

Wood Physics/Mechanical Properties

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Stabilization of hygro-deformation and interaction between earlywood and latewood in Chinese fir

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Abstract: The alternating arrangement of earlywood (EW) and latewood (LW) in wood growth reflects an optimization structure, where anatomical differences lead to varying properties. This study analyzed the stabilization characteristics of hygro-deformation in Chinese fir, and compared the dimensional responses of intact growth rings and with those of isolated EW and LW during step-wise desorption and adsorption. During both desorption and adsorption, both LW and EW exhibited rapid hygro-deformation initially, followed by stabilization. The stabilization of dimensional changes lagged behind stabilization of moisture content based on evaluating their rates of change. Isolated EW showed significant reductions in hygro-deformation compared to when LW was present, due to the removal of LW's restraining effect. The radial and tangential shrinking differences in EW before and after isolation were 0.40 and 0.46 %, respectively, as relative humidity decreased from 97 % to 0. The corresponding values were 0.58 and 0.71 % during adsorption (0 → 97 % RH). These results highlight the impact of EW-LW interaction on the hygro-deformation of Chinese fir and are helpful to elucidate the complex nature of wood-water relations.

Keywords: growth ring; isolation; digital image correlation (DIC); shrinking and swelling; restraining effect

1 Introduction

In regions with distinct seasonal changes, trees develop wood in annual growth increments, forming recognizable growth rings. These rings reflect the tree's growth throughout different seasons. In softwoods, there are significant structural differences between earlywood (EW) and latewood (LW) (Siau 2012). EW forms at the beginning of the growing season under favorable conditions, featuring larger, thinner-walled cells that enhance water transport and nutrient flow. In contrast, LW develops towards the end of the growing season when growth slows, characterized by smaller, thicker-walled cells that provide the wood's overall strength and structural stability. The alternating arrangement of EW and LW across growth rings represents an iterative optimization process for adaptive growth (Eder et al. 2008; Wei et al. 2024).

Both EW and LW cells consist of cellulose, hemicellulose, and lignin. Cellulose provides the fundamental structural, hemicellulose supports cell wall flexibility, and lignin contributes rigidity to the cell wall. These components are hygroscopic to varying degrees, i.e., they absorb or release moisture depending on the ambient environment. This moisture exchange causes the wood to swell or shrink during moisture adsorption or desorption. Understanding the hygro-deformation (swelling and shrinking) of EW and LW is crucial for managing the dimensional stability of wood (Krzemień et al. 2015; Pang et al. 1999; Perré and Huber 2007).

Key structural factors affecting the hygro-deformation include density and microfibril angle (MFA) (Kollmann and Cote Jr 1968; Siau 2012). Denser woods tend to deform more than less dense one. Higher MFA, such as in juvenile wood (Garcia et al. 2022) or compression wood (Zhan et al. 2021), leads to greater longitudinal and less transverse shrinking. The variations in the hygro-deformation along the radial and tangential directions wood has been attributed to arrangement of EW and LW, presence of ray cells, differences in the cell composition along the parallel and perpendicular direction of the S₂ cell wall layer, difference of MFA in radial and tangential walls, as well as the influence of the middle

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lamella (Arzola-Villegas et al. 2019; Ross 2010; Skaar 2012). It is widely reported that, at certain moisture content (MC) changes, LW generally exhibits more significant hygro-deformation than EW (Garcia et al. 2022; Lanvermann et al. 2014; Liu et al. 2023; Yin et al. 2023). EW and LW shrink and swell at different rates, resulting in anisotropic hygro-deformation, particularly along radial and tangential directions. In the radial direction, EW and LW are arranged in series, while in the tangential direction, they are arranged parallel, with LW dominating movement and forcing EW to deform more significantly (Ma and Rudolph 2006; Ouyang et al. 2022). Consequently, dimensional variations are larger in the tangential direction (5–10 %) compared to the radial direction (2–6 %) (Garcia et al. 2020a). This differential shrinking contributes to crack and impacts wood drying quality (Fu et al. 2023).

Research on hygro-deformation of EW or LW is typically conducted at the tissue (Fu et al. 2021; Patera et al. 2018; Redman et al. 2016), cell (Joffe et al. 2016; Rafsanjani et al. 2014; Yin et al. 2023) and cell wall levels (Gao et al. 2024; Larsson et al. 2024; Li et al. 2024; Paajanen et al. 2022). While some studies focus on EW and LW separately (Almeida et al. 2014; Patera et al. 2013; Perré and Huber 2007), other examines EW and LW behaviors when both are present (Lanvermann et al. 2014, Patera et al. 2018, Zhan et al. 2023). It is reported that the strain concentrations occur along the EW-LW interface (Krzemień et al. 2015), with large hygro-deformation of EW due to the restraining effect of LW. In the previous study (Zhan et al. 2023), digital image correlation (DIC) technique was employed to capture the intra-ring

variation of hygro-deformation from EW and LW, and to qualitatively observe the restraining effect exerted by adjacent LW from the previous growth ring on EW. However, the quantitative evaluation of this restraining effect has not yet been reported. The present study served as a follow-up to Zhan et al. (2023). First, the stabilization durations of both dimensional and MC within the growth ring were analyzed to determine whether they stabilize simultaneously. Subsequently, EW and LW regions were physically isolated, and their hygro-deformation was re-measured. Finally, the restraining effect was quantitatively assessed by comparing hygro-deformation before and after isolation.

2 Materials and methods

2.1 Materials

Three samples of air-dried Chinese fir wood (*Cunninghamia lanceolata* [Lamb.] Hook.) were obtained with dimensions of 5 mm × 3 mm × 0.5 mm (radial × tangential × longitudinal, R × T × L), each containing the intact 17th growth ring. These samples were water-saturated and polished with a cryomicrotome HM 560 (Micom, Germany) removing 2-μm thin transverse slices, and were then fully equilibrated over distilled water for over 4 weeks. Following sorption and hygro-deformation experiments, the samples were mechanically divided into isolated EW (~4 × 3 × 0.5 mm³, R × T × L) and LW (~0.5 × 3 × 0.5 mm³, R × T × L) regions. Figure 1 illustrates the detailed sampling procedure, a

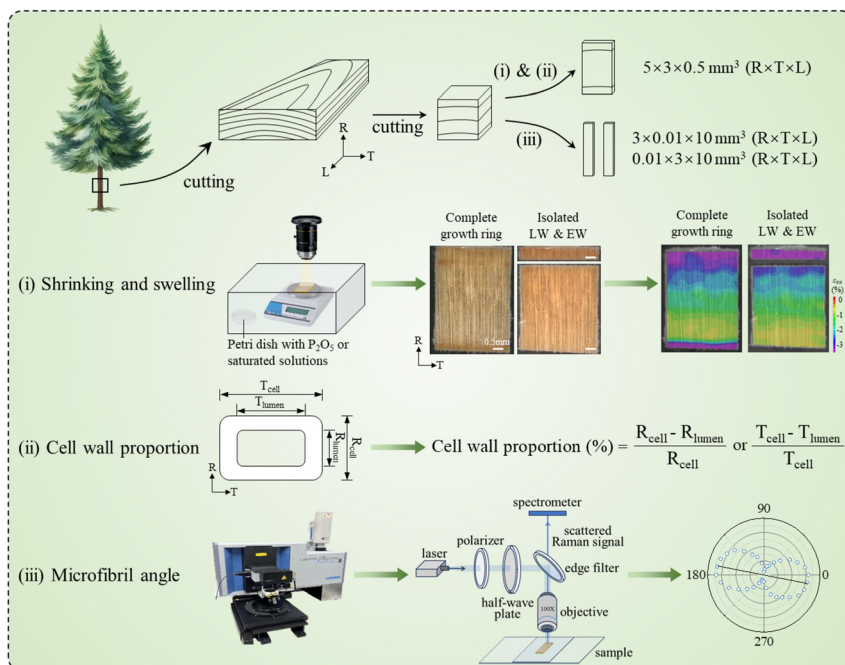


Figure 1: Sampling procedure and three major characterizations: (i) shrinking and swelling, (ii) cell wall proportion, and (iii) microfibril angle.

typical sample with the intact growth ring and the isolated EW and LW regions were shown in step (i) for hygro-deformation and cell wall proportion experiments (step ii). Additionally, sections measuring $3 \times 0.01 \times 10 \text{ mm}^3$ ($R \times T \times L$) and $0.01 \times 3 \times 10 \text{ mm}^3$ ($R \times T \times L$) were also cut from both EW and LW regions for step (iii) – MFA determination. The average air-dried density of the samples was approximately 370 kg/m^3 .

