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ORIGINAL

Evaluation strategy of softwood drying stresses during conventional drying: a "mechano-sorptive creep gradient" concept

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Abstract The detection and analysis of drying-induced stresses in wood are of fundamental importance for quality evaluation and grading of kiln-dried lumber, and thus, various such procedures have been developed commercially. In this paper, a softwood drying-induced stress evaluation concept was proposed that is based on the drying rheology and wood mechano-sorptive mechanism. The evaluation variables for the drying-induced stresses included moisture content gradient (MCG) and mechano-sorptive creep strain gradient (MSCG), both of which are calculated through the lumber thickness. The softwood species needle fir (*Abies nephrolepis*) was processed into flat-sawn lumber pieces of 40 mm $\times$ 120 mm in cross section and was further kiln-dried in conventional laboratory dryers. Width deformation changes along the thickness of lumbers were measured by a slicing method. Shrinkage and elastic and viscoelastic creep strains in the tangential direction were measured quantitatively. Based on the dynamic free shrinkage functions for this softwood species, determined according to small specimen tests, the mechano-sorptive creep strain variables were calculated theoretically. By comparing the mechano-sorptive creep strain differentials between wood surface and its center section, a conspicuous corresponding trend could be revealed between this difference and those of the shrinkage strain differences. A combined variable set, which includes the moisture content differences and mechano-sorptive creep differences between the wood surface and its core section, was proposed based on this research test. The mechano-sorptive creep gradient concept was defined to formulate the drying stress and strain development during conventional drying. After some further

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mathematical approximations, these newly proposed variables were recommended to estimate the magnitude of drying stress during the mid- and final stages of softwood drying. The effectiveness of this theoretical inference was further verified according to the experimental results of the needle fir drying test.

List of symbols

A	Material constant, determined based on the physical properties of the wood species
B	Material constant, determined based on the physical properties of the wood species
c	Wood center layer
D	Measured dimension (mm) of the shrinkage specimen
c_η	Viscous coefficient (dimensionless)
E	Modulus of elasticity (MOE, MPa)
L	Width of the specimen (mm)
M	Wood moisture content (%)
s	Wood surface layer
T	Temperature (°C)
t	Times (min)
x	Coordinate along thickness (mm)

Greek letters

α	Shrinkage coefficient (1/100%)
α_{ve}	Correction coefficient (dimensionless)
ε	Drying strain component
η	Material viscoelastic coefficients (MPa · min)
σ	Drying stress inside the wood (MPa)

Subscripts

e	Elasticity
fs	Free shrinkage
FSP	Fiber saturation point
ms	Mechano-sorptive
$n = 0$–3	Deformation dimensions of the slice specimens
o	Green state
s	Kiln-drying state
N	Shrinkage
ve	Viscoelasticity

Superscripts

$s \dot{-} c$	Differences between the surface and center of wood

Introduction

In commercial lumber applications, the evaluation and analysis of wood drying stress and its associated shape deformation play a fundamental role in the quality assessment and grading of the final products (McMillen 1955; Ugolev and Skuratov 1992; Pang 2000). During lumber drying and thermal post-treatment, a significant amount of residual drying stress will be left inside wood as combined results of the intrinsic material properties, the dynamic and interactive deformation behaviors occurring during the heat and mass transfer process, and/or the non-appropriate execution of wood drying schedule (Salinas et al. 2015; Zhan and Avramidis 2017). From the material mechanics point of view, the key to avoiding lumber checking and detrimental deformation is the reasonable forecasting and analysis of drying stress (Keey et al. 1999; Zhan 2007; Allegretti and Ferrari 2008; Watanabe et al. 2014; Jantawee et al. 2016).

For more than three decades, given the great technical difficulties in the measurement of stress and strain of softwood lumber during drying (Allegretti and Ferrari 2008; Watanabe et al. 2014; Jantawee et al. 2016), the main research efforts have shifted from the classical elastic–plastic mechanics theory to drying rheology and mechano-sorptive mechanism (Ugolev 1976; Rice and Youngs 1990; Hanhijarvi 1998, 1999, 2000a, b; Ugolev 2005; Mohssine et al. 2007; Zhan et al. 2009a, b, c; Lazarescu et al. 2009, 2010; Lazarescu and Avramidis 2010; Zhan and Avramidis 2011a, b). The mechano-sorptive creep theory has been successfully applied to the analysis of wood drying stress and strain, and these studies were mainly focused on lumber transversal direction, which is decisive for the evolvement of drying deformation and formation of drying cracks (Zhan et al. 2009a, b, c; Zhan and Avramidis 2011a, b).

Some previous researches have concluded that wood drying strains (deformations) can be separated into elastic strain, viscoelastic strain, mechano-sorptive creep strain, free shrinkage strain, both theoretically and in practice (Rice and Youngs 1990; Hanhijarvi 1998, 1999, 2000a, b; Pang 2000; Ugolev 2005; Zhan et al. 2009a, b, c; Zhan and Avramidis 2011a, b; Ugolev 2014). Hanhijarvi (1998, 1999, 2000a, b) elucidated the deformation properties of two European softwood species in transversal directions in association with high-temperature drying systematically. Some researchers also provided experimental investigations and mathematical modeling of the wood drying stress and deformation based upon the mechano-sorptive creep theory (Pang 2000; Zhan et al. 2009c; Zhan and Avramidis 2011a, b). Although a number of studies on the mechano-sorptive properties of lumber boards during drying are reported in the literature, a qualitative and theoretical elucidation of the interrelationships between the drying stress and mechano-sorptive creep deformation has only been mentioned by a few works (Zhan 2007; Tu et al. 2007).

