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Drying Characteristics of Mongolian Scots Pine (*Pinus sylvestris* var. *mongolica*) Square Timber under Different High-Temperature Drying-Set Treatments

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ABSTRACT: To investigate the effects of different high-temperature drying-set treatment processes on the drying characteristics of 120 mm thick Scots pine (*Pinus sylvestris* var. *mongolica*) square timber, six drying schedules were designed. Temperature and moisture content distribution, drying rate, checking behavior, and residual stress variations were measured and analyzed. The results showed that a surface temperature exceeding 100°C during the drying-set stage was essential for promoting effective surface shrinkage and forming a stable drying-set layer. The 105°C treatment failed to achieve this condition, resulting in severe surface checking. In contrast, the 120°C treatment provided suitable conditions for forming a stable drying-set layer. Among the investigated schedules, the schedule with a drying-set temperature of 120°C and a duration of 10 h exhibited the lowest surface-checking area. Although the surface temperature exceeded 100°C under the 135°C treatment, the heating rate of the surface layer increased with treatment duration (reaching a maximum of approximately 12.5°C/h), resulting in an increased temperature difference between the surface and interior layers and an elevated risk of surface checking. After drying, the residual stress of the high-temperature drying-set treated groups was reduced by 72.41%–86.89% compared with the control group. Among the investigated drying schedules, the schedule involving saturated steam softening at 95°C for 12 h followed by drying-set treatment at dry-bulb/wet-bulb temperatures of 120°C/90°C for 10 h exhibited the best overall performance. This schedule reduced the drying cycle to 5.9 d, representing a reduction of 9.23%–52.80% compared with the other schedules. It also produced a residual stress of 0.29%, and a surface checking area of 51.69 mm², corresponding to reductions of 56.85%–88.04% relative to other schedules. These findings provide new insights into moisture migration and stress evolution during high-temperature drying-set treatment, supporting the optimization of drying strategies for large-section wood products.

KEYWORDS: *Pinus sylvestris* var. *mongolica*; high-temperature drying set; pretreatment; surface checking; moisture content

1 Introduction

In the context of the “dual-carbon” strategy, sustainable construction has attracted increasing attention due to the demand for low-carbon materials and improved building performance [1,2]. Modern timber structures have attracted increasing attention because of their low carbon footprint, attractive appearance, and good thermal insulation properties. Consequently, the demand for large-section square timber has increased steadily [3]. Scots pine (*Pinus sylvestris* var. *mongolica*) is one of the major plantation species in northeast China and possesses excellent mechanical properties. Large-section boxed-heart square timber (100–150 mm in cross-section) is therefore widely used as a structural material in timber construction [4].

However, its large cross-section and pronounced differences in wood properties between the pith and sapwood restrict moisture migration during drying. As a result, severe anisotropic shrinkage occurs, leading to a high risk of surface checking [5,6]. Therefore, the efficient and high-quality drying of large-section boxed-heart square timber has become an important research focus in wood drying.

To address drying-induced checking in large-section square timber, previous studies have mainly focused on two approaches: pretreatment techniques and combined drying techniques. Listyanto et al. [7], Kang et al. [8], and Wang et al. [9] demonstrated that pretreatment techniques, such as laser drilling and longitudinal grooving, can increase the drying rate, reduce the moisture content gradient, and inhibit surface checking. However, these techniques have not been widely adopted because they reduce mechanical strength and increase processing costs.

Among combined drying techniques, high-frequency heating-based methods have received the greatest research attention. High-frequency heating technologies have been investigated for accelerating wood drying and improving drying efficiency [10,11]. Zhao and Lee [12] and Lee et al. [13] further demonstrated that high-frequency vacuum drying can reduce the moisture content gradient and surface residual stress, thereby inhibiting surface checking. However, the large-scale application of these technologies remains limited because of the high capital investment and operating costs of the required equipment.

Japanese researchers developed a drying technology that combines high-temperature drying-set treatment with subsequent conventional drying, which can effectively inhibit surface checking and accelerate the drying process [14,15]. The key component of this technology is the high-temperature drying-set treatment, which involves steam softening followed by high-temperature and low-humidity treatment. During the softening stage, wood is treated with saturated humid air or saturated steam at 85°C–98°C. Previous studies have demonstrated that steam pretreatment can reduce drying defects [16]. Subsequently, the wood is rapidly dried under high-temperature and low-humidity conditions (dry-bulb temperature: 105°C–140°C; wet-bulb temperature: 75°C–95°C). Saturated steam treatment at approximately 95°C followed by high-temperature and low-humidity treatment at 110°C–120°C has been reported to effectively induce drying-set formation [15]. During this stage, restrained shrinkage occurs in the surface layer, and the tensile creep generated in the surface layer is fixed during subsequent drying, forming a setting layer (i.e., drying set) and suppressing surface checking [17].

Katagiri et al. [18] reported that the drying set developed in the surface layer was approximately 3% at 120°C, which was substantially higher than the value at 80°C (approximately 1%). This indicated that higher drying-set temperatures were more effective in suppressing surface checking. Hermawan et al. [19] found that high-temperature, low-humidity pretreatment at 135°C or 150°C effectively prevented surface checking in boxed-heart sugi timber. However, excessive treatment intensity increased the risk of internal checking. Kang et al. [20] reported that a high-temperature drying-set treatment at 120°C with a dry-bulb/wet-bulb temperature difference of 30°C for 12–16 h was the optimal pretreatment condition for preventing surface checking in boxed-heart larch square timber. These studies indicate that setting temperature and treatment duration are critical parameters affecting drying-set development and drying quality.

High-temperature treatment has been widely studied for modifying wood properties, including dimensional stability and mechanical performance [21]. Hermawan et al. [17] suggested that elevated temperatures promote the softening of lignin and hemicellulose in the wood cell wall, thereby facilitating molecular chain slippage. Hermawan and Fujimoto [22] identified the difference between mechanosorptive creep in the surface layer and compressive creep in the inner layer as the primary driving factor for drying checks. Gao [23] reported that during subsequent conventional drying, the stress state in the surface layer changes from tension to compression. High-temperature drying-set treatment suppresses surface checking

by reducing the tensile stress before stress reversal rather than directly inducing stress reversal during the setting stage.

However, systematic investigations of the process parameters of high-temperature drying-set treatment for large-section boxed-heart square timber remain limited in China. In addition, the drying characteristics associated with different drying schedules have not been comprehensively investigated. Therefore, this study investigated plantation-grown Scots pine boxed-heart square timber with a cross-section of 120 mm. The softening stage was conducted using saturated steam at 95°C for 12 h, followed by high-temperature drying-set treatment under different conditions. The subsequent drying stage was performed using low-temperature conventional convective drying. During the entire drying process, timber temperature, moisture content variation and distribution, residual stress, and surface checking were systematically measured and analyzed. The aim was to provide fundamental data for developing high-quality drying schedules for large-section boxed-heart square timber.