2.2 Sorption and hygro-deformation experiment

Before conducting the hygro-deformation tests, the surface evenness of the samples was assessed using a digital microscope (VHX-7000, Keyence Company, Japan) to ensure they were free of warping, thereby avoiding any interference with subsequent in-plane deformation measurements. The desorption, adsorption and corresponding shrinking and swelling experiments followed the methodology outlined by Zhan et al. (2023). Successively, the intact growth ring samples and isolated LW and EW samples underwent the desorption and adsorption processes. Relative humidity (RH) levels of 97, 75, 58, 33, or 0 % were maintained using saturated salt solution (K_2SO_4 , NaCl, MgCl_2 or NaBr) or P_2O_5 in a sealed container. An electronic analytical balance (Mettler Toledo ME204, $\pm 0.1 \text{ mg}$) was placed in the sealed container for measuring mass change, i.e. MC, of the wood sample. At each humidity level, MC values were recorded periodically at 0, 3, 6, 9, 12, 24, 36, 48, 60, 72, 96, 120 and 144 h. Cross-sectional morphology was imaged using the focal length adjusted digital microscope without removing the samples from the sealed container, thereby preventing any MC variation during observation (Figure 1). The microscope was equipped with a 12.22-megapixel complementary metal–oxide–semiconductor image sensor, providing a resolution of $6,144 \times 4,608$ pixels. Three samples each of the intact growth ring and isolated LW or EW samples were replicated to determine average MC and hygro-deformation values. A representative sample was selected to display in-plane strain distribution.

The hygro-deformation was assessed using DIC analysis (VIC-2D software, Correlated Solution Inc., United States), with the following steps (Garcia et al. 2020a, b; Zhan et al. 2023): (i) selecting the area of interest (AOI): approximately 15 mm^2 ($2,567 \times 3,679$ pixels²) for the intact growth ring sample; (ii) dividing the AOI into evenly spaced virtual grids (subsets: 113), step size selection (28) and predefining the correlation criterion, interpolation, thresholding and post-processing to calculate the full-field strain; and (iii) extracting strain data from 2D contour plot through lines across the

growth ring. The strains in the X (ε_{TT}) and Y (ε_{RR}) directions represented tangential and radial deformations, respectively. Shrinking or swelling strain was determined by comparing images of the equilibrated sample at 97 or 0 % RH as a reference, following the definition used for wood shrinking or swelling (Peng et al. 2012). Shrinking strain was treated as negative and swelling strain as positive to depict dimensional changes during moisture desorption and adsorption.

2.3 Hygro-deformation difference between isolated and intact LW/EW

The hygro-deformation differences were calculated as follows:

$$\Delta\varepsilon_{\text{RR-EW}} = \varepsilon_{\text{RR-grEW}} - \varepsilon_{\text{RR-iEW}} \quad (1)$$

$$\Delta\varepsilon_{\text{TT-EW}} = \varepsilon_{\text{TT-grEW}} - \varepsilon_{\text{TT-EW}} \quad (2)$$

$$\Delta\varepsilon_{\text{RR-LW}} = \varepsilon_{\text{RR-iLW}} - \varepsilon_{\text{RR-grLW}} \quad (3)$$

$$\Delta\varepsilon_{\text{TT-LW}} = \varepsilon_{\text{TT-iLW}} - \varepsilon_{\text{TT-grLW}} \quad (4)$$

where $\Delta\varepsilon_{\text{RR}}$ and $\Delta\varepsilon_{\text{TT}}$ represent the radial and tangential hygro-deformation differences, respectively. The subscripts “gr” and “i” denote measurements taken from samples within the intact growth ring and after isolation, respectively. Specifically, the hygro-deformation differences were evaluated for both the desorption process from 97 % RH to 0 and the adsorption process from 0 to 97 % RH.

2.4 Cell wall proportion

After hygro-deformation experiments, the isolated EW and LW were placed in an environmental scanning electron microscope (FEI Quanta FEG 600, FEI Company, USA) for determination of cell wall proportion. The cross-section images of EW and LW were obtained at an acceleration voltage of 4 kV in a low-vacuum mode. The cell wall proportion was quantified by calculating the ratio of cell wall thickness to cell thickness for both radial and tangential directions separately (Figure 1, step ii). For each direction, measurements were taken from 20 cells in either EW or LW to ensure replicability.

2.5 MFA

The 10- μm -thick section was mounted on a glass slide with a drop of deionized water, and the coverslip was sealed with

nail polish to prevent water evaporation. MFA determination employed polarized confocal Raman microscopy (Xplora HR Evolution, Horiba Jobin Yvon, Japan) following the methods by Gierlinger et al. (2009) and Zhang et al. (2023). The imaging employed a 100 $\times$ oil immersion lens (NA 1.40) and a 532 nm laser with 100 % intensity. A 600 mm grating was used with a wavenumber range of 100–3,900 cm^{-1} and an integration time of 20 s. Raman spectra were obtained by rotating a half-wave plate in 5° increments to vary laser polarization, capturing measurements at 10° interval across a full 360° polarization range to analyze Raman intensity as a function of polarization angle. MFAs on both the tangential and radials wall were evaluated with five replicates each in EW and LW.

2.6 Statistical analysis

The statistical software, SPSS version 17.0 (SPSS Inc, Chicago, IL, USA) was used for data analysis. Significant effects of sampling location (EW or LW) and RH level on hygro-deformation (difference) stress were analyzed by Duncan's multiple comparison test ($p = 0.05$).

3 Results and discussion

3.1 Hygro-deformation during desorption and adsorption

The hygro-deformation behavior of Chinese fir during desorption (Figures 2 and 3) and adsorption (Figures 4 and 5) is presented. Figures 2 and 4 display the full-field distributions of radial strains (ϵ_{RR}), while Figures 3 and 5 show tangential strains (ϵ_{TT}). In Figures 2b, 3b, 4b, and 5b, the evolution of strain over time is shown alongside the corresponding changes in MC. MC represents the average value for the intact growth ring sample, with the sampling locations for LW, EW and restrained EW indicated in the bottom-right subfigure of Figure 2a. Previous studies (Patera et al. 2018; Zhan et al. 2023) attributed the larger hygro-deformation of restrained EW at the growth ring interface to the mechanical restraint imposed by the previous LW on EW. Throughout both the desorption and adsorption processes, LW consistently exhibited greater dimensional changes compared to both restrained EW and unrestrained EW, regardless of humidity levels. Specifically, when comparing dimensions at 97 % RH to those at RH of 0 after desorption, the values of ϵ_{RR} and ϵ_{TT} for LW were -3.0% and -4.2% , respectively, while the corresponding values for EW were -1.1% and -3.3% . After fully adsorption from RH

of 0 back to 97 %, ϵ_{RR} reached 2.82 % for LW and 1.04 % for EW, while ϵ_{TT} values were 3.64 % and 2.78 %, respectively.

