

A new method of determining growth stress and relationships between associated wood properties of *Eucalyptus globulus* Labill.

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Summary

A new method developed at CSIRO allows longitudinal growth strain and dynamic Young's modulus in the fibre direction to be measured on the same specimen. From these two properties, longitudinal growth stress can be readily calculated by multiplying the two. In this study, growth strain, density and dynamic Young's modulus were measured on fifty-four specimens removed from 10-y-old plantation-grown trees of *Eucalyptus globulus* Labill. The correlation between growth strain and density was found to be significant but weak ($r^2 = 0.27$, $P < 0.05$). There was no significant relationship between growth strain and Young's modulus. The large variation in growth strain (coefficient of variation = 62%) but a relatively small variation in Young's modulus (coefficient of variation = 18%) resulted in a strong linear correlation between growth strain and growth stress.

Keywords: wood properties; wood strength; growth stress; strain; modulus of elasticity; Young's modulus; wood density; forest plantations; *Eucalyptus*

Introduction

Eucalypts are planted all over the world for commercial purposes. Species such as *Eucalyptus grandis*, *E. globulus*, *E. camaldulensis* and *E. tereticornis* are known to develop large growth stresses. Like many other wood properties, longitudinal growth strain varies within trees (around the periphery of the stem and along the stem) and among trees. Growth stress, the product of growth strain and the modulus of elasticity, thus varies similarly. Growth stress is an important wood property that can seriously degrade log quality and limit sawn recovery. Knowledge of its variability and its relationship to other key wood properties, together with efficient methods for its measurement, are essential for evaluating wood quality of sawlog resources and for improving their processing.

A high degree of association between longitudinal growth stress and respectively volumetric shrinkage, modulus of elasticity (MOE), density, percentage of thick-walled fibres and lignin content was found by Nicholson *et al.* (1972) in a single 30-y-old *E. regnans* tree. The study was extended to ten 32-y-old trees of *E. regnans* several years later (Nicholson *et al.* 1975). These trees

ranged from having slight lean to being moderately or severely bent up to 6 m from ground level. Close within-tree associations were found between longitudinal growth stress, density, MOE, volumetric shrinkage and fibre structure, and the associations became stronger in trees that had severe sweep or bends. However, no indication was given of the relationships when data from all the trees were combined.

Within-tree and among-tree relationships between growth strain, density, MOE, microfibril angle and compressive strength were examined by Boyd (1980). Wood specimens were obtained from 17 vigorous regrowth trees — 16 *E. regnans* and one *E. obliqua* — 40 y old. Eleven trees had a slight lean, and the rest had moderate vertical displacement. The samples were taken from positions 50 mm apart around the periphery of the tree stems. Significant positive within-tree relationships were found between growth strain and respectively MOE and density in only 9 and 10 of the 17 trees studied (mostly the crown-reorienting trees), but no significant among-tree relationships were found between growth strain, MOE and density.

Chafe (1990) investigated relationships between longitudinal growth strain, density, MOE and maximum compressive strength of wood specimens obtained from eleven 36-y-old trees of *E. regnans* and ten 8-y-old trees of *E. nitens*. Using the combined data for each species in the analysis, highly significant positive relationships were found between growth strain and density for *E. regnans*, but not for *E. nitens*. There was no significant relationship between growth strain and MOE for either species, a result similar to that of Boyd (1980). However, MOE was significantly correlated with density for both species.

Malan and Gerischer (1987) also examined relationships between growth stress and wood properties, but adopted an approach quite different from that of Nicholson *et al.* (1972, 1975) and Boyd (1980). Rather than using correlation analysis, they investigated the significance of differences in the means of density and a number of anatomical properties between highly stressed and little-stressed trees, and the pith-to-bark variability of these properties. They arbitrarily identified highly stressed and little-stressed trees of 27-y-old *E. grandis* on the basis of the severity of end splitting of logs. Mean density in highly stressed trees

was significantly greater than in little-stressed trees, primarily because the pith-to-bark increase in density was steeper in the highly stressed trees.

