Perpendicular Mechano-Sorptive Strains during Moisture Desorption from *Eucalyptus nitens* Specimens

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The purpose of this paper was to determine the mechano-sorptive strains produced during desorption of moisture from *Eucalyptus nitens* specimens, from a perspective of modeling wood drying stresses. *Eucalyptus nitens* samples were tested in the radial and tangential directions. The mechano-sorptive strain was measured by cantilever bending during desorption. The runs were performed in a conditioning chamber at constant low temperature and variable equilibrium moisture content. Four load levels were considered for testing. The results showed that the mechano-sorptive strain during desorption of moisture was proportional to applied stress and reached the maximum value in the tangential direction. Also, the mechano-sorption coefficient depended on wood orientation and reached the maximum value of 5.46 × 10^{-2} in the tangential direction.

Keywords: Cantilever bending; Drying deformations; Drying stresses; Mechano-sorption coefficient.

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INTRODUCTION

Chile has approximately 0.74 million hectares of *Eucalyptus* plantations available for industrial processing, and approximately 30% contain *Eucalyptus nitens* (INFOR 2015). *E. nitens* plantations are mainly distributed in the VIII and X regions, and they are the fastest growing species in Chile. *E. nitens* plantations grow as fast as 77 m^3/ha/year (INFOR 1989), and they are well adapted to the cold winter conditions in Southern Chile (INFOR 2004).

The volume of wood from *E. nitens* available in Chile for commercial use is estimated to reach 7 million m^3 per year in 2040 (INFOR 2015). This abundance is an incentive for processing this species into solid wood products for domestic and international markets. Unfortunately, the development of commercial solid products from this species is currently limited by the sawlog performance due to longitudinal growth-strains (Valencia *et al.* 2011) and drying difficulties due to their propensity of surface and internal checking, collapse, and higher transversal shrinkage (Ananías *et al.* 2009, 2014; Sepúlveda *et al*. 2016). A more comprehensive understanding of the drying properties of *E. nitens* is essential for the successful processing of this species in commercial solid wood products.

E. nitens is highly prone to internal checking (Leandro *et al.* 2008; Rebolledo *et al.* 2013). *E. nitens* of lower density tends to be associated with higher internal intra-ring checking. The drying of *E. nitens* solid wood is also limited by collapse propensity (Ananías *et al.* 2009, 2014; Sepúlveda *et al.* 2016).

During the initial stages of drying, the surface layers shrink and exert compressive stresses on the core-wood, inducing drying stresses. These behaviors change with moisture content and temperature variations during drying. The drying stresses cause permanent and transitory deformations on the wood, *i.e.*, warping and internal checking. For *E. nitens*, Pérez *et al.* (2013) observed that drying stresses in tension at the wood surface were higher at the early stage of wood drying, and the compression stresses at the wood surface increased to the maximum magnitude in late stages of drying of flatsawn boards.

Mechano-sorptive (MS) strain occurs when wood is subjected to stresses and changes in the moisture content (MC) (Armstrong and Kingston 1962). This strain is greater than the strain that occurs under constant MC conditions, is temperature-dependent, and is greater when the wood is under load (Mårtensson 1994). Lazarescu *et al.* (2009) indicated that MS strain can be interpreted as accelerated creep due to the variation in the equilibrium moisture content (EMC). Additionally, they noted that MS strain is the result of the transient redistribution of stresses associated with MC variation, which ruptures hydrogen bonds. In wood drying, MS strain is responsible for the mitigation of drying stresses that otherwise might result in surface checking and cause severe losses (Langrish 2013). Hassani *et al.* (2015) reported that MS strain is greater in the perpendicular direction than in the parallel direction.