Zhan and Avramidis (2011a, b) qualitatively analyzed the influence of drying temperature and lumber cross-sectional configuration on the rheological properties of Canadian hemlock lumber. There was an explicit coincidence between the free shrinkage and mechano-sorptive creep deformation at the same drying temperature for this softwood species, suggesting the importance of the free shrinkage function for the theoretical description of wood drying mechano-sorptive creep. Langrish's work on solar cyclic drying of Australian eucalyptus timber demonstrated that, with the proper modulation of the external drying conditions, the mechano-sorptive strains can further accelerate the mitigation process of drying stresses for both the initial drying stage and the entire drying cycle (Langrish 2013).

Based on wood mechano-sorptive mechanism, this study aimed to evaluate the mechanical stress properties of lumber boards during conventional drying. A through thickness mechano-sorptive creep gradient (MSCG) concept was defined herein and further combined with the shrinkage deformation gradient (SDG) and moisture content gradient (MCG) through lumber thickness, forming a parameter set for the theoretical calculation of the drying stress inside the kiln-dried lumber boards.

Materials and methods

Materials

A green needle fir (*Abies nephrolepis* Maxim) log with an average diameter of 350-400 mm and 4.0 m in length was used in this work. The log was sourced from Yichun, Northeastern China, with an average basic density of 330 $\pm$ 20 kg/m^3.

Free shrinkage test

For the preparation of the free shrinkage specimens, altogether five locations were marked along the radial direction on the cross section of the log and then cut accordingly (Fig. 1). Sticks were cut along this log that were 40 mm in the tangential, 40 mm in the radial and 1500 mm in the longitudinal direction. Four straight lines were labeled on the four side surfaces of each stick along the longitudinal direction so that the shrinkage measurement positions could be determined uniformly.

The free shrinkage samples were cut successively in the longitudinal direction (10 mm in thickness) from these five sticks. All samples were then packed in PE bags and put inside a fridge to keep them in a green condition. For each shrinkage test, 40 specimens (20 specimens for the subgroup 1 and 20 for the subgroup 2) were taken out and submerged in distilled water until all were saturated with moisture. All samples were weighed in advance and their three dimensions measured with a digital caliper. The shrinkage tests were carried out at constant temperatures of 40 and 80 °C (Fig. 2) inside a GDS-150 Environmental Test Chamber (Xinda Test Equipment Inc., Suzhou, PR China), with a conditioning temperature accuracy of ±0.5 °C and RH accuracy of ±3%. The samples were first conditioned to initial 99% RH in the conditioning chamber for 24 h and then taken out for determination of weight and dimensions. They were then put back into the chamber, the RH was tuned to 95%, and this test condition was maintained for 24 h, after which their weights and dimensions were measured again. The test was repeated every 24 h for

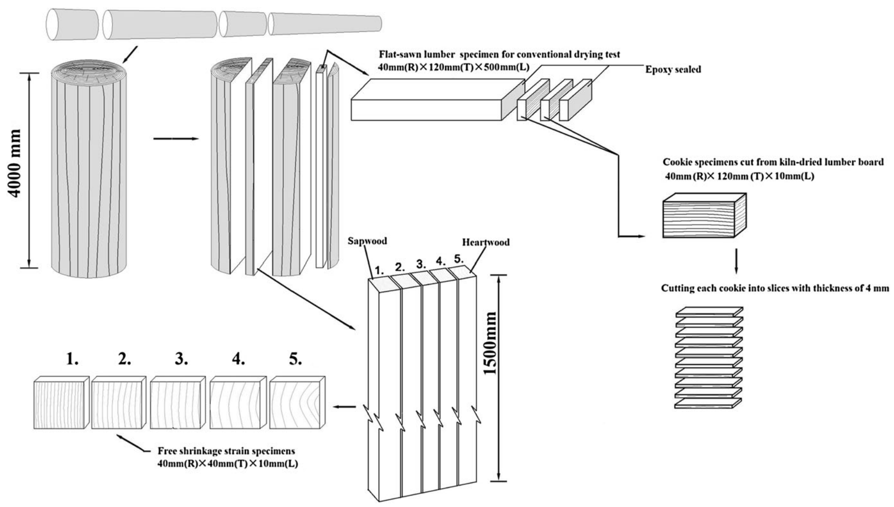

Fig. 1 Cutting strategy of the free shrinkage specimens and creep strain specimens

a RH decrease of 5% until it reached 50%. Thereafter, this test proceeded but with a RH decrease of 10% every 24 h until the average moisture content of samples decreased to 3.0% or below. All the samples were oven-dried at 103 ± 2 °C for 24 h, and the final weights and dimensions were determined accordingly. To apply free shrinkage values to the drying stress, a non-dimensional strain equation was used for the shrinkage strain S_{TorR},

$$S_{T \text{ or } R} = \frac{D_0 - D_s}{D_0} \tag{1}$$

where D_0 is the green state dimension (mm) of the shrinkage specimens, in either the tangential or radial direction; D_s equals the actual dimension (mm) of the same