2 Materials and Methods

2.1 Materials

The specimens consisted of Scots pine boxed-heart square timber with dimensions of 1200 mm (L) × 120 mm (T) × 120 mm (R). The timber was obtained from the Daxing'anling forest region, Heilongjiang Province, China. The average initial moisture content was 117.88%, and the average log diameter class was 25 cm. After harvesting, the timber was stored under refrigerated conditions until use.

2.2 Experimental Equipment

The equipment used consisted of a high-temperature drying chamber (Harbin Halei Co., Ltd., Harbin, China; operating temperature range: 25°C–150°C; relative humidity range: 15%–100%), a constant-temperature and humidity chamber (Model PL-150, Beijing Hongzhan Instruments Co., Ltd., Beijing, China; operating temperature range: −40°C to 150°C; relative humidity range: 20%–98%), and an electric forced-air drying oven (Model 101-2AB, Tianjin Taisite Co., Ltd., Tianjin, China; operating temperature range: 10°C–250°C).

2.3 Methods

2.3.1 Specimen Preparation and Moisture Content Measurement

After natural thawing, 100 mm was removed from both ends of the timber to minimize the influence of end moisture loss. The remaining material was sawn into specimens measuring 500 mm (L) × 120 mm (T) × 120 mm (R). As shown in Fig. 1a, 10-mm-thick test pieces were prepared from both ends of each specimen for initial moisture content determination. Each test piece was divided into 25 subsamples. The moisture content of each subsample was measured using the oven-dry method and calculated according to Eq. (1). The moisture content distribution of the timber was determined based on these 25 subsamples, and the average value of the two end test pieces was taken as the initial moisture content of the timber. For each drying schedule, three replicate specimens were prepared for drying experiments and subsequent evaluations, including moisture content distribution, drying rate, surface checking, and residual stress measurements. A separate specimen was prepared exclusively for temperature monitoring during the softening and drying-set stages. The temperature-monitoring specimen was excluded from subsequent measurements because drilling holes for probe installation could compromise specimen integrity.

$$MC_i = \frac{m_i - m_{0i}}{m_{0i}}, \quad (1)$$

where: MC_i is the moisture content of subsample i (%), m_i is the mass of subsample i before oven drying (g), and m_{0i} is the oven-dry mass of subsample i (g).

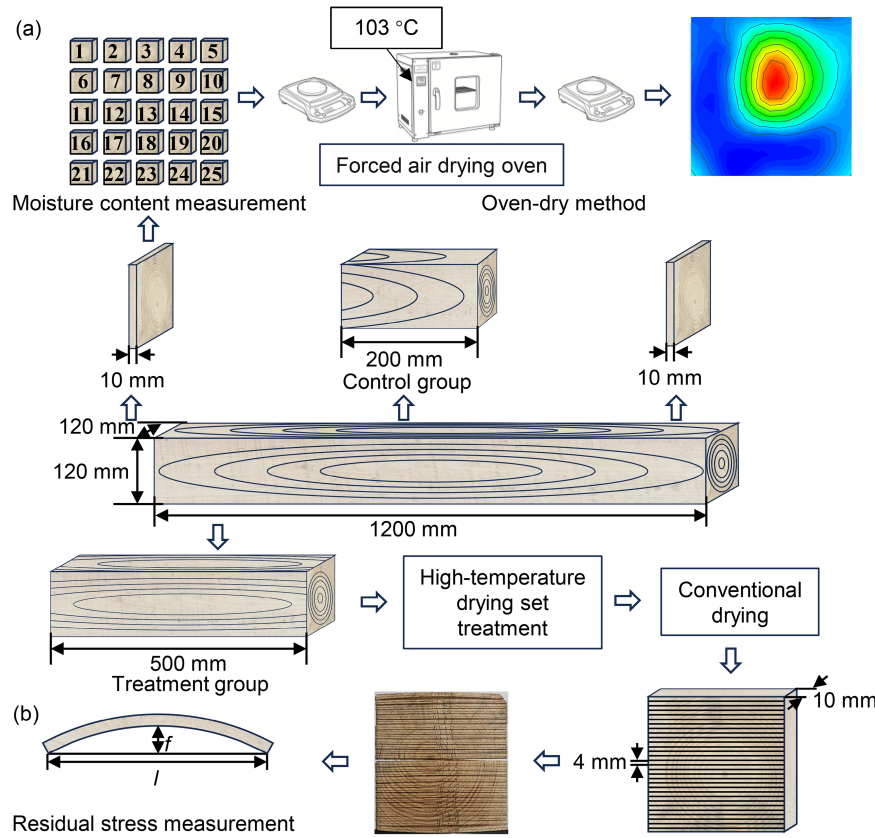


Figure 1: Schematic diagram of specimen preparation and testing procedures. (a) Moisture content distribution measurement; (b) Residual stress measurement.

2.3.2 Temperature Measurement

Before temperature monitoring, the temperature measurement system was calibrated to minimize zero-drift effects. As shown in Fig. 2, temperature probes were arranged at designated locations within the temperature-monitoring specimen. Holes approximately 2 mm in diameter were drilled, and the probes were inserted into the holes. The probe holes were then sealed with silicone sealant to prevent interference from the drying medium. Temperature data were recorded at 1-min intervals.

2.3.3 Drying-Set Treatment and Subsequent Drying

Before the high-temperature drying-set treatment, the ends of the timber specimens were sealed with silicone sealant. Timber specimens of the same dimensions were stacked around the test specimens to ensure uniform circulating airflow through each layer of the stack. The drying-set treatment schedules were designed based on previous studies and preliminary experiments. The drying-set treatment temperatures (105°C, 120°C, and 135°C) were selected based on previous studies [15,19,20] and preliminary experiments to represent different treatment intensities under high-temperature and low-humidity conditions (the corresponding relative humidities calculated from the dry-bulb and wet-bulb temperatures were 38.38%, 34.96%, and 26.84%, respectively). The treatment durations were selected with reference to effective

treatment periods reported in previous studies and further adjusted through preliminary experiments. Excessively prolonged treatment durations may induce cracking during the drying-set stage, compromising specimen integrity and affecting subsequent drying and defect evaluations. The high-temperature drying-set treatment was conducted in a high-temperature drying chamber. The drying-set treatment schedules are listed in Table 1. After completion of the softening and drying-set treatments, moisture content distribution was determined for the specimens assigned for moisture-content measurement using the oven-dry method. The specimens were not weighed during these stages to avoid interrupting the high-temperature treatment process. After removing 100 mm from both ends, 10-mm-thick test pieces were collected for moisture content measurement.

