RECOVERY OF MECHANICALLY INDUCED RESIDUAL STRESSES IN DENSIFIED SOFTWOODS CREATED DURING A DENSIFICATION PROCESS

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Abstract. Mechanical densification technology has been used to increase density and mechanical properties of low-density wood. After the densification process, some internal stresses created during densification can be temporally "locked" in wood, which is defined as mechanically induced residual stresses. When the densified wood is exposed to wet conditions, these mechanically induced residual stresses along with swelling stresses can be released with time, which might result in dimensional instability causing warping. This study aimed at examining mechanically induced residual stresses in densified softwoods and simulating the stress-releasing process by means of a mathematical model. Balsam fir and eastern white pine were used for undensified wood specimens and densified wood specimens that were compressed at three compression ratios (CRs) of 0.25, 0.50, and 0.60. Specimens compressed at 0.50 and 0.60 CR plus one control group of undensifed specimens (ie CR = 0) was used to calculate model parameters, and ones at 0.25 CR were used to verify the model developed. Total residual stresses were directly measured by soaking softwood specimens in hot water of 60°C. It was found that 1) about 50% of

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maximum total residual stress in densified fir and pine specimens could be released in the first several minutes after soaking in the hot water; 2) the mechanically induced residual stresses increased with increasing CR; 3) the mechanically induced residual stresses released from pine were slightly larger than those from fir; and 4) the mathematical model developed in terms of CR could well simulate the release of mechanically induced residual stress with increasing time.

Keywords: Densified softwoods, mathematical model, stress recovery, residual stresses.

INTRODUCTION

Mechanical densification technology has been used to increase density and mechanical properties of low-density wood (Inoue et al 1990; Norimoto 1993; Ito et al 1998; Uhmeier et al 1998; Kamke and Sizemore 2005; Wang and Cooper 2005; Blomberg and Persson 2007; Lamason and Gong 2007; Cloutier et al 2008; Kutnar et al 2011). During the process of radially densifying wood (in the wood ray direction), the dimension of wood could be decreased to a large extent, especially under hygrothermal environment. Although there was no macroscopic failure observed on the surface of wood at a proper selected compression level, it can be seen, at the microscopic level, that buckling of cell walls occurred and volume of lumens decreased (Norimoto 1993). In the course of wood densification in a hot press, the external compressive load increases with increasing compressed deformation, which creates internal stresses stored in the densified wood. When the densified wood is removed from the press, only a small amount of internal stresses, called elastic springback, caused by irreversible swelling from compressed wood elements and mats (Halligan 1970), can be released directly. The rest are still locked in the densified wood. These locked internal compressed stresses can be called residual stresses. In other words, residual stresses are partially recoverable internal stresses that are generated in manufacturing of densified wood caused by buckled cell walls and are temporally "locked" in densified wood.

Densified wood is a promising value-added product that helps use low-density wood resources. It can be used for appearance wood products such as flooring, staircases, and tabletops. However, residual stresses play an important role on dimensional instability of densified wood products in service. Moist environments can cause densified wood to distort, twist, bend, or warp by releasing residual stresses. To save materials and decrease manufacturing cost, densified wood is often used as the face layer of a laminated product. Differential dimensional changes between laminates caused by residual stresses could warp the laminated wood product (Blomberg and Persson 2007).

Dry wood, the moisture content of which is below the FSP (about 25%), can swell when adsorbing moisture. During this swelling, internal stress occurs to counterbalance a changeably external stress, maintaining a constant dimension of wood. For undensified wood, internal stress results from the swelling of normal cell walls only, whereas the magnitude of the stress is determined by the swelling coefficient, modulus of elasticity (MOE), and moisture content changes. Therefore, it is regarded as physical residual stress. Comparatively, residual stress released from densified wood is caused by the shape recovery and swelling of buckled cell walls. The stress induced by the buckled cell walls can be referred to as mechanically influenced swelling pressure according to Perktiny and Kingston (1972). It is highly dependent on the degree of compression during the densification process. In this study, this kind of swelling pressure/stress was deemed mechanically induced residual stress.