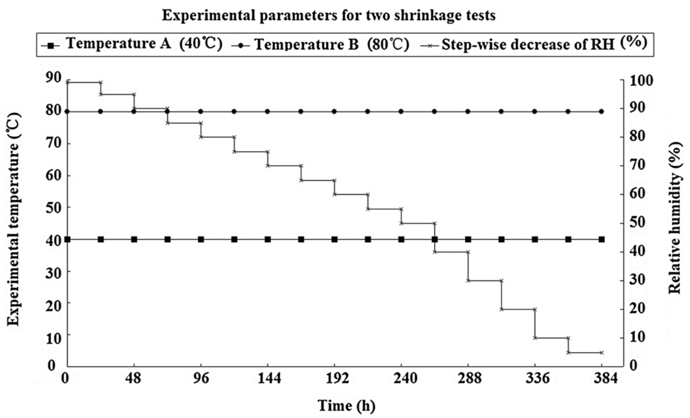

Fig. 2 Free shrinkage test conditions

specimen at a specified temperature and moisture content range. The actual shrinkage strain under specified conditions was the average value of 20 specimens.

Conventional drying test

Needle fir lumber specimens were cut from a green log with an average diameter of 350 $\sim$ 400 mm and 4000 mm in length (Fig. 1). The specimens were mainly flat-sawn and free of visual defects, and had straight grains. The specimens were planed on four sides to final dimensions of 40 mm (*R*) $\times$ 120 mm (*T*) $\times$ 1700 mm (*L*). Then they were further cut to the final dimensions of 40 mm (*R*) $\times$ 120 mm (*T*) $\times$ 500 mm (*L*) for drying tests. Epoxy resin was painted on the two ends of each specimen to prevent moisture from escaping.

Drying tests were carried out inside a GDS-150 Environmental Test Chamber (Xinda Test Equipment Inc., Suzhou, PR China). The detailed drying schedules are shown in Table 1. During the drying test, the temperature was kept constant at 80 °C (except during the initial pretreatment stage). After a preheating process, the RH decreased progressively according to the actual moisture content changes.

There were all together three duplicate tests for this conventional drying. In each test, twelve lumber specimens were dried from green condition (MC $>$ 45%) and their weights were monitored by an electric balance (every 4–8 h) until their MCs reached the final targeted ones (<8%). The moisture content and transverse deformation specimens were slices of 20 mm thickness cut with a circular saw. The cutting lines were depicted on deformation specimens immediately, and the transverse deformation slices were cut along the specimen thickness direction (Fig. 1). Figure 3 shows the cutting diagram of the deformation specimens based upon previous work (Zhan and Avramidis 2011b).

Table 1 Drying schedule of the needle fir drying test

Stages of moisture content	Drying temperature (°C)	Relative humidity (%)	Equilibrium moisture content (%)
Preheating	80	99	23.5
>35%	80	94	17.7
35–30%	80	90	15.5
30–27%	80	85	13.6
27–24%	80	80	11.9
24–21%	80	75	10.4
21–18%	80	70	9.2
18–15%	80	65	8.4
15–12%	80	60	7.5
12–8%	80	50	6.1
<8%	80	35	4.5

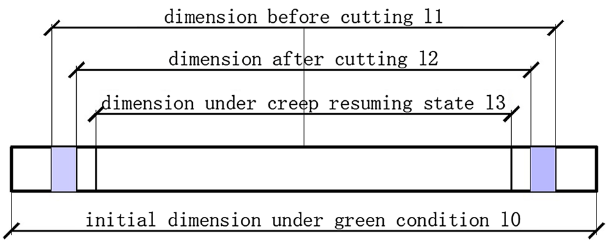

Fig. 3 Dimensional changes in strain slice during wood drying

Measuring procedure for the drying deformation components

Based upon linear viscoelastic and wood drying mechano-sorptive theories (Zhan and Avramidis 2011a, b), the one-dimensional transversal deformation mechanism during wood drying may involve the following components, namely shrinkage strain ε_N, instantaneous elastic strain ε_e, time dependent viscoelastic strain $\varepsilon_{\mathrm{ve}}$, MC-related mechano-sorptive creep strain $\varepsilon_{\mathrm{ms}}$ and finally the free shrinkage strain $\varepsilon_{\mathrm{fs}}$:

$$\varepsilon_{\mathrm{fs}} = \varepsilon_N + \varepsilon_e + \varepsilon_{\mathrm{ve}} + \varepsilon_{\mathrm{ms}} \tag{2}$$

