The Impact of Growth Stress on Sawn Distortion and Log End Splitting on 32-Year-Old Plantation Blue Gum
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Prepared for the

Forest & Wood Products Research & Development Corporation

by

J. Li Yang and S. Pongracic

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EXECUTIVE SUMMARY

Objectives

- To quantify the relationship between sawn timber distortion and log end splitting with growth strain measured at the surface of standing trees.
- To investigate the impact of log end splitting on sawn volume recovery.
- To use wood characteristics estimated from breast height cores to identify trees prone to excessive sawn board distortion and log end splitting.

Key Results

- Log end splits were not severe overall and appeared mostly as small cracks on the large ends of the logs, and were far fewer on the small ends. Severe end splitting occurred only in two out of thirty logs, where the total split length on the log surface exceeded 400 mm.

- The estimated loss of sawn recovery was equivalent to 1% of the log volume, or approximately 4% of the dried board volume, assuming end splits in the dried boards were docked. This equates to $3.66 in lost product for an average log of 0.38m$^3$ (200 mm radius and 3000 mm length) or $9.63 per cubic metre of logs, if log volume recovery of dried sawn product is 26% and an average price of dried sawn timber is $914/m$^3$. For a mill processing 40,000 m$^3$ of logs per annum, this equates to an annual loss of $385,000.

- A multi-saw re-saw was used to re-saw green slabs that had been cut to commercial thickness to produce boards with straight edges or acceptable spring. The estimated loss of sawn recovery due to removal of the curved edges in the slabs in this process was 6% of the log volume. This equates to $7.20 in lost product for an average log of 0.38m$^3$ (200 mm radius and 3000 mm length) or $18.95 per cubic metre of logs, if log volume recovery of green sawn product is 38% and an average price of green sawn timber is $360/m$^3$. For a mill processing 40,000m$^3$ of logs per annum, this would be an annual loss of $758,000. While neither the end-split loss nor the curved-edge off-cut loss will ever be entirely eliminated, it would be worthwhile for a mill owner to have an indication of the extent of the loss, via a wood quality index, in order to better negotiate log prices.

- Spring before and after drying was not significantly correlated. Spring increased by an average of 5 mm during drying. On an average, 43% of the dried boards produced from a log exceeded 10 mm spring. These boards will require shortening or sizing cuts at a later stage to meet the spring specifications for appearance grade products.

- Mean displacement (an indication of surface strain), when multiplied by DBHOB, was significantly correlated with log end splits when the split severity was expressed as SI-1-LogEnd ($R^2=0.33$, $p<0.01$) or SI-2-LogEnd ($R^2=0.36$, $p<0.01$). Mean displacement, when divided by DBHOB, was also significantly correlated with spring in the dried boards ($R^2=0.33$, $p<0.01$) and with the percentage of dried boards where spring exceeded 10 mm ($R^2=0.43$, $p<0.01$).

- The average total tangential shrinkage (normal shrinkage plus collapse) of the core specimens was approximately 12%. The total average radial shrinkage was quite high at 7%. On an individual log basis, the tangential shrinkage of cores was not significantly correlated with log end splits or the displacement.

- MFA was significantly and negatively correlated with spring in the dried boards ($R^2=0.18$, $p<0.05$), the percentage of boards where spring exceeded 10 mm ($R^2=0.31$, $p<0.01$), and the displacement ($R^2=0.18$, $p<0.05$). MFA and the displacement jointly accounted for 39% of the variation in the percentage of dried boards with greater than 10 mm spring.
Cellulose crystallite width exceeded 3.4 nm, the suggested threshold value between normal wood and tension wood, in 12 trees and its cumulative occurrence took 20-36% of the tree diameter, indicating quite high presence of tension wood in these trees.

Density and cellulose crystallite width, as tree means, and the percentage of cellulose crystallite width measurements that exceeded 3.4 nm per tree, were not significantly correlated with any parameters describing log end splits, or spring in the dried boards, or the displacement.

Application of Results

Mean displacement showed good potential to be used in conjunction with DBHOB in the prediction of a number of important quantities such as log end split severity (Split Index 2), spring in the dried boards and the percentage of excessively distorted dried boards.

New methods were developed to:

- quantify the overall severity of log end splitting using split indices, and
- determine the loss of sawn recovery associated with growth stress release by estimating the volume of the curved-edge off-cuts.

Both methods are simple and practical to use in future research and may be refined into a usable tool for in-field/in-mill use.
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INTRODUCTION

Eucalyptus globulus Labill. is the most extensively planted eucalypt species in Australia, with an Australian estate of approximately 395,000 ha in June 2002 (NFI 2003).

The majority of these blue gum plantations have been targeted for wood chip export. Of the total blue gum estate in Australia, a substantial area is more than 150 km from the shipping ports; a distance beyond which it is currently considered uneconomic to transport woodchips. In addition, much of the area planted with blue gum within an economic transport zone may not be under any contract for sale as woodchips. Growing plantations to produce logs suitable for a wider range of products could be of economic benefit to individual farmers and tree growers, and to the rural community, by increasing income and providing additional employment.

One of the key factors limiting higher-value use of young eucalypts as sawlogs is high growth stress (Malan 1997; Garcia 1999; Muneri et al. 1999; Waugh 2000; Maree and Malan 2000; Yang et al., 1996, 2002a; Yang and Waugh 2001). The release of residual internal stresses results in:

- log end splitting;
- flitch/cant moment and further splitting of the log end splits during sawing;
- sawn board distortion and thickness variation; and
- reduced choices of sawing patterns.

Sawn board distortion of various severities has been reported in plantation blue gum (Thomson and Hanks 1990; Brennan et al. 1992; Waugh and Yang 1993; Moore et al. 1996; Northway and Blakemore 1996; Yang and Waugh 1996). Recent studies on 59, 10-year-old blue gum trees showed that distortion alone caused up to 40% rejection of sawn boards as feedstock¹, and the log surface strain and log diameter in combination accounted for up to 42% of the total variation in the percentage of excessively distorted boards (Yang et al. 2002a).

Utilizing plantation-grown eucalypt material for sawn timber is not common in Australia. The results of various studies have differed and inconclusive. Very little is known about the quantitative effect of growth stresses on sawn timber quality and recovery. Also, there is no eucalypt breeding program in Australia for reducing growth stress because little is known about threshold levels of growth stress, the heritability of wood properties that govern growth stress, and the genetic correlations between these properties and other key wood properties. This project aimed to investigate the connections between the strain estimated at the surface of standing trees and sawn timber distortion and log end splitting.

The objectives of this project were to:

1. Quantify the relationship between sawn timber distortion and log end splitting with the strain estimated at the surface of standing trees.
2. Investigate the impact of log end splitting on sawn timber recovery.
3. Use wood characteristics that were measured on cores taken at tree breast height to identify trees prone to excessive sawn board distortion and log end splitting.

¹ AS2796.1 defines feedstock as sawn and partially processed boards intended for further processing into sawn or milled products, and may be supplied at any moisture content. The spring limit for boards of 40x100x3600 mm as feedstock is 42 mm.
The expected outcomes were an improved understanding of the potential for plantation grown eucalypts to produce high quality sawlogs by providing information on:

1. Estimation of the strain at tree periphery in blue gum;
2. The impact of surface strain and other wood properties on sawn timber recovery of plantation grown logs that were selected for processing in conventional sawing systems; and

This project was conducted on logs selected for a CSIRO Forestry and Forest Products project that was established with support from the Department of Sustainability and Environment (DSE) of Victoria. These logs were believed to contain low occurrence of tension wood and were capable of being sawn in a conventional sawmill. These two projects were conducted concurrently to maximize the research opportunities.