To properly use densified wood, an in-depth understanding of the evolution of mechanically induced residual stresses is necessary. This study was aimed at analyzing residual stresses in densified wood and modeling the recovery process of residual stresses when subjected to moisture. The findings could assist in design and use of densified wood products.

MATERIALS AND METHODS

Materials

Wood species tested were balsam fir (*Abies balsamea* [L.] Mill.) and eastern white pine (*Pinus strobus* L.). Mean oven-dried density values of fir and pine used in this study were 320 kg/m^3 (standard deviation [SD] = 10 kg/m^3) and 430 kg/m^3 (SD = 40 kg/m^3), respectively. Overall specimen dimensions were 30 mm long (longitudinal direction) ×30 mm wide (tangential direction) ×25 mm thick (radial direction). Specimens were grouped based on density (each group had similar average density and SD). Each group had five specimens. Specimens were vacuum-soaked in water at room temperature (about 21°C) until they were saturated. The water-saturated specimens of fir and pine had an average initial moisture content of about 270 and 260%, respectively. Three compression ratios (CRs) were used in this study, 0.25, 0.50, and 0.60. CR was defined as the ratio of diminished thickness to initial thickness. The largest CR chosen in this study was 0.60, which could resist any irreversible damage in cell walls, eg crushing (Gong et al 2006). As a comparison, a control group of undensified wood (CR = 0) was also tested, and the stresses measured were defined as physically induced residual stresses. Three groups of specimens at CR of 0, 0.50, and 0.60 were used to determine the parameters of the mathematical model developed, whereas the other group of specimens at CR 0.25 was used to verify the model. The selection of 0.25 CR as a verification group was based on Fukuta et al (2007) who found that a turning point at about 0.40 CR existed in the increasing curve of the modulus of rupture (MOR) with increasing CR for thermomechanically compressed Japanese cedar (*Cryptomeria japonica D. Don*). After the turning point, MOR increased faster than before the point. Therefore, using 0.50 CR to determine the model parameters could produce more reasonable results. There were 20 specimens for each species. A group of five soaked specimens was mounted in a jig and compressed using a universal test machine at a loading rate of 1 mm/min until the top platen reached the thickness gauges. The whole densification process was performed at room temperature, which ensured that no thermal degradation would happen in wood during heat treatment (Fig 1). The jig with five compressed wood specimens was fastened using four bolts prior to removal of load, stored in a conditioning chamber (20°C and 65% RH) for 2 da, oven-dried at 103°C, and restored in the chamber for 1 wk. Thereafter, specimens were removed from the jig with a stable final thickness (radial dimension).

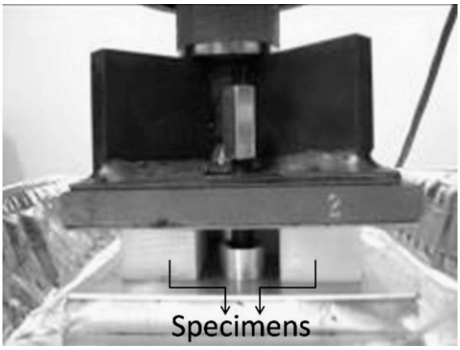

Figure 1. Experimental setup for wood densification.

Methods

The released stresses of a specimen were measured using a universal testing machine with a

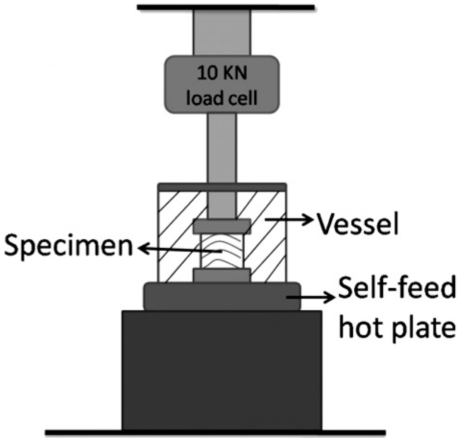

Figure 2. Experimental setup for measurement of total residual stress.