Figure 1 shows the cutting diagram of the drying strain specimens based on the previous work (Zhan 2007). Full schedule pictures for both preparation of free shrinkage specimens and slicing procedure of drying strain specimens can also be found in Zhan and Avramidis (2011a, b). These drying deformation components could be calculated by the following equations:

$$\varepsilon_N = \frac{(l_1 - l_0)}{l_1} \tag{3}$$

$$\varepsilon_e = \frac{(l_2 - l_1)}{l_1} \tag{4}$$

$$\varepsilon_{\mathrm{ve}} = \frac{(l_3 - l_2)}{l_1} \tag{5}$$

$$\varepsilon_{\mathrm{fs}} = \frac{(l_0 \cdot (1 - (M_{\mathrm{FSP}} - M) \cdot \alpha) - l_0)}{l_1} = \frac{((M - M_{\mathrm{FSP}}) \cdot \alpha) \cdot l_0}{l_1} \approx (M - M_{\mathrm{FSP}}) \cdot \alpha \tag{6}$$

$$\varepsilon_{\mathrm{ms}} = \frac{(l_0 \cdot (1 - (M_{\mathrm{FSP}} - M) \cdot \alpha) - l_3)}{l_1} \tag{7}$$

where l_0 is the initial width of the surface-planed lumber under green conditions (mm), l_1 is the width of the specimen before cutting (mm), l_2 is the width of the specimen after cutting (mm) and l_3 is the width of the specimen after sealing the slice with polyvinyl chloride (PVC) films under room temperature conditions for 24–48 h (mm), α is the shrinkage coefficient and "$M - M_{\mathrm{FSP}}$" $= \Delta M$ is the differences between the *FSP* (M_{FSP} = 30% at the temperature of 20 °C) and the actual MCs inside wood.

Drying stress and strain modeling

As wood begins to dry down to the fiber saturation point (FSP), its shrinkage will take place accordingly. The wood free shrinkage deformation herein is defined as an independent deformation component, the quantity of which is in proportion to the moisture content (MC) differences between the FSP and its real-time state. By excluding the influence of environmental temperature, if the current MC of a piece of lumber is equal to *M*, then the free shrinkage ε_{fs} can be approximately determined by Eq. (6).

The influences of temperature, MC range, wood tissue position on the dynamic free shrinkage behavior were experimentally determined by Zhan et al. (2009c) and Zhan and Avramidis (2011a, b), for Chinese larch and Canadian hemlock species, respectively.

The instantaneous elastic strain ε_e was calculated based on the following equation:

$$\varepsilon_e = \frac{\sigma}{E} \tag{8}$$

where σ is the elastic mechanical stress inside the wood (MPa) and E is the transversal mechanical MOE (MPa) as a function of wood MC (%) and temperature T (°C), which is formulated by the following equation:

$$E = E(M, T) \tag{9}$$

The transverse MOE variable could be determined by the DMA test of small dimension specimens, and the mathematical formulation of the function $E(M, T)$ for needle fir species was based on the methodology used by Zhan (2007). The detailed preparation of the DMA specimens and the experimental setups could be found in the author's previous work (Zhan et al. 2009c).

The viscoelastic strain component ε_{ve} was modeled by the following equation based upon some other researchers' work (Pang 2000; Tu et al. 2007):

$$\varepsilon_{ve} = \frac{\sigma}{E_{ve}} \cdot \left(1 - e^{\frac{-t \cdot E_{ve}}{\eta_{ve}}}\right) \tag{10}$$

where E_{ve} (MPa) and η_{ve} (MPa·min) are the viscoelastic coefficients and t is the time variable (min).

Equation (10) was further simplified into this final term:

$$\varepsilon_{ve} \approx \frac{\sigma}{E \cdot \alpha_{ve}} \tag{11}$$

where E is the transversal mechanical MOE, α_{ve} (dimensionless) is the correction coefficient of E_{ve}.

The mechano-sorptive creep strain ε_{ms} was calculated as a sum of two independent deformations, namely the recoverable component plus the non-recoverable part, according to the following equation:

$$\varepsilon_{ms} = \sigma \cdot m \cdot \varepsilon_{fs} + \frac{\sigma}{E_{ms}} \cdot \left(1 - e^{\left(-c_{\eta} \cdot \sum \triangle M\right)}\right) \tag{12}$$

where m is the mechano-sorptive coefficient (1/MPa), E_{ms} is the corresponding MOE coefficient belonging to the mechano-sorptive mechanism (MPa), c_{η} is the viscous coefficient (dimensionless) and ΔM is the MC differences between one desorption (or adsorption) stage.

Mechano-sorptive creep gradient (MSCG) through the thickness of lumber

Until now, the significance of mechano-sorptive mechanism on wood drying lied in its role as a major contributing factor for the drying stress relaxation, mainly due to a complicated moisture cycling mechanism near the lumber surface (Zhan and Avramidis 2011a, b; Langrish 2013). Nevertheless, a theoretical and sophisticated formulation between wood drying stress and the mechano-sorptive variable has not yet been proposed maturely. Consequently, the drying stress (or residual stress) inside a kiln-dried lumber board cannot be quantitatively analyzed and graded precisely. Given this kind of context, a new variable, namely the through thickness mechano-sorptive creep gradient (MSCG), was proposed herein.

