RELATIONSHIPS AND ESTIMATES OF LONGITUDINAL GROWTH STRESS IN 
_Eucalyptus dunnii_ AT DIFFERENT AGES

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ABSTRACT – The objective of this study was to obtain estimates of longitudinal growth stresses in standing trees of the _Eucalyptus dunnii_ Maiden at eight, thirteen, fifteen and nineteen years of age and to determine their relationships with wood characteristics. The longitudinal growth stresses were indirectly measured by the “CIRAD-Forêt” method and estimated from both the dynamic modulus of elasticity and the modulus of elasticity in tension parallel to the grain. The longitudinal residual strain (LRS) and the estimates of the longitudinal growth stresses tended to increase with the age of the material. The LRS correlated positively and significantly with all the growth stresses estimates. The largestes magnitudes were at 13, 15 and 19 years of age. The basic density presented high, positive and significant correlations with the dynamic modulus of elasticity, estimated in the longitudinal direction, for wood saturated and at 12% moisture content, for all the ages assessed. All the growth stresses estimates presented high, positive and significant correlations between themselves.

Keywords: Growth stress, longitudinal residual strain and standing tree.
1. INTRODUCTION

Growth stresses in trees cause significant waste of wood due to defects, such as warping and splits, that appear immediately after felling the tree and when sawing the logs. As this phenomenon is variable, it has been studied aiming to determine how it is influenced by factors related to the tree growth, such as forest management, silviculture, heredity, soil, climate etc. and which practices can be used to minimize it (POLGE and THIERCELIN, 1979). In *Eucalyptus* the growth stress is perhaps the most important property when it is used for solid wood.

These growth stresses are found in the trunk of green trees and can be longitudinal, tangential and radial (KUBLER, 1987). The longitudinal growth stresses are the most intense and variable. For this reason they have been subject of various studies.

Growth stresses originate in the cambium region of the tree trunks, during maturation of the cells (WILHELMY and KUBLER, 1973). They tend to contract longitudinally and, at the same time, expand laterally. Since these cells are integral parts of the tree tissues, they are almost completely prevented from suffering these dimensional alterations (WILHELMY and KUBLER, 1973). According to Wilkins (1986) there are two more accepted hypotheses to explain the cause of these tensions, one proposed by Watanabe and Boyd, that associates the swelling of the cell wall and consequent traction of the cellulose molecule to lignin deposition; and another by Kubler, who proposed that the shortening of the peripheral cells results from the contraction of the cellulose crystals of the microfibrils in the S2 layer.

After felling the tree down, the peripheral zone of the log, under traction, tends to contract and the central part, under compression, to expand (MALAN, 1979). These growth stresses are in equilibrium in the standing tree, acting as a way of giving them stability (van WYK, 1978), but as soon it is felled, deformations and end splits occur on the logs (FERRAND, 1983).

The objective of this study was to obtain longitudinal growth stresses estimates in *Eucalyptus dunnii* Maiden trees at 8, 13, 15 and 19 years of age.

2. MATERIAL AND METHODS

*Eucalyptus dunnii* trees at 8, 13, 15 and 19 years of age were used. The populations were established...
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by saplings derived from seeds, and each tree was considered as a different genotype. Twelve trees were assessed at eight years and 16 trees at the other ages, totaling 60 trees. The trees were randomly selected in the plantations, taking care to choose the most representative according to the diametric classes. Trees from the borders and those that presented disease symptoms were not selected. The 15 year-old trees were cultivated at São João dos Cavaleiros farm, while the others were cultivated at Rio da Areira farm.

This material was supplied by the Procopiak Corp., located at Canoinhas region, on the Northern plateau of Santa Catarina State, Brazil. The latitude is 26°10´S and longitude 50°23´W of Greenwich and the altitude 734 m. According to the Köppen classification, the climate is the Cfa type, temperate climate without a dry season and rainfall well distributed throughout the year. The average annual temperature is 18°C and the rainfall varies from 1800 to 2400 mm (SECRETARIA DE ESTADO DA AGRICULTURA E POLÍTICA RURAL DE SANTA CATARINA, 2003).

