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ORIGINAL ARTICLE

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Effect of pretreatment with high temperature and low humidity on drying time and prevention of checking during radio-frequency/vacuum drying of Japanese cedar pillar

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Abstract This study investigated the effect of pretreatment with high temperature and low humidity (HT-LH) on characteristics of radio-frequency/vacuum (RF/V) drying of boxed heart timber of Japanese cedar (150 × 150 mm in cross section, 3600 mm long). From green to approximately 15% moisture content, the drying times including HT-LH treatment were 170 h for the nonkerfed control, 190 h for the kerfed control, and 150 h for both the kerfed and nonkerfed HT-LH specimens. Surface checks were effectively prevented by the HT-LH treatment while the kerfed HT-LH specimens were free from surface checks. In order to prevent the formation of internal checking during RF/V drying, it is suggested that HT-LH treatment should finish around the fiber saturation point.

Key words High-temperature with low humidity · Compressive loading · Radio-frequency/vacuum drying · Surface and internal check

Introduction

Recent investigation has shown that both builders and residents of wooden houses in Korea prefer exposed structural timbers. Due to revised construction laws in Korea, the maximum heights of roofs and eaves can reach 18 m and 15 m, respectively. Therefore, the need for structural timbers with large cross sections is expected to gradually increase.

However, during drying, pillars with large cross sections can incur severe surface checking because most of the pillar contains juvenile wood and pith and moisture must migrate over a long distance from the core to the surface. In addition, long drying periods are required. Of note, the moisture content (MC) of the core is not easily lowered to below 19%, which is the level necessary to protect against decay. These problems not only spoil the appearance of the timber, but also cause decreased durability and insulation, cracking of beams, and force up the cost of wooden houses.

It was found that drying time could be shortened because a driving force to accelerate the flow rate of moisture in wood was induced by radio-frequency/vacuum (RF/V) drying due to a difference in the absolute pressure between the shell and core of wood, which forms with dielectric heating.[1–4] Several problems that accompany the drying process were partly resolved when RF/V drying was applied to pillars with large cross sections. Nevertheless, it is reported that RF/V drying has limited success in preventing surface checks for long pillars with large cross sections and thickness.

Meanwhile, internal checking has been noted when high-temperature drying was used after pretreatment at high temperature and low humidity (HT-LH), although the pretreatment was effective in preventing surface checks. Moreover, an excessively long drying period was required when air drying was carried out after the HT-LT pretreatment.[5,6] Hence, the desired effects of effective prevention of surface and internal checks, a shortened drying period, and even distribution of MC in each pillar are still sought after.

The present study was conducted to investigate the effect of HT-LH pretreatment on RF/V drying of domestic Japanese cedar (*Cryptomeria japonica*) pillar with a cross section of 150 × 150 mm and a length of 3600 mm.

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Materials and methods

Preparation of specimens

Twelve green Japanese cedar (*Cryptomeria japonica*) logs were obtained from a log seller in the southern part of Korea. One boxed heart timber with a cross section of 150 × 150 mm and fixed length of 3600 mm was sawn from each log. Six of the timbers were used for kerfing treatment and the others were used for the control treatment. The longitudinal kerfs with widths of 3 mm and depths of 50 mm from one surface of the timber were sawn with a circular saw. Three specimens were randomly selected from both kerfed and nonkerfed specimens, respectively, for HT-LH treatment, and the remainder of specimens were controls. The number of specimens and the initial moisture contents for each treatment are shown in Table 1.

HT-LH treatment

Three specimens selected from both kerfed and nonkerfed specimens, respectively, were subjected to HT-LH treatment in a high-temperature dryer (SKD-50HP; Shinshiba; volume capacity 14 m^3) under the drying conditions shown in Table 2. All treated specimens were stacked in the upper part of the chamber. The remainder of the space inside the chamber was filled with dummy boxed heart timbers. A top plate was covered on the top of the stack to prevent twisting of pillars.