To assist in the comprehension of this report, several terms are defined below:

1. Unless otherwise specified, ‘growth strain’ and ‘growth stress’ refer to the longitudinal strain and stress at tree stem surface, respectively.
2. The surface strain in this study was estimated using a CIRAD-foret method, which measures the longitudinal displacement of two reference points after the release of stresses at the stem surface. These displacement values are neither surface strain, nor growth strain, but are often loosely referred to as growth strain for convenience. In several places of this report, the words ‘growth strain’ refer to the longitudinal displacement measured by the CIRAD-foret method.
3. The experiments were designed to measure wood properties at breast height and collect data from butt logs and from sawn boards from the butt logs. Hence, the data primarily represents the lower section of the tree stems. For reasons of readability, however, words like ‘tree mean’ or ‘tree average’ have occasionally been used to refer to ‘log average’ or ‘log mean’ in this report.
4. This project only intended to determine total shrinkage (normal shrinkage plus collapse). In other words, no re-conditioning treatment was applied to the shrinkage specimens and only total radial and tangential shrinkages are documented. For ease of reading, total radial shrinkage and total tangential shrinkage are abbreviated as radial and tangential shrinkage respectively.
MATERIAL AND METHODS

Tree selection
Sixty dominant or co-dominant straight trees with good stem form were selected from a 32-year-old thinned plantation of *E. globulus* grown at South of Traralgon in central Gippsland, Victoria (Fig. 1). The trees were owned by Grand Ridge Plantations. Thirty trees that showed relatively low occurrence of tension wood were selected for a DSE funded project (Washusen *et al.* 2004). These same 30 trees were used in this project for wood property measurements at breast height and assessment of sawn timber recovery of the butt logs.

Fig. 1. The 32-year-old blue gum plantation where the study trees were collected.

Growth strain estimation
Growth strain at breast height was estimated using a CIRAD-forêt method at four circumferential locations corresponding to the North, South, East and West cardinal directions.

With the CIRAD-forêt method (Fig. 2), a piece of bark (approximately 200 mm long and 100 mm wide) is removed from a standing tree to reveal the fresh wood surface. Using a guide that helps vertical alignment, two notched pins are punched into the wood, and a small indentation is made at the same time at the mid-distance between the two pins. The nominal distance between the two pins is 45 mm. A steel measurement frame that is connected to a digital dial gauge, reading to 0.001 mm resolution, is then hung on the upper pin, with its spring feeler touching the lower pin. The gauge reading is set to zero prior to drilling. A hole of 20 mm in diameter is manually drilled at the small indentation in the radial direction to a depth of 20 mm or until the gauge reading stabilizes. The distance between the two pins, or between the top and bottom edges of the hole, increases in the longitudinal direction if the wood is under tension and vice versa. The displacement (d) between the two pins is displayed by the gauge and recorded. The longitudinal strain ($a_L$) can be estimated using the equation $a_L = \frac{F \cdot d}{E_L \cdot a_L}$. F is a function of the hole diameter, the original distance between the two pins, MOE values in the longitudinal and tangential directions, shear modulus parallel to the wood grain, and Poisson coefficient. Stress can be determined from the strain value and the longitudinal Young’s modulus ($E_L$), using: $\sigma_L = -E_L \cdot a_L$. Since it is impractical to obtain F value for each single wood specimen, mean F is often used in the calculation of $a_L$ values for different wood
specimens from the same tree species. In other words, F is treated as a constant for wood specimens from the same tree species, and the estimated strain values, \( a_1 \), only vary with, and are proportional to, the displacement values \( d \). Because of this, users of the CIRAD-forêt method usually only report the displacement values \( d \) and use it as an estimate of the longitudinal strain. Detailed information about the CIRAD-forêt method can be found in Baillères (1994) and Yang et al. (2002b).

The angle of spiral grain was observed in the debarked window and visually estimated and recorded.

Increment core collection
Two diametrical cores were taken from each tree at breast height in the North-South direction. Two shorter increment cores (30 mm length) were also taken from the East-West side of the tree respectively, adjacent to and below the displacement measurement locations (Fig. 3).

![Fig. 3. The type of cores and their circumferential locations at breast height.](image)

SilviScan measurements
One set of the diametrical cores were treated with nearly pure ethanol (99.7 – 100% v/v) to replace water so that drying collapse was prevented or minimized. These cores were dried at room temperature and processed into SilviScan-2 samples, 2 mm thick in the tangential direction and 6 mm high in the longitudinal direction. SilviScan-2 was used to scan these
samples at 20 µm incremental steps for density (at nominal moisture content 10%), and at 5 mm incremental steps for microfibril angle (MFA) and cellulose crystallite width.

**Shrinkage measurements**

The 2nd set of the diametrical cores was sawn to strip specimens with a nominal 9 x 9 mm cross-section area (tangential x longitudinal). The tangential dimension of each green specimen was measured at several locations along the specimen length and the average was taken as the mean green tangential dimension (MGT). Due to variations in core processing and manual measurements, the mean green tangential dimension varied between specimens. Thin lines were marked on the transverse surface of each specimen at 5 mm spacing starting from the pith (Fig. 4). The specimens were dried in a 12% equilibrium moisture content (EMC) room. The radial distance between each pair of pre-marked lines and a tangential dimension at each pre-marked line were then measured (Fig. 4).

**Fig. 4.** A shrinkage specimen (a trimmed core) and the marked lines for measuring radial and tangential dimensions along the specimen length.

Radial shrinkage for the section between each pair of the pre-marked lines was calculated as the difference between 5 mm and the radial distance between the pre-marked lines after drying, and divided by 5 mm (Equation 1).

\[
\text{Radial shrinkage (RS)} = \frac{(5-R)}{5} \times 100 \% \quad (1)
\]

Mean specimen radial shrinkage was calculated as the difference in total specimen length before and after drying, and divided by the total green (before drying) specimen length (Equation 2).

\[
\text{Mean radial shrinkage} = \frac{\text{green length} - \text{dry length}}{\text{green length}} \times 100 \% \quad (2)
\]

Tangential shrinkage at each pre-marked line was calculated as the difference between the mean green tangential dimension (MGT) and the tangential dimension at the line after drying (T), and divided by the mean green tangential dimension (Equation 3).

\[
\text{Tangential shrinkage (TS)} = \frac{(\text{MGT}-T)}{\text{MGT}} \times 100 \% \quad (3)
\]

The number of radial and tangential shrinkage values for a specimen depended on the length of the specimen. The mean tangential shrinkage for the North and South radii of a log, and the mean radial and tangential shrinkage of a log, were also calculated for all the logs.

**Sawing**

The 30 trees were harvested in April 2003, transported to the Black Forest Sawmill in Victoria the following day and stored under water spray. The characteristics of log end splits (split length on log end, split length on log surface, and split width at log periphery) were measured for each butt log the day before sawing in June 2003. The length of radii corresponding to the four cardinal directions was also measured on the large end of each log.
A combination of colours and print patterns was used to identify the four quarters (North-East, East-South, South-West, and West-North) on the large end of each log to assist with identification of the boards within each log (Fig. 5).

The logs were quarter-sawn at the Black Forest Sawmill in late June 2003. The sawing strategy, as outlined in Fig. 6, was to break down the log into two halves and break each half into three flitches using a twin edger, quarter-saw the flitches into 28 mm thick slabs at a two-man re-saw bench (a circular saw), and area the slabs to widths using a multi-saw re-saw.

Some of the slabs were sawn to widths at the two-man bench. The nominal kerf widths were 6 mm for the break-down twin edger, 5 mm for the two-man bench, and 5 mm for the multi-saw re-saw. The nominal width of the central flitch was set to satisfy two conditions: it was approximately one third of the log diameter and not smaller than 130 mm. This 130 mm was
the sum of the thickness of four quarter-sawn green boards and three saw kerf (4x28 + 3x6 = 130 mm). Because the logs were large, the width of the cant could be set at 130 mm, 164 mm or 198 mm. The nominal green dimensions of the boards were 28x57x3000 mm, 28x77x3000 mm, 28x105x3000 mm, 28x140x3000 mm, and 28x163x3000 mm. The most common dimensions were 28x105x3000 and 28x77x3000 mm.