Notably, these values were lower than those reported for Chinese fir in the literature (Cheng 1985; Jiang and Lu 2012; Yao et al. 2017), as well as for other coniferous species with comparable densities (Perré and Huber 2007; Thybring and Fredriksson 2023; Watanabe et al. 1998). The variation in hygro-deformation of wood was closely related to density and MFA, and also influenced by the content of lignin and hydrophilic extractives (Eder et al. 2020; Jankowska et al. 2017). In addition, the origin of hygro-deformation variability should also consider structural differences within the wood; even two trees of the same species can exhibit significant differences in EW shrinking (Almeida et al. 2014). In terms of anisotropy, LW show a lower $\epsilon_{TT}/\epsilon_{RR}$ ratio (1.4) than EW (3.0) when RH decreased from 97 % to 0, indicating that EW was more anisotropic. Both ratios were higher than those reported in the literature, where LW is generally considered to be nearly isotropic (Patera et al. 2018; Perré and Huber 2007).

The dimensional changes after full stabilization as a function of difference of MC (ΔMC) are shown in Figure 6. It could be found that the dimensional changes exhibited a quasi-linear relationship with ΔMC , regardless of anatomical tissue type or direction. Notably, the radial deformation (ϵ_{RR}) (Figure 6a and c) differed significantly between LW and (restrained) EW, whereas the differences in tangential deformation (ϵ_{TT}) were relatively minor (Figure 6b and d). This reduction variation in ϵ_{TT} may be attributed to the dominant influence of LW, which constrained the tangential deformation of adjacent EW, resulting in a more uniform overall response across the growth ring (Ouyang et al. 2022).

3.2 Stabilization of hygro-deformation and MC

Based on the results in Figures 2–5, it was observed that ϵ_{RR} and ϵ_{TT} , along with MC, changed rapidly at the start of the desorption or adsorption before stabilizing, expectedly. However, the stabilized periods differed between dimensional changes and MC. To precisely evaluate the stabilizations of dimension and MC, the variations of dimension and MC with logarithmic time were plotted in Figures 7–10. Taken desorption at 0 humidity as an example, MC tended to be constant after 48 h (indicated as the purple arrows, bottom subfigure in Figures 7g and 8g), whereas ϵ_{RR} and ϵ_{TT} stabilized after 108 h (black arrows in Figures 7g and 8g), similar results could be seen during adsorption (Figures 9 and 10). The desorption or adsorption process involved not only sorption equilibrium but also a time-dependent

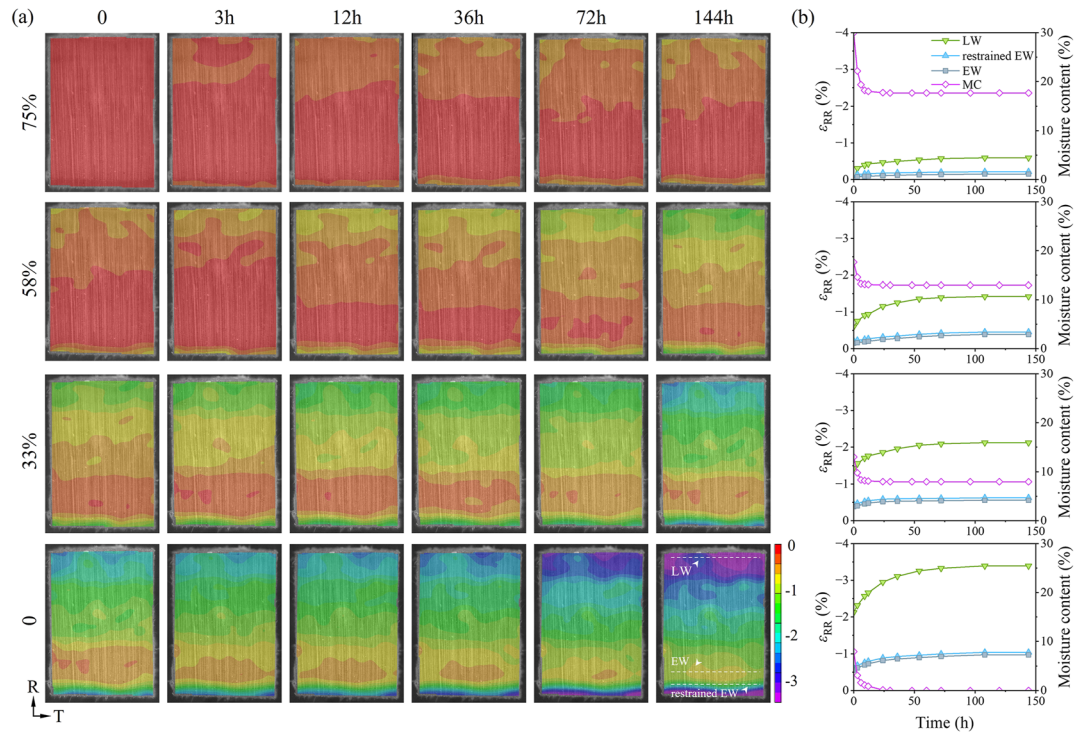


Figure 2: Changes in shrinking in radial direction (ϵ_{RR}) with stepwise RH decrements (97 % $\rightarrow$ 75 % $\rightarrow$ 58 % $\rightarrow$ 33 % $\rightarrow$ 0): full-field distribution of ϵ_{RR} (a) and its time-dependent value along with MC variation (b). The values of ϵ_{RR} shown in (b) were averaged from the sampling positions indicated in the bottom-right subfigure of (a). Full-field distributions of ϵ_{RR} in (a) after 144 h desorption were cited from Zhan et al. (2023).

