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ORIGINAL ARTICLE

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Effect of external compressive load on tangential strain behavior in Japanese larch log cross sections during radio-frequency/vacuum drying

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Abstract This study investigated the effect of a compressive load of 0.092 MPa on the history of the tangential strains in Japanese larch (*Larix leptolepis* Gordon) log cross sections subjected to external compressive load during radio-frequency/vacuum drying. The external compressive load of 0.092 MPa played a role in inducing cracking in the outer zone of the log cross section, combining with other tensile strains. However, it also played a role in reducing the heart checks in the core of log cross section when exerted on the cross section of log cross section.

Key words Compressive loading · Radio-frequency/vacuum drying · Heart check and cracking in log cross section

Introduction

As a form of woody material for the manufacture of artifacts and high-value items, log cross sections possess some distinctive merits in sawing and natural beauty. However, the drying of log cross sections is much more difficult than lumber or timber drying, because checks and cracks are likely to develop. Research has shown that the occurrence of checks and cracks is mainly related to nonuniform shrinkage stresses.[1–4]

The drying process of log cross sections subjected to external compressive loading during radio-frequency/vacuum (RF/V) drying can be considered as a shrinking process under both external compressive load and restraint from internal stresses in vacuum. Therefore, a comprehensive understanding of shrinkage behavior is essential to prevent the formation of checks and cracks.

When small wood was subjected to an external constant compressive load during RF/V drying, as in the previous study,[5] the shrinkage of the small wood was significantly increased in the loading direction because of a mechanosorptive effect, whereas the shrinkage was restrained in the direction perpendicular to the loading direction based on Poisson's ratio.

The shrinkage of large wood (lumber or timber) during conventional drying is significantly different from that of small wood under constant load in that there are more kinks of stresses inside large wood. Thus, large wood is fully or partly constrained by these stresses during the entire drying process.

The restrained tangential shrinkage and the free tangential shrinkage in log cross sections under conventional drying are considerably different. Moreover, the restrained tangential shrinkage is different at different positions on the same growth ring (Kato et al. 1978).[3] Therefore, it can be inferred that the shrinkage in a log cross section is subjected to complicated stresses, and the stresses may be different in different positions inside the cross section. Because of these factors, the comprehensive effect of these stresses on shrinkage behavior at the different stages of drying and at different radial positions in Japanese larch (*Larix leptolepis* Gordon) log cross sections is not well understood. Thus, the tangential strain behavior, and its history in the process of shrinking subjected to various kinds of stresses and their interactions are also not clear.

Although some research on tangential strain related to checks and cracks of log cross sections during both conventional drying[1–3,6–8] and RF/V drying[4,9] have been conducted, few reports can be found on this subject related to compressive load during RF/V drying. This study was carried out to investigate the history and distribution of tangential strains in Japanese larch log cross sections subjected to compressive load during RF/V drying to provide a theoretical basis for the prevention of checks and cracks.

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Materials and methods

Preparation of materials

Eight green Japanese larch (*Larix leptolepis* Gordon) logs with a length of 360 cm and average diameter of 23 cm were obtained from a saw mill. About 30-cm-long log cross sections were cut from both ends of each log, and then two 1-cm-thick log cross sections for measuring initial moisture contents (MC) were prepared from the remainder of each log. Two 3.5-cm-thick log cross sections, one of which was for compressive load testing (L) and the other for load-free testing (C), were sawn off the remaining portion of the log. The total number of specimens amounted to 80 pieces. The log cross sections for control treatment were debarked. The heartwood area of the log cross sections used in our test averaged 84.4%. The diameters of the specimens were 22 cm and the average green MC of the specimens was 42.0%.

