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HYGROMECHANICAL STRAINS DURING THE DRYING OF *Eucalyptus nitens* BOARDS

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ABSTRACT

Collapse and drying stresses are currently induced during the drying of *Eucalyptus nitens* in solid wood products. The purpose of this study was to investigate these drying stresses by measuring hygromechanical strains during the drying of *Eucalyptus nitens* boards.

Small samples of *Eucalyptus nitens* wood were oriented in the radial and tangential directions and tested to determine the hygromechanical strains during the drying process. This experimental work consisted of cantilevered bending tests conducted under variable relative humidity conditions. Tests were performed in a conditioning chamber at 30 °C with an equilibrium moisture content ranging from 22 to 12% under four levels of stress: 0, 10, 20 and 30% of the rupture load. The strains were determined using strain gauges, and the total deflection was measured with a linear variable differential transformer.

The results show that in hygromechanical strains during the drying of *Eucalyptus nitens*, both the surface deformation and mechano-sorption strain were found to be proportional to the applied stress and reached their maximum values in the tangential direction. The total deflection increased 0,18 mm/mm with a surface deformation of 0,20 mm/mm, and the mechano-sorptive strain provides a greater contribution with a value of 0,11 mm/mm, thus corresponding to 59% of the total deformation. In attempts to improve the drying schedules of *Eucalyptus nitens* to develop solid wood products, mechano-sorptive behavior may be applied to relieve collapse and drying stress.

Keywords: Deflection, deformation, drying stresses, mechano-sorption, wood drying.

INTRODUCTION

The complex mechanical behavior of wood should be considered to understand wood behavior during the drying and desorption processes. It has been demonstrated that the mechanical behavior during wood drying is strongly dependent on temperature, relative humidity, time and applied load, among others factors (Moutee *et al.* 2010). During the drying process, wood experiences differential shrinkage between the surface and the core, which induces the development of mechanical stresses

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across the structure (Pang 2002, Clair 2012). Shrinkage begins to develop on the wood surface when the moisture content (MC) decreases below the fiber saturation point (FSP), and the shrinkage is restrained by the internal region that remains above the FSP. Thus, the external surfaces generate tension in the direction of the undeveloped shrinkage, placing the internal regions under compression and generating tension in the opposite direction (Salinas *et al.* 2015).

The stress level caused by drying depends on several factors, such as the drying temperature, drying time, wood species, sawing pattern, board thickness, ring width, growth rate (Keey *et al.* 2000, Pang 2000). These stress-induced deformations are recognized as an important cause of wood instability and decreased quality in the final wood product. It is well known that the total deformation that occurs during drying involves free shrinkage and mechano-sorptive, elastic instantaneous and visco-elastic creep components (Kang *et al.* 2004).

When the MC is below the FPS, wood will shrink, and wood shrinkage is greater in the tangential direction than the longitudinal direction. When wood is subjected to changes in the MC under a load, greater deformations are observed than when wood is under conditions of constant humidity (Mårtensson 1994).

Mechano-sorption (MS) strain is a phenomenon that occurs when wood is subjected to stresses and changes in the MC (Armstrong and Kingston 1962). This strain is considered to be greater than the strain that occurs under constant MC conditions (Mårtensson 1994). MS strain is also temperature dependent and is greater when the wood is under load (Erikson 1994). Lazarescu *et al.* (2009) indicate that MS strain can be interpreted as accelerated creep due to the variation in the equilibrium moisture content (EMC). Additionally, they note that MS strain is the result of the transient redistribution of stresses associated with the variation in the moisture content, which causes the rupture of hydrogen bonds. In wood drying, MS deformation is responsible for the mitigation of drying stresses that otherwise might result in surface checking and cause severe losses (Langrish 2013). Additionally, Fu *et al.* (2013) show that mechano-sorption is dependent on the radial position of the log. Hassani *et al.* (2015) indicate that MS strain is greater in the perpendicular direction than in the parallel direction.

When wood samples are subjected to drying (desorption), the strain rate increases. Experimentally, wood has been observed to exhibit greater deformation under variable conditions (temperature and relative humidity) than under constant conditions.

During the drying at low temperature of *Eucalyptus nitens* in solid wood products, collapse and drying stresses are induced. During drying of the *E. nitens* boards, it was preliminarily observed that internal strain developed and reached its maximum level at approximately 1/4 of the treatment duration (Sepúlveda *et al.* 2015).

The objective of this study was to determine the mechanical deformations and total deflection produced in *E. nitens* wood during the drying process. This paper presents the results of laboratory experiments involving samples arranged in the tangential and radial directions in a cantilevered bending test during the drying process, with variable relative humidity conditions and under different load levels.