Several authors have proposed correlations for the calculation of the MS strain (Leicester 1971; Ranta- Maunus 1993). The most simplified form is as follows,

$$\frac{\partial \varepsilon_{ms}}{\partial t} = m * \sigma * \frac{\partial MC}{\partial t} \tag{1}$$

where m is a constant known as the mechano-sorption coefficient (1/MPa), with a positive value for adsorption (wetting) and a negative value for desorption (drying), σ is stress (MPa) and *MC* is moisture content. Equation 1 assumes a linear dependence of the MS strain on the stress and the MC variation.

To improve the drying schedules of *E. nitens* for the development of solid wood products, MS behavior may be applied to relieve collapse and drying stresses. Drying stresses can be used to predict the deformation tendency during *E. nitens* drying (Pérez *et al.* 2013). There is some evidence that drying stresses mitigate the collapse during drying (Blakemore 2011). MS strains also relax the drying stresses of hardwoods (Langrish 2013). Zhan and Avramidis (2011) showed that MS strain is the most important deformation component by which the shrinkage-induced drying stress could be released effectively.

This study reports the perpendicular MS strains produced during desorption of *E. nitens* specimens, from a perspective of potential drying processes of solid wood.

EXPERIMENTAL

Materials

The materials consisted of 18 specimens (9 radial and 9 tangential) of *Eucalyptus nitens* Deane & Maiden sapwood prepared from the first log of 3 twelve-year-old trees, with a breast height diameter (BHD) of approximately 34 cm. The specimens were stored in a conditioning chamber at 22% equilibrium moisture content and used to prepare samples that were perfectly oriented according to the two transversal axes. The final dimensions of the samples were 110 mm (length) × 25 mm (width) × 7 mm (thickness).

Methods

A cantilever bending test was conducted during the desorption process (Pérez *et al.* 2016). During the test, one end of each sample was firmly secured to a metal support, and a load was applied at the free end of the sample (Fig. 1). The tests were performed in a conditioning chamber at a constant temperature of 30 °C and variable relative humidity (RH) conditions with an equilibrium moisture content (EMC) from 22 to 12%. The air velocity in the drying chamber was 1.5 m/s. Four load levels were considered for the tests: 0, 10, 20, and 30% of the rupture load. The experimental conditions for each test are shown in Table 1.

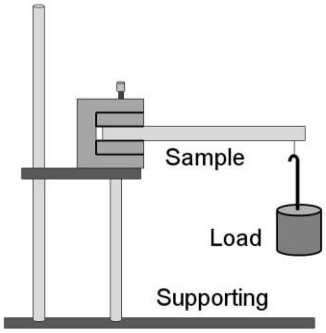


Fig. 1. Cantilever experiment set-up

Table 1. Experimental Conditions

Direction	Temperature (°C)	EMC Variation (%)	Rupture Load (g)	Level Load (g)				N Boards
				0%	10%	20%	30%	
Radial	30	22 – 17 17 – 12	4898	0	490	980	1470	12
Tangential	30	22 – 17 17 – 12	2973	0	297	594	891	12

