Pairing Test and Longitudinal Growth Strain: Establishing the Association

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Abstract

Where a log is sawn along the pith to produce two half-round posts the outward warp or bending has been attributed to the presence of growth stress in the standing tree. However this association has not been studied thoroughly. The paper compares the outward bending on sawing along the grain and corresponding growth strains in small diameter logs from 10-year-old *Eucalyptus nitens*. Sixty-three trees were felled and from each tree two logs, each 1.3 m long, were extracted. Longitudinal growth strain was measured at approximately mid-length on opposite sides of each log using the strain gauge method. The acoustic velocity along the logs was measured using a resonance-based tool to estimate modulus of elasticity. Subsequently logs were sawn into two half rounds along the length and the bending of the two halves was quantified by measuring the opening at both ends of the log. A strong positive relationship was observed between average growth strain in the logs and the opening on sawing within each group of logs i.e. butt logs and upper logs. The magnitude of opening in the upper log was about 2.5 times the opening in the butt log. This difference was found to be associated with the log dimensions and taper. A mathematical model was developed that calculated the force (growth stress) necessary to induce this warp. Its validity was tested against the experimental results. The model equation can effectively be used to predict the magnitude of distortion in logs on sawing knowing the growth strain and *vice versa*. This could be helpful in adopting the appropriate sawing/processing of each log based on its expected distortion. Alternatively, the equation can be used to predict the growth strain level in trees. Although totally destructive in nature, this approach could formulate an alternative method for the rapid screening or selecting young eucalyptus trees having low growth strain during the early stages of selective propagation in tree-breeding programs.

Key Words: *Eucalyptus nitens*, growth-stress, strain, pairing-test, warp

Introduction

Growth stress is one of the important wood quality parameters for many hardwoods and particularly for eucalypts species. Though beneficial for tree growth, a high magnitude of these inherent stresses causes serious concerns in processing of logs for sawn timber. A prior knowledge of magnitude of growth strains in trees/logs and extent of degrades during processing due to these stresses is of significant importance in adopting appropriate processing techniques to get quality timber, in sorting logs for their rational utilization, and in tree breeding programmes in the selection and propagation of low-stress trees for the large-scale production of timber from these hitherto stress-prone species.

Much research has been carried out in understanding the mechanism of growth stress development, measurement of growth strains, variability in growth stresses within and between species and its relationship with physical and mechanical properties of wood (Boyd 1977, Archer 1986, Kubler 1987, Yamamoto and Okuyama 1988, Chafe 1990, Okuyama 1993, Yang and Waugh 2001, Aggarwal *et al.* 2002, Chauhan and Walker 2004). It is well accepted that growth stresses are generated in the newly-formed xylem cells at the vascular cambium, which tend to contract longitudinally and expand laterally against the restraining forces of adjoining, fractionally older wood cells. This generates tensile stresses in the longitudinal direction and compressive stresses in the tangential direction. Longitudinal tensile growth stresses generated by newly-formed cells ever-so-slightly compress all existing wood cells resulting in an easing of tensile stresses in the adjacent recently-formed cells a little further from the cambium. This progressive easing of growth stress produces a gradient in tensile stresses with a maximum at stem periphery to zero at about one third of radius from periphery and then progressively larger compressive stresses towards the pith so counter balancing the tensile stresses toward the periphery (Archer 1986). The gradient in longitudinal growth stress in the radial direction results in warping in timber on sawing.

Many studies have concentrated on investigating stress distribution patterns inside the tree using a diametral plank and assessing the change in length and bending of the strips ripped from the plank (Boyd 1950; Wilhelmy and Kubler 1973; Saurat and Gueneau 1976). The steepness of the gradient would depend on peripheral growth strains and the stem diameter. According to Kubler (1959), for a given growth strain at the periphery, small diameter logs show steeper growth stress gradients across the diameter. Therefore, sawn boards from a small diameter log show greater distortion than sawn from a large diameter log with the same peripheral strain. However, Raymond *et al.* (2002) raised concerns over validity of the theoretical relationships between growth stress gradients in logs and deflection in boards sawn from the logs of *Eucalyptus globulus* and have advocated reconsideration of the many existing relationships.