MATERIALS AND METHODS

The material consisted of 18 samples of *Eucalyptus nitens* sapwood (9 radial and 9 tangential) collected from three 12 year-old trees, without grain deviation.

These pieces were then stored in a conditioning chamber at 30° C and 93% of relative humidity with a mean value of 22% of EMC and used in the preparation of samples oriented parallel to the two perpendicular orthotropic axes (radial and tangential). There were 12 samples for each direction, and the final dimensions were 110 mm (length) x 25 mm (width) x 7 mm (thickness).

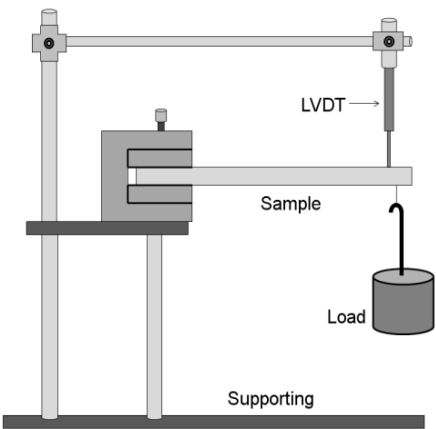


Figure 1. Schema of experimental cantilever test.

The experimental work consisted of a cantilever bending test performed during the drying process (Moutee *et al.* 2005, Segovia *et al.* 2013). During the test, one end of each sample was firmly secured to a metal support, and a load was applied to the sample’s free end (Figure 1). The tests were performed in a conditioning chamber at a constant temperature of 30 °C with variable relative humidity (RH) conditions and an EMC of 22 to 12%. 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.

Table 1. Experimental data.

Direction	Temperature (°C)	EMC variation (%)	Rupture load (g)	Level load (g)				N samples
				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

Note: the rupture load value is the average of 10 repetitions.

The rupture load value was obtained in samples previously conditioned to 22% of the EMC, using the same experimental setup by manually and progressively increasing small loads at the free ends of the samples until the rupture point was reached. For each direction, the rupture load value represents the average of 10 repetitions.

The surface deformation measurement of the samples was performed using strain gauges (calibrated according to the producer’s conditions) bonded to the upper face within 25 mm of the assurance area. At the same time, the maximum deflection was determined using linear variable differential transformer (LVDT) displacement sensors located 15 mm from the free ends of the samples. The load application point was located 5 mm away from the LVDT and 10 mm from the free ends of the samples (Figure 2).

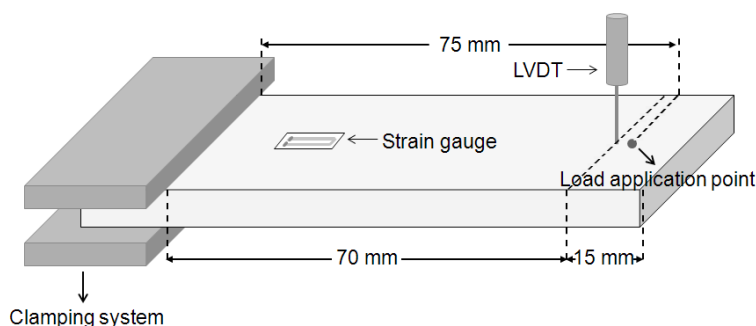


Figure 2. Schema of location of LVDT load application point.

The strain gauges and the LVDT were connected to a data acquisition system (Stress Analysis Data System 5000), which allowed the monitoring of information in real time and recorded the data every second.

The shrinkage deformation was measured in the free load sample, and the instantaneous or elastic deformation was measured after the load application. The MS strain was obtained by subtracting the instantaneous and shrinkage deformation of the total deformations.

To determine the EMCs, three control samples were placed in the conditioning chamber, thus allowing the MC variation to be monitored over time. Samples were weighed daily using a balance with an accuracy of 0,001 g. At the end of conditioning, the oven-dry weights of the samples were obtained and used to calculate the average moisture content of the samples over time.

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

RESULTS AND DISCUSSION

Figure 3 shows the evolution of the total deflection at 30 °C under variable RH conditions (Table 1) with applied loads equal to 10, 20 and 30% of the rupture load for the two perpendicular directions. During the first 48 hours of loading, the total strain was observed. After the first change in RH from 93% to 83%, the EMC changed from 22% to 17%, demonstrating an increase in total strain. With the next RH change from 83% to 67%, the EMC changed from 17% to 12%, and the total strain increased again for the two directions.