The longitudinal residual strain (LRS) was measured with the CIRAD-Forêt instrument (growth stress gauge), and was carried out at 1.30 m of height on the tree stem (DBH). The cardinal positions were marked around the stem. The stress wave emission methodology was applied in the same place, in the diametral direction of the stem, in the Northwest and Eastwest orientation. During the measuring, the diameters (DBH) of the trees were obtained with a tape measure. The total heights (TH) of the trees were measured after felling.

The basal 3 m long log was taken to the sawmill where two opposite slabs were removed from each, in the same position where LRS was measured. A stick measuring 5.0 x 2.5 x 50.0 cm was removed from each slab, to be submitted to the stress wave emission.

The shavings collected while measuring the LRS were used to determine the basic density according to the maximum moisture content method [Equation 1].

\[
BD = \frac{1}{\frac{Sm}{Dm}} - 0.34641 \quad \text{[Eq. 1]}
\]

where BD is the basic density, determined by the maximum moisture content method (g/cm³); Sm is the saturated in water mass, in grams; Dm is the absolutely dry mass, in grams.

The stress wave was applied to the wood stick both in the saturated and at 12% moisture content. The time of the stress wave propagation was recorded in microseconds. The same material was used to determine tension strength parallel to the grain according to the standard D-143-94 of the American Society for Testing and Materials (1997).

The dynamic modulus of elasticity was obtained by the equation 2.

\[
MOEd = BD \cdot V^2 \cdot \frac{1}{g} \cdot 10^{-4} \quad \text{(Eq. 2)}
\]

where MOEd is the dynamic modulus of elasticity, in kgf/cm², in the diametral direction, in the standing tree, and in the longitudinal direction with wood both in the saturation and 12% moisture content conditions; V is the velocity of the stress wave, in m/s, calculated by the equation 3; g is the acceleration of gravity (9.804 m/s²) and 10⁻⁴ is the correction for the units. The longitudinal growth stress was calculated by the equation 4.

\[
V = \frac{d}{t} \quad \text{(Eq. 3)}
\]

where d is the distance in meter between transducers (debarked diameter of the stem for diametral velocity and 0.50 m for longitudinal velocity of the saturated and 12% moisture content) and t is the time in second.

\[
LGS = \frac{LRS \cdot MOE}{45} \quad \text{(Eq. 4)}
\]

where LGS is the longitudinal growth stress, in kgf/cm², with wood both in the saturated (LGS_{sat}) and 12% moisture content (LGS_{12}). LRS is the longitudinal residual strain, in mm; MOE can be either the dynamic modulus of elasticity (MOED) or the static modulus of elasticity in tension parallel to the grain (MOE_{gr}), in kgf/cm².

3. RESULTS AND DISCUSSION

Table 1 presents the average values of the Eucalyptus dunnii tree growth characteristics, the longitudinal residual strain (LRS) and the wood basic density (BD) with their respective coefficients of variation (CV). It is verified that the basic density tends to be increased with age up to 15 years and then decreased slightly at 19 years of age. This fact may be related to the wood maturation from the juvenile stage. This effect was not observed for LRS that tends to increase
with age. The coefficients of variation can be considered low, except for LRS. The LRS values are accord with Trugilho et al. (2004) and Lima et al. (2004), however lightly larger.

Table 2 presents the average velocity of the stress wave in the diametral direction (VELD), the average velocity of the stress wave in the longitudinal direction for both saturated (VELs) and 12% moisture content (VEL12) wood and the estimates of the dynamic modulus of elasticity in the diametral direction (MOEdD), modulus of elasticity in the longitudinal direction for both saturated (MOEds) and 12% moisture content (MOEd12) wood, with their respective coefficients of variation (CV). The stress wave velocity and the dynamic modulus of elasticity, in the longitudinal direction, was higher for green wood than for 12% moisture content wood, which is in line with results obtained by Kang and Booker (2002).

