Warp Recovery in Radiata Pine Lumber Using Steam Treatment

Carlos Salinas-Lira,[a,]* Luís Acuña-Alegría,[b] Víctor Sepúlveda-Villarroel,[b]
Rubén A. Ananías,[b] Linette Salvo-Sepúlveda,[b] José Torres-Mella,[b]
Felipe Cancino-Mundaca,[b] and Diego A. Vasco [c]

Steam treatment was used in this work to correct the observed warp in dried core-wood radiata pine (*Pinus radiata*) lumber that appears during the industrial drying process at high temperatures. The experimental design considered seven tests and three process variables: temperature, overload, and treatment time. The warp and moisture content before and after the treatment were measured, which allowed for assessing the efficiency of the cup recovery process of the studied thermal treatment programs. Of the analyzed types of warp (twist, bow, crook and cup), only twist was observed to be relevant to the effects of the permissible wood quality classification. The results showed that the twist recovery depends on the temperature, treatment time and overload magnitude. The best treatment results were with a steaming temperature of 100 (°C) and an overload of 3 (ton/m^3) applied for 6 (h), which allowed an average recovery value of approximately 43.1%. Moreover, there was an increase in the moisture content and wood density of 10% and 3%, respectively. Finally, the post-treatment of wood with superheated steam did not show a significant improvement to the warp recovery.

Keywords: Steaming; Juvenile wood; Pinus radiata; Twist, Thermal treatment

*Contact information: a: Grupo de Investigación en Tecnologías del Secado y Tratamientos Térmicas de la Madera, Departamento de Ingeniería Mecánica, Universidad del Bío Bío, Av. Collao 1202, Concepción, Región del Bío Bío 4051381 Chile; b: Grupo de Investigación en Tecnologías del Secado y Tratamientos Térmicas de la Madera, Departamento de Ingeniería en Madera, Universidad del Bío Bío, Av. Collao 1202, Concepción, Región del Bío Bío 4051381 Chile; c: Departamento de Ingeniería Mecánica, Universidad del Santiago de Chile, Av. Bernardo O'Higgins 3363, Santiago, Región Metropolitana 9170022 Chile; *Corresponding author: casali@ubiobio.cl*

INTRODUCTION

Sawn wood is important in Chile, with production of approximately 8.5 million (m^3/year). Of this quantity, 96.4% corresponds to *Pinus radiata* production and 2.6 million (m^3/year) is destined for foreign trade (INFOR 2017). Part of this production corresponds to core-wood lumber with the proper characteristics of juvenile wood. On an industrial scale, the proportion of juvenile wood in the market has grown because of the increasingly shorter rotation ages. Therefore, solving the problems related to juvenile wood, particularly warping during drying, has gained relevance (Langrish and Walker 2006).

Concerning the drying process of conifers, warp may cause the rejection of up to 12% of dried wood; therefore, it is a major source of losses in the wood industry during drying. Warp causes estimated economic losses of $1 billion (Tarvainen 2005). Sometimes juvenile wood includes pith, which may increase warp related rejections by up to 87% (Montón *et al.* 2015).

Typically, the drying of *P. radiata* wood occurs under accelerated conventional temperature drying (90/90, °C/°C) and high-temperature drying (HTD; 120/70; or 140/90, °C/°C) programs (Haque 2011; Ananías *et al.* 2013). For more information regarding the characterization of warp during the drying of *P. radiata* and its effects on wood production, refer to the works of Gutiérrez (1985), and Ormarsson and Cown (2007). During the drying of *P. radiata* at high temperatures, the induced deformations by warp are higher (Melo and Pavón 1987), especially when the wood thickness increases (CORFO 1989). Vásquez *et al.* (1991) found that warp occurring during the drying of *P. radiata* juvenile wood at high temperatures (HTD = 120/70, °C/°C) may be controlled with the use of suitable overloads, with twist being the main limiting factor of the process. Comparatively, in conifers, at the end of an HTD process, warp is of a lesser magnitude than during conventional drying (Arganbright *et al.* 1978; Simpson 2004; Straže *et al.* 2011). Furthermore, there is evidence that drying at high temperatures generates sawed-dried quality wood from juvenile *P. radiata*, with the presence of a spiral grain, which is promoted by the plasticization-softening of the wood and use of overloads (Kauman 1987; Haslett *et al.* 1991).