By combining Eqs. (8), (9), (10), (11) and (12) together, an algebraic expression was obtained as follows:

$$\varepsilon_{ms} = \varepsilon_{fs} - \varepsilon_{N} - \varepsilon_{e} - \varepsilon_{ve} \tag{13}$$

The difference of the mechano-sorptive creep strain between the surface and center of the lumber can be simplified as the following equation:

$$\begin{aligned} \varepsilon_{ms}(s) - \varepsilon_{ms}(c) &= \triangle \varepsilon_{ms}^{s\dot{-}c} = \triangle \varepsilon_{fs}^{s\dot{-}c} - \triangle \varepsilon_{N}^{s\dot{-}c} - \triangle \varepsilon_{e}^{s\dot{-}c} - \triangle \varepsilon_{ve}^{s\dot{-}c} \\ &= \alpha \cdot \triangle M^{s\dot{-}c} - \triangle \varepsilon_{N}^{s\dot{-}c} - \left(1 + \frac{1}{\alpha_{ve}}\right) \cdot \frac{1}{E} \cdot \Delta\sigma^{s\dot{-}c} \end{aligned} \tag{14}$$

where "s" refers to lumber surface, "$\boldsymbol{c}$" refers to the center and $\triangle \varepsilon_{ms}^{s\dot{-}c}$, $\triangle \varepsilon_{fs}^{s\dot{-}c}$, $\triangle \varepsilon_{N}^{s\dot{-}c}$, $\triangle \varepsilon_{e}^{s\dot{-}c}$ and $\triangle \varepsilon_{ve}^{s\dot{-}c}$ refer to the deformation differences between the surface and center of lumber for the mechano-sorptive creep, free shrinkage strain, shrinkage strain, elastic strain and viscoelastic strain, respectively, where $\triangle M^{s\dot{-}c}$ refers to the MC differences between the surface and center of lumber, $\Delta\sigma^{s\dot{-}c}$ refers to the drying stress differences between the surface and center of lumber.

By reorganizing Eq. (14), a quantitative formulation between the drying stress and mechano-sorptive creep variables was obtained as follows:

$$\Delta\sigma^{s\dot{-}c} = \left(\frac{\mathrm{E} \cdot \alpha_{ve}}{1 + \alpha_{ve}}\right)\left(\alpha \cdot \triangle M^{s\dot{-}c} - \triangle \varepsilon_{N}^{s\dot{-}c} - \triangle \varepsilon_{ms}^{s\dot{-}c}\right) \tag{15}$$

where the component $\triangle M^{s\dot{-}c}$, $\triangle \varepsilon_{N}^{s\dot{-}c}$ can be measured manually during drying tests.

After a further simplifying conversion, below expression is obtained:

Let $\left(\frac{E\cdot\alpha_{ve}}{1+\alpha_{ve}}\right) = A > 0$

$$\Delta\sigma^{s\dot{-}c} = A\cdot\left(\alpha\cdot\Delta M^{s\dot{-}c} - \Delta\varepsilon_{N}^{s\dot{-}c} - \Delta\varepsilon_{ms}^{s\dot{-}c}\right) \tag{16}$$

where the constant A (MPa) can be determined based on some previous works on softwood mechanical properties.

According to Eq. (16), which was deduced based upon viscoelasticity and wood drying mechano-sorptive creep mechanism, the mechanical stress state of a kiln-dried wood could be quantitatively determined through the measurement of MC, shrinkage and mechano-sorptive creep.

Based upon the evolvement characteristics of the drying stress of kiln-dried lumber (McMillen 1955; Pang 2000; Tu et al. 2007; Zhan et al. 2009a; Salinas et al. 2015; Sepulveda-Villarroel et al. 2016), the drying stress differences between the surface and center of wood could approximate to the following expression:

$$\begin{aligned}\Delta\sigma^{s\dot{-}c} &\approx |\sigma(s)| + |\sigma(c)| \approx A\cdot\left|\alpha\cdot\Delta M^{s\dot{-}c} - \Delta\varepsilon_{N}^{s\dot{-}c} - \Delta\varepsilon_{ms}^{s\dot{-}c}\right| \\ &\approx A\cdot\left(\left|\alpha\cdot\Delta M^{s\dot{-}c}\right| + \left|\Delta\varepsilon_{N}^{s\dot{-}c}\right| + \left|\Delta\varepsilon_{ms}^{s\dot{-}c}\right|\right)\end{aligned} \tag{17}$$

According to Eq. (17), the drying stress differences between the surface and center of wood, which equal the absolute value sum of drying stress for these two components approximately, can be further estimated through the absolute value sum of the variables $\alpha\cdot\triangle M^{s\dot{-}c}$, $\triangle\varepsilon_{N}^{s\dot{-}c}$ and $\triangle\varepsilon_{ms}^{s\dot{-}c}$.

By dividing both sides of Eq. (17) by the displacement Δx, namely the half of thickness, the respective gradient variables in association with the difference variables for drying stress, MC, shrinkage and mechano-sorptive strain are obtained, as described by the following equation:

$$\begin{aligned}\frac{\Delta\sigma^{s\dot{-}c}}{\Delta x} &\approx \frac{A\cdot\left(\left|\alpha\cdot\triangle M^{s\dot{-}c}\right| + \left|\triangle\varepsilon_{N}^{s\dot{-}c}\right| + \left|\triangle\varepsilon_{ms}^{s\dot{-}c}\right|\right)}{\Delta x} \\ &= A\cdot\left(\frac{\left|\alpha\cdot\triangle M^{s\dot{-}c}\right|}{\Delta x} + \frac{\left|\triangle\varepsilon_{N}^{s\dot{-}c}\right|}{\Delta x} + \frac{\left|\triangle\varepsilon_{ms}^{s\dot{-}c}\right|}{\Delta x}\right)\end{aligned} \tag{18}$$

According to Eq. (18), the drying stress variable is composed of three factors, namely moisture content gradient (MCG), shrinkage deformation gradient (SDG) and mechano-sorptive creep gradient (MSCG), which are all defined as through lumber thickness.