The mean stress wave velocity in the diametral direction (VELD) was lower than that observed in the longitudinal direction (VELs), for saturated specimens. This fact was probably associated to the acoustical damping caused by the crossing the lignin, that is an amorphous and inelastic polymer (Matos, 1997). This reduction in the stress wave velocity possibly occurred because the wave passed throughout regions with different properties in the diametral direction of the stem.

This fact suggests the existence of internal defects commonly found in Eucalyptus dunnii, such as knots and kino veins. The low stress wave velocity reflects in the low value of the dynamic modulus of elasticity in the diametral direction (MOEdD). In spite of the reduced values of the dynamic modulus of elasticity a tendency of growth was observed associated with the increase of the age. The coefficients of variation were higher for MOEdD than both MOEds and MOEd12, except for eight years of the trees age.

Table 3 presents the average values of the modulus of elasticity (MOE), tension strength parallel to the grain (TSg) and the estimates of the longitudinal growth stresses using MOE (LGSt), MOEds (LGSts) and MOEd12 (LGSt12) with their respective coefficients of variation (CV).

| Age (years) | Farm       | DBH (cm) | TH (m) | LRS (mm) | BD (g/cm³) | VELD (m/s) | VELsat (m/s) | VEL12 (m/s) | MOEdD (kgf/cm²) | MOEds (kgf/cm²) | MOEd12 (kgf/cm²) |
|-------------|------------|----------|--------|----------|------------|------------|-------------|-------------|----------------|----------------|-----------------|
| 8           | Rio da Areia | 25.70    | 27.41  | 0.107    | 0.478      | 347.35     | 3,859.56    | 5,045.98    | 571.36         | 71,417.96      | 121,078.82      |
| CV (%)      |            | 17.96    | 6.56   | 23.66    | 12.62      | 6.76       | 6.67        | 3.19        | 17.54          | 22.81          | 17.08           |
| 13          | Rio da Areia | 38.00    | 36.80  | 0.113    | 0.511      | 439.78     | 4,076.95    | 5,209.45    | 1,065.91       | 87,048.72      | 141,645.72      |
| CV (%)      |            | 14.24    | 8.95   | 33.02    | 8.57       | 25.32      | 5.14        | 3.28        | 53.26          | 14.26          | 11.22           |
| 15          | São João   | 42.50    | 43.53  | 0.111    | 0.547      | 498.65     | 4,362.09    | 5,325.18    | 1,463.99       | 106,581.50     | 158,445.44      |
| CV (%)      |            | 15.61    | 5.57   | 26.64    | 5.25       | 20.25      | 4.24        | 3.18        | 53.58          | 11.37          | 8.53            |
| 19          | Rio da Areia | 47.20    | 44.46  | 0.123    | 0.483      | 578.21     | 4,088.51    | 5,276.17    | 1,692.89       | 82,910.37      | 137,816.48      |
| CV (%)      |            | 13.59    | 3.68   | 35.88    | 8.56       | 20.06      | 6.03        | 3.88        | 37.67          | 15.71          | 12.22           |

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The modulus of elasticity in tension parallel to the grain ($MOE_T$) was superior to both the dynamic modulus of elasticity obtained in the longitudinal direction and to wood at 12% moisture content ($MOE_{12}$), at all ages assessed. This reflected directly on the estimates of the longitudinal growth stress used in $MOE_T$. This estimate ($LGSt$) was higher than that obtained by Boyd (1950) *apud* Gaiotto (1993) (70 to 280 kgf/cm$^2$). Trugilho et al. (2002) assessed *Eucalyptus* clones at six years of age planted in Minas Gerais State, Brazil, and reported longitudinal growth stress ranging from 139 to 448 kgf/cm$^2$, using $MOE_T$ obtained for wood with 12% moisture content. The growth stress estimates presented the same behaviour as $LRS$ (Table 1), increasing with the age of the material.