RF/V drying experiment

RF/V dryer and stacking

The internal dimensions of the rectangular chamber of the RF/V dryer used in this experiment were 600 cm long, 120 cm wide, and 67 cm deep. The maximum output of its RF generator, which was used at a fixed frequency of about 13 MHz, was 25 kW. The specimens were stacked in the chamber, covered with a flexible rubber sheet, and compressively loaded by a pressure of 10 000 kgf/m^2 (~98 kPa) during drying. A positive electrode plate connected to the RF generator was placed in the centric position in the chamber while the negative plates grounded to the chamber itself were placed on the top and bottom of the stack. The specimens were stacked in two layers on and underneath the positive plate; moreover, kerfed and nonkerfed specimens, and HT-LH and control specimens were arranged side by side. For the kerfed specimens, the direction of kerf depth was parallel to the direction of the compressive pressure in order to restrain widening of kerf during drying, and to reduce the ratio of tangential to radial shrinkage of the specimen.

RF/V drying conditions

The drying conditions used in this experiment are shown in Table 3. The ambient vapor pressure was kept at an absolute value of 50–70 mmHg. The wood temperature was controlled by a Teflon-sheathed platinum 100 Ω sensor with a diameter of 3 mm, which was inserted into a nonkerfed control specimen stacked in the upper part of the chamber. The RF generator was set on for 8 min and off for 2 min.

Table 1. Number of specimens and initial moisture content for each treatment

Wood type	Treatment	Quantity	Initial MC (%)
Nonkerfed	Control	3	107.7
	HT-LH	3	93.4
Kerfed	Control	3	89.5
	HT-LH	3	64.3

MC, Moisture content; HT-LH, high temperature with low humidity

Table 2. Treatment conditions and times for each stage of HT-LH treatment

Stage	Dry bulb temperature (°C)	Wet bulb depression (°C)	Equilibrium moisture content (%)	Treatment time (h)
Steaming	95	0	–	12
HT-LH	120	27	3.3	64
Cooling	Off	Off	–	25
Total time				101

Table 3. Wood temperature schedule for the radio-frequency/vacuum (RF/V) drying test

Drying time (h)	Wood temperature (°C)
0–24	40
24–48	42
48–72	44
72–96	46
96–120	48
120–final	52

Drying characteristics, surface checking, twisting

The moisture content and the drying rate during drying for kerfed and nonkerfed, and HT-LH and control specimens (one sample for each treatment) were obtained from the weight measured at 24-h intervals after the dryer was stopped. The total length, maximum width, number of surface checks on the four surfaces, the area of the checks, and maximum twist were surveyed after drying.

Kerf widening rate

The kerf widening rate was calculated using Eq. 1, based on the kerf width of the specimen before and after drying.

$$\text{Kerf width (\%)} = (W_a - W_b)/W_b \times 100\% \quad (1)$$

where W_a is kerf width after drying and W_b is kerf width before drying.

Distribution of final moisture content, case hardening, internal checking

A distribution of the MC and the case hardening of the sampled specimens stacked in the upper part were surveyed after drying at the positions shown in Fig. 1. Specimens with sides of 23 mm (Fig. 1, point A_i) were sawn from the sampled specimens and analyzed for final MC. The case hardening was surveyed in the directions both parallel to (Fig. 1, point B_i) and perpendicular to (Fig. 1, point C_i) the pressure in the chamber.

Results and discussions

Drying time and drying rate

The decrease of MC and drying rate for each specimen during HT-LH treatment and RF/V drying are shown in Figs. 2 and 3. The drying times required for the main drying stages are presented in Table 4.

The MCs of nonkerfed HT-LH and kerfed HT-LH specimens were lowered to about 25% 19%, respectively, after 101 h of HT-LH treatment. This difference can be attributed to the difference in initial MC rather than the effect of kerfing, considering the average drying rate during the same period.