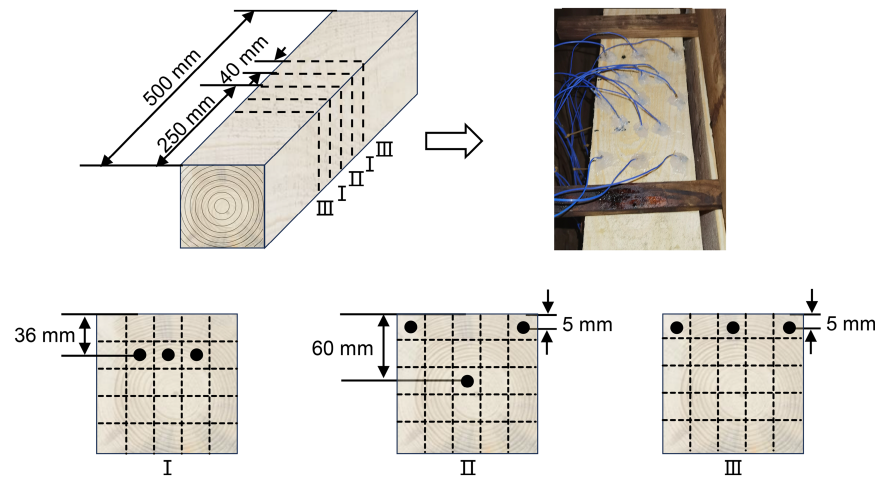


Figure 2: Locations of temperature detection probes in the timber specimen. I, II, and III represent the three probe arrangements.

Table 1: High-temperature drying-set treatment schedules.

Schedule	Softening Treatment			Drying-Set Treatment		
	DB ¹ /°C	WB ² /°C	Time/h	DB ¹ /°C	WB ² /°C	Time/h
R1	95	95	12	105	80	12
R2	95	95	12	105	80	14
R3	95	95	12	120	90	10
R4	95	95	12	120	90	12
R5	95	95	12	135	95	6
R6	95	95	12	135	95	9

Note: ¹DB: dry-bulb temperature; ²WB: wet-bulb temperature.

Subsequent drying was performed using conventional convective drying. The drying schedule was set at a dry-bulb temperature of 70°C and a wet-bulb temperature of 60°C. The specimens were dried to a final moisture content of approximately 11%. During subsequent drying, specimen mass was recorded periodically. After drying, moisture content distribution was determined for the designated specimens using the oven-dry method. The 10-mm-thick test pieces were collected from the end and middle regions of the specimens, covering the surface, middle, and core layers of the cross-section.

2.3.4 Residual Stress Measurement

Residual stress was measured using the slicing method. After drying, 10-mm-thick test pieces for residual stress measurement were prepared from the ends of the treated specimens, as shown in Fig. 1b. The test pieces were then sliced into 4-mm-thick laminae. The laminae were placed in a well-ventilated environment for 24 h to equilibrate their moisture content. Their length and deflection were subsequently measured.

For the control group, 10-mm-thick test pieces for residual stress measurement were prepared from green timber obtained from the same original material. The test pieces were then sliced into 4-mm-thick laminae. The laminae were placed in a constant-temperature and humidity chamber until their moisture content reached the same level as that of the dried treated specimens. They were then placed in a ventilated environment for 24 h, after which their length and deflection were measured using an image-based measurement system. Residual stress was calculated according to Eq. (2).

$$Y = \frac{f}{l}, \quad (2)$$

where: Y is the residual stress of the lamina (%), f is the deflection of the lamina after conditioning (mm), and l is the length of the lamina after conditioning (mm).

3 Results and Analysis

3.1 Temperature Distribution and Variation

The temperature–time curves of different timber layers under various high-temperature drying-set treatments are shown in Fig. 3. Saturated steam at 95°C was applied during the softening stage. The temperature of each layer increased continuously. The surface layer stabilized first, followed by the middle layer and the core layer. The temperatures of the surface and middle layers stabilized at approximately 92°C, while that of the core layer stabilized at approximately 90°C. The temperature difference among the layers was $\leq 2^\circ\text{C}$.

During the high-temperature drying-set stage, the temperatures of the middle and core layers gradually increased and finally stabilized between 92°C and 97°C under all processes. However, the surface temperature differed among the treatments. Under the 105°C treatment (R1, R2), the surface temperature stabilized at approximately 97°C and remained below 100°C throughout the treatment. Under the 120°C treatment (R3, R4), the surface temperature increased above 100°C during the later stage and remained relatively stable thereafter. Under the 135°C treatment (R5, R6), the surface temperature exceeded 100°C, while the heating rate continuously increased, reaching 12.30°C/h for R5 and 12.66°C/h for R6.

Under atmospheric pressure, the evaporation temperature of free water is approximately 100°C. Whether the wood temperature exceeds 100°C depends on the presence of free water. Therefore, wood temperature can indirectly reflect the occurrence of drying shrinkage. Under the 105°C treatment (R1, R2), the surface temperature remained below 100°C throughout the process, indicating that effective drying shrinkage was not achieved in the surface layer. Under the 120°C treatment (R3, R4), surface shrinkage occurred. The surface evaporation rate was balanced with the internal moisture migration rate, and moisture continuously migrated from the interior to the surface. Most of the supplied heat was consumed by moisture evaporation rather than sensible heating of the wood. Therefore, the surface temperature remained relatively stable. Under the 135°C treatment (R5, R6), the surface evaporation rate was much higher than the internal moisture migration rate. As a result, the surface moisture content decreased rapidly, whereas internal moisture migration remained limited. More heat was consumed for sensible heating of the wood, resulting in a nonlinear increase in surface temperature.