Table 4 presents the matrix of correlations obtained between the characteristics assessed in wood for each age. It is observed that the basic density (BD) correlated positively and significantly at the level of 5% probability, but with low magnitude, with the stress wave velocity, in the longitudinal direction, for green ($VEL_{sat}$) and the 12% moisture content ($VEL_{12}$) wood and with the dynamic modulus of elasticity (MOEd), diametral direction, at all the ages assessed. The correlation between BD and the longitudinal growth stress ($LGSt$) using the modulus of elasticity the tension parallel to the grain was only positive and significant for the age of 15 years. Lima et al. (2004) found some result in eucalypts with similar age. The BD presented positive and significant correlation with the longitudinal growth stress estimates using the dynamic modulus of elasticity, longitudinal direction in both green ($LGS_{sat}$) and 12% moisture content ($LGS_{12}$) wood at the ages of eight and 15 years.

The longitudinal residual strain ($LRS$) correlated positively and significantly with the estimates of the longitudinal growth stress ($LGS_{sat}$, $LGS_{12}$ and $LGS_{120}$), and with greatest magnitude at 13, 15 and 19 years of age. This fact indicated that the $LRS$ participated decisively in the estimate of the longitudinal growth stress, because its influence on the estimates of these stresses was greater than that of the modulus of elasticity. It also indicated that $LRS$ can be used as an indirect and reliable estimate of the longitudinal growth stress in the standing tree.

The modulus of elasticity in tension parallel to the grain test ($MOE_T$) did not correlate with the stress wave velocity in the diametral direction ($VEL_D$) at any age. However, it correlated positively and significantly with the stress wave velocity in the longitudinal direction and in green wood ($VEL_{sat}$), at all the ages, and with the stress wave velocity in the longitudinal direction and in wood with 12% of moisture content ($VEL_{12}$) at 13, 15 and 19 years of age. The $MOE_T$ presented positive and significant correlation with the longitudinal growth stress estimates obtained using the dynamic modulus of elasticity, for green ($LGS_{sat}$) and with 12% of moisture content ($LGS_{12}$) wood at all the ages.

The stress wave velocity in the diametral direction presented non-significant and low magnitude correlation with the stress wave velocity in the longitudinal direction, and green wood condition, at the ages.

All the estimates of the longitudinal growth stress presented high, positive and significant correlations. This fact indicated that determining the longitudinal growth stress for saturated wood is sufficient to estimate its level of variation within the tree.

Table 3 — Average values of the tension strength parallel to grain and the estimates of the longitudinal growth stresses

| Age (years) | Farm       | TS$_t$ (kgf/cm$^2$) | MOE$_T$ (kgf/cm$^2$) | Stress (kgf/cm$^2$) |
|-------------|------------|----------------------|-----------------------|---------------------|
|             |            |                      |                       | $LGS_t$ $LGS_{sat}$ $LGS_{12}$ |
| 8           | Rio da Areia | 1385                 | 1692                  | 368 153 261 |
| CV (%)      | 18.66                  | 19.81                  | 25.84 27.29 22.49    |
| 13          | Rio da Areia | 1558                 | 2132                  | 544 220 358 |
| CV (%)      | 22.18                  | 19.23                  | 43.48 38.16 36.63    |
| 15          | São João    | 1800                 | 2604                  | 648 265 392 |
| CV (%)      | 24.59                  | 14.03                  | 33.58 33.36 31.37    |
| 19          | Rio da Areia | 1609                 | 2122                  | 602 233 384 |
| CV (%)      | 20.30                  | 15.96                  | 46.49 43.89 41.46    |
4. CONCLUSIONS

The results observed permits the following conclusions:

- Longitudinal residual strain (LRS) tended to increase with the age of the material;

- The stress wave velocity was much lower in the radial direction, probably due to the internal defects of the wood and crossing the lignin component, which is an amorphous and inelastic polymer;

- The stress wave velocity and the dynamic modulus of elasticity, obtained in the longitudinal direction, increased from the green condition to the 12% of moisture content wood;

- The modulus of elasticity of the tension parallel to the grain test was superior to the dynamic modulus of elasticity in the longitudinal direction and with wood in the 12% of moisture content condition at all ages assessed, that reflected directly on the estimates of the longitudinal growth stress;