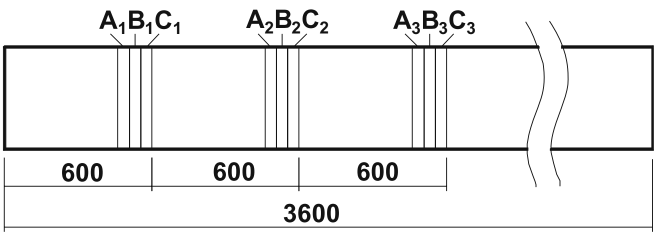

Fig. 1. Sawing diagram of the specimens to survey a the distribution of moisture content (MC) and the case hardening. (unite: mm).Dimensions are given in millimeters. Ai, Specimen for measuring moisture content; Bi, specimen for prong test (parallel to mechanical compressive load); Ci, specimen for prong test (perpendicular to mechanical compressive load)

Surface checking and internal checking

Surface checking

The extent of surface checking for all specimens surveyed after RF/V drying are presented in Fig. 4. The extent of surface checking for kerfed HT-LH specimens was low and

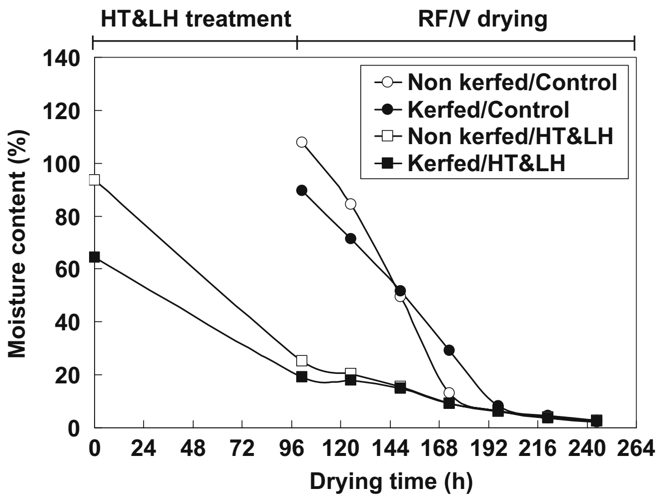

Fig. 2. Behavior of MC as a function of drying time during radio-frequency/vacuum (RF/V) drying and the effect of pretreatment at high temperature and low humidity (HT-LH)

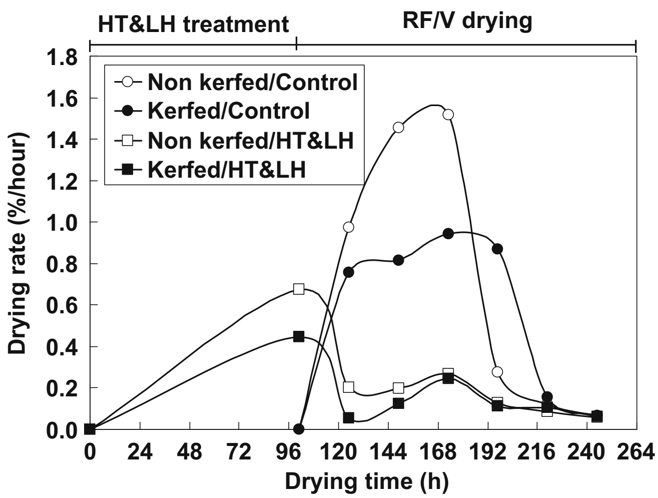

Fig. 3. Behavior of drying rate as a function of drying time during RF/V drying and the effect of HT-LH pretreatment

Table 4. Times required for HT-LH treatment and the RF/V drying test

Wood type	Treatment	Initial MC (%)	HT-LH treatment		RF/V drying time (h)[a]	Total time (h)
			Time (h)	MC (%)		
Nonkerfed	Control	107.7	–	–	170	170
	HT-LH	93.4	101	25.2	49	150
Kerfed	Control	89.5	–	–	190	190
	HT-LH	64.3	101	19.2	49	150

[a]Times required to obtain 15% MC were obtained by interpolation

very slight for nonkerfed HT-LH specimens, with an average length of 20.8 cm/piece and average area of 4.2 cm^2/piece. It was reported that during HT-LH treatment, the tensile stress on the surface of the pillar became large, inducing compressive stress on the surface at the end of drying, and closing the opened surface checks.[5]