10-kN load cell (Fig 2). A bottom bearing platen was used to ensure uniform distribution of stress across the surface of the specimen. The gap between two stainless steel plates was fixed at the original thickness of the specimen. The specimen was placed in a vessel filled with water. The water was heated to 60°C and poured into the vessel prior to the test, and then it was maintained at 60 ± 2°C via a self-feed hot plate. The temperature of 60°C assisted in the release of residual stress stored in wood and helped avoid overheating, which could cause damage to the load cell. A small initial load of 0.045 kN was applied to the specimen before water was poured into the vessel. Load, cross-head movement, and elapsed time were recorded through a data logger. The measurement was stopped until the load levelled off, at which point the corresponding stress reached its maximum value. Three of five specimens were picked from each group for measuring residual stress of each specimen. This guaranteed that three specimens were successfully tested from each group in case of any operation errors during testing.

A mathematical model was then developed based on average stress and corresponding time of three groups of specimens with 0, 0.50, and 0.60 CR. A nonlinear curve fitting method was chosen to determine the model parameters, which was realized via Origin 8.0 software (OriginLab 2010).

RESULTS AND DISCUSSION

Stresses Released from Fir and Pine

Increases of total residual stress (σ_t) with increasing time for all undensified and densified fir and pine specimens are shown in Fig 3. As previously mentioned, σ_t includes two components: physically induced residual stress (σ_p) and mechanically induced residual stress (σ_m). σ_p exists in both undensified and densified wood specimens, but σ_m only occurs in densified wood specimens. Maximum σ_m can be, thereby, calculated by subtracting maximum σ_p from maximum σ_t. Mean values with SD of maximum σ_t and time needed to reach 50 and 100% of maximum σ_t, mean values of maximum σ_m, and ratios of σ_m/σ_t are summarized in Table 1.

Figure 3 and Table 1 show that all fir and pine specimens share a similar time-dependent trend that can be visually divided into two phases: a quick increase of stress to about 50% of maximum σ_t within the first few minutes (phase I) and a slow increase of stress until achieving a constant value (ie maximum stress) (phase II). It was interesting that the time for reaching 50% of maximum σ_t was almost independent of CR. Mean time needed in phase I for pine specimens was about 25% higher than that for fir specimens. Comparatively, maximum σ_t and σ_m and total time needed for reaching maximum σ_t

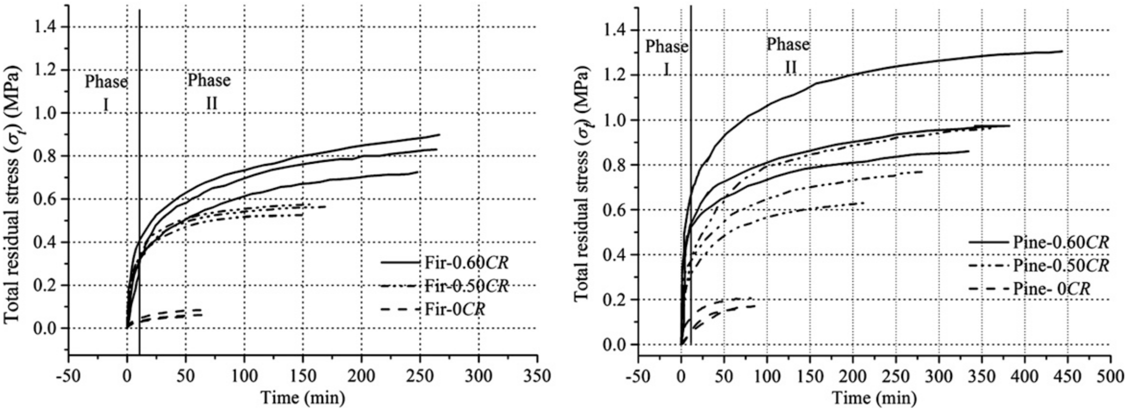

Figure 3. Total residual stresses released from fir (left) and pine (right) during soaking process.