In most published reports, MOE and growth strain were not assessed in the same specimens. Rather, MOE was determined on end-matched specimens (Nicholson *et al.* 1972, 1975; Boyd 1980; Chafe 1981, 1985, 1990) or specimens taken from nearby wood (Aggarwal *et al.* 1998; Muneri *et al.* 1999).

The objectives of the present study were (a) to explore a new method of determining growth stress using an approach that avoided felling and allowed various wood properties to be measured on the same small specimens, and (b) to examine relationships between growth strain, MOE and density measured in this way.

Materials and methods

Advantage of our method of determining Young's modulus

The method we used in this study for determining longitudinal growth stress involves the measurement of growth strain (Nicholson 1971) and the dynamic Young's modulus of small beams (8.5 mm × 1.7 mm × 85 mm, radial × tangential × longitudinal) measured in the fibre direction. There are several advantages in this approach. As Young's modulus can be determined directly from the small wood segments used for growth strain measurement (Nicholson 1971), no additional wood need be removed from the stem. Second, the small beam specimen represents most of the radial and longitudinal dimension of the wood segment used for assessing growth strain. This provides a high degree of matching of material used in the various tests. In previous studies, the same specimens were used for growth strain and density (Chafe 1990), but MOE was determined on larger, nominally end-matched specimens since only static testing was available at the time (Nicholson *et al.* 1975; Boyd 1980; Chafe 1990).

Specimens for testing

The specimens used in this study were collected as part of research already published (Yang and Fife 2000; Yang *et al.* 2001). In summary, 59 trees of 10-y-old *E. globulus* were sampled from three provenances (Jeeralang, King Island and south-eastern Tasmania) grown at two sites (Heath and Johnstons) in the Mt Gambier region of South Australia. Growth strain was measured at three equi-spaced positions around the stem circumference at heights of 1.3, 2.5, 4.3 and 6.1 m. The measurement required the removal of a wood segment (Nicholson 1971), the nominal dimensions of which were 90 mm × 20 mm × 10 mm (longitudinal × tangential × radial). All segments were dried from green to nominal 17% moisture content (MC) in a 17% equilibrium moisture content room, reconditioned in saturated steam for half an hour, then equilibrated to 12% MC (nominal).

For the present study, 59 segments were selected from the 2.5 m height, one segment per tree. They represented the entire range of the growth strain values at that height. They were further machined to yield a new specimen per segment. The new specimen was 85 mm × 1.7 mm × 8.5 mm (longitudinal × tangential ×

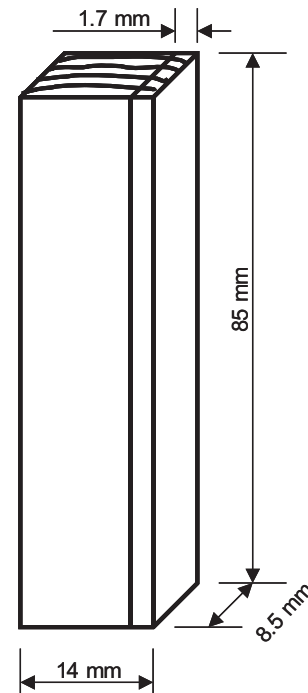


Figure 1. Removal of a small beam specimen of 85 mm × 1.7 mm × 8.5 mm (longitudinal × tangential × radial) from a trimmed growth strain segment for dynamic MOE testing

radial) to simulate a small beam (Fig. 1). Five specimens were rejected due to unsatisfactory quality. Density at 12% MC was calculated from the weight and dimensions of each remachined sample.