On the other hand, the average area of surface checks was 57.8 cm^2/piece for nonkerfed control specimens and 28.9 cm^2/piece for kerfed control specimens, which are relatively slight despite being much more extensive than for the HT-LH specimens. This difference may be because the tensile stress, which occurs on the specimen surface during the initial stage of drying, could be relieved by the accelerated flow of moisture from the core toward the shell due to dielectric heating during RF/V drying.[3] The extent of surface checking for the kerfed specimens, regardless of whether HT-LH treatment was used, was remarkably less for kerfed specimens than that for nonkerfed specimens.[7]

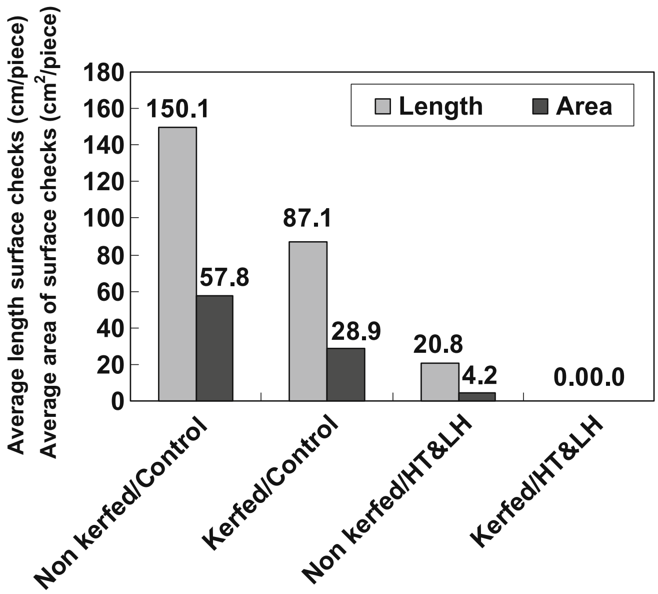

Fig. 4. Extent of surface checking for wood specimens following RF/V drying

Internal checking

Total numbers and lengths of internal checks of specimens used to survey the MC during drying, surveyed after RF/V drying, are presented in Table 5. Internal checking of dried specimens was absent in all specimens except for kerfed HT-LH specimens. Although internal checks easily occur because tensile stress in the core is largely formatted at the final stage of drying due to a large set originating in the shell of specimen,[8] it is likely that internal checks were effectively prevented in this study. This is because the ratio of tangential shrinkage to radial shrinkage of the specimen could be reduced by applying compressive mechanical pressure to the tangential surface of specimens[9] and RF/V drying was applied after the middle stage of drying.[1,10] The serious internal checking inside some specimens in this experiment can be explained by the large tensile stress being already formatted in the core during HT-LH treatment because the MC of the specimen was below 20% after HT-LH treatment. Therefore, it is desirable to stop HT-LH treatment around the fiber saturation point in order to effectively prevent the internal checks caused by RF/V drying.

Twist and kerf widening rate

Sample twist and kerf widening rate of all specimens measured after drying are shown in Table 6. The data for twist of kerfed specimens showed no significant difference between control specimens and those subjected to HT-LH treatment. For nonkerfed specimens, twist was significantly less for HT-LH specimens than control specimens. The difference in longitudinal shrinkage, which depends on the location of pith and the presence of compression wood, affects twist more than the drying schedule;[11] thus, explanation of twist data should be made with care. The kerf widening rates of controls (209%) and HT-LH specimens (196%) are not significantly different.

Distribution of final moisture content

The distribution of moisture content in the transverse and longitudinal directions inside individual specimens after RF/V drying is shown in Fig. 5. Regardless of kerfing and HT-LH treatment, the moisture gradient tended to be

Table 5. Extent of internal checking for each wood type treated with RF/V drying

Wood type	Treatment	Initial MC[a] (%)	Distance from end surface (cm)					
			60		120		180	
			TN (/piece)	TL (cm)	TN (/piece)	TL (cm)	TN (/piece)	TL (cm)
Nonkerfed	Control	107.7	0	0	0	0	0	0
	HT-LH	25.2	0	0	0	0	0	0
Kerfed	Control	89.5	0	0	0	0	0	0
	HT-LH	19.2	5	10.1	7	19.8	4	7.3