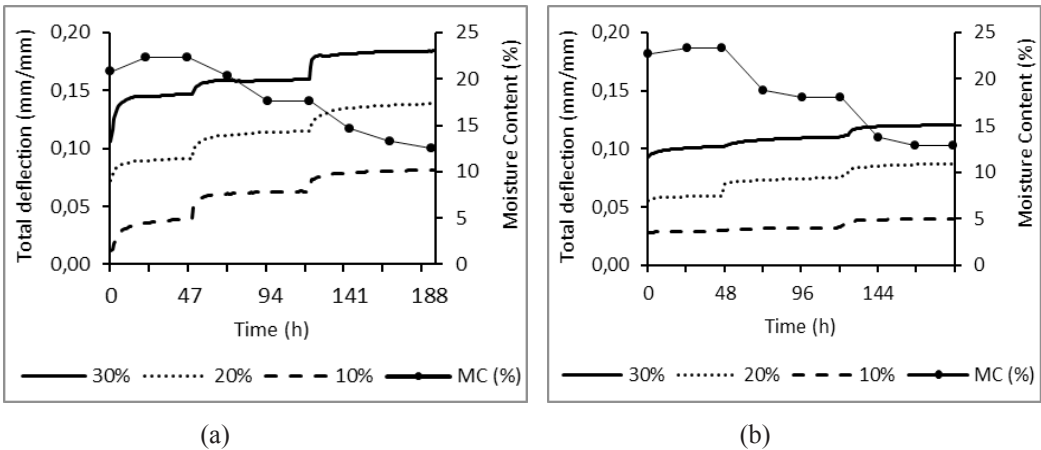


Figure 3. Total deflection during drying of *Eucalyptus nitens* boards. (a) radial and (b) tangential.

The maximum strain was observed in samples oriented in the tangential direction, with an average value of 0,183 mm/mm; the radial samples were observed to reach 0,12 mm/mm for the greatest load (30% of the rupture load).

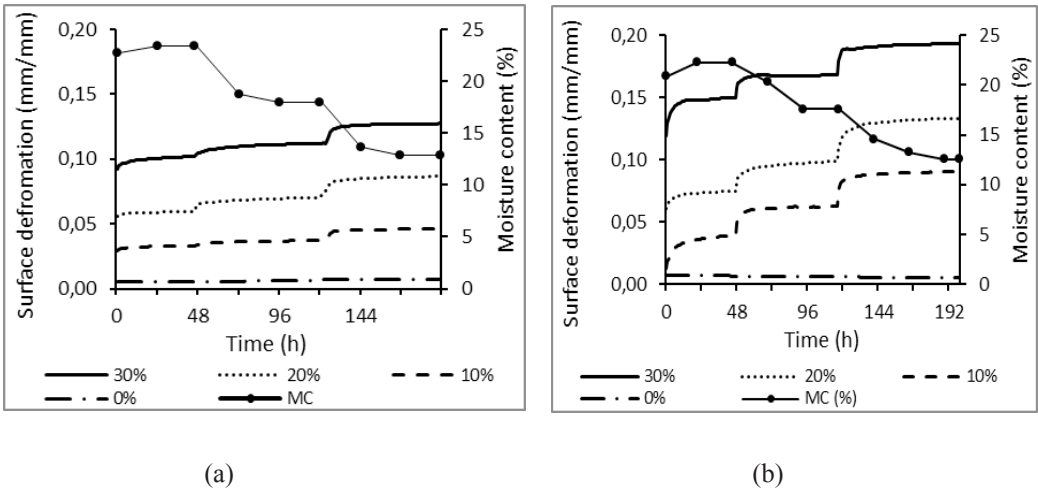


Figure 4. Surface deformation during drying of *Eucalyptus nitens* boards. (a) radial and (b) tangential.

Figure 4 shows the results of surface deformation in relation to the variation of the wood MC for the four load levels and the two perpendicular directions. The curve at 0% of the rupture load corresponded to the deformation for free shrinkage. At 10%, 20% and 30% of the rupture load, instantaneous deformation occurred immediately upon loading and was proportional to the applied load (elastic behavior). After the first change in RH, when the wood moisture content decreased from 22% to 17%, the surface deformation increased rapidly, demonstrating the occurrence of MS deformation

and coincides with the description of the phenomenon of mechano-sorptive creep that consists in an increase of creep deformation during any desorption (Hunt and Shelton 1988).

The surface deformation was found to be proportional to the applied load level and reached its maximum value in the tangential direction. These average values were 0,19; 0,13 and 0,09 mm/mm for 30, 20 and 10% of the rupture load, respectively. For the radial direction, the value of the surface deformation was 0,12 for 30% of the rupture load.