External compressive loading and load-free treatment

The space inside a vacuum chamber was divided into a compressive loading part and a load-free part (Fig. 1). The log cross sections stacked in the compressive loading part were loaded on their cross sections with a pressure of 0.091–0.093 MPa when a vacuum pump was turned on or off. The air pressure in the vacuum chamber during RF/V drying was 0.0083–0.0103 MPa. The pressure resulting from the difference in absolute pressure between the inside and the outside of the vacuum chamber was applied to an insulation plate located underneath a 3-mm-thick flexible rubber sheet covering the vacuum chamber while the chamber was evacuated. The pressure was transmitted to supporting boards, a top grounded plate, and finally to the log cross sections stacked in the compressive loading part (Fig. 1). The top load resulting from the insulation plate, the supporting boards, and the grounded plate was neglected in the loading part.

The log cross sections in the load-free part were kept free from compressive load by the presence of a 14-mm void between the insulation plate and the top grounded plate, even when a vacuum pump was on (Fig. 1). The top load resulting from the insulation plate and the supporting boards was transmitted to the bottom of the chamber in the load-free part.

The log cross sections were solid stacked in eight layers between an electric charge plate and the ground plates in both the compressive loading part and the load-free part. A log cross section with the temperature sensor was positioned in the lower part.

RF/V drying

The inside dimensions of the chamber connected to the RF heater were 102 cm wide, 274 cm long, and 40 cm high. The log cross sections were heated in 10-min cycles by a 7 kW RF generator at a fixed frequency of about 13 MHz, with the generator being turned on for 8 min and then off for 2 min. The central electrode plate connected to the RF generator was positive, while the top and bottom plates grounded to the chamber itself were negative. The drying temperature of the wood was set from 42° to 53°C, and automatically monitored and controlled by a Teflon-sheathed platinum sensor inserted into the log cross section.

Measuring tangential strains in log cross sections

To investigate the history of the tangential strains during RF/V drying, a set of two log cross sections (one piece for each treatment) at a time were taken out of the drier at different stages of drying. Based on literature methods,[9–11] a gauge installation position was marked on the outer peripheral surface of each specimen. The position was lightly polished with an abrasive paper (no. 80) and cleaned with compressed air to ensure that the strain gauge was well bonded to the wood. A strain gauge (LFLA-10-11, Tokyo Sokki Kenkyujo, Japan) was peripherally bonded with