**Estimate of the loss of recovery due to distortion in green slabs**

The original work plan was to measure spring in green slabs. However, this plan had to be aborted later for safety reasons. Rather than measuring the distortion in slabs directly, the impact of distortion in slabs on sawn recovery was assessed indirectly by estimating the volume of the curved-edge off-cuts as explained below.

The re-saw process was to turn slabs into boards. This process usually yielded two curved-edge off-cuts from each slab, which often differed in size and shape. Two simple situations are illustrated in Fig. 7. In one situation, only one board was cut from a slab; in the second situation, two boards were cut from a slab (Fig. 7).

The off-cut A (Fig. 7) typically has one curved edge, one nominal straight edge, and a thickness similar to the board (28 mm in this case). It can be further divided into two components, the curved-edge component (A1 in Fig. 7) and the straight-edge component (A2 in Fig. 7). The volume of the off-cut A was generally but not significantly larger than the volume of the off-cut B (Fig. 7).

![Fig. 7. Illustration of two off-cut pieces (the shaded area A and B) from each slab in two simple re-saw situations and how to estimate the volume of these off-cuts by approximating a curved-edge object as a triangle-shaped object (C). H is the point of maximum width.](image)

Most of the curved-edge off-cuts from the convex side (A in Fig. 7) were recovered during sawing. The maximum width of each off-cut (H in Fig. 7) was measured after sawing. The remaining spring in sawn boards was measured at the green chain during sawing.

The volume of the curved-edge off-cuts per slab was estimated under two assumptions: (1) the sizing cuts took place on both sides of a slab and the two off-cuts A and B were of equal
volume, and (2) each off-cut was approximately a triangle-shaped object (object C in Fig. 7). The approximate volume of a curved-edge off-cut can then be calculated from the height of the triangle (H) and the length and thickness of the board (3000 mm and 28 mm, respectively) using Equation 4. The approximate volume of the curved-edge off-cuts per slab was twice the volume of the triangle-shaped object.

$$\text{Volume} = \frac{\text{length (3000mm)} \times \text{height (H)} \times \text{thickness (28mm)}}{2} \quad (4)$$

**Drying**

To treat the blue gum boards against lyctid, the green boards were block-stacked and dipped in a 10% m/v solution of Diffusol Wood Preservative Concentrate (a diffusible Boron formulation), then wrapped in plastic for 6 weeks, prior to drying. The boards were dried at the sawmill using its drying schedule. See Washusen *et al.* (2004) for details of the drying schedule.

**Measurement of spring and end splits in dried boards**

After drying, spring and the length of end splits that were linked to the initial log end splits were measured (Fig. 8). These splits had a distinct stained appearance when viewed from the end of the boards. Bow was not measured before and after drying because it was small.

In assessing board distortion, the spring limit of 10 mm was adopted from the CSIRO-FFP grading criteria for appearance sawn products that are 100 mm wide and 3000 mm long. These grading criteria were very similar to the current Australian Standard for hardwood sawn and milled products (AS 2796.1) but defined the limit for each type of defects more precisely. The proportion of dried boards that exceeded 10 mm spring was calculated for each log as the number of dried boards exceeding the 10 mm limit divided by the total number of dried boards from that log, expressed as a percentage. This expression not only reflects the severity of board distortion but also has a practical meaning to sawmills to assist them to identify the source of lost sawn recovery and lost productivity.

It was assumed that the dried boards would be end-docked so that the end splits are removed and the boards are cut to commercial lengths simultaneously. The volume of the docked ends per board was equal to the total effective length of the splits in that board multiplied by the cross-sectional size of that board. The volume of the docked ends for a log is the sum of the docked-end volume of all the boards from that log. The presence of wide splits may cause some complication to the calculation. When a single-saw system is used to cut a log
containing wide splits, the sawyer tends to cut through the major split (the saw line is parallel with the splits, Fig. 9). The flitch on each side of the saw would be under size at its end (Fig. 9), therefore the potential effect of a wide split on sawn recovery is twice as much as that of narrow splits. This situation was rare in this study as the log end splits were less than 6 mm wide.

**RESULTS AND DISCUSSION**

**General observations on the trees**

The mean DBHOB was 461mm, ranging from 372 to 580mm. Eleven trees showed noticeable spiral grain of up to 20° at the stem surface. Spiral grain was observed in at least one debarked window in every tree, and was seen in all four debarked windows of one tree.

Almost every butt log had a much longer radius at the West side and consequently a much shorter radius at the East side (Table 1). The difference in growth ring width between the West and East sides was much greater near the pith, indicating the eccentric growth occurred at greater pace when the trees were young.

**Table 1.** Mean values of radii and the displacement at each cardinal direction (n =30).

<table>
<thead>
<tr>
<th>Properties</th>
<th>North</th>
<th>East</th>
<th>South</th>
<th>West</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean radius (mm)</td>
<td>204</td>
<td>197</td>
<td>207</td>
<td>257</td>
<td>216</td>
</tr>
<tr>
<td>Mean radius / DBHOB (%)</td>
<td>50</td>
<td>43</td>
<td>45</td>
<td>56</td>
<td>47</td>
</tr>
<tr>
<td>Mean displacement (mm)</td>
<td>0.094</td>
<td>0.087</td>
<td>0.088</td>
<td>0.103</td>
<td>0.093</td>
</tr>
</tbody>
</table>

**Growth strain**

The displacement varied from 0.012 to 0.218 mm among individual measurements. The West (wider) side of the trees had the highest displacement (Table 1). Whilst this seems to indicate a connection between the pith eccentricity and the displacement magnitude (Table 1), surface strain cannot always predict pith eccentricity or vice versa (Nicholson *et al.* 1975). This is because growth strain changes in response to the tree needs and environmental conditions.
Such variation is a dynamic process and can be independent of the wood structure that is formed earlier and does not change much with time (e.g. growth ring width). As a support evidence to this point, no significant difference in the displacement was found between any two cardinal directions or between one cardinal direction and the tree average displacement. This also suggests that for this plantation, one displacement measurement per tree at a random circumferential location would be sufficient to obtain an indication of average tree surface strain.

The maximum displacement per tree was highly correlated with and significantly higher than the mean displacement (p<0.01). It was also significantly higher and closely correlated with the displacement at each cardinal direction (R^2=0.766 for North; R^2=0.606 for South; R^2=0.717 for East; R^2=0.632 for West). In contrast, the displacement between the cardinal directions was correlated at a low or modest level, with R^2 ranging from 0.16 to 0.54.

There was no apparent connection between the displacement and the presence or degree of spiral grain. Wood that had straight grain or small spiral grain (e.g. 5°) could have low (0.040 mm) or high displacement value (0.140 mm), and wood that had large spiral grain (e.g. 20°) could also have low (0.066 mm) or high displacement value (0.125 mm).

Log end splits
Log end splits normally occur as 4 splits (like a cross) or 3 splits. They were not severe overall and appeared as small cracks about 1 to 2 mm wide on the large ends of most logs. Only in 16 logs, the log surface splits had been wide enough and could be observed next to the large log ends. No log surface splits were observed next to the small log ends. Severe end splits occurred in only two logs where the split width was 3 mm or above and the total split length on the log surface was greater than 400 mm. The extent of the splits on the log surface could not be accurately determined with the naked eye because the mud filled these splits almost completely. The overall low level of end splitting may be attributed to stronger mechanical properties of blue gum in comparison to other species such as E. regnans.

The small log ends had noticeably far fewer splits, which also appeared as fine cracks. End splits on the small log ends were therefore recorded as zero. Splits on the small log end were rarely aligned with those on the large log end, as frequently observed in logs of other species.

Overall, wide splits (3 mm and above) split longer along the log axis. However, relationship between the split width on log ends and the split length on log surface did not seem to be consistent for narrower splits. A reliable regression between split width on the log ends and split length on the log surface will be very useful in log quality assessment as it enables the split length to be predicted from the split width, which is easily measurable on the log ends. However, such a relationship was not forthcoming from this study partly because the data set was skewed towards zero.