- The growth stress estimates presented the same performance tendency as LRS, that is, to increase with the age of the material;

- The basic density presented higher, positive and significant correlations with the dynamic modulus of elasticity estimated in the longitudinal direction for the green condition and 12% of moisture content wood, at all ages assessed;

- LRS correlated positively and significantly with all the estimates of the longitudinal growth stress, and with greatest magnitude at 13, 15 and 19 years of age;

- The LRS can be considered an indirect and reliable estimate of the longitudinal growth stresses;

- All the longitudinal growth stresses estimated presented high positive and significant correlations between themselves.

Table 4 – Matrix of correlation obtained between the characteristics assessed in the wood for age

| Age     | BD   | LRS  | VELO | VELOsat | VELO12 | MOEdD | MOEdsat | MOEd12 | LGSsat | LGS12 |
|---------|------|------|------|---------|--------|-------|---------|--------|--------|--------|
| Eight years |      |      |      |         |        |       |         |        |        |        |
| BD 1.0  | -0.17 | -0.22 | 0.51* | 0.50* | 0.59* | 0.87** | 0.95** | 0.68** | 0.65** |
| LRS 0.44 | 0.10 | 0.47 | 0.63* | 0.49 | 0.73** | 0.63* | 0.52* | 0.57* | 0.47 |
| TSp 0.37 | 0.20 | 0.33 | 0.39 | 0.36 | 0.57* | 0.42 | 0.41 | 0.50* | 0.49 |
| LGS 0.18 | 0.69** | 0.62* | 0.43 | 0.44 | 0.65* | 0.36 | 0.23 | 0.70** | 0.70** |

| Thirteen years |      |      |      |         |        |       |         |        |        |        |
| BD 1.0 | -0.14 | -0.01 | 0.15 | 0.08 | 0.10 | 0.68** | 0.80** | 0.17 | 0.15 |
| LRS 0.30 | 0.25 | -0.15 | 0.74** | 0.71** | -0.13 | 0.73** | 0.66** | 0.55* | 0.49* |
| TSp 0.33 | -0.14 | 0.06 | 0.66** | 0.54* | 0.06 | 0.69** | 0.58** | 0.19 | 0.09 |
| LGS 0.08 | 0.96*** | -0.45* | 0.63** | 0.67** | -0.45* | 0.52* | 0.47* | 0.96** | 0.95** |

| Fifteen years |      |      |      |         |        |       |         |        |        |        |
| BD 1.0 | 0.46* | -0.15 | 0.31 | 0.05 | -0.06 | 0.71** | 0.67** | 0.64** | 0.58** |
| LRS 0.49* | 0.32 | -0.26 | 0.71** | 0.74** | -0.25 | 0.76** | 0.87** | 0.54* | 0.53* |
| TSp 0.17 | 0.03 | 0.29 | 0.34 | 0.23 | 0.27 | 0.33 | 0.27 | 0.14 | 0.10 |
| LGS 0.58** | 0.90** | 0.12 | 0.44* | 0.39 | 0.15 | 0.62** | 0.66** | 0.96** | 0.97** |

| Nineteen years |      |      |      |         |        |       |         |        |        |        |
| BD 1.0 | 0.09 | -0.34 | 0.17 | 0.18 | -0.11 | 0.65** | 0.79** | 0.25 | 0.26 |
| LRS 0.09 | 1.0 | 0.06 | 0.61** | 0.59** | 0.10 | 0.48* | 0.41 | 0.96** | 0.97** |
| TSp 0.00 | 0.61** | -0.11 | 0.71** | 0.63** | -0.10 | 0.54* | 0.38 | 0.67** | 0.62** |
| LGS 0.04 | 0.97** | -0.02 | 0.69** | 0.63** | 0.01 | 0.53* | 0.41 | 0.96** | 0.94** |

* and ** Significant at the levels of 5 and 1%, respectively, by the t-test.
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