The spiral grain and fibrillar angle induce the formation of warp during drying as they favor the anisotropy of longitudinal contraction (Haslett *et al.* 1991; Ormarsson and Cown 2005). One characteristic of *P. radiata* juvenile wood is the high presence of spiral grain (Moore *et al.* 2015) and a high fibrillar angle (Alteyrac 2015). Straže *et al.* (2011) observed that, in addition to the effect of the spiral grain, the curvature radius of the growing rings near the pith affects the twist during drying of European conifer. The presence of pith increases the warp during drying (Shelly *et al.* 1979; Simpson and Tshernitz 1998). Moreover, during wood compression, the fibrillar angle is increased (Xu *et al.* 2009) and it exhibits a higher spiral grain growth (Thomas and Collings 2016).

A high temperature under a wet environment tends to plasticize and soften the matrix of hemicellulose, cell wall lignin, and middle lamella lignin (Hillis and Rozsa 1978). Moreover, superheated steam stimulates this lignin softening phenomenon (Hasllet *et al.* 1999; Hasllet and Dakin 2001). At a moisture content of 10% in *P. radiata* wood, the softening temperature of lignin is approximately 140 °C to 145 °C (Riley *et al.* 1999).

Notably, during drying at high temperatures, the softening of lignin induces plasticity and adjustments of the cellulose microfibrils in the hemicellulose and lignin matrix, and in the same fibers in between the middle lamella lignin (Mackay 1973). The adjustment of fibers is likely to cause a new equilibrium position of the fibers (Gutierrez 1985). For this reason, the implementation of overloads, along with steam at high temperatures, reduces the effect of warping, particularly in juvenile wood close to the pith (Frühwald 2006). In the case of drying juvenile *P. radiata* wood, an additional overload over the wood pile has been suggested (CORFO 1989; Keey *et al*. 2000; Langrish and Walker 2006).

Drying with superheated steam at an atmospheric or high pressure otherwise favors softening and the previously described relaxation phenomenon (Pang 2004). Likewise, the dimensional stability of wood is improved using this method (Lenth and Kamke 2001; Lenth and Haslett 2003). There are several works related to the drying of conifers (Vermaas and Kuun 1989; Alvarez-Noves and Fernandez-Golfin Seco 1994; Tarvainen *et al*. 1999) and broad leaves (Rosen *et al*. 1983; Perré *et al*. 2000) at high pressures. Therefore, during the final conditioning treatment, when the wood moisture content is approximately 12%, the softening of lignin with superheated steam at a high pressure is helpful in warp recovery during drying (Pang and Pearson 2004). The recommended pressurization time is 1 h, since lower times do not significantly reduce the warp, and times longer than 4 h may cause thermal degradation of wood (Haslett and Bates 1997).

The primary objective of the present study was to obtain the optimum thermal treatment conditions for the recovery of warped dried core-wood *P. radiata*. Three variables were analyzed during the process: the temperature, overload, and time.

EXPERIMENTAL

A load of 196 pieces of dried lumber, composed of the interior wood of *P. radiata* (41 mm × 138 mm × 3200 mm), was provided by an Chilean sawmill (Nacimiento, Chile) and was analyzed. The lumber, initially destined for the international structural wood market, was randomly selected from a set of lumber that had been rejected because of inadmissible warp during drying. Table 1 presents the parameters of the industrial drying process.

Table 1. Industrial Drying Parameters of *P. radiata* Lumber

Process Stage	$T_{\text{dry bulb}}$ (°C)	$T_{\text{wet bulb}}$ (°C)	Time (h)
Heating	90	90	3
Drying	80	60	48
Conditioning	90	90	6

Lumber dimensions: 41 mm × 138 mm × 3200 mm

The experimental design was made up of seven tests of steaming processes (four saturated and three superheated), two levels of overload (1.5 and 3, ton/m^3), three temperatures of steaming, one temperature of saturation (T_1), two superheated temperatures (T_2), and five treatment times, with three times at T_1 (t_1) and two times at T_2 (t_2). For each test, 28 wood samples were used, for a total of 196 samples (Table 2). The drying tests were conducted in a multipurpose dryer with a 10 (m^3) of volumetric capacity (LAB-3.5e, Neumann, Concepción, Chile), located at the Laboratory of Drying Technologies of University of Bío Bío.