Testing, measurements and analysis

Dynamic Young's modulus in the fibre direction was determined from these specimens using a new technique developed at CSIRO for measuring the dynamic MOE of very small axial strips (Ilic 2001a, 2002), which in turn was based on a technique used for measuring the dynamic longitudinal MOE of larger specimens (Ilic 2001b). In brief, the end of the test specimen is hit with a thin steel needle, setting up vibration in the fibre direction which is then detected by a wide-bandwidth microphone (TIP300A). The MOE is determined following spectral analysis of the natural frequency of vibration.

The spectral analysis system in this study was similar to that described by Ilic (2001b), except that the Sony microphone previously used was replaced by one with greater bandwidth (PCB — Piezotronics, TIP300A). Flicking the end of the beam with a thin steel needle induced the longitudinal vibration. This vibration was detected by the microphone and fed to the spectrum analyser set to a high sampling rate (100 kHz) to enable high frequencies to be accurately detected. The frequency resolution in all tests was 50 Hz. Characteristic frequencies ranged from 15 to 25 kHz.

The dynamic longitudinal elastic modulus (E_L) was calculated from the standard solution of the wave equation for longitudinal vibrations of a slender rod with free-free support condition, using the following equation (also described in Ilic 2001b):

$$E_L = 4L^2 f_m^2 \rho / m^2, \tag{1}$$

where E_L = dynamic longitudinal elastic modulus (Pa), L = length of the specimen (m), f_m = the resonant frequency (Hz), m = mode of vibration (where $m = 1, 2, 3, \dots$, for example, f_1 = fundamental mode, f_2 = first harmonic, etc.), and ρ = wood density at 12% MC (kg m^{-3}).

The wave velocity in the longitudinal direction V_L (m s^{-1}) of the natural fundamental mode is given by:

$$V_L = 2Lf_1, \tag{2}$$

where V_L corresponds to the velocity of sound along a uniform bar.

Bolza and Kloot (1963) found that the difference in MOE (centre-point static bending) between the 12% MC condition and the green condition for 23 eucalypt species (3 ash, 6 box and 14 gum species) ranged between 17% and 40% (mean 28%). Also, our data on *E. regnans* (Ilic 2001b), *E. delegatensis* and *E. globulus* (unpublished) have shown that dynamic Young’s modulus determined in longitudinal mode is about 30% higher than in flexure mode. To scale our 12% MC dynamic Young’s modulus values determined in longitudinal mode to green Young’s modulus values determined in flexure mode in this study, we reduced the 12% MC dynamic Young’s modulus values in longitudinal mode by 58% ($28\% + 30\%$).

As the measured growth strain values were well below the limit of proportionality for wood (Kollmann and Côté 1984), growth stress could be calculated by multiplying growth strain and the Young’s modulus (green condition) according to Hooke’s Law (Panshin and de Zeeuw 1980). We examined the relationships between growth strain and, respectively, Young’s modulus and density. We did not attempt to examine the relationship between density and Young’s modulus because the dynamic modulus was derived from density.

Results and discussion

Mean values of properties

Basic statistics of growth strain, density, Young’s modulus and growth stress are shown in Table 1. There was a large variation in growth strain but variation was relatively small in density and dynamic Young’s modulus. Since one specimen is unlikely to be representative of the wood around the periphery at a given height, between-tree variability of these properties was not described from the existing data.

Relationships between properties

A strong simple linear relationship was found between growth strain and growth stress ($r^2 = 0.94$, Fig. 2). A strong correlation between growth strain and growth stress has also been observed in young plantation-grown trees of *E. nitens* ($r^2 = 0.82$, Table 1 in Chafe 1985), but only a modest relationship ($r^2 = 0.39$) was apparent in regrowth trees of *E. regnans* based on tree mean values per height (Table 1 in Chafe 1981). The respective coefficients of

variation (CV) for growth strain and MOE are 62% and 18% in this study (Table 1), 31% and 15% in Chafe (1985), and 22% and 16% in Chafe (1981). Since growth stress is the product of growth strain and MOE, and MOE is far less variable than growth strain, the correlation between growth stress and growth strain becomes stronger with increasing variability of growth strain.