Spring in sawn boards before and after drying
Of the total 503 boards, 26% (129 boards) showed various amounts of spring in the green state, mostly below 10 mm except in 15 boards (Table 2). Assuming the boards remained straight or sprung little after passing the multi-saw re-saw, some of these 129 boards would have come out from the two-man bench, which was unable to produce straight boards from a cant that already had spring.

Spring not only increased in these 129 boards but also formed in other originally straight boards during drying. Spring increased by an average 5 mm during drying and reached severe magnitude (e.g. spring > 30 mm) in some boards (Fig. 10). The maximum increase in spring in a single board was 37 mm. Most boards sprang in the same direction during drying but seven boards sprang in the opposite direction. Only 6 boards remained straight during drying.
Spring measured after drying is the distortion from the release of log internal stress plus the
distortion caused by differential longitudinal shrinkage during drying (Kliger et al. 1996). It
was found that spring before and after drying was not significantly correlated.

Table 2. Data for spring and the lost recovery due to sizing cuts and docking of end splits.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Sample size</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring in green boards (mm)</td>
<td>129 boards</td>
<td>6</td>
<td>4</td>
<td>2 - 20</td>
</tr>
<tr>
<td>Spring in dried boards (mm)</td>
<td>503 boards</td>
<td>11</td>
<td>7</td>
<td>0 - 40</td>
</tr>
<tr>
<td>Spring in dried boards (mm)</td>
<td>30 logs</td>
<td>11</td>
<td>3</td>
<td>7 - 21</td>
</tr>
<tr>
<td>Boards with greater than 10 mm spring (%)</td>
<td>30 logs</td>
<td>43.0</td>
<td>23.6</td>
<td>0 - 87.5</td>
</tr>
<tr>
<td>Width of curved-edge off-cuts (mm)</td>
<td>368 boards</td>
<td>24</td>
<td>13</td>
<td>5 - 82</td>
</tr>
<tr>
<td>Volume of curved-edge off-cuts per log (%)</td>
<td>30 logs</td>
<td>6.0</td>
<td>1.9</td>
<td>1.1 - 9.6</td>
</tr>
<tr>
<td>Volume of end docking per pre-docking</td>
<td>30 logs</td>
<td>3.76</td>
<td>3.02</td>
<td>0.7 - 13.5</td>
</tr>
<tr>
<td>board volume (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume of end docking per log (%)</td>
<td>30 logs</td>
<td>0.97</td>
<td>0.76</td>
<td>0.2 - 2.9</td>
</tr>
</tbody>
</table>

It was found that every log, except one, yielded dried boards with greater than 10 mm spring.
The mean percentage of dried boards exceeding 10 mm spring for the 30 logs was 43% and
reached 88% for one log (Table 2).

Generally, the dried boards need to be trimmed down to appropriate sizes and to remove
excessive spring to make saleable wood products in the next stage. The recovery and value of
the final sawn products will be affected by the magnitude of spring before trimming. This was
not determined in this study as it was beyond the project scope. It will be a very useful and
interesting exercise in future studies to quantify these losses.

Fig. 10. A dried board that developed severe spring (40 mm) during drying.

There was no apparent link between spring in the dried boards and the spiral grain observed
on the log surface. However, a log would have a high number of largely distorted dried
boards if it had both large surface strain (the displacement) and large spiral grain. For
example, the log that had the highest percentage of boards with greater than 10 mm spring
had an average displacement of 0.129 mm and spiral grain of 20° on two opposite sides of the
log. This log had a smaller DBHOB of 379 mm, which could have also contributed to the
larger spring in the boards.
End splits in dried sawn boards

Forty-seven percent of the dried boards had end splits. The longest end split was 810 mm and the average length was 165 mm. End splits in the dried boards are a combination of initial log end splits and their possible extension during drying in response to differential longitudinal shrinkage across the boards.

Loss of recovery due to removal of curved edges and end splits

The loss of sawn recovery occurs at several processing stages. Whereas saw kerf is a major source of the loss, this project only dealt with sizing cuts that remove the curved edges in green slabs and end-docking\textsuperscript{2} that removes end splits in the dried boards.

The loss of sawn recovery due to removal of the curved edges in slabs per log was calculated as the volume of the curved-edge off-cuts divided by the log volume and multiplied by 100. The average loss was found to be 6\% for the 30 logs (Table 2) and reached over 8\% for five logs. If the recovery of green sawn boards is 38\% and the volume loss of the curved-edge off-cuts is 6\%, then for an average log of 0.38m\textsuperscript{3} (200 mm radius and 3000 mm length), the green recovery would drop from 38\% (0.14m\textsuperscript{3}) to 32\% (0.12m\textsuperscript{3}). At an average price of $360/m\textsuperscript{3} for green sawn timber, the value of the lost recovery is $7.20 ($360 \times 0.02m\textsuperscript{3}) per log or $18.95 per cubic metre of logs. While this value seems low on a log basis, a mill must also consider that the costs of removing the curved edges may have a significant effect on the efficiency of the mill. The 6\% loss of log volume is partially associated with the quarter-sawn strategy and may be reduced if the logs were back-sawn. On the other hand, the loss could have been higher if a normal log sample from this plantation were used in this study. Also, the removal of spring in the dried boards would incur additional loss of wood and loss of productivity.

Approximately 4\% of the dried board volume would be lost as a result of end docking (Table 2). This value drops to approximately 1\% if the loss is expressed as a percent of log volume (Table 2). If the recovery of dried sawn product is 26\% and the volume loss of dried sawn product due to end docking is 4\%, then for an average log of 0.38m\textsuperscript{3} (200 mm radius and 3000 mm length), the lost volume due to end docking would be 0.004m\textsuperscript{3} (0.38m\textsuperscript{3} x 26\% x 4\%). At an average price of $914/m\textsuperscript{3} for dried sawn product, the value of the lost product is $3.66 ($914 \times 0.004m\textsuperscript{3}) per log or $9.63 per cubic metre of logs.

The above analysis shows that the loss in product value at $18.95/m\textsuperscript{3} due to sizing cuts is almost twice the loss in product value at $9.63/m\textsuperscript{3} due to log end splitting\textsuperscript{3}. While neither the end split loss nor the curved-edge off-cut loss will ever be entirely eliminated, it may be worthwhile for a mill owner to have an indication of the extent of the loss, via a wood quality index, in order to better negotiate log prices.

Relationship between surface strain and severity of log end splits

The length of end splits on the log surface was given more attention in data analysis because of its greater impact on sawn recovery than other features of the end splits. End splits at the small ends of the logs were excluded from data analysis because the displacement was measured at tree breast height, being much closer to the large ends of the logs.

A simple way to describe the severity of log end splits is to use the split length on the log surface without considering the split length on the log ends. It was found that the split length on the log surface was significantly and weakly correlated with only the displacement in the North-East quarter\textsuperscript{3} of the tree stem. The sign of the correlation was not consistent for data from the other three tree cross-sectional quarters, being positive for the North-East quarter but negative for the North-West and South-West quarters. The skewed data set seem to be the

\textsuperscript{2} It is assumed that end docking was applied at a later processing stage to remove end splits in the dried boards.

\textsuperscript{3} The displacement for the North-East quarter is the average of displacement measured on the North side and displacement measured on the East side of the tree stem.
main reason (quite a few tree cross-sectional quarters had zero values for the split length on the log surface). For the same reason, the correlation was weak between the tree mean displacement and the sum of the lengths of all the splits on the surface of the corresponding log.

To overcome the skewed data problem, another method was developed to use split indices to quantify the severity of log end splits. Both indices included the split length on the log ends and on the log surface. The Split Index 1 (SI-1) and Split Index 2 (SI-2) for a single split were calculated using Equations 5 and 6, respectively. In deriving SI-2, the following assumptions were made to simplify the calculation: (1) each split has a split plane inside the log, which has the shape of an isosceles right-angled triangle, regardless whether the split has extended to log periphery or not, and (2) when a split propagates from the periphery down on the log surface (SL_{END} > 0), the inner split plane also extends at the same distance along the log axis (Fig. 11).