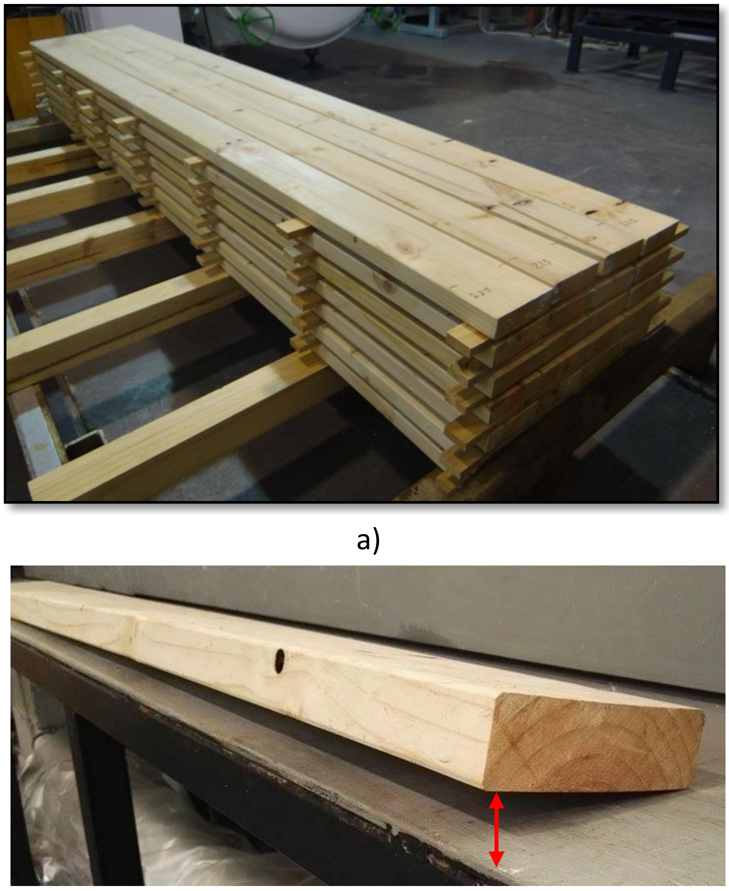
Table 2. Experimental Design: Parameters of the Study

Test	**Overload** (ton/m^3)	**Temperature** (°C)		**Time** (h)	
		T_1	T_2	t_1	t_2
1	1.5	100	-	6	0
2	3	100	-	6	0
3	1.5	100	-	3	0
4	1.5	100	-	12	0
5	1.5	100	140	6	0.5
6	1.5	100	140	6	2
7	1.5	100	160	6	0.5

Prior to the thermal treatment, each of the 196 samples was assessed to determine the warp (twist, bow, and cup), mean dimensions (length, width, and thickness), mass, and moisture content (MC), according to the Chilean standards NCh176/1.Of84 (1984), NCh176/2.Of86 (1988) and NCh993Of.72 (1972).

The moisture content (MC) of the timber was determined by using Eq. 2, and the warps were measured on an ad-hoc table, where the timbers were positioned keeping certain edges on the table's surface. Then each type of warp was measured according to the standard. Figure 1b shows how the timbers ware positioned on the table to measure the twist warp.

Then, the load was divided into seven groups of 28 samples, which were encased using 25 (mm) thick separators (Fig. 1a) and put into the dryer to apply the thermal treatment, according to the experimental design that is detailed in Table 2.


a)

b)

Fig. 1. Analyzed P. radiata lumber: a) wood stacked with dimensions of 41 mm × 138 mm × 3200 mm, b) Lumber on the table ready for twist measure.