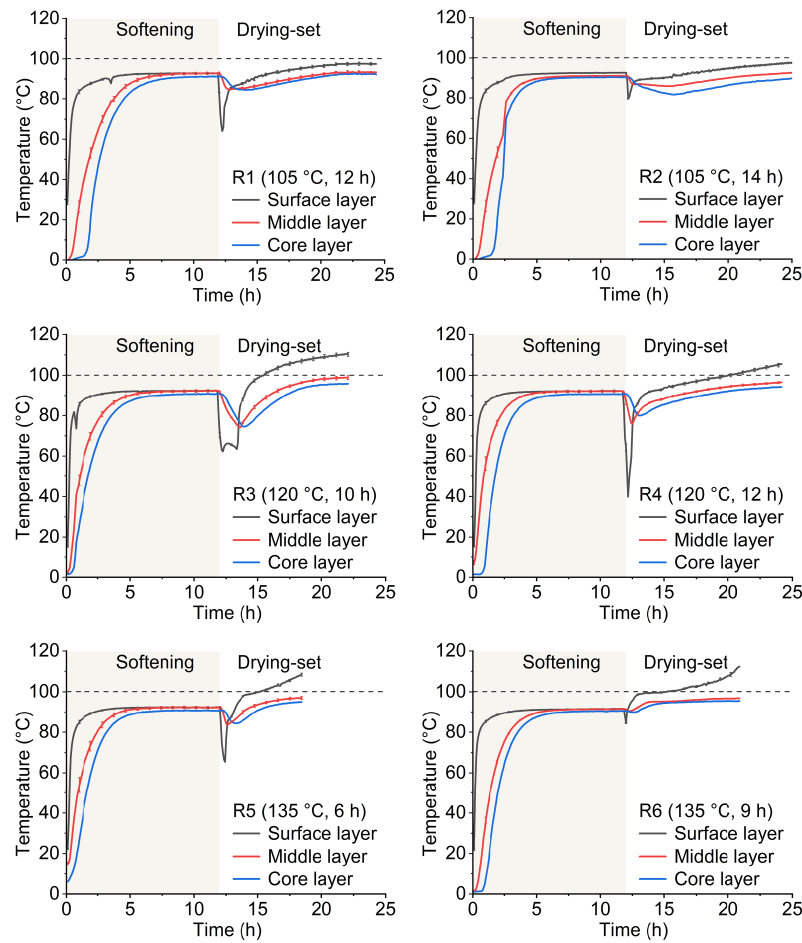


Figure 3: Temperature–time curves of each timber layer under different high-temperature drying-set treatments. Error bars represent the variation among temperature monitoring points within the same layer.

In summary, the optimal drying-set temperature under the conditions investigated in this study was 120°C. The effectiveness of high-temperature drying-set treatment in inhibiting surface checking depends on rapid shrinkage of the softened surface layer, which promotes the formation and fixation of the drying-set layer [24]. Under the 105°C treatment (R1, R2), the surface temperature remained below 100°C, preventing effective drying shrinkage and the formation of a sufficient drying-set layer. This condition was unfavorable for surface checking inhibition. Under the 135°C treatment (R5, R6), the temperature difference between the surface and interior continuously increased, from 6.02°C to 11.49°C for R5 and from 4.91°C to 15.66°C for R6. The increased temperature gradient induced higher thermal stress and consequently increased the risk of surface checking.

3.2 Moisture Content Variation and Distribution

Because differences in initial moisture content existed among timber specimens, specimens with comparable initial moisture contents within each drying-set schedule were selected for drying-rate comparison to reduce the influence of initial moisture content on drying behavior.

The moisture content–time curves of timber under different drying schedules are shown in Fig. 4. The entire drying process was divided into the softening stage, the high-temperature drying-set stage, and

the subsequent drying stage. During the softening stage, the moisture content decreased under all drying schedules, and greater reductions were observed for timber with higher initial moisture contents. The average moisture content reduction was approximately 8.78%. The most rapid moisture loss occurred during the high-temperature drying-set stage, accounting for 40.50%–79.46% of the total moisture content reduction. During the subsequent drying stage, the drying rate gradually decreased until the end of drying. The drying cycles of groups R1–R6 ranged from 5.9 to 12.5 days, with R3 showing the shortest drying cycle.

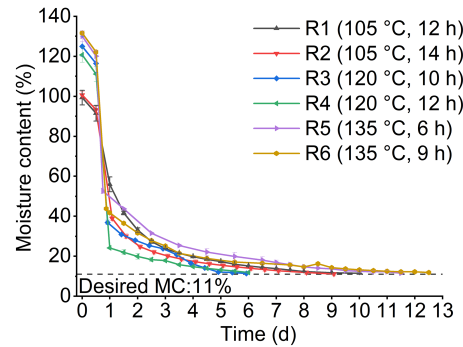


Figure 4: Moisture content–time curves of timber under different drying schedules. Error bars represent the variation within the measurements obtained from the same specimen.

The drying rates during the softening–drying-set stage, subsequent drying stage, and the overall process under different drying schedules are listed in Table 2. The drying rate was highest during the softening–drying-set stage. Under the same treatment duration, increasing the drying-set temperature to 120°C significantly increased the drying rate by 122.61%. However, only a limited increase was observed when the temperature was further increased to 135°C. The effect of extending treatment duration on the drying rate varied with drying-set temperature, with variation rates of 31.49%, 0.87%, and –2.70% at 105°C, 120°C, and 135°C, respectively.

Table 2: Drying rates under each drying schedule during the softening–drying-set stage, subsequent drying stage, and entire process.

Schedule	Softening– Drying-Set/(%·d ⁻¹)	Subsequent Drying/(%·d ⁻¹)	Entire Process/(%·d ⁻¹)
R1 (105°C, 12 h)	43.38	4.94	8.79
R2 (105°C, 14 h)	57.04	3.47	9.86
R3 (120°C, 10 h)	95.74	5.10	19.19
R4 (120°C, 12 h)	96.57	2.32	16.82
R5 (135°C, 6 h)	103.09	3.83	10.30
R6 (135°C, 9 h)	100.31	2.75	9.58

Note: Drying rates were calculated from the drying curves shown in Fig. 4 based on individual specimens with comparable initial moisture contents within each drying-set schedule.

The relatively high drying rate during the softening–drying-set stage was mainly attributed to the high-temperature, low-humidity environment and the high initial moisture content of the timber. During this stage, the drying rate was jointly controlled by surface evaporation and internal moisture migration. As shown in Fig. 3, under the 105°C drying-set treatment (R1, R2), the surface temperature remained below 100°C throughout the process, and the surface evaporation rate remained relatively stable. When the

treatment duration was extended by 2 h, the temperatures of the middle and core layers gradually increased. This promoted both internal moisture migration and surface evaporation during the later drying-set stage, thereby significantly increasing the overall drying rate.

Under the 120°C drying-set treatment (R3, R4), the surface temperature increased above 100°C and remained relatively stable. The surface evaporation rate was balanced with the internal moisture migration rate, while the drying-set layer generated resistance to moisture migration. Therefore, extending the treatment duration had a limited effect on further increasing the drying rate [25].

For the R5 and R6 groups (135°C drying-set treatment), the surface heating rate increased continuously with treatment time, rising from 0.29 to 12.30°C/h for R5 and from 0.05 to 12.66°C/h for R6. During wood drying, moisture migration is not uniform, and distinct wet and dry zones separated by an evaporation interface may develop [26]. Under the 135°C treatment, the surface evaporation rate substantially exceeded the internal moisture migration rate, causing the evaporation front to move inward. Consequently, the moisture migration path was extended, and more heat was consumed for sensible heating of the wood rather than moisture evaporation, resulting in a reduced drying rate.