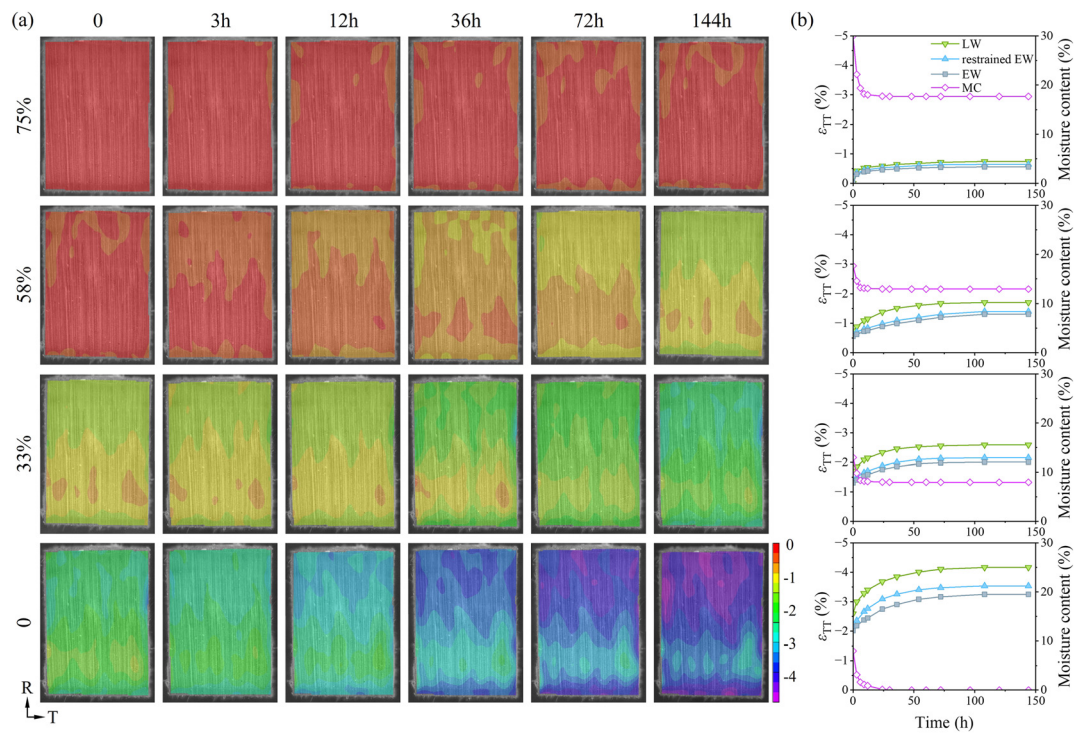


Figure 3: Changes in shrinking in tangential direction (ϵ_{TT}) with stepwise RH decrements (97 % $\rightarrow$ 75 % $\rightarrow$ 58 % $\rightarrow$ 33 % $\rightarrow$ 0): full-field distribution of ϵ_{TT} (a) and its time-dependent value along with MC variation (b). Sampling positions in (b), refer to Figure 2. Full-field distributions of ϵ_{TT} in (a) after 144 h desorption were cited from Zhan et al. (2023).

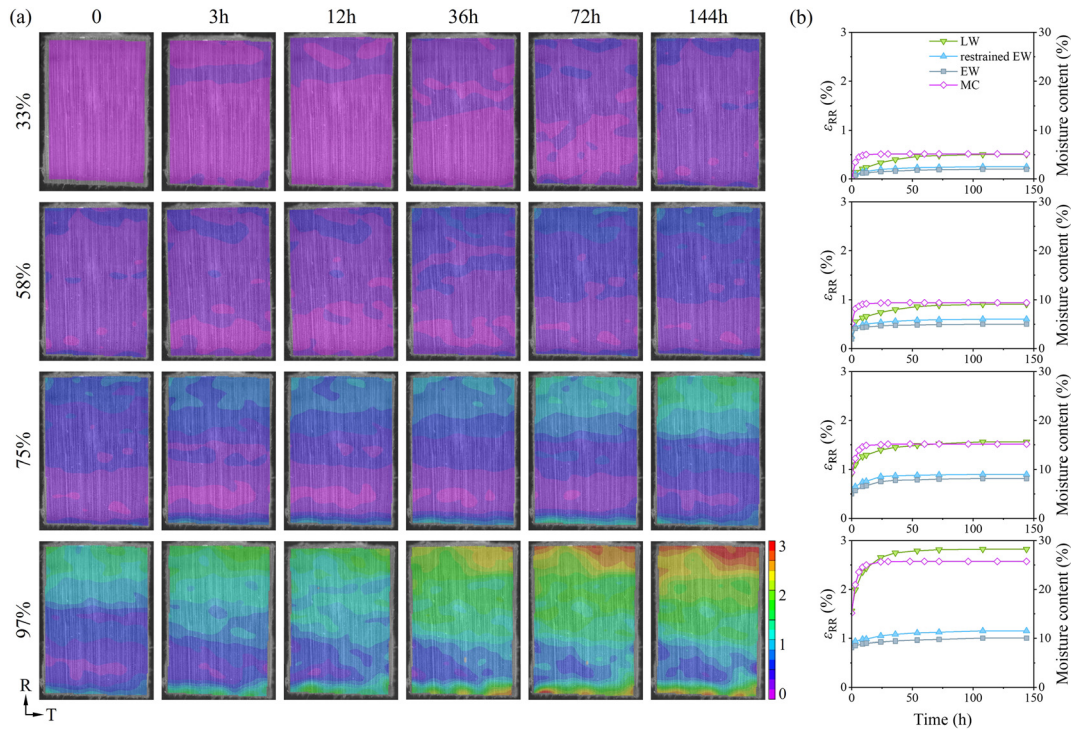


Figure 4: Changes in swelling in radial direction (ϵ_{RR}) with stepwise RH increments (0 → 33 % → 58 % → 75 % → 97 %): full-field distribution of ϵ_{RR} (a) and its time-dependent value along with MC variation (b). Sampling positions and arrows in (b), refer to Figure 2. Full-field distributions of ϵ_{RR} in (a) after 144 h adsorption were cited from Zhan et al. (2023).

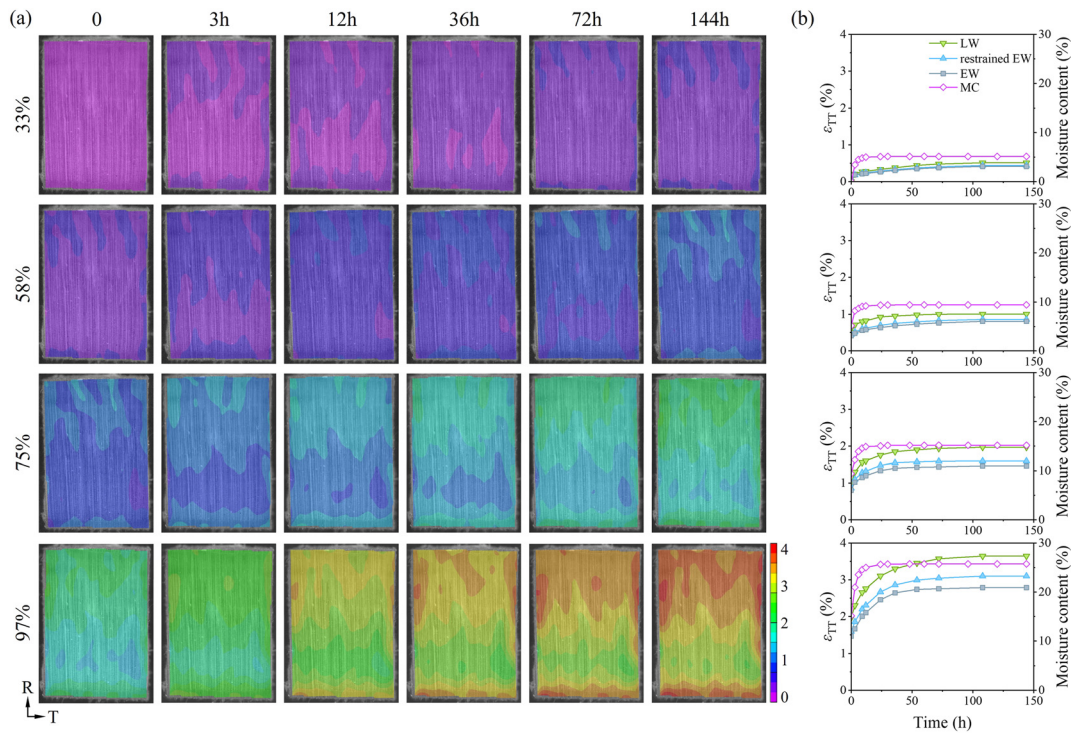


Figure 5: Changes in swelling in tangential direction (ϵ_{TT}) with stepwise RH increments (0 → 33 % → 58 % → 75 % → 97 %): full-field distribution of ϵ_{TT} (a) and its time-dependent value along with MC variation (b). Sampling positions in (b), refer to Figure 2. Full-field distributions of ϵ_{TT} in (a) after 144 h adsorption were cited from Zhan et al. (2023).