After thermal treatment, the lumber was subjected to overload and cooled at room temperature for 24 h. The determination of the warp, mass, and MC of the lumber was performed with the Chilean standard NCh933.Of72 (1972). Accordingly, the warp was classified using the criterion that is shown in Table 3.

In this study, to perform the analysis of warp recovery, the slight defect classification (L) was considered to be the permissible level. Therefore, a slight warp was considered unimportant.

Table 3. Performed Classification of the Lumber Warp

Classification	Twist (mm)	Bow (mm)	Crook (mm)	Cup (mm)
No defects (ND)	0	0	0	0
Slight (L)	6.9	20	5.5	2.8
Moderate (M)	13.8	40	11	5.5
Severe (S)	20.7	60	16.5	8.3
Unacceptable (U)	> 20.7	> 60	> 16.5	> 8.3
These values are valid for lumber with a 138-mm width and 3200-mm length				

According to the authors' opinion, the concept of permissible level allows a better assessment of the treatments regarding the recovery of warps, understanding that the treatment is not necessary when the defects are minor. In such a case, the analysis of the results mainly used the average warp recovery index (I_{RA}, %), which was calculated with,

$$I_{\mathrm{RA}} = \frac{1}{N}\sum_{i=1}^{N}\left(C_{\mathrm{pre}} - C_{\mathrm{post}}\right)_{\mathrm{i}} * 100 \text{ with } C_{\mathrm{pre}} \neq 0 \tag{1}$$

$$C_{\mathrm{pre}} = max\left[0, \frac{A_{\mathrm{pre}} - A_{\mathrm{adm}}}{A_{\mathrm{pre}}}\right]$$

$$C_{\mathrm{post}} = max\left[0, \frac{A_{\mathrm{post}} - A_{\mathrm{adm}}}{A_{\mathrm{pre}}}\right]$$

where C_{pre} is the pre-treatment warp coefficient, C_{post} is the post-treatment warp coefficient, A_{pre} is the pre-treatment warp (mm), A_{post} is the post-treatment warp (mm), N is the number of lumber and A_{adm} is the maximum permissible warp level (L) (mm), according to Table 3. The maximum function allows for the discarding of estimated values that are classified as slight warp.

Moreover, Eqs. 2 and 3 allowed for the calculation of the MC (%) and apparent density (ρ, kg/m^3) on a dry basis, respectively,

$$MC = 100 * \frac{m_{\mathrm{w}} - m_{\mathrm{d}}}{m_{\mathrm{d}}} \tag{2}$$

$$\rho = \frac{m_{\mathrm{d}}}{V_{\mathrm{d}}} \tag{3}$$

where m_{w} and m_{d} are the wet and actual wood mass (kg), respectively, and V_{d} is the volume of the actual mass (m^3). An analysis of variance ANOVA and Tukey's honest significance test were done to determine the existence of several testing variations (Montogomery 2004).

RESULTS AND DISCUSSION

From the results of the assessed warp, both before and after the thermal treatments, the average values, variance, and maximum permissible value were considered to be L (slight defect), according to the criteria of Table 3. The results are summarized in Table 4. The following results were obtained: (1) cupping was not observed, which was positively influenced by the drying and subsequent brushing; (2) bowing and crooking were negligible because the permissible values were not overwhelming; therefore, these defects did not imply a severe quality failure; and (3) concerning the quality, the most critical warp phenomenon was twist, which was classified as unacceptable (U). These results agreed with those reported in previous studies (Melo and Pavón 1987; Vásquez *et al.* 1991). The MC, both before and after the thermal treatment, was less than the allowable limit (12%), which met the dry wood requirement (UNE 56544 2011). An increase in the heterogeneity was observed, which caused the increase in the MC standard deviation from 1% to 3.2%. In summary, of the five analyzed variables (twist, bow, crook, cup, and MC), only the twist presented average values higher than the admissible value. Consequently, this study included a detailed analysis of the twist. Table 5 shows, for each experiment, the number of lumber according to the classification of defect given in Table 3. It is observed that 100% of the beams present twist defects, being more than 90% of moderate (M) or severe (S) level.