After the final thermal conditioning, if the MCG of the kiln-dried lumber was decreased to near 0%, Eq. (18) can be further simplified in the following forms:

$$\frac{\Delta\sigma^{s\dot{-}c}}{\Delta x} \approx \frac{A\cdot\left(\left|\triangle\varepsilon_{N}^{s\dot{-}c}\right| + \left|\triangle\varepsilon_{ms}^{s\dot{-}c}\right|\right)}{\Delta x} = A\cdot\left(\frac{\left|\triangle\varepsilon_{N}^{s\dot{-}c}\right|}{\Delta x} + \frac{\left|\triangle\varepsilon_{ms}^{s\dot{-}c}\right|}{\Delta x}\right) \tag{19}$$

$$\frac{\Delta\sigma^{s\dot{-}c}}{\Delta x} \approx \frac{A\cdot\left(B + \left|\triangle\varepsilon_{ms}^{s\dot{-}c}\right|\right)}{\Delta x} = A\cdot\left(\frac{B}{\Delta x} + \frac{\left|\triangle\varepsilon_{ms}^{s\dot{-}c}\right|}{\Delta x}\right) \tag{20}$$

where the constant A can be determined based on the physical properties of the specified species, constant B can be determined by measuring the initial green widths and the ongoing shrinkage deformation along the boards' width direction. These two expressions are suitable for the evaluation of the residual stress states of kiln-dried softwood lumbers.

Results and discussion

Free shrinkage deformation

The experimentally determined relationship between the free shrinkage and wood MCs is depicted in Fig. 4, showcasing the similar trends to larch lumber (Zhan et al. 2009c). An approximate linear function was chosen to describe the relationship between the free shrinkage strain and wood MCs. Consequently, the shrinkage coefficient α (tangential) equals 0.0028 (1%) and 0.0032 (1%) at a temperature of 40 and 80 °C, respectively.

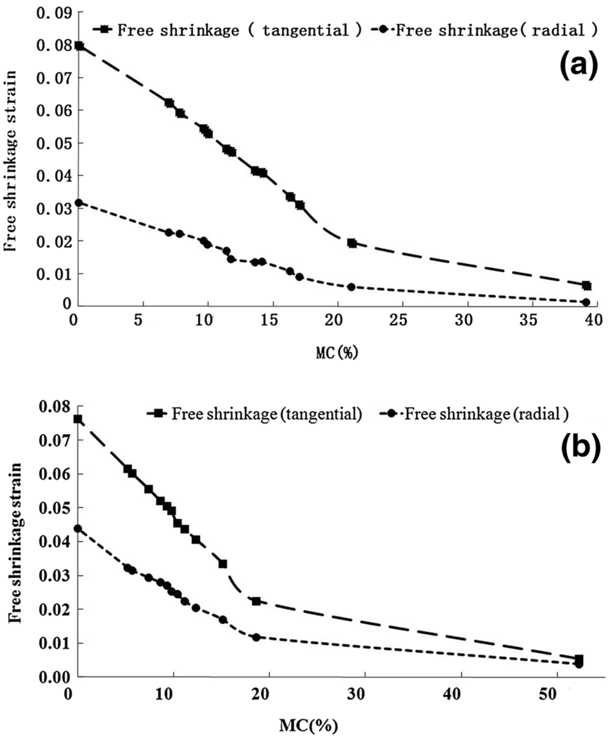

Fig. 4 Free shrinkage behaviors of the needle fir lumber. **a** At a temperature of 40 °C and **b** at a temperature of 80 °C

Drying curves and MC gradients along thickness

Wood mechano-sorptive creep is a complicated deformation behavior and is highly dependent on wood MCs, MC changes and MC evolvement histories. The drying curves and through thickness MCG are shown in Fig. 5. The MCG first showed a general increasing trend when the drying test proceeded. It reached the maximum 10.3% within 36 h, with the corresponding MCs of the surface, average and center being 19.5, 24.5 and 29.8%, respectively. Subsequently, the MCG decreased gradually, approaching zero within 120 h, and then fluctuated near the zero line until the end, suggesting that the component $\alpha \cdot \triangle M^{s \dot{-} c}$ in Eq. (18) could be omitted during the mid- and final stages of softwood drying.

Elastic strain and drying stress mode

Detailed development information for the elastic strain on the surface and center is depicted in Fig. 6. The experimental results on instantaneous elastic strain could be further used to describe the drying stress modes for needle fir lumber. The basic mode of drying stress and strain for needle fir wood was consistent with some previous work (Zhan 2007). The maximum values of the tensile stress occurred while the MC was 19.5 and 17.9%, for the surface and center section, respectively.