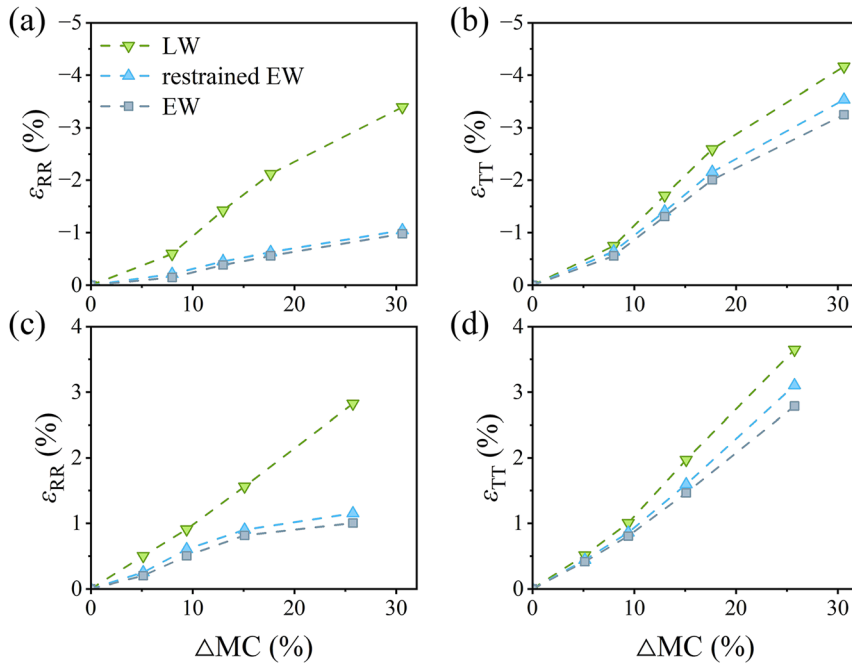


Figure 6: Relationships between strain ϵ_{RR} (a, c) and ϵ_{TT} (b, d) and difference of MC (ΔMC) during desorption (a, b) and adsorption (c, d) processes.

macromolecular relaxation of the wood polymers. As water molecules were absorbed, hemicelluloses and other amorphous polymers within the cell wall softened and transitioned toward a rubbery state. This softening facilitated stress relaxation, enabling internal polymer conformation, which contributed to a delayed dimensional response even when MC remained constant (Brémaud and Gril 2021; Hunt and Gril 1996; Uehara et al. 2025). Consequently, shrinking or swelling did not perfectly track changes in MC; instead, the internal polymer relaxation led to hysteresis and a time lag in dimensional adjustment.

In this study, MC and strains were not monitored continuously, but rather measured at several specific time points. Therefore, the exact time required for stabilization among MC and strains could not be determined. Nevertheless, the available results allowed for a comparative analysis of the differences in the stabilization behavior between MC and strains. These delayed stabilization of ϵ_{RR} and ϵ_{TT} relative to MC contrasts with findings from the literature (Ma et al. 2010; Nopens et al. 2019; Ouyang et al. 2022). Ouyang et al. (2022) observed that the size of *Catalpa bungei* samples stabilized immediately once MC reached equilibrium, using real-time dynamic vapor sorption combined with a digital microscope. Besides, Ma et al. (2010) reported that the dimensional change of *Picea sitchensis* Carr. occurred more rapidly than MC change. However, the stabilization periods

of dimension and MC reported in this study were not comparable with published literature due to variations in environmental conditions. Since maintaining constant humidity was challenging when temperature fluctuated, various methods were used to control RH, such as saturated salt solutions in this study, and humidity generators in the reported literature. Besides, this non-simultaneous behavior could be associated with variations in sample size and the characterization of length scales as well. The sample size used in this study ($5 \times 3 \times 0.5 \text{ mm}^3$, $R \times T \times L$) was smaller than those reported in the literature: $20 \times 20 \times 1.5 \text{ mm}^3$ ($R \times T \times L$) (Nopens et al. 2019), and $20 \times 20 \times 4 \text{ mm}^3$ ($R \times T \times L$) (Ma et al. 2010). When examined sample sizes across multiple growth rings, the observed length scale was typically restricted to the macro scale. Ouyang et al. (2022) reported using samples of $8 \times 4 \times 4 \text{ mm}^3$ ($R \times T \times L$), but measured dimensional change across a series of cells from one vessel to another. According to Rafsanjani et al. (2014), the hygro-deformation of wood cell wall was substantially larger than the one of wood tissues with the growth ring and wood samples made of several growth rings, because the interactions between cell wall layers, cell wall and middle lamella, and between cells contributed to deformation at the cell wall and cellular scales (Zhan et al. 2023). Benefiting from the full-field hygro-deformation provided by DIC, the analysis in this study was able to focus on the dimensional changes within a few cells.

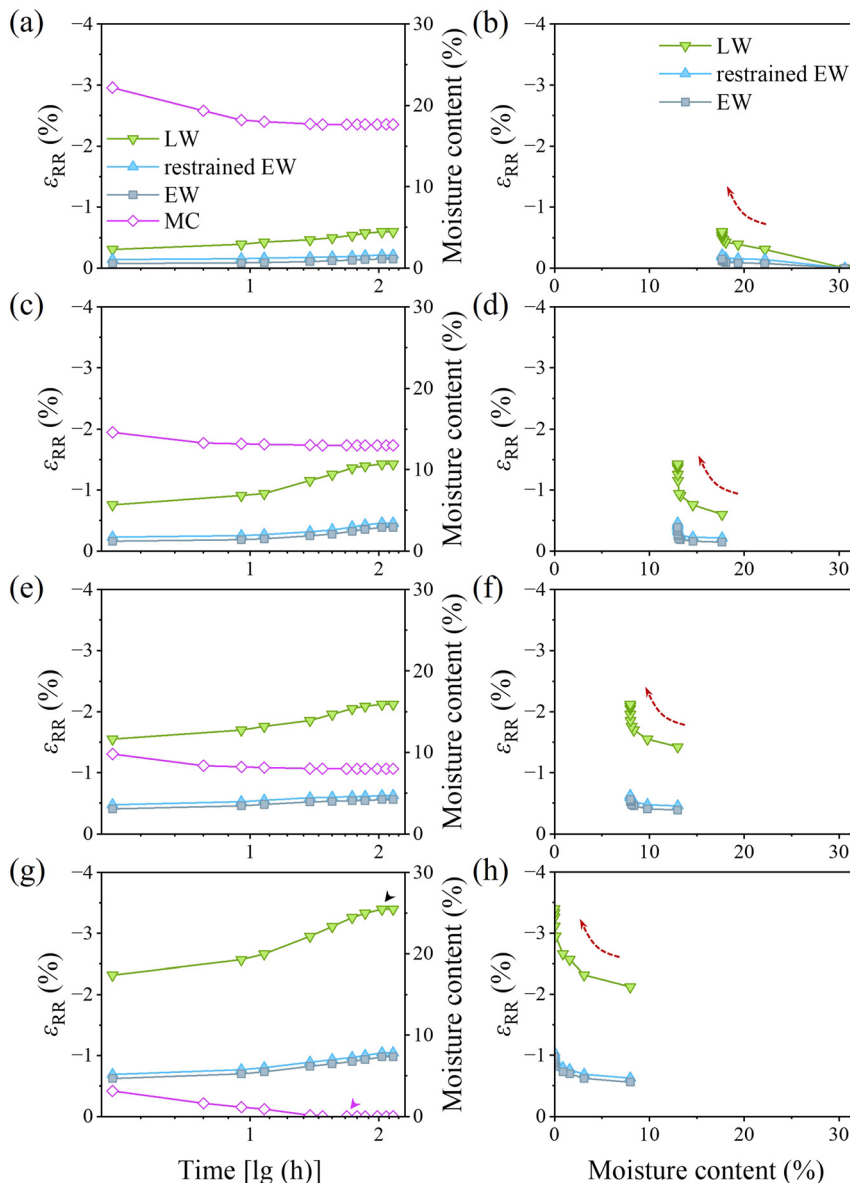


Figure 7: MC and ε_{RR} as a function of logarithmic desorption time (a, c, e, g), and corresponding evolutions of ε_{RR} versus MC (b, d, f, h). RH level: 75 % (a, b), 58 % (c, d), 33 % (e, f) and 0 % (g, h). The purple and black arrows in (g) indicated the stabilized duration of MC and dimension, respectively.

