4	81.4	236.7	16.6
Green density (kg m^{-3})	1124	25.5	1066.4	1181.1	2.3
Basic density (kg m^{-3})	495	49.2	326.9	638.9	9.9
CWdensity at 12% mc (kg m^{-3})	556	47.3	453.0	682.3	8.5
OW density at 12% mc (kg m^{-3})	655	72.5	518.9	865.6	11.1
CW MOE_{dyn} at 12% mc (GPa)	7.84	1.02	5.95	9.96	13.0
OW MOE_{dyn} at 12% mc (GPa)	12.21	2.26	6.40	17.74	18.5
Radial shrinkage (%)	1.8	0.29	1.36	2.61	15.8
CW volumetric shrinkage AR(%)	6.0	1.25	3.88	8.86	20.8
OW volumetric shrinkage AR (%)	7.9	1.56	4.50	11.28	19.9
Average volumetric shrinkage AR (%)	6.9	1.31	4.31	10.07	18.9
Collapse (%)	10.3	4.95	0.45	20.61	49.7
Average OW LWFL (mm)	0.82	0.05	0.71	0.96	6.1
Average OW fibre width (µm)	21.3	1.13	18.22	23.68	5.3
Average OW cell wall thickness(µm)	5.21	0.30	4.38	5.92	5.7

CW = corewood, OW = outerwood, AR = after reconditioning, LWFL = length-weighted fibre length

between longitudinal Young's modulus and growth strain in normal wood measured at several positions around the periphery in the green condition. In the present study, however, no significant relationship was observed between average tree growth strain and dynamic MOE of either outerwood or corewood. McKimm *et al.* (1988) also did not observe any significant correlation between the magnitude of growth stress and other strength properties.

Correlation between basic density and growth strain was not significant in the sampled trees. The absence of any relationship between growth strain and basic density in *E. nitens* was also reported by Chafe (1990), although a significant positive relationship between basic density and growth strain has been demonstrated for *E. grandis* (Malan and Gerischer 1987), *E. regnans* (Chafe 1990) and *E. globulus* (Yang *et al*. 2002). Lack of any consistent and reproducible direct relationships of growth strain/stress with basic density and MOE, as reported in the literature and from this study, suggests that these properties are not influenced unduly by the magnitude of growth strain in vertical, straight trees. Any significant relationships observed elsewhere appear to be species-dependent and specific to the particular studied samples and sampling methodology. Results of any one study can be generalised only with considerable caution.

However, we observed several other significant and moderately strong relationships amongst wood properties. Basic density showed a strong negative correlation with moisture content in green condition ($r = 0.95$), which was to be expected. A moderate but significant negative correlation between basic density and collapse suggests that wood with extremely low basic density would tend to show severe collapse. Collapse is often associated with thin-walled fibres; Chafe (1985b) observed negative correlation between collapse and basic density measured in increment core samples at different heights from eight trees of 43-y-old *E. regnans*.

Table 2. Pearson correlation coefficients for various wood properties

Variables	1	2	3	4	5	6	7	8	9	10	11
1 Average tree growth strain	1.00										
2 Green mc	–0.09	1.00									
3 Green density	0.23	–0.47**	1.00								
4 Basic density	0.13	–0.95**	0.67**	1.00							
5 CW MOE_{dyn} (12% mc)	0.01	–0.55**	0.09	0.47**	1.00						
6 OW MOE_{dyn} (12% mc)	0.26	–0.59**	0.33	0.57**	0.53**	1.00					
7 Radial shrinkage	0.29	–0.06	0.04	0.08	0.42*	0.17	1.00				
8 CW volumetric shrinkage	0.17	0.17	0.12	–0.11	–0.02	0.17	0.35	1.00			
9 OW volumetric shrinkage	0.56**	0.06	0.17	–0.00	0.04	0.31	0.45**	0.73**	1.00		
10 Average volumetric shrinkage	0.42*	0.12	0.16	–0.05	0.02	0.28	0.43*	0.91**	0.94**	1.00	
11 Collapse	0.36*	0.51**	–0.11	–0.46**	–0.34	–0.18	0.12	0.70**	0.70**	0.75**	1.00
12 Average OW LWFL	–0.06	0.00	–0.05	0.04	0.11	0.44*	–0.05	–0.22	–0.16	–0.20	–0.21

* significant at $P < 0.01$; ** significant at $P < 0.001$
CW = corewood, OW = outerwood, AR = after reconditioning, LWFL = length-weighted fibre length

Significant higher correlations between density and MOE are partially influenced by the autocorrelation, as dynamic MOE is determined by both density and acoustic velocity.