TN, Total number of the internal checks; TL, total length of internal checks
[a] MC after HT-LH treatment or before RF/V drying

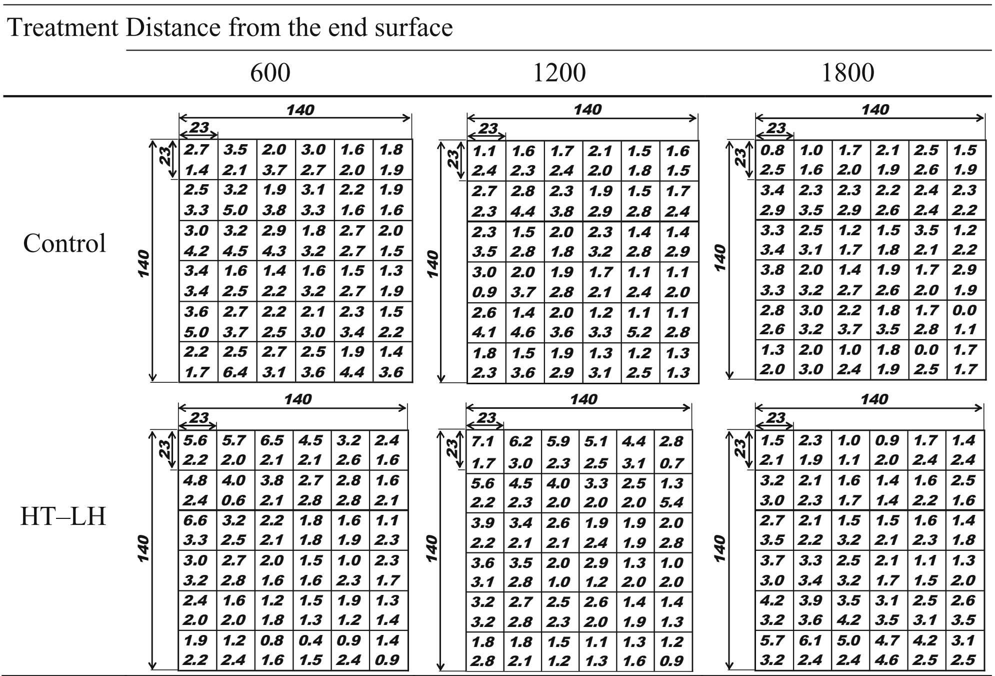

Fig. 5. Distribution of MC inside individual positions of specimens after RF/V drying. *Italic*, data for kerfed specimens; Roman, data for nonkerfed specimens. Dimensions given in millimeters

Table 6. Kerf widening rate and twist for each wood type after RF/V drying

Wood type	Treatment	Twist (mm/3.6 m)			Kerf widening rate (%)
		Minimum	Average	Maximum	
Nonkerfed	Control	9	36	59	–
	HT-LH	6	12	17	–
Kerfed	Control	8	19	36	209
	HT-LH	16	21	27	196

Table 7. Case hardening for wood after RF/V drying

Wood type	Treatment	Distance from end surface of specimen (cm)					
		60		120		180	
		Parallel[a]	Perpendicular[a]	Parallel[a]	Perpendicular[a]	Parallel[a]	Perpendicular[a]
Nonkerfed	Control	1.03	0.96	1.01	1.02	1.03	1.00
	HT-LH	1.02	1.13	1.03	1.13	1.01	1.09
Kerfed	Control	1.03	1.11	1.00	1.00	0.99	1.01
	HT-LH	0.98	1.05	0.99	1.05	0.98	1.06

[a] Orientation to applied pressure

gradual. However, the final MC distribution in Fig. 5 was obtained when the final MC was less than 7% at maximum. Therefore, it is estimated that the distribution of final MC would be more even if the maximum final MC was less than 15%. It is likely that the dispersion of moisture content is large at 15%, because it will decrease with drying time.