Growth strain was significantly correlated with density at a moderate level ($r^2 = 0.27$, Fig. 3). This result is compatible with those found for 12.5-y-old *E. grandis* by Wilkins and Kitahara (1991) and regrowth *E. regnans* by Chafe (1990). Examination of Figure 1 in the latter paper indicates the correlation coefficient to be between 0.6 and 0.7 (r^2 between 0.36 and 0.49). However, other studies show that growth strain and density are not always clearly related. Chafe (1990) found no relationship between these properties in *E. nitens*. While Nicholson *et al.* (1975) found a relationship in each of 10 study trees of regrowth *E. regnans*, Boyd (1980) found it in only 10 of 17 study trees (mostly *E. regnans*). Interestingly, the relationship became stronger in trees that were more bent or leaning (Nicholson *et al.* 1975; Boyd 1980), suggesting an association of other wood properties with growth strain.

Table 1. Basic statistics of growth strain, density, Young’s modulus and growth stress from 54 [5 specimens were discarded] specimens of 10-y-old *E. globulus* (one specimen per tree)

Statistics	ϵ ($\times 10^{-6}$)	Density (kg m^{-3})	$E_{12\%MC}$ (GPa)	E_{green} (Gpa)	σ_{green} (MPa)
Average	1127	698	22.4	9.4	10.9
SD	699	97	4.1	1.7	7.5
CV (%)	62	14	18	18	69
Min.	20	509	13.5	5.7	0.1
Max.	2892	972	29.6	12.4	32.7

Density = density at 12% MC.

ϵ = growth strain measured in felled logs.

$E_{12\%MC}$ = dynamic Young’s modulus determined in longitudinal mode on specimens at 12% MC.

E_{green} = dynamic Young’s modulus equivalent to flexure mode and at green condition. $E_{\text{green}} = E_{12\%MC} \times (1 - 0.28 - 0.3)$.

σ_{green} = growth stress (green condition). $\sigma_{\text{green}} = E_{\text{green}} \times \epsilon$.

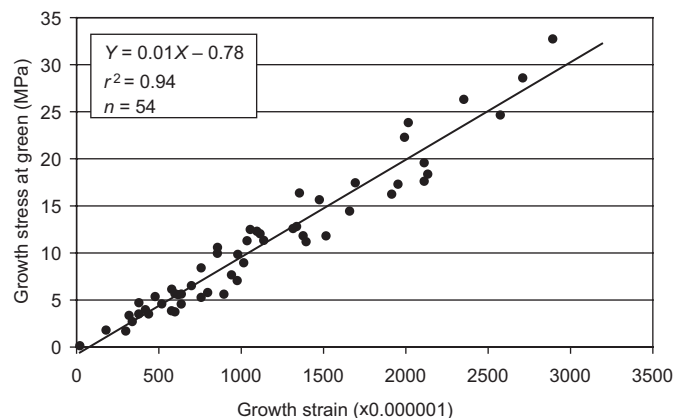


Figure 2. Relationship between growth strain and growth stress at green condition in 10-y-old *E. globulus*

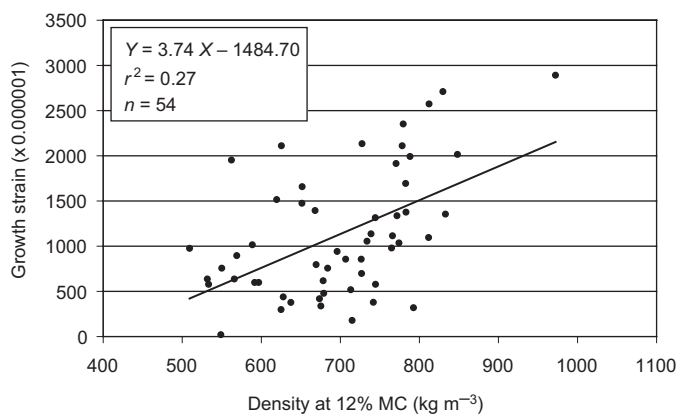


Figure 3. Relationship between growth strain and density at 12% MC in 10-y-old *E. globulus*