We also observed that the collapse shrinkage had very little influence on the acoustic velocity in the samples. Figures 1 and 2 show the acoustic velocity and dynamic MOE before and after reconditioning. The acoustic velocity after reconditioning was found to be higher than that before reconditioning by about 1.6%. However, the dynamic MOE decreased substantially (up to 34%) after reconditioning, depending on the amount of collapse recovery. The decrease in MOE was mainly due to decrease in wood density as the wood volume increased with the recovery of collapse during reconditioning. In Figure 3, the ratio of dynamic MOE before and after reconditioning was plotted against collapse recovery for each of the samples. Samples with high collapse showed large differences in dynamic MOE before and after reconditioning.

Comparing the groups of trees with high and low growth strain, average growth strain in the low-strain group was 508 με, while in the highest-strain group it was 1350 με. Table 3 shows the average values of significantly different wood properties for the lowest- and highest-strain groups of trees.

Volumetric shrinkage of outerwood from the low-strain group was significantly lower ($\alpha = 0.01$) than that of the high-strain group, which was likely as a significant correlation was obtained between the two variables for the complete data set. There was no significant difference between the lowest- and highest-strain groups in green density, green dynamic MOE, basic density, density at 12% mc, or corewood and outerwood density. The interesting results of this analysis were the significant differences in radial shrinkage and collapse in low- and high-strain trees at the $\alpha = 0.05$ level, while the correlation analysis showed a poor association of these properties with growth strain. The significant difference in collapse indicated that wood from trees showing low growth strain would have less probability of severe checking since the severity of internal checking generally increases with collapse. A visual comparison of the discs from the lowest- and the highest-strain groups showed the difference in severity of checking in the wood of low- and high-strain trees (Fig. 4). The magnitude of checking and distortion was generally less in the discs from the trees with mean growth strain less than 600 με than in the discs from the high-strain group. The results suggest that screening of trees based

Table 3. Average values of various wood properties in the lowest and highest growth strain groups. Values in parentheses are coefficient of variation (%).

Wood property	Lowest strain group	Highest strain group
OW MOE at 12% mc (GPa)*	10.74 (20.5)	12.86 (10.2)
Radial shrinkage AR (%)*	1.64 (15.3)	1.92 (21.5)
CW volumetric shrinkage AR (%)*	4.98 (13.0)	6.01 (18.0)
OW volumetric shrinkage AR (%)**	6.31 (19.1)	8.88 (13.7)
Av. volumetric shrinkage AR (%)**	5.65 (15.9)	7.45 (12.4)
Collapse (%)*	6.42 (54.0)	12.74 (34.3)

* $\alpha = 0.05$, ** $\alpha = 0.01$, OW = outerwood, CW = corewood, AR = after reconditioning