The moisture content distribution maps shown in Figs. 5–8 were selected from representative specimens to illustrate characteristic moisture migration patterns during different drying stages. Because moisture distribution along the pith region exhibited considerable spatial variation, averaging among specimens was not performed.

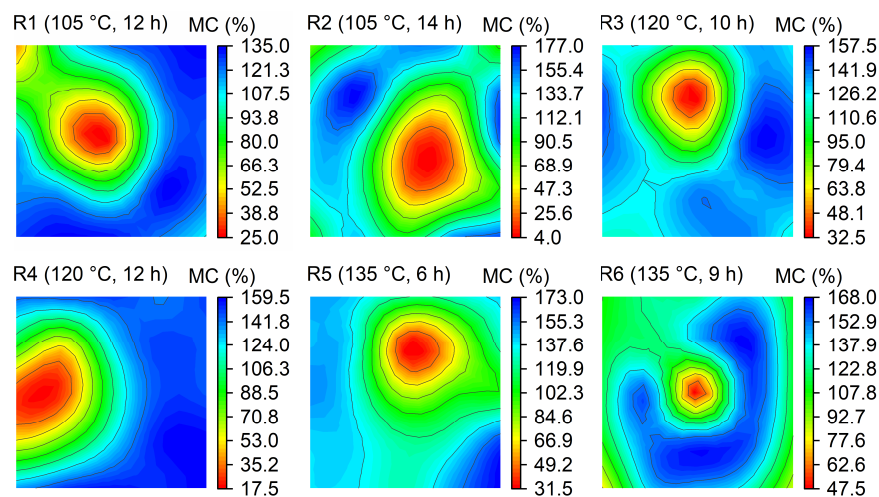


Figure 5: Moisture content distribution at the initial state under each drying schedule. The color bar indicates moisture content (%).

Fig. 5 shows the initial moisture content distribution under each drying schedule. High moisture contents were observed in the surface layer (114.62%–139.82%) and middle layer (93.56%–152.20%), whereas the core layer exhibited much lower values (25.47%–34.71%). The overall moisture content distribution was highly non-uniform.

Fig. 6 shows the moisture content distribution after softening. The moisture content distribution in the surface and middle layers became more uniform, and the moisture content gradient between the middle and core layers decreased by 3.81%–18.22%. After the softening treatment, the wood cell wall structure was partially altered [27], increasing wood permeability and promoting moisture redistribution [28], thereby reducing the moisture content gradient.

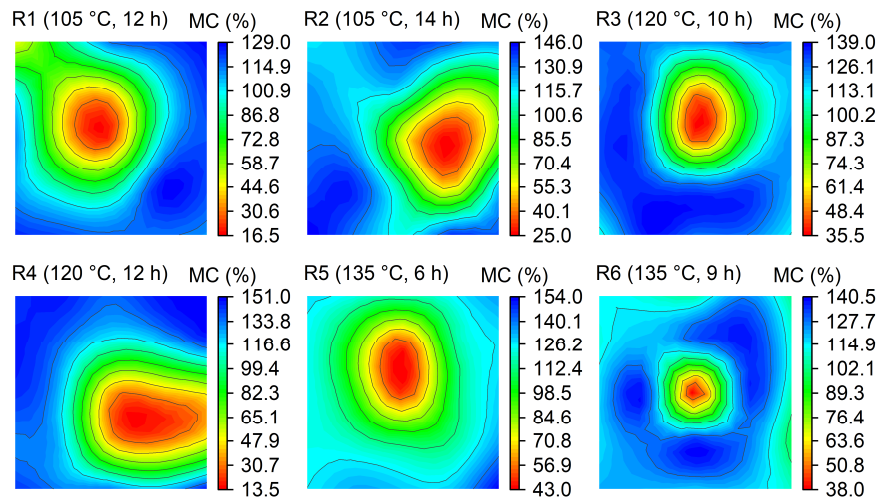


Figure 6: Moisture content distribution after softening under each drying schedule. The color bar indicates moisture content (%).

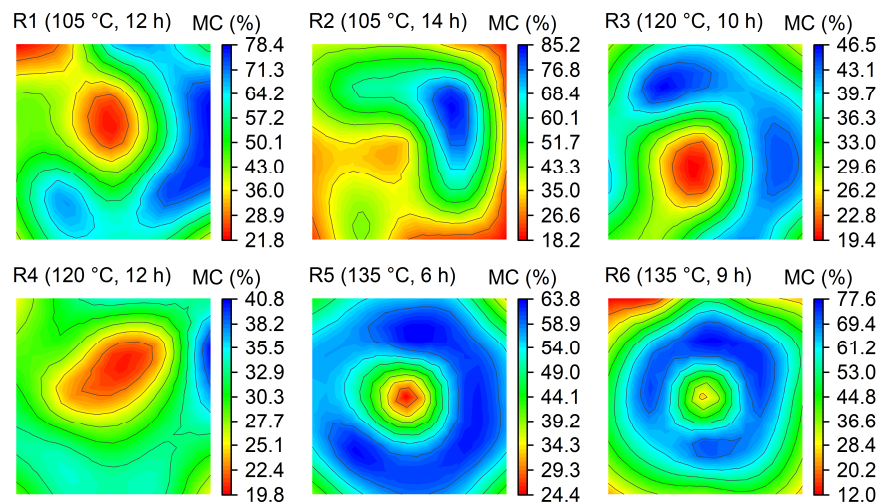


Figure 7: Moisture content distribution after drying-set treatment under each drying schedule. The color bar indicates moisture content (%).

Fig. 7 shows the moisture content distribution after the drying-set treatment. Significant differences were observed among the different drying schedules. Under the same drying-set temperature, extending the treatment duration resulted in a greater reduction in moisture content in the middle layer. Under the 135°C drying-set treatment (R5, R6), a distinct high-moisture-content region formed in the middle layer and was clearly separated from the surface and core layers. With prolonged treatment, the size of this region decreased. This phenomenon was consistent with the temperature distribution and drying rate results. At 135°C, the surface evaporation rate substantially exceeded the internal moisture migration rate, causing the evaporation front to move inward and resulting in moisture accumulation in the middle layer. With extended treatment duration, internal moisture gradually migrated outward, reducing the extent of the high-moisture-content region.

Fig. 8 shows the moisture content distribution after drying completion. The moisture contents of the surface layer (5.97%–8.41%) and middle layer (6.43%–11.89%) were relatively low, whereas the core

layer exhibited higher values (8.54%–16.56%). The overall distribution became relatively uniform, although slightly higher moisture content remained in the core layer.