Additionally, it can be observed in Figures 3 and 4 that the curves show the same trend under load. Consequently, either of these two measurement techniques appears to be suitable for strain determination.

Table 2. Average deformations: instantaneous, free shrinkage and mechano-sorption (MS).

Direction	Load level	Total deformation (mm/mm)	Instantaneous deformation (mm/mm)	Shrinkage deformation (mm/mm)	MS deformation (mm/mm)
Radial	30%	0,1273 (0,0010)	0,0507 (1,3E-17)	0,00517 (7,9E-05)	0,0714 (0,00097)
	20%	0,0867 (0,0011)	0,0319 (6,9E-18)		0,0548 (0,00098)
	10%	0,0461 (0,0005)	0,0205 (1,7E-18)		0,0256 (0,00046)
Tangential	30%	0,1934 (0,0018)	0,0671 (2,1E-17)	0,01144 (7,8E-05)	0,1148 (0,0019)
	20%	0,1335 (0,0023)	0,0436 (6,1E-18)		0,0899 (0,0024)
	10%	0,0905 (0,0021)	0,0332 (2,2E-18)		0,0573 (0,0022)

(Standard deviations)

Table 2 shows the instantaneous deformation, free shrinkage and MS deformation results for each perpendicular direction measured. The maximum value of the instantaneous deformation was 0,0671 in the tangential direction. This value is higher than the results obtained by Langrish (2013), reported a value of 0,0148 for cyclic drying from 45 to 55°.

Additionally, the MS strain is proportional to the load level and contributes significantly to the total deformation (Table 3).

Table 3. Effect of load level on MS strain (test de Kruskal-Wallis).

Variable	Load level (%)	N	Mean	D.E.	Median	H	p
MS strain	30	384	0,034	0,002	0,0028	558,7929	<0,0001
MS strain	20	384	0,059	0,0024	0,0056		
MS strain	10	384	0,092	0,003	0,0079		

The perpendicular MS strains during the desorption of *E. nitens* boards depended significantly on the wood orientation (Table 4). Higher MS strain values developed in the tangential direction; in this anatomical orientation, the MS strain reached a maximum value of 0,11 mm/mm for the highest load level, corresponding to 59% of the total deformation.

Table 4. Effect of anatomical direction on MS strain (test de Kruskal Wallis).

Variable	Direction	N	Mean	D.E.	Median	H	p
MS strain	Radial	576	0,044	0,0020	0,0042	277,9064	<0,0001
MS strain	Tangential	576	0,079	0,0037	0,0071		

Additionally, the MS strain was higher when the MC decrease. As shown in Figure 5, this variation was significant.

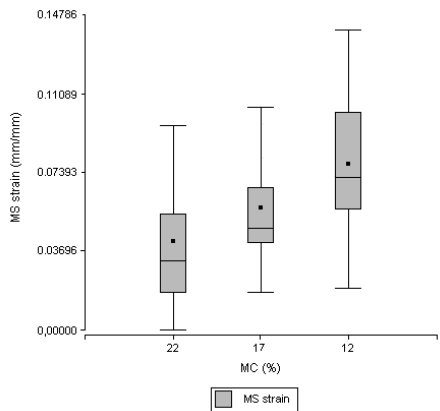


Figure 5. Effect of moisture content on MS strains.

These findings can be used as indicators of hygromechanical behavior for mitigation of collapse and drying stresses when processing quarter-sawn wood. Chen and Gu (2006) and Langrish (2013) show that the MS strain relaxes the drying stresses during conditioning. The drying of solid *E. nitens* wood is limited by its propensity to collapse (Ananías *et al.* 2014) and, according to Blakemore (2011); drying stresses mitigate the collapse during the drying of eucalypts. Perpendicular MS strains during the drying of *E. nitens* boards are dependent on the orientation of the wood, and higher values of MS strains are developed in the tangential direction.

CONCLUSIONS

The significant contribution of MS strain to total deformation was confirmed.

In the tangential direction, the MS strain reached a maximum value of 0,11 mm/mm for the higher load level, corresponding to 59% of the total deformation.

The surface deformation and total deflection were proportional to the applied stress in the two directions. Both reached their maximum values in the tangential direction, with values of 0,2 mm/mm and 0,183 mm/mm, respectively.

Attempting to improve the drying schedules of *Eucalyptus nitens* for the development of solid wood products, mechano-sorptive behavior may be applied to relieve collapse and drying stresses.

Future work should include a model of the drying stresses to improve the drying of *Eucalyptus nitens* wood.

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