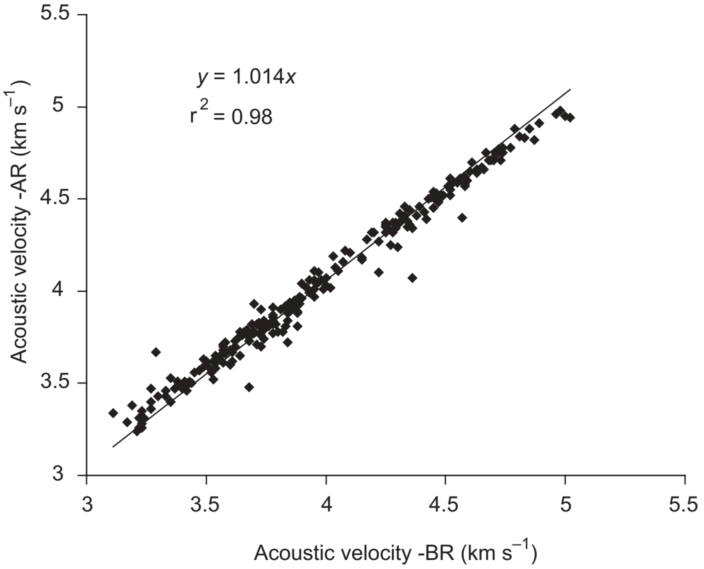

Figure 1. Acoustic velocity in samples before (BR) and after (AR) reconditioning

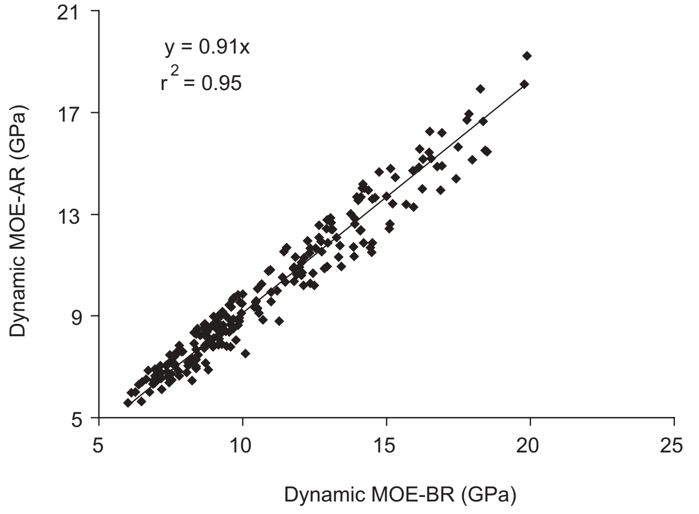

Figure 2. Dynamic MOE before and after reconditioning

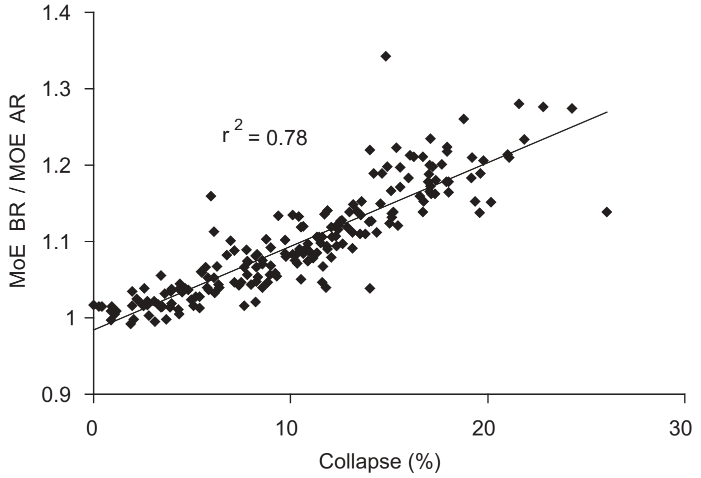

Figure 3. Relationship between the ratio of dynamic MOE before and after reconditioning and collapse in the sample

on the level of growth strain could result in the selection of trees with less drying degrade. However, as there were fewer trees in the low- and high-strain groups, these results are indicative only and need to be confirmed with a larger sample.

There was no significant difference in length-weighted fibre length, fibre width and cell wall thickness between the groups. These results contrast with other results on various eucalypt species. Malan and Gerischer (1987) found statistically significant differences in fibre length and double-wall thickness in low- and high-stressed trees of 28-y-old *E. regnans*. Cell wall thickness has often been related to the magnitude of growth stresses, and thick-walled fibres were found to be associated with the high growth stresses in normal and leaning stems (Nicholson *et al.* 1972; Boyd 1977). The results obtained in this study are in agreement with Wilkins and Kitahara (1991), who found no statistically significant relationship between the level of peripheral growth strain and fibre length, vessel diameter or ray width of wood from 12.5-y-old *E. grandis* trees. The absence of any relationship between fibre properties and growth strain in this study might be attributed to the age of sample trees, as Malan and Gerischer (1987) suggested that highly stressed trees in general exhibit a rapid increase in fibre length and cell wall thickness with increasing age. In most studies where fibre properties were found to be associated with growth stress level, the studied trees were mature (28–30-y old).

In the analysis discussed so far, outerwood and corewood properties have been treated separately and their individual relationships with growth strain have been explored. Since the sampled trees in this study were of similar size, the magnitude of the surface growth strain should indicate the growth stress gradient in the stem, i.e. high growth strains would result in a steep gradient in growth stress from periphery to pith within the stem. It was anticipated that the stress gradient within the stem could be related to some wood property gradient. Malan and Gerischer (1987) observed a steep gradient in wood density and some anatomical characteristics in highly stressed trees of *E. grandis*. In our study, the difference between the outerwood and corewood properties was considered to be an indicator of that wood property gradient within the stem. Wood density, dynamic MOE and volumetric shrinkage differentials were calculated as the absolute differences between the average outerwood values and the average corewood values of the corresponding property. Volumetric shrinkage differential exhibited a strong positive relationship with growth strain ($r = 0.70$, $P < 0.001$). Trees with high growth strain showed a large difference in volumetric shrinkage (Fig. 5).