The "pairing test" i.e. measuring outward warp after splitting the stem length-wise along the pith has been associated with the growth stress gradient in the stem. However the magnitude of outward bending with peripheral growth strains has not been investigated thoroughly. In this paper, authenticity of the pairing test as an indicator of the growth strain level in small diameter logs of *Eucalyptus nitens* has been tested. A mathematical model to predict the extent of warping in two halves on splitting along the length is also reported.

Materials and Methods

Sixty-three trees from a 10-y-old *Eucalyptus nitens* plantation were selected for the study. The plantation was located on the Port Hills near Gebbies Pass, some 30 km from the University of Canterbury. The plantation was on a north-easterly sloping site and generally exposed to strong winds. The trees were grown from seedlings of uncertain genetic origin. 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) was extracted. Both large and small end diameters of each extracted log were measured. The small billet (300 mm long) extracted at the breast height was used to determine the green density of the wood.

Growth Strain Measurement

Longitudinal growth strains were measured at approximately mid-length on two opposite sides (on the upslope and downslope sides) of each log, using the strain gauge method. KYOWA 120 ohm wire-strain gauges with a gauge factor of 2.05 were used for the study. A portion of the bark was removed carefully without damaging the cambium with a hand chisel. The cambial surface was scraped with a sharp blade to remove the differentiating xylem. The wood surface was wiped with cotton to remove excess moisture and cleaned with ethyl alcohol and slightly roughened to achieve good adhesion of strain gauge on the wood surface. The strain gauge was glued onto the clean surface using cyanoacrylate-based glue, and after the glue had fully cured the centre-line of the gauge located and two points were marked, 17.5 mm above and below the centre point. The strain gauge was 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 (20 mm wide and 20 mm deep) above and below the gauge using a 8 mm diameter hand drill. The distance between the opposed edges of the 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 slots, the released strain was recorded. The average of two growth strain measurements was taken as the growth strain value of the log.

Acoustic Velocity Measurement

Acoustic velocity in each log was measured using a resonance based tool “Woodspec”. The acoustic velocity is determined from the frequency of many tens of reverberations of the acoustic signal within the sample and is governed by the average stiffness of the log. Each log was tapped at an end using a small hammer and reverberation of the sound waves along the log was captured. A Bruel & Kjaer DeltaTron accelerometer with $1mV/ms^{-2}$ and the frequency range of 0.1 Hz to 8 KHz was used as the transducer. Acoustic velocity (c) is calculated from the fundamental frequency (f) and the sample length (*l)* using following relationship:

$$c = 2 \times l \times f$$

Pairing Test

After growth strain and acoustic velocity measurements, logs were sawn into two half rounds along the length using a band saw. The sawing was done in the plane perpendicular to the sides of strain measurement. Immediately after sawing, the two halves were re-assembled to reconstruct the log and were clamped together using a G-clamp at the centre point. Both half-rounds bowed in the outward direction. The opening-up at both ends of the logs was measured using a digital vernier caliper. The measurement of distortion on sawing the logs was taken to be the mean of the two opening gaps between the two sawn half-rounds measured at both ends. The process of log sawing and measurement of openings are shown in Figure 1.

Figure 1: Log sawing and opening measurement

Results and Discussion

An enormous amount of variation was observed in growth strains and opening in logs on sawing in the measured logs. Table-1 shows the mean values of each of these variables along with their variation.

Table-1: Mean values and range of measured variables

Variables	Butt log			Second log		
	Mean (Sd)	Min.	Max.	Mean (Sd)	Min.	Max.
Growth strain (10^{-6})	933 (454)	340	2600	855(346)	371	1610
Acoustic velocity (km/s)	2.87 (0.23)	2.32	3.44	3.07 (0.25)	2.42	3.85
Log opening (mm)	19.05 (6.38)	8.8	38.3	47.29(18.19)	21.3	92.8

A large variation in growth strains and log opening provided an opportunity to confirm the association between the two variables. A Pearson's correlation analysis between butt log and second log for all three variables indicated strong association of each of the variables between the two log segments (Table-2). Also a strong correlation was evident between log opening and growth strains variables in both log segments whereas acoustic velocity did not exhibit relationship with either growth strain or log opening.