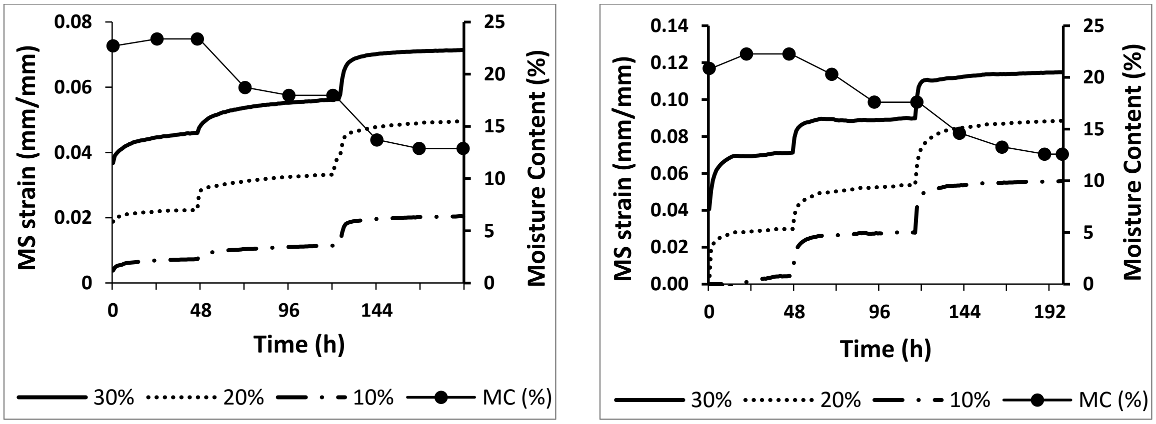
The total deformation measurement of the samples was performed using strain gauges (calibrated according to the manufacturer's conditions) bounded on the upper face to 25 mm of assurance area. The load application point was located 10 mm from the free end of the sample. The shrinkage deformation was measured in the free load sample, and the instantaneous deformation was measured after the load application. In this case, the viscoelastic strain was considered negligible. The MS strain was obtained by subtracting of the total deformation of the loaded samples the instantaneous and shrinkage deformation. The coefficient was obtained from Eq. 1.

To determine EMCs, three control samples were placed in the conditioning chamber, which allowed for monitoring of MC variation over time. Samples were weighed every day, using a balance with an accuracy of 0.001 g. At the end of the tests, the oven-dry weights of the samples were used to calculate the average moisture content over time.

A statistical analysis (Kruskall-Wallis test) was performed to evaluate the effect of load level and anatomical orientation on the MS strains and MS coefficient.

RESULTS AND DISCUSSION

Figure 2 shows the perpendicular MS strains during desorption of *E. nitens* samples in both the radial and tangential directions. Each curve represents the average of three replications. The MS strains were proportional to load level, and MS strains increased when moisture content decreased. These results are in concordance with those reported by Fu *et al.* (2013). Increased strain was noted at 48 h, after the first RH change from 93% to 83%, and for an EMC change from 22% to 17%. MS strain increased again for both directions with the next RH change from 83% to 67% and for an EMC change from 17% to 12%. These results confirmed the MC effect under loading on MS strains. The same conclusion was reported by Rice and Youngs (1990) and Fu *et al.* (2016), who confirmed that MS strain is a function of moisture change and increases with decreased moisture content.



(a) **(b)**

Fig. 2. Perpendicular mechano-sorptive strains during desorption of *Eucalyptus nitens* samples in the (a) radial and (b) tangential directions

Table 2 shows the MS strain results and mechano-sorption coefficient (*m*) for each perpendicular direction measured and load level. The perpendicular MS strains during desorption of *E. nitens* specimens depended significantly on the wood orientation (Fig. 3). Higher MS strain values developed in the tangential direction. In this anatomical orientation, the MS strain reached a maximum value of 0.1148 mm/mm for the highest load level, corresponding to 59% of the total deformation.

This result is in concordance with previous studies that indicate that MS strain is the major component of total strain (Rice and Youngs 1990; Zhan and Avramidis 2011). The higher values of MS strain in the tangential orientation, could be explained by cell wall thickness differences. According to Leandro *et al*. (2008) the cell wall thickness of *E. nitens* in tangential direction was about 12% higher than radial direction.

Table 2. Results for MS Strain and Mechano-Sorption Coefficient (three replications)

Direction	Load Level	MS Strain (mm/mm)			*m* (1/MPa)		
Radial	30%	0.0706	0.0732	0.0703	1.96E-02	2.04E-02	1.96E-02
	20%	0.048	0.0506	0.0497	1.77E-02	1.86E-02	1.83E-02
	10%	0.0205	0.0205	0.0203	1.34E-02	1.34E-02	1.33E-02
Tangential	30%	0.1147	0.1149	0.1147	5.35E-02	5.36E-02	5.35E-02
	20%	0.0786	0.0784	0.0786	5.08E-02	5.07E-02	5.08E-02
	10%	0.0458	0.0459	0.0459	5.44E-02	5.46E-02	5.46E-02