![Diagram of symbols used in calculating Split Index 2 (SI-2). The shaded area is the inner split plane.](image)

**SI-1-Single**

\[
SI-1\text{-Single} = \frac{SL_{\text{END}} + SL_{\text{SURFACE}}}{R_{\text{MEAN}}} \tag{5}
\]

**SI-2-Single**

\[
SI-2\text{-Single} = \frac{[(SL_{\text{END}} \times A / 2) + (SL_{\text{SURFACE}} + B) \times SL_{\text{END}} / 2]}{R_{\text{MEAN}}^2} = \frac{[(SL_{\text{END}} \times SL_{\text{END}} / 2) + (SL_{\text{SURFACE}} \times SL_{\text{END}})]}{R_{\text{MEAN}}^2} \tag{6}
\]

Where:

- \( SL_{\text{END}} \) = split length on the log end
- \( SL_{\text{SURFACE}} \) = split length on the log surface
- \( R_{\text{MEAN}} \) = mean radius of the log end
- \( A \) = a shorter side of the isosceles right-angled triangle and equals \( SL_{\text{END}} \)
- \( B \) = part of the inner vertical side of the split plane and equal to \( SL_{\text{SURFACE}} \) when \( SL_{\text{SURFACE}} > 0 \)

There is little knowledge about the actual shape of the split plane in published literature. The actual shape may be quite different from an isosceles right-angled triangle; it may vary between logs and may easily take a three-dimensional shape in the presence of deviated wood grain. The assumptions for Equations 5 and 6 are relatively crude and can be improved in the future.
Neither of the split indices has a unit since SI-1 was weighted by the mean radius and SI-2 was weighted by the mean radius squared (this weight factor is equivalent to the log cross-sectional area while p is a constant).

The split indices can also be calculated for a log end. SI-1-LogEnd equates to the sum of all SI-1-Single values at a log end. Similarly, SI-2-LogEnd equates to the sum of all SI-2-Single values at a log end. One advantage of SI-1-LogEnd and SI-2-LogEnd is that they reflect the overall splitting severity of a log end, therefore are more adequate for data analysis. The other advantage is that zero SI-1-LogEnd and SI-2-LogEnd values can be avoided unless a log end does not have any splits at all.

Relationships between the displacement and the split indices within each individual cross-sectional quarter of the logs were examined by using the split index (SI-1 or SI-2) for individual splits and the displacement values from the corresponding cross-sectional quarters. It was found that the displacement was positively and weakly correlated with both SI-1 and SI-2 (p<0.05) only for the North-East and South-East quarters, and there was no significant relationship for the other two quarters. This indicated that a single strain value cannot well predict the severity of a split on the same side of the log. During the process of displacement measurement, drilling on one side of the tree stem is unlikely to have much of an effect on the stress field on the other side of the tree stem. This is especially true for large trees as used in this study. However, when a tree stem is cross cut, the development of end splits may not be independent from each other. If this is true, it may then partly explain why the split indices for individual splits were not or were only weakly correlated with the displacement for any cross-sectional quarter of the logs.

Relationships between mean displacement and SI-1-LogEnd and SI-2-LogEnd were also examined. The relationship at the log-end level was much stronger. The $R^2$ was 0.25 for the correlation between mean displacement and SI-1-LogEnd, and was 0.28 for the correlation between mean displacement and SI-2-LogEnd. By bringing DBHOB into the relationship, the $R^2$ values were considerably improved to 0.33 and 0.36 respectively (Fig. 12 and 13). These results are quite encouraging, considering both DBHOB and the displacement are easy to measure in the field.

\[ y = 0.09x + 1.55 \]
\[ R^2 = 0.32 \]
\[ N = 30 \]

![Fig. 12. Relationship between mean displacement multiplied by DBHOB and SI-1-LogEnd (p<0.01).](image)
Relationship between surface strain and volume of curved-edge off-cuts
There was no significant relationship between mean displacement and the volume of the curved-edge off-cuts (p>0.05). Using other forms of the displacement values (e.g. maximum displacement, or mean displacement divided by DBHOB) did not improve the relationship. This indicates that the distortion of flitches and slabs at the release of log internal stresses during sawing is a complex matter. Despite the lack of a correlation, the release of log internal stresses during sawing remains to be the most important cause of distortion in flitches, slabs and green boards. To understand how flitches and slabs move during sawing and how the movement is linked to log internal stresses, sophisticated stain measurement system and mechanical modelling will be needed.

Relationship between surface strain and spring in dried boards
Spring in the dried boards was positively correlated with mean displacement at breast height ($R^2 = 0.25$, p<0.01). The correlation became stronger ($R^2 = 0.33$, Fig. 14) if the displacement was divided by DBHOB. DBHOB was used as a weighting factor because it has a large influence on growth strain gradient across tree stem. A relationship between the displacement and spring in the dried boards does not appear intuitive because spring in the dried boards contained a drying-distortion component. The reason that they were moderately correlated is probably because some of the wood properties that determine the displacement are also the properties that affect the spring formation in boards during drying. There was no significant correlation between the maximum spring in the dried boards and mean displacement of logs.

The percentage of dried boards with greater than 10 mm spring was significantly correlated with mean displacement divided by DBHOB (Fig. 15). This result is similar to that of a previous study on 59, 10-year-old blue gum trees, which found the surface strain and DBHOB in combination explained 42% of the total variation in the percentage of excessively distorted boards (Yang et al. 2002a). The similarity in results inspires confidence in the validity of surface strain and log diameter as predictors of excessive distortion because the experimental methods and the spring limit were considerably different between the two studies.
Relationship between log end splits and volume of curved-edge off-cuts
Neither SI-1-LogEnd, nor SI-2-LogEnd, was significantly correlated with the volume of the curved-edge off-cuts. This was not surprising as the split indices are indicators of the overall split severity of the log ends whereas the volume of the curved-edge off-cuts is an indirect measure of spring in slabs. Log end splits and spring in slabs are both fundamentally linked to log internal stress but their formation and magnitude also depend on other factors.

Relationship between log end splits and volume of end docking
Some green sawn boards will inevitably contain end splits when the initial log end splits cannot be avoided during sawing. These splits may become longer during drying. The length of an end split in a dried board thus equals the length of the initial log end split plus the length of the new extension during drying. The volume of the lost wood due to log end splits will be over-estimated if any split length in dried boards is used to determine the volume of the lost wood. Another potential source of over-estimation is associated with the sawing system at Black Forest Sawmill that cut these logs. The twin-saw edger at this mill uses two “dogs” to hold and position the logs in log breakdown, which may have initiated new splits or worsened the existing splits. To prevent over-estimation, only the initial log end splits that were present in the dried boards were measured. These splits were quite easy to recognise as they were still covered with dry mud or stained with soiled water.

Fig. 14. Relationship between mean displacement divided by DBHOB and mean spring in the dried boards (p<0.01).

Fig. 15. Relationship between mean displacement divided by DBHOB and the percentage of the dried boards with greater than 10mm spring (p<0.01).
Significant and positive correlations were found between the volume of end docking (as a percentage of log volume) and SI-1-LogEnd ($R^2 = 0.31$, $p<0.01$) and SI-2-LogEnd ($R^2 = 0.32$, $p<0.01$). The volume of end-docking will also be affected by log size, sawing strategy and board dimensions, as these parameters determine how likely the log end splits can be prevented from occurring in sawn boards. Once a board is cut, the cross-sectional size of the board will determine the volume of end docking for a given length of end split; the smaller the cross-sectional size, the less the volume of end docking.