Table 1. Summary of maximum stresses measured from fir and pine.[a]

Compression ratio (CR)	Maximum σ_t (MPa) Mean (SD)		Time to reach maximum σ_t (min); mean (SD)		Time to reach 50% of maximum σ_t (min); mean (SD)		Maximum σ_m (MPa); mean		Ratio of the maximum σ_m/σ_t (%)	
	Fir	Pine	Fir	Pine	Fir	Pine	Fir	Pine	Fir	Pine
0	0.08 (0.02)	0.18 (0.03)	60.00 (5.00)	81.00 (6.50)	10.00 (1.00)	13.60 (4.50)	0	0	0	0
0.50	0.54 (0.03)	0.74 (0.18)	157.00 (11.50)	284.00 (42.50)	11.00 (1.50)	12.50 (5.00)	0.46	0.58	85.18	78.37
0.60	0.82 (0.09)	1.09 (0.22)	259.00 (10.00)	372.00 (58.00)	13.00 (3.00)	14.50 (4.50)	0.74	0.91	90.24	83.48

[a] σ_t, total residual stress; σ_m, mechanically induced residual stress; SD, standard deviation.

of densified fir and pine specimens were highly dependent on CR, showing that the larger CR was, the higher maximum σ_t and σ_m could reach, and the longer time was needed.

Table 1 also shows that, overall, maximum σ_t and σ_m of pine specimens were larger than those of fir specimens. Especially for the control group of 0 CR, mean value of maximum σ_t ($\sigma_t = \sigma_p$) for fir specimens was low (0.08 MPa), whereas that for pine specimens was 0.18 MPa. The latter is about 2.6 times greater than the former. This might be attributed to the formation of physically induced residual stress in undensified wood specimens, which is a product of MOE and strain. Strain is a product of swelling coefficient of wood and moisture content change. MOE and swelling coefficient in the radial direction of undensified pine were about 1.5 and 2.0 times larger than those of undensified fir, respectively (FPL 2010).

However, mean values of maximum σ_t of densified pine specimens with 0.50 and 0.60 CR were about 37 and 32% larger, respectively, than densified fir specimens. These results suggest that σ_m dominated σ_t in densified wood specimens. The high ratios of maximum σ_m and σ_t shown in Table 1 support this finding. It is reasonable to assume that the magnitude of σ_m of fir and pine specimens at the same CR level was affected by wood density. Density of pine tested in this study was about 34% higher than that of fir. Because more wood substance exists in pine, a higher compressive load is required to densify pine wood at the same CR level, which generates more mechanically induced residual stresses to be stored in densified pine wood. In Table 1, maximum σ_m of pine at two CRs of 0.50 and 0.60 was larger than that of fir, giving an increase of about 26 and 23%, respectively. This explanation has also been verified by Gong et al (2006) who studied the effect of CR of pine and fir on flexibility of densification and discovered that fir is more compressible than pine.

Also, SD values (Table 1) of both maximum σ_t and σ_m of fir were smaller than pine because fir has a more homogeneous structure than pine from the wood anatomy point of view, eg fir does not have resin canals.

Modeling of Mechanically Induced Residual Stress

This study focused on modeling the release of mechanically induced residual stress (σ_m) with increasing time in the compression direction (ie radial direction) of densified wood specimens. Thus, the lateral expanding stress was not considered. Friction between specimens and load heads was also ignored.