Mechano-sorptive creep strain and mechano-sorptive creep gradient (MSCG)

The mechano-sorptive creep strain and its through thickness gradient are depicted in Fig. 7. As drying tests proceeded, the mechano-sorptive creep strain for both the surface and center increased gradually until the mid-stage (average MCs around 12%). Concurrently, the quantity of the surface mechano-sorptive strain was always bigger than that of the center section, giving rise to the accumulation of the MSCGs.

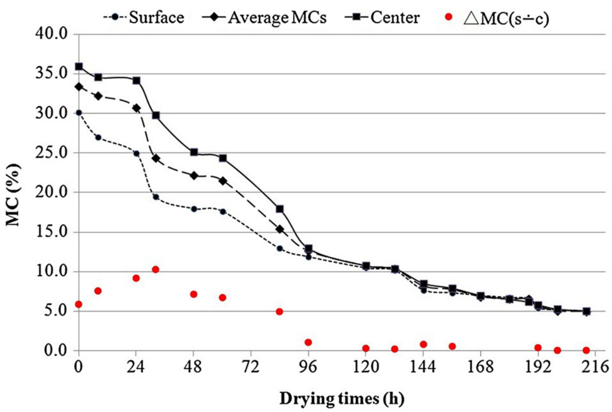

Fig. 5 Drying curves and MC gradients through thickness during a full drying cycle

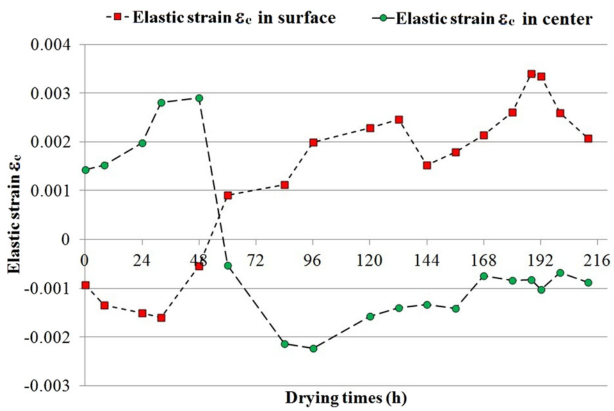

Fig. 6 Elastic strain evolvement during a full drying cycle

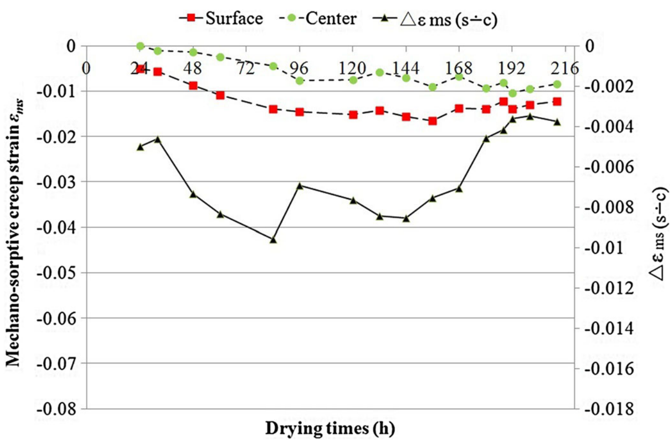

Fig. 7 Mechano-sorptive creep evolvement during a full drying cycle

The shrinkage strains and its through thickness gradient are shown in Fig. 8. Comparing the drying deformation information in Figs. 7 and 8, the actual quantities of the mechano-sorptive strain were on average one-fifth of those of shrinkage deformations. Nevertheless, during the whole drying process, especially at the mid- and final stages, the $\Delta\varepsilon_N^{s\dot{-}c}$ and $\Delta\varepsilon_{\mathrm{ms}}^{s\dot{-}c}$ were in the similar order of magnitude, showing the same decreasing trend during the final stages.

Estimated drying stress differences $\Delta\sigma^{s\dot{-}c}$

Based upon the algebraic relationship between drying stress difference variable $\Delta\sigma^{s\dot{-}c}$ and its three main component variables, namely $\alpha \cdot \Delta M^{s\dot{-}c}$, $\Delta\varepsilon_N^{s\dot{-}c}$ and $\Delta\varepsilon_{\mathrm{ms}}^{s\dot{-}c}$, the drying stress difference changes as a function of drying times are depicted in Fig. 9, which were calculated approximately based on Eq. (17).