**Shrinkage characteristics and relationships**

The average tangential shrinkage was 11.9% with standard deviation of 3.4%. The average radial shrinkage was 6.8% with standard deviation of 1.2%. The tangential shrinkage was comparable with that of 59, 10-year-old blue gum trees of Jeeralang province (Yang et al. 2002c) but the radial shrinkage was almost twice as high in this study. The typical pattern of tangential shrinkage along a tree radius is similar to that for trees 6 and 52, generally increasing from the pith towards the bark (Fig. 16). A few trees were exceptions such as tree 5 (Fig. 16). In almost every specimen, tangential shrinkage decreased sharply in the sapwood zone because sapwood normally collapses very little during drying. It is unclear from the current data whether tangential shrinkage would more or less stabilise after trees reach certain age.

Mean radial shrinkage measured on the trimmed core specimens from the North and South radii was significantly correlated with the displacement measured on the corresponding side of the tree stems. The relationship holds when radial shrinkage and the displacement were respectively averaged over the North and South radii. Mean tangential shrinkage, however, was significantly correlated with the displacement only for the North radius after excluding two outliers ($R^2 = 0.36$, $p<0.01$, negative correlation). The potential of using the displacement measurements as an indicative of mean tangential shrinkage along the full radius therefore remains doubtful.

Tangential shrinkage was significantly and negatively correlated with spring in the dried boards ($R^2=0.19$, $p<0.05$), but the meaning of this relationship is not clear. High tangential shrinkage (either individual measurements or mean values) can be a good indicator of tension wood; the co-presence of tension wood and normal wood in a board can cause the board to distort during drying due to a large longitudinal shrinkage differential across the board during drying. From this point of view, tangential shrinkage should be positively correlated with spring in dried boards. To improve our understanding of this matter, further studies need to be carried out on a board basis to ensure the data is more closely matched.
Mean tangential shrinkage was not significantly correlated with the split indices or the volume of the curved-edge off-cuts, indicating it has little potential as a quick, approximate, and non-destructive method to segregate logs into high or low splitting classes.

**SilviScan data and relationships**

The statistics for the area-weighted SilviScan measurements are given in Table 3. The correlation coefficients for correlations between wood quality measurements (the displacement and SilviScan data) and log quality parameter (SI-2) and product quality parameters (spring, loss of sawn recovery, tangential shrinkage) are given in Table 4.

**Table 3.** Data for area-weighted density, microfibril angle (MFA), modulus of elasticity (MOE), and cellulose crystallite width.

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Sample size</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>30 logs</td>
<td>775</td>
<td>41</td>
<td>697 - 867</td>
</tr>
<tr>
<td>MFA (degree)</td>
<td>30 logs</td>
<td>12.4</td>
<td>1.6</td>
<td>10.2 – 18.6</td>
</tr>
<tr>
<td>MOE (GPa)</td>
<td>30 logs</td>
<td>19.6</td>
<td>2.4</td>
<td>13.5 – 24.8</td>
</tr>
<tr>
<td>Cellulose crystallite width (nm)</td>
<td>30 logs</td>
<td>3.30</td>
<td>0.05</td>
<td>3.21 – 3.42</td>
</tr>
</tbody>
</table>

**Table 4.** Correlations coefficients for correlations between wood quality measurements and product quality parameters.

<table>
<thead>
<tr>
<th></th>
<th>Displacement</th>
<th>SI-2</th>
<th>Volume of curved-edge off-cuts (%)</th>
<th>Volume of end docking (%)</th>
<th>Spring in dried boards (mm)</th>
<th>% boards exceeding 10 mm spring</th>
<th>Tangential shrinkage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>-</td>
<td>0.53**</td>
<td>n.s.</td>
<td>n.s.</td>
<td>0.53**</td>
<td>0.56**</td>
<td>n.s.</td>
</tr>
<tr>
<td>Displacement / DBHOB</td>
<td>0.95***</td>
<td>0.39*</td>
<td>n.s.</td>
<td>n.s.</td>
<td>0.61***</td>
<td>0.65***</td>
<td>-0.38*</td>
</tr>
<tr>
<td>Density</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Cellulose ↔ crystallite width</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>MFA</td>
<td>-0.44*</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>-0.43*</td>
<td>-0.58**</td>
<td>0.53**</td>
</tr>
<tr>
<td>MOE</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>0.38*</td>
<td>0.49**</td>
<td>-0.50**</td>
</tr>
</tbody>
</table>

*: p<0.05, **: p<0.01, ***: p<0.001

Density was not significantly correlated with mean displacement, the volume of the curved-edge off-cuts, the volume of end docking, spring in the dried boards, the percentage of dried boards with greater than 10mm spring, and tangential shrinkage (Table 4), but was significantly and positively correlated with MOE ($R^2$=0.28, p<0.01) and cellulose crystallite width ($R^2$=0.26, p<0.01).

MFA was negatively correlated with mean displacement ($R^2$=0.18, p<0.05, Table 4). Similar negative relationships have been reported for several hardwood species (Okuyama et al. 1990, 1994; Yamamoto et al., 1992; Wahyudi et al., 1999), although the MFA and the displacement in this study were not measured on the matched specimens - the MFA was the tree average whereas the displacement was the mean displacement at tree surface at breast height. MFA was also negatively correlated with spring in the dried boards ($R^2$=0.18, p<0.05) and with the percentage of dried boards having greater than 10mm spring ($R^2$=0.31, p<0.01, Table 4). This clearly indicates the role of MFA in board distortion during drying. The negative correlations of these two quantities with MFA may be explained as follows. When MFA (either individual measurements or mean values) becomes smaller, tension wood is more likely to be present in the wood, hence the possibility of board distortion during drying increases as when normal wood and tension wood co-exist in a board, it will give rise to a larger longitudinal shrinkage.
differential across the board during drying. The percentage of dried boards with greater than 10mm spring was more closely correlated with MFA, in comparison to the mean spring of the dried boards (Table 2), probably because it had a much wider data range.

Significant and positive correlation was found between mean MFA and tangential shrinkage ($R^2=0.28$, $p<0.01$) in this study and requires some explanation. Decreasing MFA normally results in increasing tangential shrinkage (Harris and Meylan, 1965; Yang et al. 2003). This is because normal tangential shrinkage occurs across wood grain; the smaller the MFA, the larger the normal transverse shrinkage will be, given other conditions are the same. For hardwoods however, as MFA gets small, the likelihood of tension wood occurrence increases and there is a greater propensity for the wood to collapse during drying. By putting these two phenomena together, a negative correlation between MFA and (total) tangential shrinkage is possible. These results are evidence again that MFA has a potential to be used in the prediction of several important parameters that describe board distortion, in particular the percentage of dried boards exceeding a spring limit. In wood utilization, small MFA is normally preferred because it gives the wood a higher MOE assuming everything else is equal. However, many major eucalypts already have a modest to high MOE that is adequate for the appearance product market. Therefore, breeding for larger MFA in species that already have high MOE as a trade-off for reduced drying distortion may not necessarily cause a dilemma to wood quality improvement.

Cellulose crystallite width showed a general pattern of increasing from the pith with tree age (Fig. 17). There was little difference between the weighted (3.30 nm, Table 3) and the unweighted mean cellulose crystallite width (3.28 nm). The between-tree variation in the weighted mean cellulose crystallite width was relatively small, ranging from 3.21 to 3.42 nm (Table 3). The weighted mean cellulose crystallite width was significantly correlated with only density ($R^2=0.22$, $p<0.01$), but not with any other parameters measured in this study (Table 4).

It was recently suggested that 3.4 nm was the threshold value of cellulose crystallite width to separate tension wood from normal wood in blue gum (Washusen et al. 2004). If 3.4 nm is taken as the threshold value for blue gum, then 12 trees in this study contained appreciable amounts of tension wood, judging by the fact that tension wood took 20 to 36% of the diameter in these trees. The mean cellulose crystallite width of these 12 trees was 3.34 nm. It is also interesting to note that the mean cellulose crystallite width of the 30 trees in this project (3.30 nm) was much higher than the mean cellulose crystallite width (2.88 nm) of 59, 10-year-old blue gum trees from three provenances grown in Mt Gambier area (Yang et al. 2003). In fact, almost every single measurement of cellulose crystallite width in this project was above 3.0 nm (Fig. 17). The large difference in cellulose crystallite width between the two studies was partially caused by the difference in equipment operating conditions of SilviScan-2 when samples were scanned two years apart (pers. comm. R Evans). If cellulose crystallite width had negligible effect on green sawn recovery and board distortion as shown in this study, future studies on this property should be focused on its quantitative effect on internal check development during drying in the context of tension wood so that threshold values can be established for tree improvement.