In Fig 3, the release of σ_t with increasing time reveals a viscoelastic nature of wood. The well-known term rheology has been widely accepted to explain the phenomena of creep or stress relaxation under certain conditions. In this study, the wood specimens were constrained with a constant uniaxial dimension and soaked in 60°C water. The release of σ_t as a reaction of restricted movement of wood also followed the nature of rheology. Thus, the term rheology was used here in a broader sense (Thoemen et al 2006).

Many useful models developed to describe the rheology behavior of wood materials have been presented. In these models, elastic springs and viscous dashpots in various combinations are commonly used to represent creep or stress relaxation of wood (Gittus 1975; Wu et al 2009). The simplest viscoelastic models include Maxwell, Kelvin, Linear, and Burger. In addition, Kamke and Kutnar (2010) used a modified Hooke's law to examine the stress–strain response of wood during transverse compression in high temperature and saturated steam conditions. By examining the σ_t time curves shown in Fig 3, the widely used Kelvin model (ie a spring and a dashpot in parallel) was borrowed with an additional correction item to simulate σ_t:

$$\sigma_t(\tau) = a\left(1 - e^{\frac{-\tau}{b}}\right) + \tau^c \quad (0 \le \tau \le 1) \qquad (1)$$

where a, b, and c are empirical constants, which were obtained simply by means of a nonlinear curve fitting method (OriginLab 2010) (Table 2).

In Eq 1, to facilitate the simulation, a concept of relative time (τ) was introduced, which is the ratio of $\tau = t_i/t$, where t_i is a given time and t is total time when σ_t achieves a stable value. From the mathematics viewpoint, coefficient a governed the leveling off of a curve at a certain value (ie maximum stress) when τ approaches 1, whereas coefficients b and c controlled the curvature change of the curve. The curve fitting results given in Table 2 reveal that coefficients a and c varied with CR, whereas coefficient b was almost constant at 12 regardless of testing conditions. Therefore, b was fixed at 12. The relationships of coefficients a and c with CR for fir and pine are shown in Fig 4. Fir and pine had the same trends, a nonlinear increase of a, and an approximately linear decrease of c with increasing CR. A nonlinear regression equation comprising a linear and an exponential term was used here because it can well describe the quickly increasing part of a beyond 0.50 CR (Fig 4, left).

Table 2. Regression coefficients used in a mathematical model of total residual stress.

	Fir			Pine		
Compressed ratio (CR)	*a*	*b*	*c*	*a*	*b*	*c*
0	−11.2	12	0.90	−10.0	12	0.74
0.50	−5.4	12	0.48	−2.0	12	0.25
0.60	−2.5	12	0.33	1.0	12	0.13

Therefore, coefficients a and c in Eq 1 can be replaced using the functions of CR, as shown in Eq 2:

$$\begin{gathered}\sigma_t(\tau) = (p_1 CR + q_1)e^{CR}\left(1 - e^{\frac{-\tau}{12}}\right) \\ + \tau^{(p_2 CR + q_2)} \\ (0 \le \tau \le 1, 0 \le CR \le 0.60)\end{gathered} \qquad (2)$$

where the regression coefficients of p_1, q_1, p_2, and q_2 are listed in Table 3.

Especially when CR is equal to 0, σ_p can be derived with Eq 3:

$$\begin{gathered}\sigma_p(\tau) = q_1\left(1 - e^{\frac{-\tau}{12}}\right) + \tau^{q_2} \\ (0 \le \tau \le 1, CR = 0)\end{gathered} \qquad (3)$$

The total residual stresses of fir and pine released with increasing relative time calculated