A moderate but significant relationship of growth strain was observed with density differential ($r = 0.42$, $P = 0.002$) and with dynamic MOE differential ($r = 0.31$, $P = 0.04$). The relationships between wood property gradients and growth strain in the stem need to be further explored with large diameter trees, as the average diameter under bark of the selected trees was small (14–15 cm), and because some of our samples representing outerwood and corewood were taken from adjacent positions in the radial direction. With larger stems, samples with a clear distinction between outerwood and corewood could be obtained. Such a relationship warrants further investigation, as the shrinkage differential assessment can indicate both growth stress and drying related distortions.

Figure 4. Differences in checking in the discs from low strain and high strain trees: <600 microstrain (left); >1200 microstrain (right)

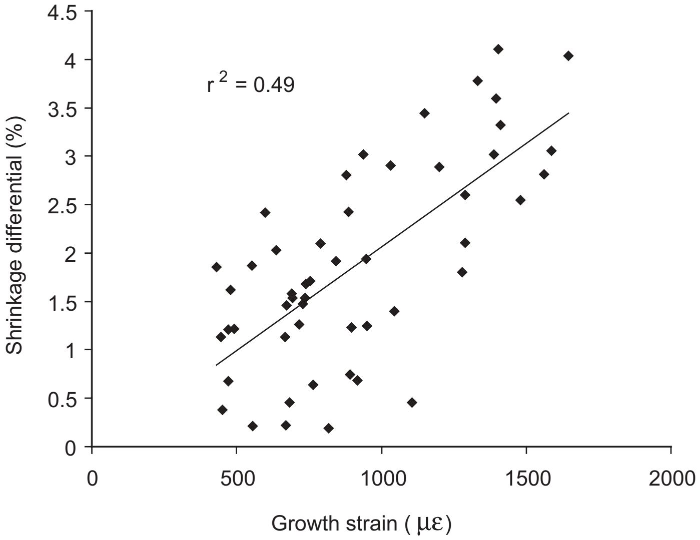

Figure 5. Association between volumetric shrinkage differential and mean tree growth strain

Conclusions

Amongst all the wood properties studied, only those related to shrinkage showed some association with growth strains. Volumetric shrinkage differential showed the best correlation with surface growth strain ($r = 0.70$) suggesting that the gradient in shrinkage behaviour is associated with the surface strain in the tree. The significant differences in collapse, radial shrinkage and volumetric shrinkage in the wood from the trees with the lowest and highest strain suggest that the wood cut from trees displaying least growth strain would be expected to have significantly less checking and collapse-related degrade. Consequently, the magnitude of growth strain could possibly provide a useful basis for initial screening of *E. nitens* trees to lessen collapse-related defects, as well as degrade during processing related to growth stress, without having any influence on wood stiffness (as a low correlation was found between growth strain and dynamic MOE).

Acknowledgements

We would like to acknowledge Nikko-Canterbury Forest Ltd for providing wood material for the study. We thank numerous colleagues at the University of Canterbury for help during the study.

References

Aggarwal, P.K., Chauhan, S.S. and Karmarkar, A. (2002) Variation in growth strains, volumetric shrinkage and modulus of elasticity and their interrelationship in *Acacia auriculiformis*. *Journal of Tropical Forest Products* **8,** 135–142.

Aggarwal, P.K., Chauhan, S.S., Karmarkar, A. and Ananthanarayan, A.K. (1998) Distribution of growth stresses in logs of *Acacia auriculiformis*. *Journal of Tropical Forest Products* **4,** 87–89.

Boyd, J. (1977) Relationship between fibre morphology and shrinkage of wood. *Wood Science and Technology* **11,** 3–22.

Boyd, J.D. (1980) Relationships between fibre morphology, growth strains and physical properties of wood. *Australian Forest Research* **10,** 337–360.

Chafe, S.C. (1979a) Growth stress in trees. *Australian Forest Research* **9,** 203–223.

Chafe, S.C. (1979b) Wood hardness as a poor indicator of growth stress. *Australian Forest Research* **9,** 147–148.

Chafe, S.C. (1981) Variations in longitudinal growth stress, basic density and modulus of elasticity with height in the tree. *Australian Forest Research* **11,** 79–82.

Chafe, S.C. (1985a) Variation in longitudinal growth stress with height in trees of *Eucalyptus nitens* Maiden. *Australian Forestry Research* **15,** 51–55.