The relationships between strains and MC during desorption (right side of Figures 7 and 8) and adsorption (right side of Figures 9 and 10) were constructed. In these figures, the strain exhibited a trend of initially rapid and then slower change with decreasing (or increasing) MC. On the one hand, the desorption (or adsorption) of water molecules from (or onto) the polar groups of wood components directly caused changes in cell wall dimensions, corresponding to the initial rapid phase of strain variation with MC. Additionally, the hygro-deformation of wood was influenced by the state of moisture as well. During sorption

process, moisture gradually returned to its equilibration state. This equilibration dependent on interaction with the chemical constituents of the wood cell wall (Nakano 1994). As moisture equilibrated, changes in the size and quantity of nanopores within the wood cell wall occurred (Shi and Avramidis 2019), potentially causing slight dimensional deformations. To assess the impact of moisture state on dimensional changes, it was recommended to record real-time variations in MC and dimensions using dynamic vapor sorption and high-resolution microscopy. Additionally, further investigations could be performed to understand

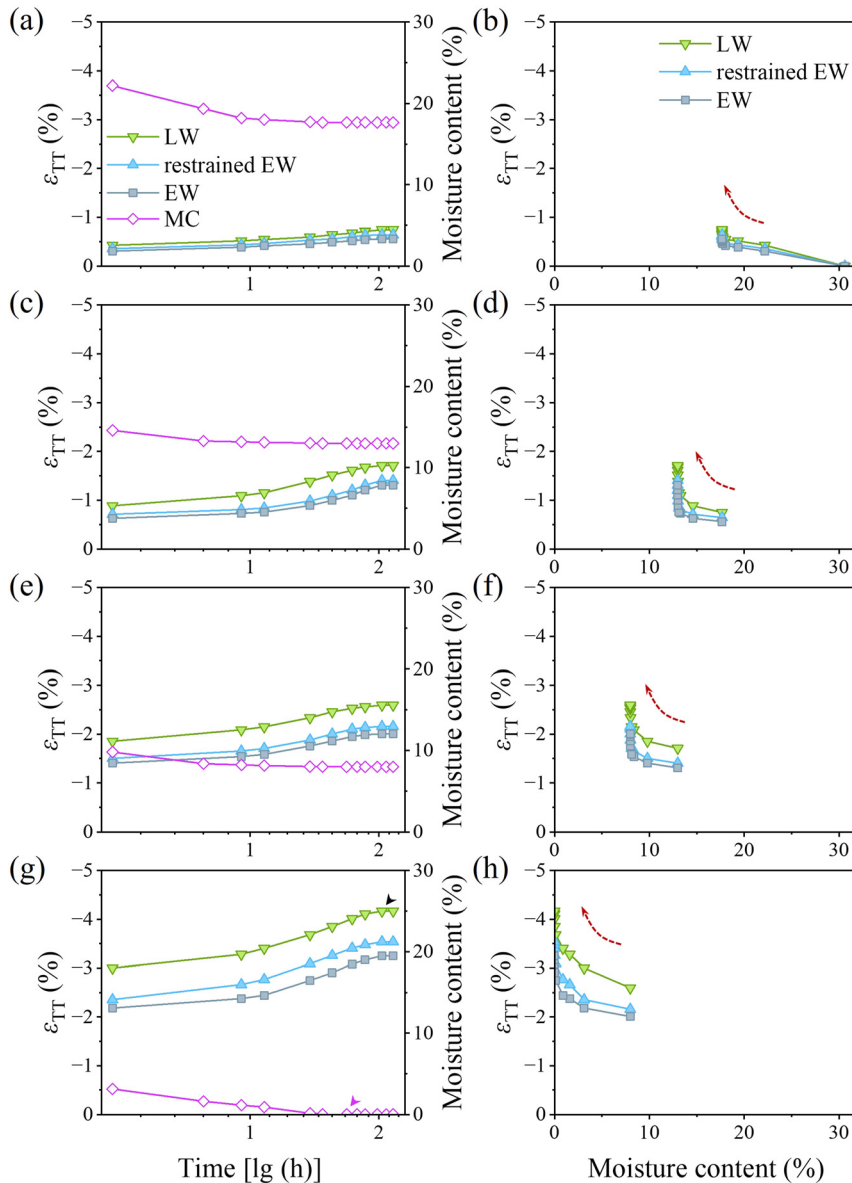


Figure 8: MC and ε_{TT} as a function of logarithmic desorption time (a, c, e, g), and corresponding evolutions of ε_{TT} versus MC (b, d, f, h). RH level: 75 % (a, b), 58 % (c, d), 33 % (e, f) and 0 (g, h). The purple and black arrows in (g), refer to Figure 7.

how RH levels affect the stabilization of dimensions, as the relationship between RH and moisture presence remained unclear (Li and Ma 2022; Telkki et al. 2013).

3.3 Hygro-deformation difference between isolated and intact LW/EW

The full-field hygro-deformation was compared between the intact growth ring samples and isolated LW and EW samples. Figure 11 shows the comparison of the shrinking results. When the intact growth ring sample was divided as two

parts as well as LW from the last growth ring was removed, the restraining effect disappeared, specifically leading to reductions in shrinking in EW. These reductions were characterized as $\Delta\varepsilon_{RR}$ (Figure 11c) and $\Delta\varepsilon_{TT}$ (Figure 11d). Besides, there were also reductions of ε_{RR} and ε_{TT} in transition wood (TW) from the isolated samples compared to that within the intact growth ring samples. However, no significant variation in ε_{RR} or ε_{TT} was found between isolated LW and LW within the intact growth ring.

Figure 12 displays the swelling results. Similarly, obvious reductions of ε_{RR} (a) and ε_{TT} were observed in EW and TW in the isolated samples. These reductions demonstrated that LW