Genetic differences will affect cellulose crystallite width invariably but site differences may have as much impact as genetics based on the data measured on 59, 10-year-old blue gum trees (unpublished$^4$). The data showed significant differences ($p<0.001$) in cellulose crystallite width between two sites and between three provenances (Jeeralang, King Island, and South East Tasmania).

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$^4$ The cellulose crystallite width data were measured during the study by Yang et al. (2002c, 2003).
The positive correlations of MOE with spring in the dried boards and with the percentage of boards with greater than 10 mm spring (Table 4) are a complex result. Whereas longitudinal shrinkage differential causes boards to distort during drying, the distortion is resisted by the stiffness of the wood. One therefore would expect a negative correlation between MOE and distortion in dried boards. One explanation for the positive correlation is provided as follows. Logs which had higher MOE also had smaller MFA because of the strong dependence of MOE on MFA as shown in this study ($R^2 = 0.67$ for correlation between tree mean MFA and MOE) and in other earlier studies (Evans and Ilic 2001; Yang and Evans 2003). When mean MFA becomes smaller, the possibility of the presence of individual tension wood bands or zones in the trees increases, hence the possibility of distortion formation during drying in the boards increases as when normal wood and tension wood co-exist in a board, it gives rise to a large longitudinal shrinkage differential across the board during drying. Although MOE increases with smaller MFA, the longitudinal shrinkage differential in the presence of tension wood might increase at a greater magnitude, so that board distortion would increase with smaller MFA (and higher MOE). The negative correlation between MOE and tangential shrinkage (Table 4) can also be explained from the view point of MFA and the link between smaller MFA and increasing possibility of tension wood presence.

CONCLUSIONS

Log end splits were not severe overall and occurred more often in the large ends of the logs. A new method was developed to quantify the overall severity of log end splitting with split indices. The estimated loss of sawn recovery due to end docking to remove end splits in the dried boards was equivalent to 1% of the log volume, or approximately 4% of the dried board volume. This equates to $3.66$ in lost product for an average log of $0.38 m^3$ (200 mm radius and 3000 mm length) or $9.63$ per cubic metre of logs, if log volume recovery of dried sawn product is 26% and the average price of dried sawn timber is $914/m^3$. For a mill processing $40,000 m^3$ per annum, the lost product value would be $385,000 per annum.

The loss of green sawn recovery associated with flitch or slab distortion was estimated based on the volume of the curved-edge off-cuts removed from the slabs. The estimated loss of green sawn recovery was equivalent to 6% of the log volume. This equates to $7.20$ in lost product for an average log of $0.38 m^3$ (200 mm radius and 3000 mm length) or $18.95$ per cubic metre of logs, if log volume recovery of green sawn product is 38% and an average price of green sawn timber is $360/m^3$. For a mill processing $40,000 m^3$ per annum, this loss would be $758,000 per annum.
The annual combined effect of log end splits and the curved-edge off-cuts on a 40,000m³ per annum sawmill would be over $1 million. This figure needs to be viewed in the context of quarter-sawn strategy and relatively low tension wood occurrence in the study logs. Understanding of the impact of log quality on sawmill profit should assist the processing industry to assess whether it is overpaying when purchasing logs.

Spring increased by an average of 5 mm during drying and reached over 10 mm in a number of the dried boards. If 10 mm was set as the spring limit, then 43% of the dried boards would have exceeded this limit and will need shortening or sizing cuts at a later stage to reduce or remove the excessive spring. This will incur further loss of wood and productivity.

Mean displacement (weighted by DBHOB) was significantly correlated with spring in the dried boards and the percentage of dried boards with greater than 10 mm spring. These relationships highlight the potential of growth strain as a sawlog quality indicator to indicate the probability of drying distortion in sawn boards, although further studies are needed on a board basis to identify the underlying wood properties responsible for these relationships.

Mean displacement (weighted by DBHOB) was significantly and positively correlated with log end splits (expressed as SI-1-LogEnd and SI-2-LogEnd), indicating the potential of using growth strain to predict the overall severity of log end splitting.

MFA was significantly and negatively correlated with the displacement, spring in the dried boards, and the percentage of dried boards with greater than 10 mm spring. Although the correlations were modest, MFA demonstrated a potential in predicting distortion in dried boards through having significant relationships with several important parameters that describe sawn product recovery and quality. MFA and the displacement jointly accounted for 39% of the variation in the percentage of dried boards with greater than 10 mm spring.

Neither density nor cellulose crystallite width, as tree means, were significantly correlated with the displacement or with any parameters that describe log end splits and board distortion.

The following work is recommended in the future to

- Develop accurate and efficient methods to determine the length of end splits on log surface, investigate the characteristics of inner split plane, and establish a relationship between the split depth inside a log and the split length on log surface.
- Develop a method to simulate the loss of green sawn recovery due to log end splits.
- Investigate the propensity and the degree of further extension of initial log end splits in sawn boards during drying, and investigate the reasons why spring developed and increased during drying and to what magnitude.
- Carry out a comprehensive study to quantify the loss of recovery at various log processing stages (log breakdown, green slab re-sawing, final sizing of dried boards).
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REFERENCES


APPENDIX A Modified CSIRO-FFP Grading Criteria
CSIRO Hardwood Appearance Product Assessment Criteria

Modified June 2002

Scope
Specifications apply to sawn eucalypt products for appearance applications and can be applied to dressed or dry rough-sawn products.

Grade Descriptions

(a) Polishing grade:
The wood will be graded in its entirety, on the worst defect and will be free of decay, stain, kino pockets, knots, borer and termite attack, end splits, wane and Lyctus-susceptable sapwood. The following specifications shall apply:

(i) Product orientation - Back-sawn products are acceptable only if graded dry, in which case, the prescribed allowance for checks will not be exceeded.

(ii) Product sizing - Minimum dimensions for dry rough-sawn products must be 3 mm greater than final dressed size and allowance must be made for shrinkage when grading green wood. Green sizing over a parcel must not vary by more than 2 mm.

(iii) Product length - Minimum 0.9 metre.

(iv) Moisture content - Average moisture content of 10%, with all pieces within the range of 7% to 12%.

In addition, the following imperfections will be allowed:

(i) Tight kino veins - Up to 1 mm in width and no greater than 1.5 mm on the graded surface. No greater than 600 mm in length for every square metre of surface and individually not exceeding 200 mm.

(ii) Spring - 8 mm in 3 metres length.

(iii) Bow - 10 mm in 3 metres length.

(iv) Surface checks - Of less than 1 mm in width and 2 mm depth, in aggregate length not more than 250 mm in 1 square metre and no more than one surface check in any 0.04 square metre (400 x 100 mm) area.

(v) Internal checks - As appearing on freshly docked ends. Must be confined to the middle of the thickness of the piece, not exceeding 1 mm in width and not exceeding 4 mm radially or extending through the late-wood. No more than 1 on any cross section less than 0.005 square metre (100 x 50 mm) area, or 2 in any larger cross-section.

(vi) Sloping grain - Not exceeding 1 in 20.

(b) Moulding grade:
The wood will be graded in its entirety, on the worst defect and will be free of decay, stain, kino pockets, borer and termite attack, end splits, wane and Lyctus-susceptable sapwood. The following specifications shall apply:

(i) Product orientation - Back-sawn products are acceptable only if graded dry, in which case, the prescribed allowance for checks will not be exceeded.

(ii) Product sizing - Minimum dimensions for dry rough-sawn products must be 3 mm greater than final dressed size and allowance must be made for shrinkage when grading green wood. Green sizing over a parcel must not vary by more than 2 mm.