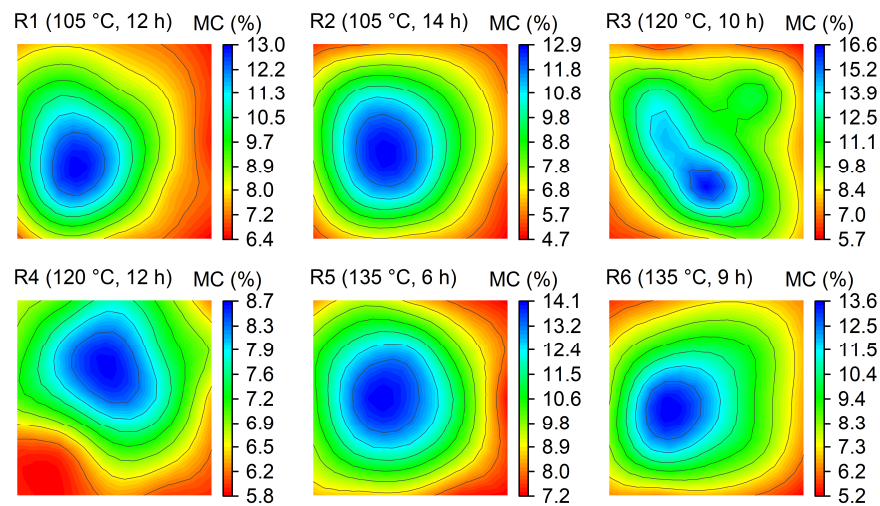


Figure 8: Moisture content distribution after drying completion under each drying schedule. The color bar indicates moisture content (%).

In summary, the R3 schedule exhibited the shortest drying cycle. The relatively low drying-set temperature of 105°C (R1, R2) resulted in prolonged drying cycles. Under the 120°C drying-set treatment (R3, R4), extending the treatment duration improved moisture content distribution uniformity but reduced the drying rate during the subsequent drying stage by 54.51%. This was mainly attributed to the reduced moisture content gradient, which weakened the driving force for bound water diffusion. Meanwhile, the moisture diffusion coefficient of wood decreased under low moisture content conditions. Under the 135°C treatment (R5, R6), although a relatively large moisture content gradient remained between the middle and surface layers, inward movement of the evaporation front lengthened the moisture migration path. In addition, the drying-set layer altered the moisture transport pathway. Consequently, the drying rate during the subsequent drying stage remained low.

3.3 Residual Stress and Surface Checking

Residual stress distribution was evaluated based on the average values of two adjacent slices from the same specimen. Because residual stress varied along the radial direction, the results were interpreted based on distribution characteristics rather than statistical comparisons among treatments.

The residual stress profiles along the thickness direction of the drying-set treated groups and the control group after drying are shown in Fig. 9. The control group is presented on the left, whereas the drying-set treated groups are presented on the right. Positive and negative values represent tensile and compressive stresses, respectively (compression: negative; tension: positive). The control group exhibited a higher mean absolute residual stress. In addition, inconsistent stress directions were observed in the surface layer, resulting in a disordered residual stress distribution, which is consistent with the heterogeneous residual stress distribution reported for large-diameter boxed-heart timber [29]. In contrast, the drying-set treated groups exhibited lower mean absolute residual stresses. Compressive stress was mainly observed in the surface layer, whereas tensile stress occurred in the core layer. In some surface regions, small or even tensile residual stresses were observed under the 120°C and 135°C drying-set treatments (R3, R4 and R5, R6), which may be related to the formation of the drying-set layer. These results indicate that high-temperature drying-set

treatment does not simply modify the original residual stress distribution of the control group but induces a stress remodeling process.

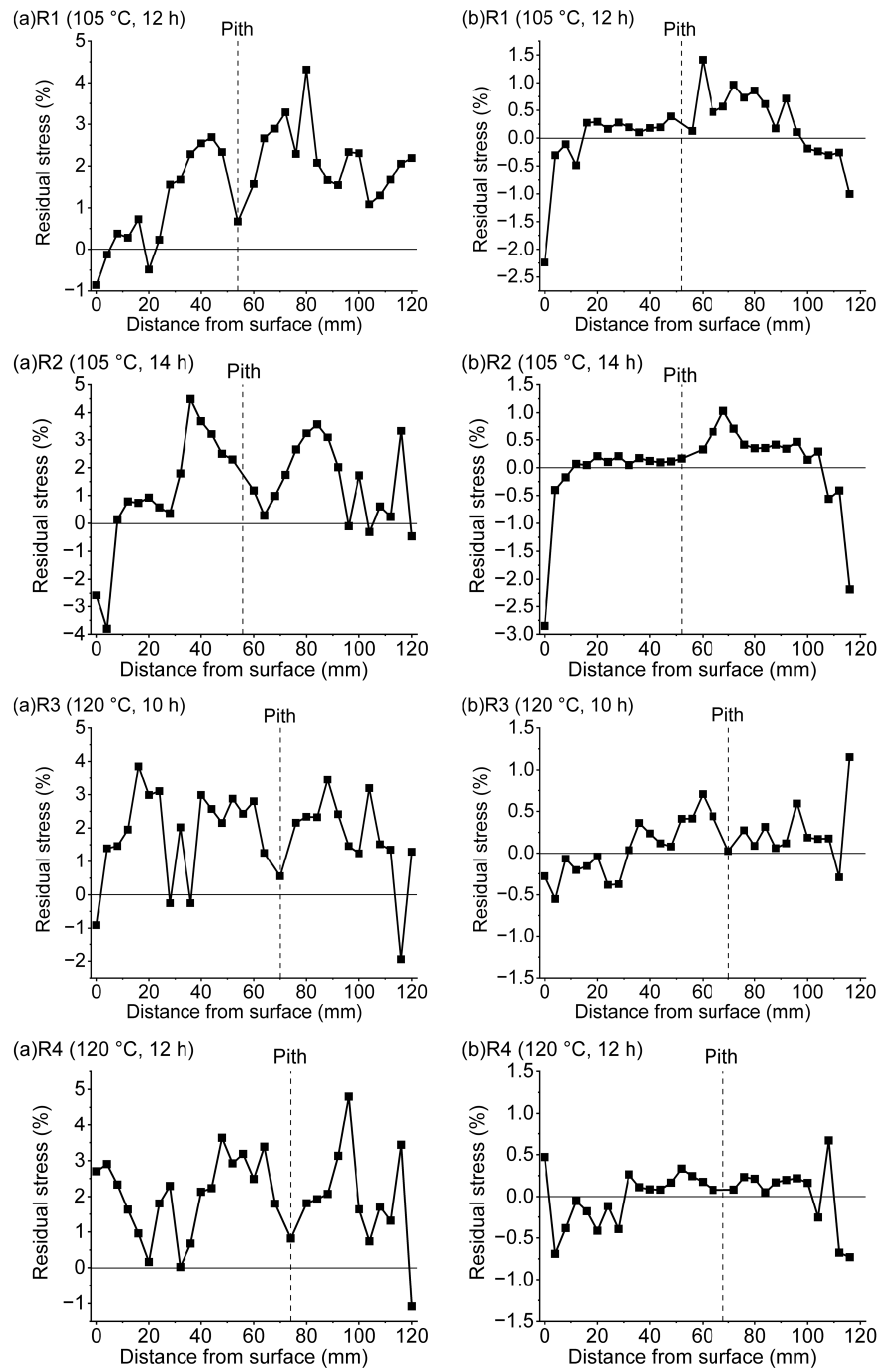


Figure 9: (Continued)