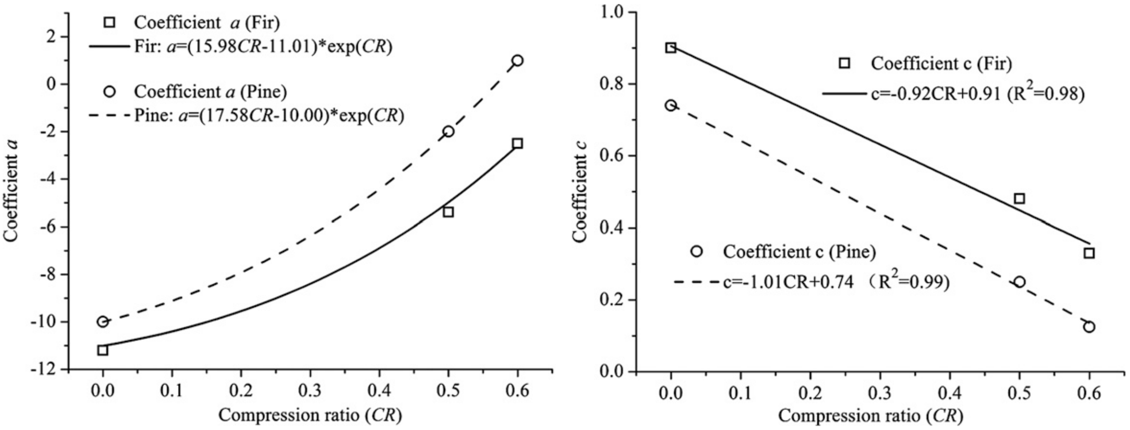

Figure 4. Relationships between coefficients a (left) or c (right) and compression ratio (CR).

Table 3. Regression coefficients used in a mathematical model of mechanically induced residual stress.

Species	Coefficient			
	p_1	q_1	p_2	q_2
Fir	15.98	−11.01	−0.92	0.91
Pine	17.58	−10.00	−1.01	0.74

by Eqs 2 and 3 are illustrated in Fig 5, which is in agreement with the curves shown in Fig 3.

Thus, σ_m can simply be obtained by deducting σ_p from σ_t at a given CR:

$$\begin{aligned}\sigma_m(\tau) &= \sigma_t(\tau) - \sigma_p(\tau)\\ &= \left((p_1CR + q_1)e^{CR} - q_1\right)\left(1 - e^{\frac{-\tau}{12}}\right)\\ &\quad + \tau^{(p_2CR+q_2)} - \tau^{q_2}\\ &(0 \le \tau \le 1, 0 \le CR \le 0.60)\end{aligned} \tag{4}$$

Verification of Developed Model

To verify the developed model, ie Eq 4, a group of three specimens densified at 0.25 CR were tested for σ_t. Mean σ_m values of densified fir and pine released with τ were then calculated by subtracting average σ_p from σ_t of each specimen, in which τ was used to ensure the consistency of sampling frequency for all specimens. Experimental and simulated σ_m results are shown in Fig 6. The evolution of simulated σ_m of densified fir and pine with τ agrees with the trend of σ_m releasing with τ observed from experimental results. At $\tau = 1$, the mean and SD of maximum σ_m values of three fir specimens were 0.27 and 0.03 MPa, respectively, whereas those of pine specimens were 0.23 and 0.04 MPa. Compares with the mean values, the simulated maximum σ_m values of fir and pine were about 0.25 and 0.21 MPa, producing a relative error of about 7.4 and 8.7%, respectively. Therefore, it can be suitable in prediction of σ_m release of densified fir and pine as CR ranges from 0-0.60.

CONCLUSIONS

In this study, the release of total residual stresses (σ_t) of densified softwood at four CRs with increasing time was directly measured. A mathematical model in terms of CR was developed to simulate the release of σ_t. Mechanically induced residual stress (σ_m), as a dominant component in σ_t, was deducted from σ_t using the developed model. Effects of CR on σ_t and σ_m were discussed as well. Based on the results and discussion, some major conclusions could be drawn:

(1) σ_t existing in densified fir and pine specimens was divided into two components, mechanically induced residual stress caused by recovery of buckled cell walls and physically induced residual stress caused by swelling of cell walls.