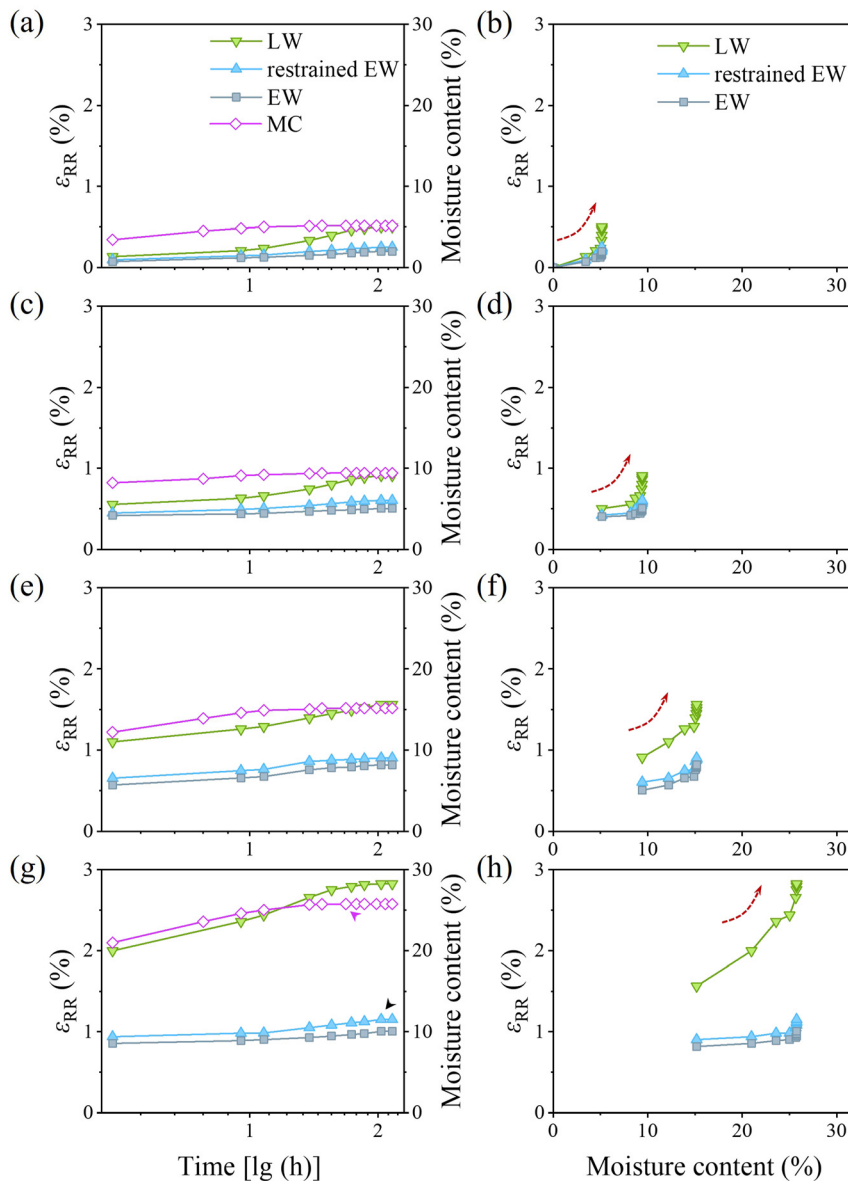


Figure 9: MC and ε_{RR} as a function of logarithmic adsorption time (a, c, e, g), and corresponding evolutions of ε_{RR} versus MC (b, d, f, h). RH level: 33 % (a, b), 58 % (c, d), 75 % (e, f) and 97 % (g, h). The purple and black arrows in (g), refer to Figure 7.

promoted hygro-deformation in both adjacent EW and TW. LW had higher stiffness and more hygro-deformation than EW and TW. In hence, EW and TW were forced to deform with LW during sorption process, attributing to higher hygro-deformation of EW and TW within the intact growth ring. The value of $\Delta\varepsilon_{TT}$ was higher than $\Delta\varepsilon_{RR}$, regardless of shrinking (Figure 11c and 11d) or swelling (Figure 12c and 12d). During desorption, the values of $\Delta\varepsilon_{TT}$ and $\Delta\varepsilon_{RR}$ were 0.46 and 0.40 %, respectively. The corresponding values were 0.58 and 0.71 % during adsorption. The variations in $\Delta\varepsilon_{TT}$ and $\Delta\varepsilon_{RR}$ were influenced by the interaction between EW and LW. This interaction originated from the structural variation.

Particularly, MFA and cell wall thickness are key determinants of wood's stiffness and hygro-deformation (Eder et al. 2020). Figure 13 provides a detailed overview of the variations in MFA and cell wall proportion in both radial and tangential walls between EW and LW. It was evident that EW exhibited higher MFAs and lower cell wall proportions compared to LW, irrespective of the wall orientation. The greater values of $\Delta\varepsilon_{TT}$ compared to $\Delta\varepsilon_{RR}$ could be explained by the more pronounced difference in MFA within the tangential wall. Specifically, LW had the lowest MFA in the tangential wall (7.6°), while its cell wall proportion (18.3 %) was lower than that in radial wall (22.2 %). It should be noted that the cell

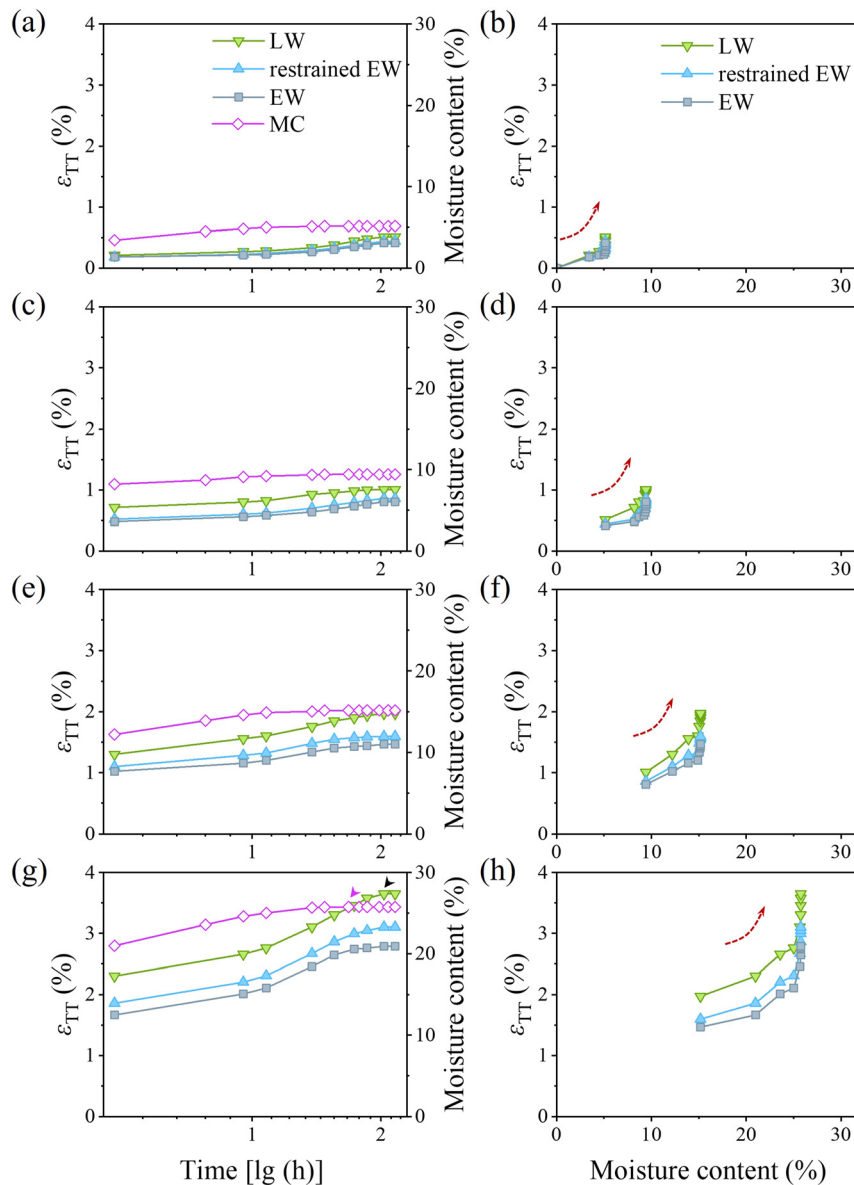


Figure 10: MC and ε_{TT} as a function of logarithmic adsorption time (a, c, e, g), and corresponding evolutions of ε_{TT} versus MC (b, d, f, h). RH level: 33 % (a, b), 58 % (c, d), 75 % (e, f) and 97 % (g, h). The purple and black arrows in (g), refer to Figure 7.