(iii) Product length - Minimum 0.9 metre.

(iv) Moisture content - Average moisture content of 10%, with all pieces within the range of 7% to 12%.

In addition, the following imperfections will be allowed:

(i) Tight kino veins - Up to 1 mm in width and no greater than 1.5 mm on the graded surface. No greater than 1 metre in length for every square metre of surface and individually not exceeding 300 mm.

(ii) Spring - 8 mm in 3 metres length.
(iii) **Bow** - 10 mm in 3 metres length.

(iv) **Surface checks** - Of less than 1 mm in width and 3 mm depth, in aggregate length not more than 300 mm in 1 square metre and no more than one surface check in any 0.02 square metre (200 x 100 mm) area.

(v) **Internal checks** - As appearing on freshly docked ends. Must be confined to the middle half of piece thickness, not exceeding 1 mm in width and not extending through the late-wood. No more than 1 on any cross section less than 0.005 square metre (100 x 50 mm) area, or 2 in any larger cross-section.

(vi) **Sloping grain** - Not exceeding 1 in 20.

(c) **Select grade:**

The wood will be graded on the best face and both edges, which must be free of decay, borer holes, kino pockets, termite galleries, end splits, wane and Lyctus-susceptible sapwood. The back will be graded to cover grade (see below) except for the exceptions listed below. The following specifications shall apply:

(i) **Product orientation** - Back-sawn products are acceptable but must be sawn so that all wood is at least 60 mm or half product width, or whichever is the greatest from the pith.

(ii) **Product sizing** - Minimum dimensions for dry rough-sawn products must be 3 mm greater than final dressed product and due allowance made for shrinkage when grading green wood. Green sizing over a parcel must not vary by more than 3 mm.

(iii) **Product length** - Minimum 0.9 metre.

(iv) **Moisture content** - Average moisture content of 10%, with no more than 10% of pieces being within the range of 12% to 15%, all remaining pieces within the range of 7% to 12%.

In addition, the following imperfections will be allowed:

(i) **Tight kino veins** - Up to 1.5 mm in width and no greater than 2.5 mm on the graded surface. No greater than 1.5 metre in length for every square metre of surface.

(ii) **Light stain only**

(iii) **Spring** - 10 mm in 3 metres length.

(iv) **Bow** - 25 mm in 3 metres length, except for lining boards and strip flooring sizes, when up to 40 mm is allowable.

(v) **Wane and Lyctus susceptible sapwood** - On lining boards and strip flooring only. On the opposite face to that graded, for 25% of the width and lower edge only, for a maximum of 25% of the sawn face.

(vi) **Knots** - Tight green knots only, less than 20% of product width and no more than three per square metre of surface area.

(vii) **Surface checks** - Of less than 1 mm in width and 3 mm depth, in aggregate length not more than 1 metre in 1 square metre of surface area.

(viii) **Internal checks** - As appearing on freshly docked ends, not exceeding 1 mm in width and not extending through the late-wood. No more than 3 in 0.005 square metre (100 x 50 mm) area.

(ix) **Holes** - No more than 2 mm in diameter and no more than 10 per square metre of surface area.

(x) **Sloping grain** - Not exceeding 1 in 15.

(d) **Standard grade:**

The wood will be graded on the best face, which must be free of decay, borer holes of more than 5 mm diameter, kino pockets, termite attack, end splits, wane and Lyctus-susceptible sapwood. The following specifications shall apply:

(i) **Product orientation** - Back-sawn products are acceptable but must be sawn so that all wood is at least 60 mm or half product width, or whichever is the greatest from the heart (or pith).

(ii) **Product sizing** - Minimum dimensions for dry rough-sawn products must be 3 mm greater than final dressed size and allowance must be made for shrinkage when grading green wood. Green sizing over a parcel must not vary by more than 3 mm.

(iii) **Product length** - Minimum 0.9 metre.

(iv) **Moisture content** - Average moisture content of 12%, within the range of 9% to 15%.

In addition, the following imperfections will be allowed:
(i) **Tight kino veins** - Up to 1.5 mm in width. No greater than 3 metre in length for every square metre of surface.

(ii) **Light stain only**

(iii) **Spring** - 10 mm in 3 metres length.

(iv) **Bow** - 25 mm in 3 metres length, except for lining boards and strip flooring sizes, where up to 40 mm is allowable.

(v) **Wane and Lyctus susceptible sapwood** - On the opposite face to that graded, for 25% of the width and lower edge only, for a maximum of 25% of the sawn face.

(vi) **Knots** - Tight green knots and epicormic shoots (burls) only, no greater than 30% of product width and no more than six per square metre of surface area.

(vii) **Surface checks** - Of less than 1 mm in width and 5 mm depth, in aggregate length not more than 2 metre in 1 square metre of surface area.

(viii) **Internal checks** - As appearing on freshly docked ends, not exceeding 1 mm in width. No more than 6 in 0.005 square metre (100 x 50 mm) area.

(ix) **Holes** - Up to 2 mm in diameter and no more than 20 per square metre of surface area. From 2 mm to 5 mm, no more than 5 per square metre of surface area. In combination, one larger hole equates to four smaller holes.

(x) **Sloping grain** - Not exceeding 1 in 10.

(e) **Utility grade:**

The sawn product will be 2.4 metre length or longer and graded on the best face, which must be free of decay, holes greater than 8 mm diameter, kino pockets, termite galleries, wane and Lyctus-susceptible sapwood. Back-sawn products are allowable but must be sawn so that the wood is a minimum distance of 50 mm from the pith. Average moisture content of 12%, with all pieces within the range of 9% to 15%.

In addition, the following imperfections will be allowed:

(i) **Kino veins** - Tight kino veins up to 1.5 mm in width unlimited. Wider, but tight kino veins, not exceeding the length of the piece.

(ii) **Stain** - Brown

(iii) **Spring** - 10 mm in 3 metres length.

(iv) **Bow** - 40 mm in 3 metres length.

(v) **Wane and Lyctus susceptible sapwood** - On the opposite face to that graded, for 25% of the width and lower edge only.

(vi) **Knots** - Tight green knots and epicormic shoots (burls) only, no greater than 40% of product width. Partially dead knot (tight on at least 50% of the knot perimeter) up to 30% of product width.

(vii) **Surface checks** - Of less than 1 mm in width unlimited. Wider checks to 2 mm in width, in aggregate length not more than 1 metre in 1 square metre of surface area.

(viii) **Internal checks** - As appearing on freshly docked ends. Of less than 1 mm - unlimited. Wider checks to 2 mm - no more than 3 per 0.005 square metre (100 x 50 mm) area.

(ix) **Holes** - Up to 2 mm in diameter unlimited. Larger holes to 8 mm diameter - no more than 10 per square metre.

(x) **Sloping grain** - Not exceeding 1 in 10

(h) **Cover grade:**

The sawn product will be 2.4 metre length or longer and graded on the worst defect or combination of defects on a piece, which must be free of termite attack, decay, wane and Lyctus-susceptible sapwood. Back-sawn products are allowed but must be sawn so that the wood is a minimum distance of 50 mm from the pith. Average moisture content of 10%, with all pieces within the range of 7% to 12%.

In addition, the following imperfections will be allowed:

(i) **Kino veins** - Tight kino veins unlimited.

(ii) **Stain** - Brown
(iii) **Spring** - 10 mm in 3 metres length.

(iv) **Bow** - 10 mm in 3 metres length.

(v) **Knots** - Tight green knots and epicormic shots (burls) only, no greater than 40% of product width. Partially dead knot (tight on at least 50% of the knot perimeter) up to 30% of product width.

(vi) **Checks** - Both internal and surface, individual checks not exceeding the lesser of half of piece thickness or two growth rings, or wider than 3 mm.

(vii) **Holes** - Up to 8 mm in diameter unlimited. Up to 20 mm, no more than 10 per square metre.

(x) **Sloping grain** - Not exceeding 1 in 10