The relationship between growth strain and density was also inconsistent when mean values of trees or logs were used in analyses. Mean peripheral growth strain of logs from 10-y-old *E. globulus* was found to increase with mean tree density at breast height ($r^2 = 0.39$, $n = 59$, Yang *et al.* 2002), and highly-stressed trees showed significantly higher average density than less-stressed trees (Malan and Gerischer 1987). In other studies, however, no significant relationship was found between the tree means of growth strain and density in regrowth *E. regnans* (Table 2 in Nicholson *et al.* 1975; Table 1 in Chafe 1981). Data on *Quercus nigra* (water oak) and *Fraxinus americana* (white ash) did not suggest any relationship between growth strain and specific gravity (Yao 1979).

No significant relationship between growth strain and dynamic Young's modulus was found in this study ($r^2 = 0.06$, Fig. 4). This result is in keeping with earlier observations on regrowth *E. regnans* (Boyd 1980; Chafe 1990) if analysed using between-tree data. This was also true for *Quercus nigra* (water oak) and *Fraxinus americana* (white ash) (Yao 1979), *E. nitens* (Chafe 1990) and 10-y-old *E. cloeziana* (Muneri *et al.* 1999). In Boyd's study (1980), each pair of growth strain and MOE data were determined from end-matched specimens, and a significant relationship was found in 10 of 17 trees. It was not certain whether this less exact match of specimens was the cause of the non-significant relationship in the other seven trees. Nicholson *et al.* (1975) reported a close within-tree relationship between growth strain and MOE, but did not indicate whether the relationship might change if the data were combined between trees.

An unexpected result from this study was that some of the specimens that had marked tension wood with high density and thick cell walls had lower MOE values (e.g. $E_{12\%MC} = 17.3$ and 19.4 GPa) than other normal wood specimens. The reason for this unusual behaviour is unknown.

Conclusions

It is convenient to estimate growth stress on stem segments used for measuring growth strain. Growth stress is estimated by measuring dynamic MOE in the fibre direction after making necessary corrections for moisture content and differences

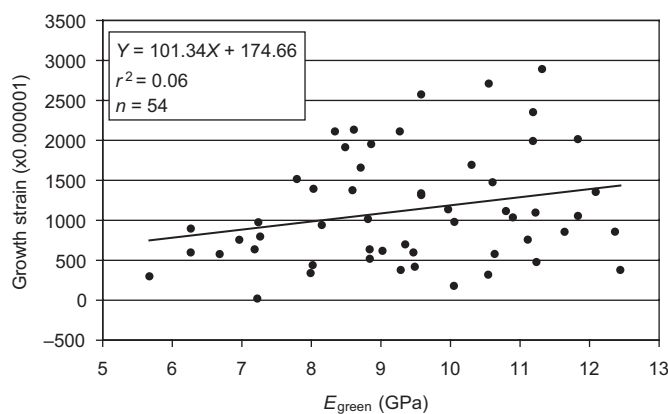


Figure 4. Relationship between growth strain and Young's modulus estimated in flexure mode at green condition in 10-y-old *E. globulus*

between assessments made in longitudinal and flexure mode. Because small segments may be removed from stems of standing trees and a MOE specimen may be obtained from a growth strain segment, actual growth stress at the tree periphery can be estimated at low cost, less destructively and with much improved precision over other methods.

This study has demonstrated a positive relationship between growth strain and density when data on individual specimens from all study trees were combined. If this result is substantiated in future studies, the implication is that breeding for lower density may help produce trees with smaller growth stresses. No relationship was found between growth strain and Young's modulus, indicating there was limited potential for using MOE to predict growth strain in *E. globulus* trees.

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