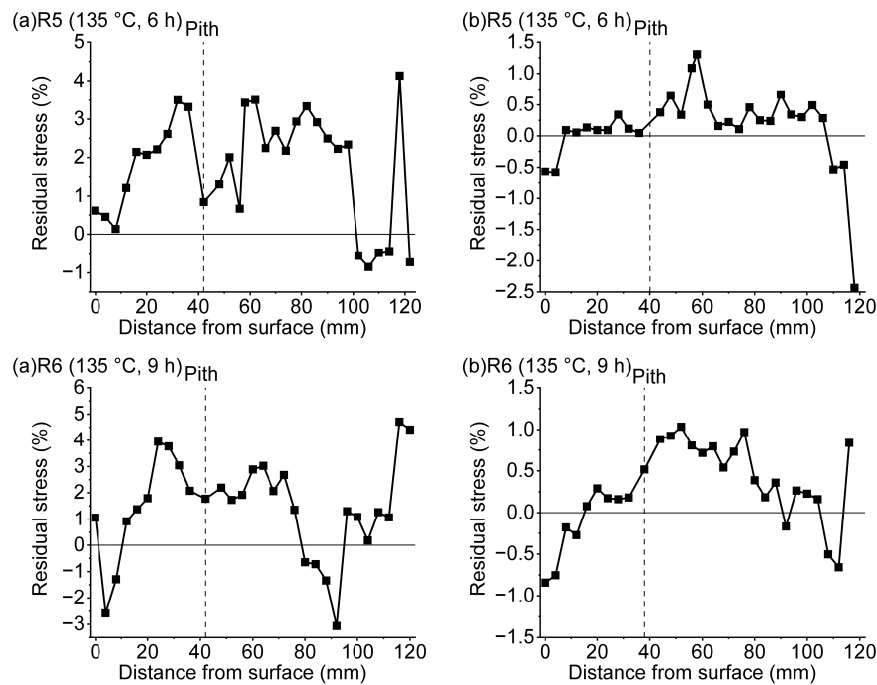


Figure 9: Residual stress distribution across the thickness of timber specimens after drying. (a) Control group; (b) Drying-set treated group.

The mean residual stress values and reduction rates for both groups under different drying schedules are summarized in Table 3. R4 exhibited the lowest residual stress and the most pronounced stress-relief effect. Residual stress was reduced by more than 72% under all high-temperature drying-set treatments, demonstrating the effectiveness of this treatment in relieving residual stress. At the same drying-set temperature, extending the treatment duration increased the residual stress reduction rate at 105°C (R1, R2) and 120°C (R3, R4), whereas an opposite trend was observed at 135°C (R5, R6). This behavior can be attributed to the combined effects of moisture content gradient and wood creep behavior. At 105°C, stress relaxation was mainly promoted by the reduction in moisture content gradient. At 120°C, both the rubbery state of wood and the reduced moisture content gradient contributed to effective stress relief. However, at 135°C, a larger moisture content gradient developed, while excessive drying intensity under 135°C increased the moisture content gradient and reduced the plastic deformation capacity of the surface layer, resulting in lower stress-relief efficiency.

Table 3: Mean residual stress values and reduction rates of the control and treated groups after drying completion.

Schedule	Control Group Mean/%	Treated Group Mean/%	Residual Stress Reduction/%
R1 (105°C, 12 h)	1.74	0.48	72.41
R2 (105°C, 14 h)	1.78	0.46	74.16
R3 (120°C, 10 h)	2.02	0.29	85.64
R4 (120°C, 12 h)	2.06	0.27	86.89
R5 (135°C, 6 h)	1.97	0.44	77.66
R6 (135°C, 9 h)	2.04	0.50	75.49

Note: Mean residual stress values were calculated from the average measurements of two adjacent slices from the same specimen, with each slice containing 32 measurement layers.

The surface checking characteristics under each drying schedule are summarized in Table 4. High-temperature drying-set treatment is primarily applied to inhibit surface checking, whereas its effect on end checking is limited. Therefore, end checking was not recorded. The surface checks exhibited an approximately rhombic shape, and the checking area was calculated using the rhombus area formula ($\text{length} \times \text{width}/2$). As shown in Table 4, R3 exhibited the smallest surface checking area, indicating that the selected drying-set conditions resulted in the smallest surface-checking area among the investigated schedules. These results demonstrate the differences in surface-checking characteristics among the investigated drying-set schedules and provide a basis for evaluating and optimizing drying-set conditions.

Table 4: Surface checking statistics of timber specimens after drying completion.

Schedule	Number of Checks	Length/mm	Width/mm	Total Area ¹ /mm ²
R1 (105°C, 12 h)	6.00 ± 0.33	48.43 ± 1.68	1.10 ± 0.04	159.82 ± 6.82
R2 (105°C, 14 h)	3.00 ± 0.33	90.01 ± 1.89	3.20 ± 0.06	432.05 ± 22.48
R3 (120°C, 10 h)	3.33 ± 0.19	53.01 ± 1.22	0.65 ± 0.04	51.69 ± 2.66
R4 (120°C, 12 h)	6.00 ± 0.33	34.44 ± 1.87	1.24 ± 0.12	128.32 ± 4.02
R5 (135°C, 6 h)	3.33 ± 0.51	92.86 ± 10.29	0.86 ± 0.01	119.79 ± 13.5
R6 (135°C, 9 h)	6.67 ± 0.19	40.31 ± 1.30	0.97 ± 0.07	136.85 ± 11.50

Note: Values are expressed as mean ± standard deviation ($n = 3$).¹The total area was calculated using the rhombus formula ($\text{length} \times \text{width}/2$).