Table 4. Warp and MC Average Values Before and After the Thermal Treatment

Warp	**Average**		**Standard Deviation**		**Permissible Value**
	Before	After	Before	After	
Twist (mm)	14.8	8.6	4.2	4	6.9
Bow (mm)	2.2	2.5	1.9	2.7	20
Crook (mm)	2.7	3.1	1.5	1.8	5.5
Cup (mm)	0.0	0.0	0.0	0.0	2.8
MC (%)	8.0	11.3	1.0	3.2	12

Table 5. Test *vs.* Number of Lumber Classified According to the Twist Level

Test	**SD**	**L**	**M**	**S**	**U**	**Total**
1	0	0	5	14	9	28
2	0	0	12	14	2	28
3	0	0	14	13	1	28
4	0	3	14	11	0	28
5	0	1	10	17	0	28
6	0	0	20	7	1	28
7	0	0	5	19	4	28
Total	**0**	**4**	**80**	**95**	**17**	**196**
(%)	**0**	**2.0**	**40.8**	**48.5**	**8.7**	**100**

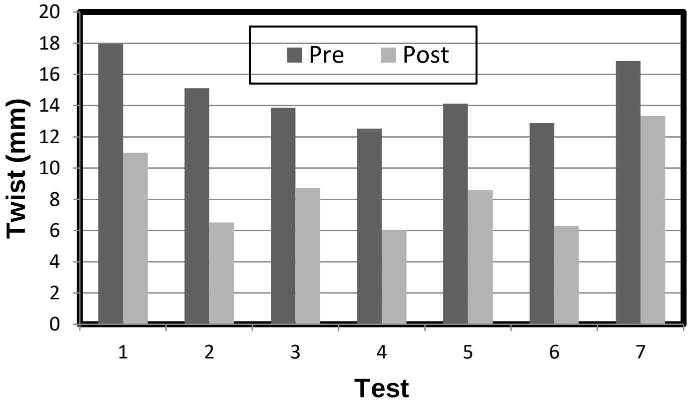


Fig. 2. Measured twist values before (Pre) and after (Post) the thermal treatment

Figure 2 shows the twist values before and after the treatment. From the comparison of all of the tests, the average twist recovery value was higher in test 2 (7.6 mm), which was slightly higher than those in tests 4 and 6. In this context, the overload, treatment time, and superheating were relevant. Test 7 garnered the lowest twist recovery value (1.9 mm), and also had the highest superheating temperature (160 °C).

Table 6 summarizes property variations after the thermal treatments with regards to the warp recovery (mainly the twist), which was described using the I_{RA}. The moisture content variation (ΔMC) in all of the tests was low (< 3%), except for test 6 (9.3%). The higher superheating time (2 h) may have explained this high ΔMC value. The increase in the density probably implied a combined effect of the steaming time, overload and MC variations. The steaming effect is defined as the wood cell-wall softening that induces a low variation of final volume, despite relatively higher MC changes, with a maximum value of 4.8%. This value corresponded to test 4, which had the highest steaming time (12 h). Considering the warp recovery index, tests 2 and 7 showed the highest and lowest values at 43.1% and 20%, respectively. The effect of overload on density, which can be observed in tests 1 and three where the density was increased by 2.7% and 3.9% for an overload of 1.5 and 3 (ton/m^3), respectively.

Table 6. Average Variation in the MC, Density (*ρ*) and Twist Recovery (I_{RA})

Test	Average Variation		Twist Recovery
	MC (%)	**ρ (%)**	**I_{RA} (%)**
1	2.3	2.7	36
2	2.9	3.9	43.1
3	1.7	1.5	31.3
4	2.7	4.8	40.9
5	2.4	4	33.4
6	2.3	2.6	38.5
7	2.3	2.6	20

Table 7 gathers the ANOVA results of the four analyses grouped according to standard test: a) overload (tests 1 and 2), b) steaming time (tests 1, 3, and 4), c) superheating time (tests 1, 5, and 6), and d) superheating temperature (tests 1, 5, and 7). The results, considering a significance α=0.05, validated the null hypothesis (H_0; $F_c < F$) for the overload, saturation time, and superheating time, but not for the superheating temperature ($F_c > F$). In this case, Tukey's honest significance test showed that test 7 was significantly different from tests 1 and 5: the recovery of warps products is influenced by superheating temperature.