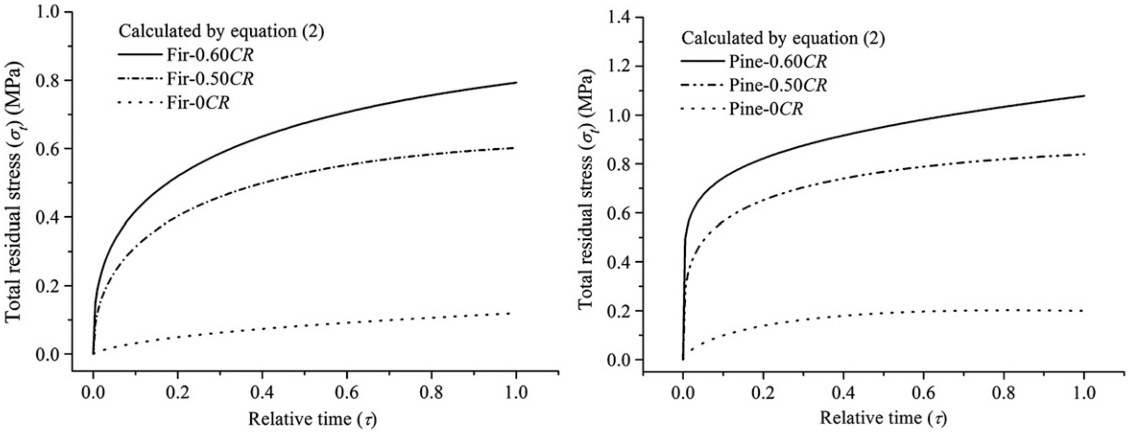

Figure 5. Simulated total residual stresses of fir (left) and pine (right) released with relative time.

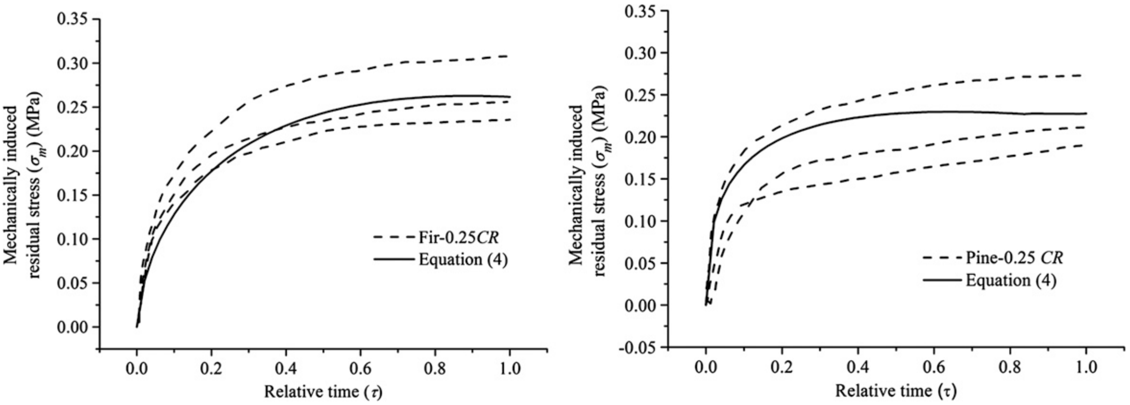

Figure 6. Experimental and simulated mechanically induced residual stresses of densified fir (left) and pine (right) with 0.25 compression ratio (CR) released with relative time.

(2) Maximum σ_t values of densifed fir and pine specimens increased with CR in a nonlinear manner. At the same CR level, maximum σ_t of pine was larger than that of fir because of the higher density of pine than fir.

(3) About 50% of maximum σ_t quickly released within the first few minutes, whereas the rest was gradually released in several hours. Total time needed to reach maximum σ_t depended on CR. This finding could assist in approximately estimating maximum σ_t.

(4) The mathematical model developed in terms of CR ranging from 0-0.60 could well describe the evolution of the release of σ_m of densified fir and pine with increasing relative time.

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