At a drying-set temperature of 120°C, an effective drying-set layer was formed in the surface layer. During the softening–drying-set stage, the surface layer underwent restrained shrinkage due to the constraint imposed by the inner layer, generating tensile stress in the surface layer [30]. Under softened conditions, tensile creep developed in the surface layer and was subsequently fixed as a drying set [31]. During subsequent conventional drying, the drying-set layer restrained shrinkage of the surface layer. Consequently, shrinkage in the inner layer exceeded that in the surface layer, causing the surface stress to reverse to compressive stress [32]. This stress reversal effectively inhibited surface checking. However, after extending the drying-set treatment duration (R4), continued shrinkage occurred in the middle layer. The stress between the fixed drying-set layer and the continuously shrinking middle layer increased, resulting in aggravated surface checking.

Under the 105°C drying-set treatment (R1 and R2), severe surface checking occurred. This was mainly attributed to the surface temperature remaining below 100°C throughout the drying-set stage, which prevented the formation of an effective drying-set layer. Consequently, stress reversal did not occur, and the surface layer remained under tensile stress during subsequent drying, which was unfavorable for inhibiting surface checking.

Under the 135°C drying-set treatment (R5 and R6), prolonged exposure to high temperature caused the surface layer to lose plasticity, increasing its susceptibility to micro-crack formation. During subsequent conventional drying, shrinkage of the inner high-moisture-content region generated tensile stress in the surface layer, resulting in fine and fragmented surface checking.

The surface checking morphology under each drying schedule is shown in Fig. 10. Under the 105°C treatment (R1 and R2), surface checks were relatively large and mainly originated from end checking and propagated along the fiber direction. In contrast, R3 exhibited smaller and more randomly distributed surface checks. Under the 135°C treatment (R5 and R6), surface checks were fine and fragmented.

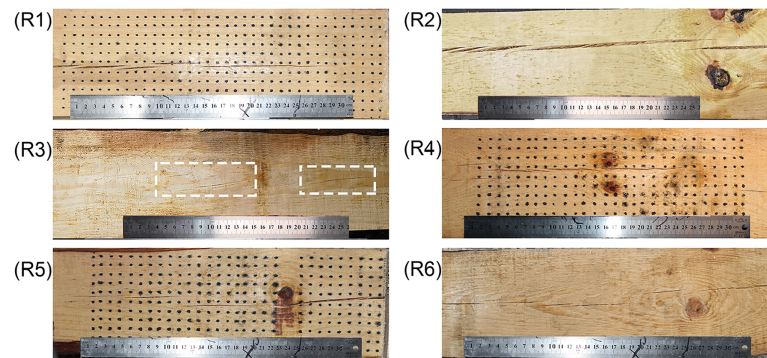


Figure 10: Surface checking morphology of timber specimens under different drying schedules. R1–R6 represent drying-set treatments at 105°C for 12 and 14 h, 120°C for 10 and 12 h, and 135°C for 6 and 9 h, respectively.

The internal checking characteristics under each drying schedule are summarized in Table 5. Internal checking characteristics varied among the investigated schedules, but no clear trend associated with drying-set temperature or treatment duration was observed. These results indicate that internal checking behavior differed among the investigated drying-set schedules, which may be related to the inherent heterogeneity of boxed-heart timber and differences in wood structure among specimens.

Table 5: Internal checking statistics of timber specimens after drying completion.

Schedule	Number of Checks	Length/mm	Width/mm
R1 (105°C, 12 h)	6.00 ± 0.33	5.34 ± 0.27	1.12 ± 0.04
R2 (105°C, 14 h)	3.33 ± 0.19	6.58 ± 0.18	1.10 ± 0.06
R3 (120°C, 10 h)	4.33 ± 0.51	7.41 ± 0.14	1.15 ± 0.10
R4 (120°C, 12 h)	8.67 ± 0.51	3.82 ± 0.23	1.08 ± 0.05
R5 (135°C, 6 h)	8.33 ± 0.19	3.02 ± 0.15	1.12 ± 0.08
R6 (135°C, 9 h)	4.00 ± 0.33	3.37 ± 0.22	1.02 ± 0.18

Note: Values are expressed as mean ± standard deviation (n = 3).

In summary, R3 was identified as the optimal drying schedule. The process consisted of softening with saturated steam at 95°C for 12 h, followed by a drying-set stage at dry-bulb/wet-bulb temperatures of 120°C/90°C for 10 h. This schedule achieved the best overall performance, including the shortest drying cycle (5.9 d), representing a reduction of 9.23%–52.80% compared with the other schedules, the lowest residual stress (0.29%), and the smallest surface checking area (51.69 mm²), which was 56.85%–88.04% lower than those of the other schedules.

4 Conclusions

- (1) The drying-set temperature was a critical factor governing the formation of an effective surface drying-set layer. Under the investigated conditions, a surface temperature exceeding 100°C during the drying-set stage promoted sufficient surface shrinkage and facilitated the formation of a stable drying-set layer. The 105°C treatment was insufficient for effective layer formation, whereas the 135°C treatment accelerated surface heating, increased the temperature gradient between the surface and inner layers, and elevated the risk of surface checking. These results indicate that appropriate drying-set intensity is essential for effective layer formation and defect control.

- (2) The softening stage played an important role in regulating moisture migration during high-temperature drying-set treatment. Saturated steam softening promoted internal moisture redistribution and reduced the moisture-content gradient between the middle and core layers by 3.81%–18.22%, thereby facilitating subsequent drying. The drying rate was highest during the softening–drying-set stage (43.38%–103.09%/d), indicating that moisture redistribution during softening and high-temperature treatment contributed to rapid moisture removal. Among the investigated conditions, the 120°C drying-set treatment achieved a favorable balance between surface moisture evaporation and internal moisture migration, resulting in improved drying efficiency.
- (3) High-temperature drying-set treatment effectively modified the residual stress distribution of large-section boxed-heart square timber after drying. Compared with the control group, the treated groups exhibited a 72.41%–86.89% reduction in residual stress. These results indicate that high-temperature drying-set treatment under appropriate conditions can effectively alleviate residual stress.
- (4) Among the investigated schedules, the treatment combining saturated steam softening at 95°C for 12 h with drying-set treatment at dry-bulb/wet-bulb temperatures of 120°C/90°C for 10 h demonstrated the best overall performance. This selected schedule achieved a drying cycle of 5.9 d, a residual stress value of 0.29%, and the smallest surface-checking area of 51.69 mm² among the investigated schedules. These results indicate that appropriate drying-set conditions can balance drying efficiency, stress regulation, and surface-checking characteristics among the investigated schedules, providing a reference for optimizing drying strategies for large-section boxed-heart timber. However, further industrial-scale validation considering energy consumption, drying cost, productivity, and kiln operation is required to assess its practical applicability.

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Ethics Approval: This study did not involve human participants, animals, or clinical data; therefore, ethics approval was not applicable.

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