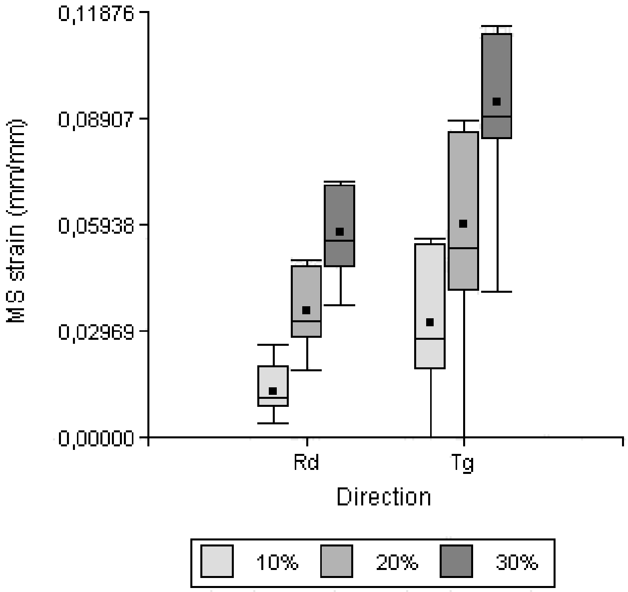


Fig. 3. Effect of direction and load level on MS strain

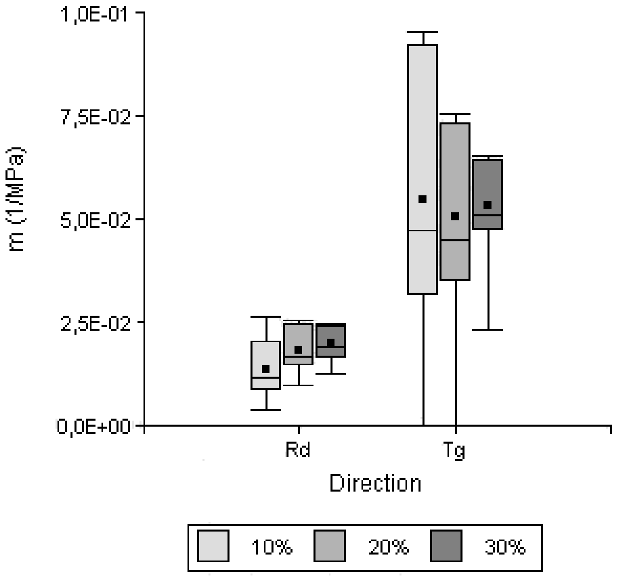


Fig. 4. Effect of direction and load level on mechano-sorption coefficient

Though the *m* depended significantly on the wood orientation, the highest values were obtained in the tangential direction, and these values were significantly different from the radial direction. The values of the coefficient among different load levels were not significantly different at the 0.05 level (Fig. 4). This conclusion coincides with those reported by Wu and Milota (1996). They reported values of *m* between 2.25×10^3 and 2.65×10^3 during moisture adsorption in Douglas fir samples, and these values were not significantly different at the 0.05 level among four different stress levels.

CONCLUSIONS

1. Perpendicular mechano-sorptive strains during desorption of *E. nitens* specimens depend on wood orientation. Higher values of MS strains developed in the tangential direction, reaching a maximum value of 0.1148 mm/mm. For the radial direction, the value was 0.071 mm/mm.
2. The mechano-sorption coefficient depends on wood orientation and reached the maximum value of 5.46×10^{-2} in the tangential direction. The values of the coefficient among three different load levels were not significantly different at the 0.05 level.
3. These data can be used as an indicator of more sensible hygromechanical behavior for mitigation of drying deformations, collapse, and drying stresses when processing quartersawn wood.

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