Table-2: Correlation matrix between different variable and log segments

Variables	Butt log strain	Butt log opening	Butt log velocity	Second log strain	Second log opening	Second log velocity
Butt log strain	1					
Butt log opening	0.83**	1				
Butt log velocity	0.13	0.07	1			
Second log strain	0.89**	0.83**	0.07	1		
Second log opening	0.83**	0.87**	0.06	0.90**	1	
Second log velocity	0.30	0.21	0.88**	0.24	0.25	1

** Significant at $P<0.01$.

It is known that the outward warping in logs during sawing has been attributed to the presence of radial gradient in longitudinal growth strains in stems (Kubler, 1987). When split into two halves, compressive stresses at the core and tensile stresses at the periphery relax resulting in longitudinal expansion of core and contraction of the surface. The association between mean growth strain in logs and opening of sawing for pooled data irrespective of log type was not very impressive with R^2 of 0.22. However, when butt and second logs analyzed separately, strong association was observed between the two variables (Fig. 2).

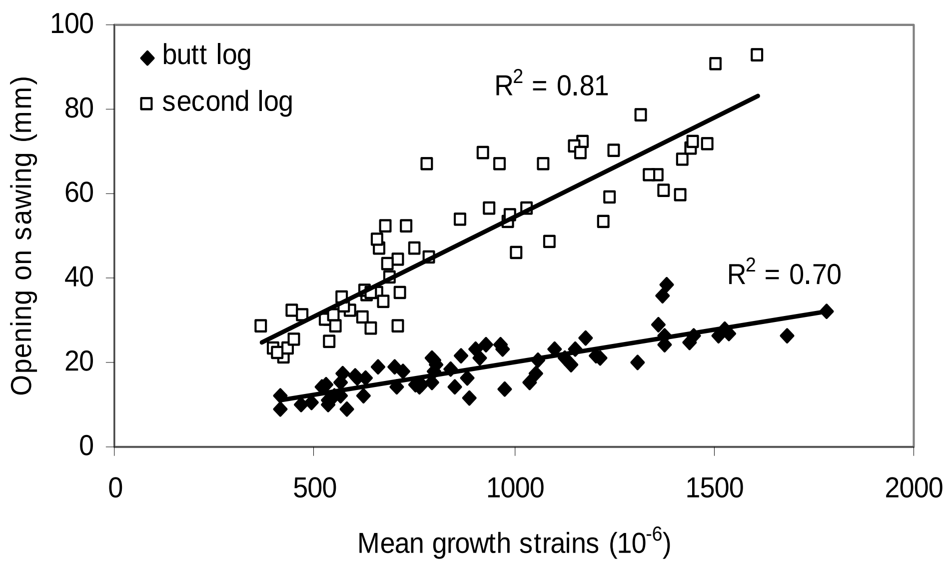

Fig.2: Relationship between growth strain and opening on sawing of logs

Logs with high mean growth strain exhibited large bending in the outward direction on sawing along the pith to give the two half-rounds in each log type. It was observed that the butt logs exhibited relatively less opening as compared to second logs. Opening in the second log was about 2.5 times the opening in the butt log. Since all the logs in a specific group (butt logs and second logs) were of the same length and had narrow range in diameter, the strong relationship between mean growth strain and opening on sawing confirms the validity of the pairing test in indicating the growth stress level for logs of very similar length and diameter.

The difference in the openings in butt logs and second logs at a given strain level is attributed to the differences in the log dimensions and was explained theoretically on the basis of bending of a tapered log of length "*l*" and large end radius (R_1) and small end diameter (R_2) and a mathematical model was developed. According to the model, the magnitude of the opening on sawing can be given by the Equation (1).

$$Y_0 = \frac{1.74\sigma_s l^2 R_a^3}{E \times R_2^2 (R_1 - R_2)^2}\left[\frac{1}{6} + \frac{R_2^3}{3R_1^3} - \frac{R_2^2}{2R_1^2}\right] \qquad (1)$$

where Y_o is the total opening (mm), R_a is the average radius of the log, R_1 and R_2 are the small end and the large end log radii respectively, E is the average elastic modulus of the log, σs is the surface growth stress. The surface growth stress is obtained from the surface growth strain "ε_l" and elasticity modulus of outerwood (*K*) using following equation (Eq. (2))

$$\sigma_s = K\varepsilon_l \qquad (2)$$

Equation (1) can be re-written as

$$Y_0 = \frac{1.74 K\varepsilon_l l^2 R_a^3}{ER_2^2 (R_1 - R_2)^2}\left[\frac{1}{6} + \frac{R_2^3}{3R_1^3} - \frac{R_2^2}{2R_1^2}\right] \qquad (3)$$