Case hardening

Data for case hardening after RF/V drying, measured from the specimens used to survey the MC during drying, are presented in Table 7. Irrespective of kerfing, HT-LH treatment, the direction against the pressure, and the distance from the end surface of the specimen, case hardening was very slight. This means that the residual stress was very small due to even distribution of final MC. However, if the final MC was set to 15%, there would be more or less difference in MC between treatments or the distance from the end surface of the specimen. It is essential that the final MC has to set up to 15% for the further observations.

Conclusions

This study investigated the effects of a pretreatment using high temperature and low humidity on the characteristics of RF/V drying of boxed heart timber of Japanese cedar (*Cryptomeria japonica*, 150 × 150 mm cross section, 3600 mm long). After 101 h of HT-LH pretreatment, the MCs of nonkerfed specimens were reduced to about 25% while those of kerfed specimens were reduced to about 19%. From green to approximately 15% MC, the drying times including HT-LH treatment were 170 h for the nonkerfed control specimens, 190 h for the kerfed control specimens, and 150 h for the both the nonkerfed and kerfed HT-LH specimens.

Surface checking of the kerfed HT-LH specimens was absent while that for nonkerfed HT-LH specimens was slight compared with control specimens. All kerfed specimens, irrespective of HT-LH treatment, showed no surface checking. Internal checking occurred only in kerfed HT-LH specimens. To prevent the formation of internal checks during the RF/V drying process, it is suggested that the HT-LH treatment should be finished around the fiber saturation point.

The difference in twist between kerfed control specimens and kerfed HT-LH specimens was only slight and twist was smaller for nonkerfed HT-LH specimens than that controls. Regardless of kerfing or HT-LH treatment, the moisture gradient tended to be gradual. Case hardening was about 1% for all specimens, irrespective of kerfing, HT-LH treatment, direction against the pressure, and the distance from the end of the specimen.

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References

1. Harris RA, Taras MA (1984) Comparison of moisture content distribution, stress distribution and shrinkage of red oak lumber dried by a radio-frequency/vacuum drying process and a conventional kiln. Forest Prod J 34:44–54
2. Kanagawa Y (1989) Resin distribution in lumber dried by vacuum drying combined with radio-frequency. Proceedings of the IUFRO International Wood Drying Symposium, Seattle, Washington, USA, pp 158–163
3. Avramidis S, Liu F, Neilson BJ (1994) Radio-frequency/vacuum drying of softwood: drying of thick western red cedar with constant electrode voltage. Forest Prod J 44:41–47
4. Lee NH, Luo JY (2002) Effect of steam explosion treatments on drying rates and moisture distributions during radio-frequency/vacuum drying of larch pillar combined with a longitudinal kerf. J Wood Sci 48:270–276
5. Tokumoto M, Takeda T,Yoshida T (2005) Effect of subsequent kiln-schedule after the high-temperature setting treatment on internal stresses of sugi boxed-heart timber without back-splittings (in Japanese). J Soc Mater Sci Jpn 54:365–370
6. Katagiri Y, Fujimoto N, Murase Y (2007) Effect of the treatment temperature on the surface drying set of sugi boxed-heart square timber. Drying Technol 25:507–510
7. Evans PD, Wingate-Hill R, Barry SC (2000) The effects of different kerfing and center-boring treatments on the checking of ACQ treated pine posts exposed to the weather. Forest Prod J 50: 59–64
8. Fujimoto N, Fujimoito H, Kawabe J, Mataki Y (1994) Drying of boxed heart square timbers I. Changes of surface stress and cross-sectional shrinkage of dehumidifier kiln-dried timbers of sugi (in Japanese). Mokuzai Gakkaishi 40:758–765
9. Li C, Lee NH (2004) Effect of compressive load on shrinkage of larch blocks under radio-frequency/vacuum heating. Wood Fiber Sci 36:9–16
10. Lee NH, Hayashi K, Jung HS (1998) Effect of radio-frequency/vacuum drying and mechanical press-drying on shrinkage and checking of walnut log cross sections. Forest Prod J 48:73–79
11. Yoshida T, Hashizume T, Fujimoto N (2000) High-temperature drying characteristics on boxed-heart square timber of karamatsu and sugi – influences of high temperature conditions with low humidity on drying properties (in Japanese). Mokuzai Kogyo 55:357–362