Table 7. Results of the ANOVA analysis grouped by study parameters

Parameter	Test	Probability	*Factor*	
			Fisher (*F*)	Critic (F_C)
a) Overload	1 and 2	0.14	4.02	2.20
b) t_1	1,3 and 4	0.11	3.11	2.30
c) t_2	1, 5 and 6	0.48	3.11	0.73
d) Temperature	1, 5 and 7	0.00	3.10	8.15

According to the treatment, a second analysis of twist recovery was performed. In this study the lumber with moderate (M) and severe (S) defects were separately analyzed. This sample corresponded to 40.8% and 48.5% of the original lumber load with twist moderate and severe, respectively (see Table 5). Results are shown in Figure 3.

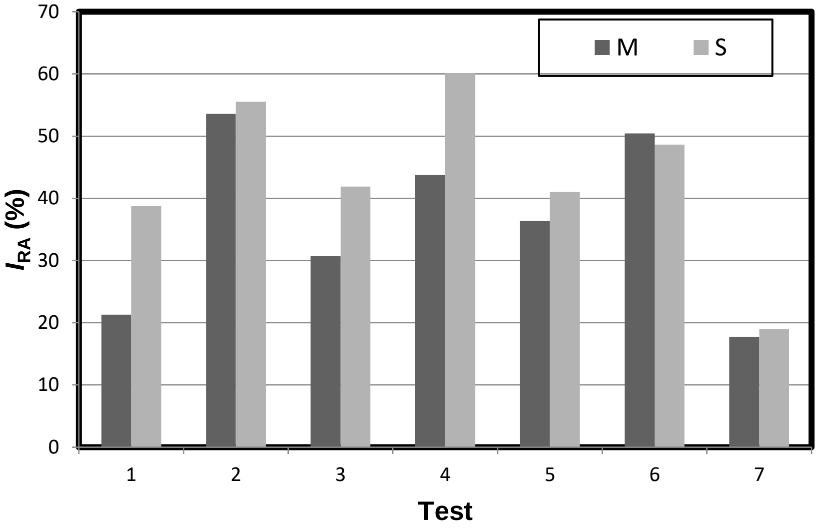


Fig. 3. I_{RA} according to the warp level: moderate (M) and severe (S)

In this figure it can be observed that tests 2, 4, and 6 showed warp recoveries of almost 50%, with test 2 presenting the most similar behavior. Nevertheless, test 4 showed better recovery for severe warp (60%). Test 7 presented the worst results with recovery values lower than 20%. Therefore, these results supported the performed analysis based on the warp recovery index that is shown in Table 6, and it allows concluding that the steaming time is an essential factor in the recovery of severe twist.

CONCLUSIONS

1. Twist was the central warp defect exhibited in the analyzed lumber. The warp recovery increased with the overload and steaming time. Superheating did not have a relevant role in warp recovery at 140 (°C), but the recovery time decreased when the superheating temperature was 160 (°C). Moreover, the average values suggested that the steaming time has a primary effect on the recovery of severe twist.
2. Twist recovery may occur equally with the following procedures: (a) steaming at 100 (°C) for 6 (h) with an overload of 3 (ton/m^3), (b) steaming at 100 (°C) for 12 (h) with an overload of 1.5 (ton/m^3), and (c) steaming at 100 (°C) for 6 (h) combined with thermal treatment at 140 (°C) for 2 (h) using an overload of 1.5 (ton/m^3).
3. The observed variations in the MC and apparent density were lower than 10% and 5%, respectively, which agreed with the results of other studies. The apparent density presented a correlation with the steaming time.
4. The ANOVA showed the existence of a significant difference in the twist recovery when the grouped tests were analyzed according to the superheating temperature,

which demonstrated that wood treatment with a superheating temperature of 160 °C is inefficient.

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