Since the acoustic velocity by single-pass transit time tools like Fakopp is influenced by the outerwood stiffness while resonance velocity is determined by the average stiffness of the log "*K*" and "*E*" can be estimated from the two velocities and wood density (ρ) using the following relationships.

$$K = \rho \times c_{transit-time}^2 \quad and \quad E = \rho \times c_{resonance}^2$$

Log opening (Y_o) was predicted for all the logs using Equation (3). In one of our study (Chauhan, 2004), ratio of acoustic velocity measured by Fakopp, a transit-time tool to the velocity measured by Woodspec was found to be about 1.12 in small diameter logs of *Eucalyptus nitens*. Correspondingly, the ratio of "*K*" to "*E*" in Equation (3) was taken as 1.25 (ratio of $c^2_{transit\text{-}time}$ to $c^2_{resonance}$). The predicted openings calculated from the equation were in good agreement with the measured openings with a strong linear relationship (Fig. 3). This implies that the model equation can effectively be used to predict the magnitude of distortion in logs on sawing knowing the growth strain and *vice-versa*.

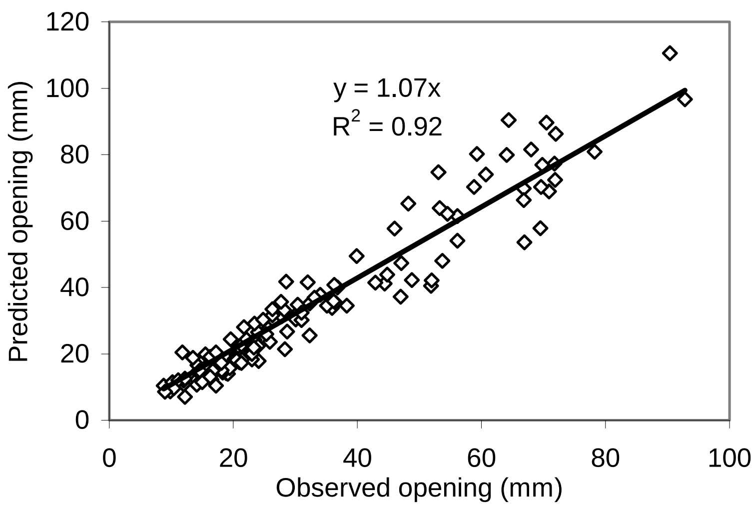

Fig. 3: Association of model predicted and observed opening of logs

These results emphasize that distortion or bending on logs of different dimensions cannot be compared directly just on the basis of peripheral strains without taking into account of the tree/log dimensions and structure. Consequently sawn timber from a large diameter log with a high level of peripheral growth strain could experience less distortion compared to that in the lumber cut from a small diameter log with a similar level of growth strain. Therefore only measuring growth strain at different points on tree or log and associating this with the possible magnitude of distortion could be misleading. In most studies on bowing or distortion of sawn timber due to growth stresses, the relationships has been explored without considering growth strains and diameters together. Raymond *et al.* (2002) compared board deflection with growth strains and tree diameter separately and found no correlation with either property, perhaps because the board deflection ought to be a function of tree diameter and peripheral strain. Muneri *et al.* (1999) demonstrated a significant improvement in accuracy in predicting bow in sawn timber from 10 year-old *E. cloeziana* by adding tree diameter with growth strains in a linear model. As Jacobs suggested that peripheral strain remains same throughout the tree's life (Kubler 1987), the ill effects of growth stresses would be amplified in small diameter trees as compared to in large diameter trees with same peripheral strains due to steep stress gradient.

There are two significant implications. Firstly, the magnitude of distortion in wood sawn from a log could be pre-assessed by using this equation where log length, diameters, taper are also taken into account with the magnitude of the growth strain. This could be helpful in adopting the appropriate sawing/processing of each log based on its expected distortion. If a log is expected to distort severely, the log/tree could be rejected or redirected to some other applications like pulping. However, this needs reliable measurement of growth strain (at least two opposite sides of the log) which could be quite time consuming as well as a costly operation. The concept while sound does not seems to be economically viable or practical.

Secondly, the equation can be used to predict the growth strain level in trees. Although totally destructive in nature, this approach could formulate an alternative method for screening or selecting young eucalyptus trees having low growth strain during the early stages of selective propagation in tree-breeding programs.

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