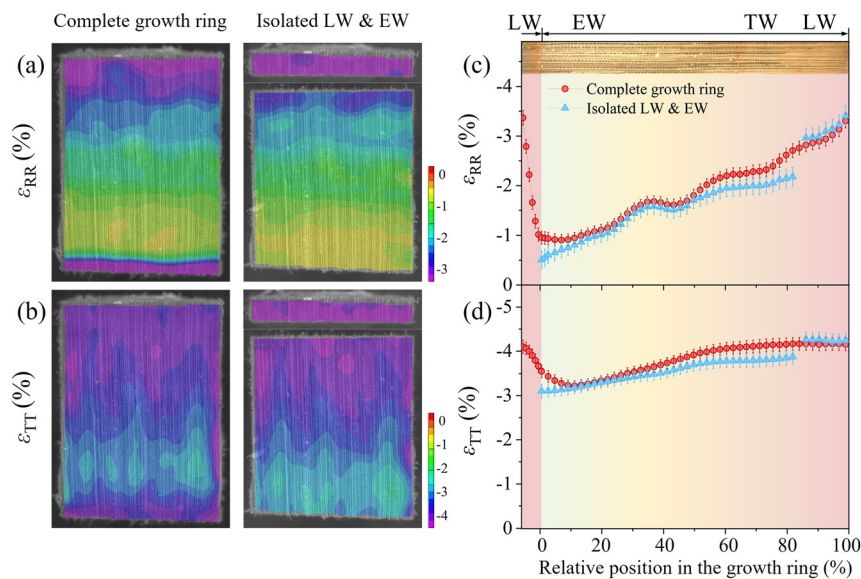


Figure 11: Comparison of shrinking results in intact growth ring samples and isolated EW and LW samples when RH changed from 97 % to 0: full-field distribution of ε_{RR} (a) and ε_{TT} (b), and corresponding relationships between shrinking strain and relative position in the growth ring (c and d). The results obtained from the intact growth ring samples were referenced from Zhan et al. (2023).

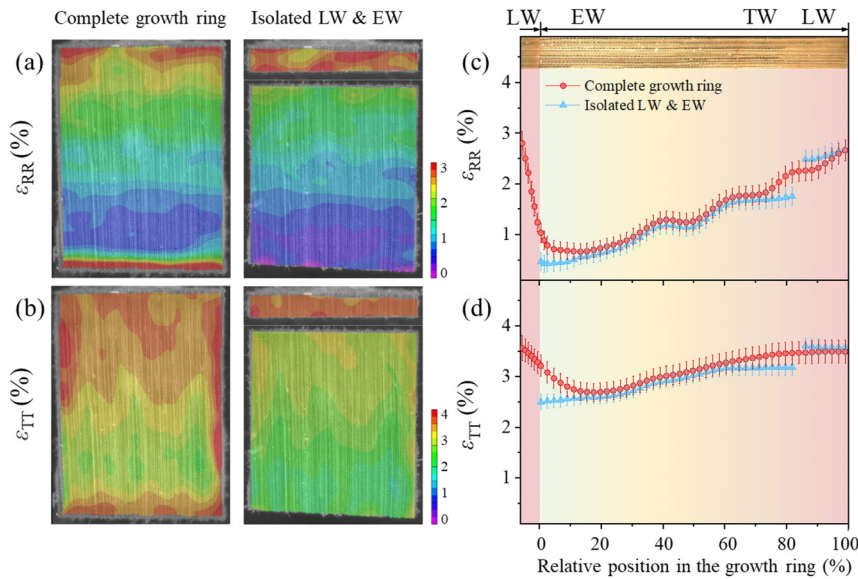


Figure 12: Comparison of swelling results in intact growth ring samples and isolated EW and LW samples when RH changed from 0 to 97 %: full-field distribution of ϵ_{RR} (a) and ϵ_{TT} (b), and corresponding relationships between swelling strain and relative position in the growth ring (c and d). The results obtained from the intact growth ring samples were referenced from Zhan et al. (2023).

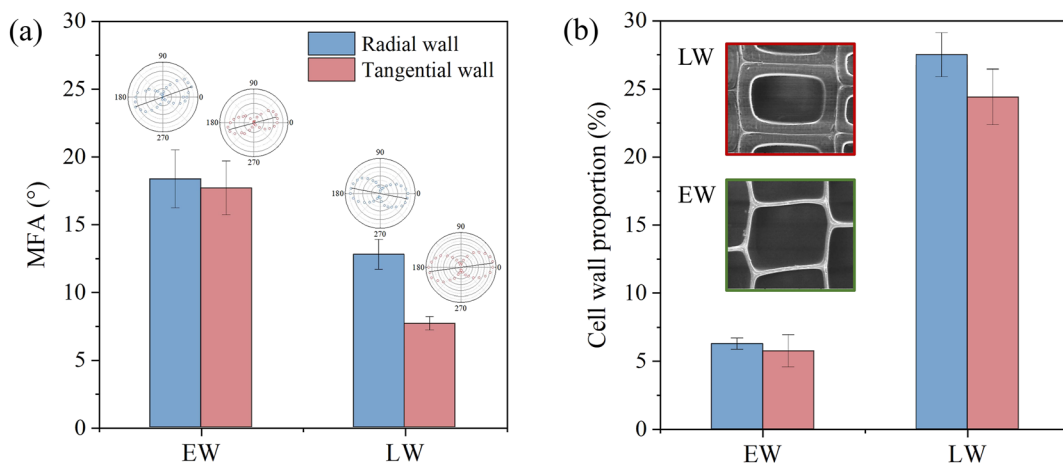


Figure 13: Variations of MFA (a) and cell wall proportion (b) of EW and LW in radial and tangential walls. Polar plots in (a) illustrated the intensity variations of the 1,096 cm^{-1} Raman band as the polarization direction of the incident laser was rotated in 10° steps. Inset in (b) presented the SEM images of LW and EW. Scale bars: 10 μm .

wall proportion in this study was lower than that reported in a previous study (Zhan et al. 2021) using the same species, as it was calculated based on a line ratio (Figure 1) rather than an area ratio.

Comparing the difference of strain in intact growth ring and isolated EW and LW is helpful to understand the interaction between EW and LW, and probably to assess the evolution of moisture variation induced stresses. When the interaction stress exceeds transverse tensile strength, the likelihood of cracking in the wood increases significantly (Qu et al. 2025). Future research could further evaluate the elastic

and even viscoelastic stresses under varying hygro-thermal conditions which simulate practical drying environments.

4 Conclusions

During both desorption and adsorption, LW and (restrained) EW exhibited rapid hygro-deformation initially, followed by stabilization. This stabilization in dimensional changes (ϵ_{RR} and ϵ_{TT}) lagged behind that observed in MC. Although no significant variation in shrinking or swelling was detected in

isolated LW compared to that within the intact growth ring, isolated EW samples demonstrated notable reductions of shrinking and swelling due to the removal of LW's restraining effect. The hygro-deformation differences in EW before and after isolation were quantified. When RH decreased from 97 % RH to 0, the differences were 0.40 and 0.46 % in radial and tangential directions, respectively. The corresponding values were 0.58 and 0.71 % during adsorption (0 → 97 % RH). The strain differences could be potentially used to evaluate the possibility for wood cracking. These results highlight the impact of EW-LW interaction on the hygro-deformation of Chinese fir and are helpful to elucidate the complex nature of wood-water relations.

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