Chafe, S.C. (1985b) The distribution and interrelationship of collapse, volumetric shrinkage, moisture content and density in trees of *Eucalyptus regnans* F.Muell. *Wood Science and Technology* **19,** 329–345.

Chafe, S.C. (1990) Relationships among growth strain, density and strength properties in two species of *Eucalyptus*. *Holzforschung* **44,** 431–437.

Clair, B., Ruelle, J. and Thibaut, B. (2003) Relationship between growth stress, mechanical–physical properties and proportion of fibre with gelatinous layer in chestnut (*Castanea sativa* Mill.). *Holzforschung* **57,** 189–195.

Kubler, H. (1987) Growth stresses in trees and related wood properties. [Review article]. *Forestry Abstracts* **48,** 131–189.

Lausberg, M.J.F., Gilchrist, K.F. and Skipwith, J.H. (1995) Wood properties of *Eucalyptus nitens* grown in New Zealand. *New Zealand Journal of Forestry Science* **25,** 147–163.

Lindstrom, H., Harris, P. and Nakada, R. (2002) Methods of measuring stiffness of young trees. *Holz als Roh- und Werkstoff* **60,** 165–174.

Malan, F.S. and Gerischer, G.F.R. (1987) Wood property differences in South African grown *Eucalyptus grandis* trees of different growth stress intensity. *Holzforschung* **41,** 331–335.

McKimm, R.J. (1985) Characteristics of the wood of young fast-grown trees of *Eucalyptus nitens* Maiden with special reference to provenance variation. I Variations in growth, strain and density associated with provenance. *Australian Forest Research* **15,** 207–218.

McKimm, R.J., Waugh, G. and Northway, R.L. (1988) Utilisation potential of plantation-grown *Eucalyptus nitens*. *Australian Forestry* **51,** 63–71.

Muneri, A. and Leggate, W. (2000) Wood properties and sawn timber characteristics of fast, plantation grown 4-year-old *Eucalyptus pilularis*. In: *Opportunities for the New Millennium*, proceedings of Australian Forest Growers 2000 Conference, September 2000, Cairns, Queensland, pp. 1–13.

Muneri, A., Leggate, W. and Palmer, G. (1999) Relationships between surface growth strain and some tree, wood and sawn timber characteristics of *Eucalyptus cloeziana*. *Southern African Forestry Journal* **186,** 41–49.

Nicholson, J.E. (1971) A rapid method for estimating longitudinal growth stresses in logs. *Wood Science and Technology* **5,** 40–48.

Nicholson, J.E., Campbell, G.S. and Bland, D.E. (1972) Association between wood characteristics and growth stress level: a preliminary study. *Wood Science* **5,** 109–112.

Nicholson, J.E., Hillis, W.E. and Ditchburne, N. (1975) Some tree growth-wood property relationships of eucalypts. *Canadian Journal of Forest Research* **5,** 424–432.

Okuyama, T., Yamamoto, H., Yoshida, M., Hattori, Y. and Archer, R.R. (1994) Growth stresses in tension wood: role of microfibrils and lignification. *Annales des Sciences Forestieres* **51,** 291–300.

Raymond, C.A. and Muneri, A. (2001) Nondestructive sampling of *Eucalyptus globulus* and *E. nitens* for wood properties. I. Basic density. *Wood Science and Technology* **35,** 27–39.

SAS Institute (1998) *SAS/STAT Users Guide*. Ver 6.12. 4th ed. The Institute, Cary NC.

Saurat, J. and Gueneau, P. (1976) Growth stresses in beech (*Fagus sylvatica*). *Wood Science and Technology* **10,** 111–123.

Wilkins, A.P. and Kitahara, R. (1991) Silvicultural treatments and associated growth rates, growth strains and wood properties in 12.5-year-old *Eucalyptus grandis*. *Australian Forestry* **54**, 99–104.

Yang, J.L. and Waugh, G. (2001) Growth stress, its measurement and effects. *Australian Forestry* **64,** 127–135.

Yang, J.L., Fife, D., Waugh, G., Dowens, G. and Blackwell, P. (2002) The effect of growth strain and other defects on the sawn timber quality of 10-year-old *Eucalyptus globulus* Labill. *Australian Forestry* **65,** 31–37.

Yoshida, M. and Okuyama, T. (2002) Techniques for measuring growth stress on the xylem surface using strain and dial gauges. *Holzforschung* **56,** 461–467.