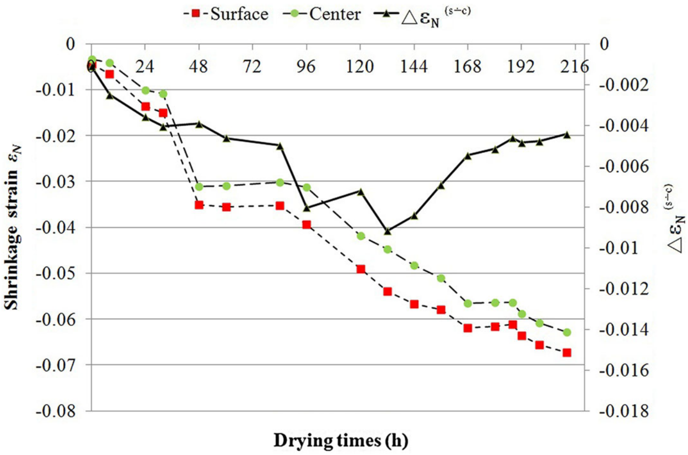

Fig. 8 Shrinkage strain evolvement during a full drying cycle

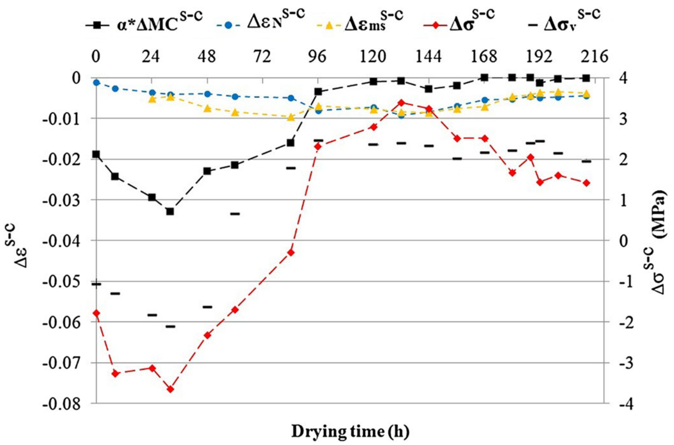

Fig. 9 Drying stress difference $\Delta\sigma^{s-c}$ and strain difference $\Delta\varepsilon^{s-c}$ evolvements during a full drying cycle

Needle fir drying could be divided into two distinctive segmentations, and the separatrix was the times when $\Delta\sigma^{s\dot{-}c}$ reached zero and the average MCs were between 13 and 15%. Ahead of this boundary, the variable $\Delta\sigma^{s\dot{-}c}$ was dominated mainly by the wood MC-induced deformation $\alpha \cdot \triangle M^{s\dot{-}c}$. Nevertheless, once $\Delta\sigma^{s\dot{-}c}$ approached zero, it will be influenced mainly by the variables $\triangle\varepsilon_N^{s\dot{-}c}$ and $\triangle\varepsilon_{\mathrm{ms}}^{s\dot{-}c}$. Given the transformation relationships between these two variables, the MSCG will determine the actual magnitude of the drying stress difference variable.

Verification of the proposed "MSCG" concept

A further drying test was carried out to verify the calculated results based on the above proposed MSCG concept. Detailed information about the calculated drying stress based on the MSCG concept and the measured one based on the slicing test is also depicted in Fig. 9.

The test results clearly show that the developing trend of the calculated drying stress differences $\Delta\sigma^{s-c}$ generally coincided with those of measured ones $\Delta\sigma_v^{s-c}$ by the slicing test. Specifically, during the initial and mid-drying stages of the drying test, there were also significant differences between these two variables, showcasing that the proposed MSCG concept is mainly suitable for the drying stress evaluation at the mid- and final stage of drying tests.

Applying the proposed "MSCG" concept to practical drying

The purpose of defining MSCG is to simplify the computation procedures of the mechano-sorptive creep and lumber drying stress, making the variables (MSCG, MCG, SDG) suitable for the commercial evaluation of the softwood drying stress and deformation defects. To achieve this goal, the lumber drying practitioners need to follow these technical steps.

(a) Obtaining the transverse free shrinkage characteristics of the specified wood species by small-dimensional specimens test;
(b) Obtaining the transverse elastic and viscoelastic coefficients by the DMA test or by numerical deduction from the known values of the tested wood species;
(c) Measuring the moisture content and actual shrinkage characteristics of the kiln-dried lumber;
(d) Calculating the moisture content gradient, shrinkage deformation gradient and mechano-sorptive creep gradient according to Eqs. (18–20);
(e) Carrying out the evaluation process based upon the MCG, SDG and MSCG.

Conclusion

Based on drying rheology and wood drying mechano-sorptive mechanism, a one-dimensional mechanical model of the softwood drying stress and deformations was established herein. The deformation mechanisms being involved in this model include shrinkage strain ε_N, elastic strain ε_e, viscoelastic strain ε_{ve}, mechano-sorptive creep strain ε_{ms} and the free shrinkage strain ε_{fs}.

A variable set, comprising mechano-sorptive creep gradient (MSCG), moisture content gradient (MCG) and shrinkage deformation gradient (SDG), all of which were through the thickness of wood, was defined as a theoretical tool being capable of estimating the drying stress state in wood. A further simplified form of this variable set shows that the variables MSCG and SDG, if being combined mathematically together, have the potential capacity of predicting the drying stress states of softwood during the mid- and final stages of drying. This inference was also supported by the experimental measure of these defined variables during the needle fir drying tests.

According to the projected drying stress information, which is provided by the proposed method, the MSCG and SDG variable sets could be combined and utilized together to predict the drying stress differences during the mid- and especially final stage of drying test. Furthermore, after being properly simplified, the proposed method could be more suitable for the evaluation of the residue stress of kiln-dried softwood lumber boards.

For the effective evaluation of the drying stress during the full drying cycle, which is carried out based on wood rheology, more accurate measures, in terms of the moisture content and wood shrinkage analysis technique, and further tests on the mechano-sorptive creep mechanism, are needed in future.

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