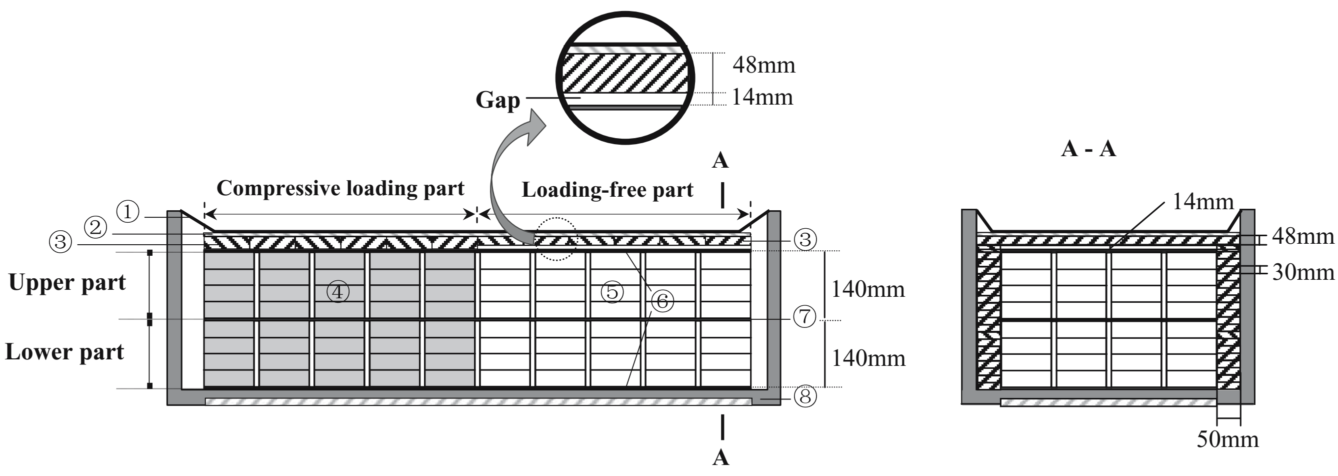

Fig. 1. The external compressive loading part and load-free part in a radio-frequency/vacuum (RF/V) drier. *1*, Rubber sheet; *2*, insulation plate; *3*, 48-mm-thick supporting boards; *4*, loaded specimens; *5*, nonload specimens; *6*, ground plate; *7*, charge plate; *8*, vacuum cell wall

strain gauge adhesive (CN-E, Tokyo Sokki Kenkyujo) on the prepared position. To seal moisture, a waterproof tape (3M Scotch VM) was glued on the strain gauge.

Three holes with diameters of 1, 3, and 5 cm were concentrically drilled from the center toward the periphery of each specimen, and then the circumferential strips with the inside diameters of 7, 9, 11, 13, 15, 17, 19, and 21 cm were sawn off the remainder of the specimen in the order of the magnitude of the diameter from small to large with a jigsaw (V-3, Tokyo Sokki Kenkyujo).

The scraps from drilling holes and the circumferential strips were oven-dried, and the MCs of the circumferential strips and scraps from each specimen were calculated. Each value of the tangential strain on the outer periphery of the specimen, which was released enough and reached maximum value after a circumferential strip or a hole was cut or drilled, was input into a strain meter (TC-31k, Han Wha Working Machinery, Korea) connected to the strain gauge, and the maximum value was recorded. The recorded value is an accumulated value of the tangential strain of the outer periphery of the specimen, reflecting a change of the tangential strain of each circumferential strip or scrap within a specimen. Therefore, the tangential strain of each circumferential strip or scrap within a specimen was calculated according to the following formula:[12]

$$\varepsilon_t = (f_b - f) \times \frac{d\theta}{df} - \frac{f_b + f}{2f} \times \theta \qquad (1)$$

where ε_t is the tangential strain of a circumferential strip or scrap within a log cross section ($\mu\varepsilon$) unite of strain, f_b is the area of the cross section of a log cross section (cm^2), f is the area of the circumferential strip or scrap cut off (cm^2), and θ is the tangential strain on the outer periphery of a log cross section when a circumferential strip or scrap is being cut ($\mu\varepsilon$), that is, the measured tangential strain.

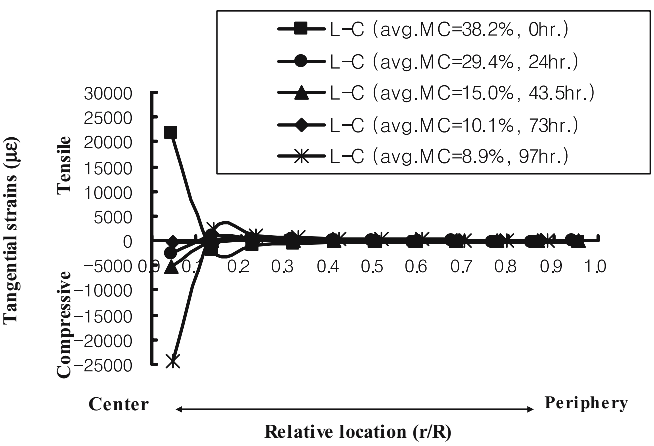

Fig. 2. A history of the tangential strains from the center to the bark of a loaded control (*L-C*) specimen at different stages of drying. *r*/*R* is the relative measure of distance from the pith where *r* is the radius from the cross section center and *R* is the radius of the cross section sample

Results and discussion

The tangential strain histories with decreasing MC at different radial positions in the loaded and load-free control treatment specimens are shown in Figs. 2, 3, 4, and 5.

The patterns of the distribution of the original tangential strains in both L-C and NL-C specimens in the green state

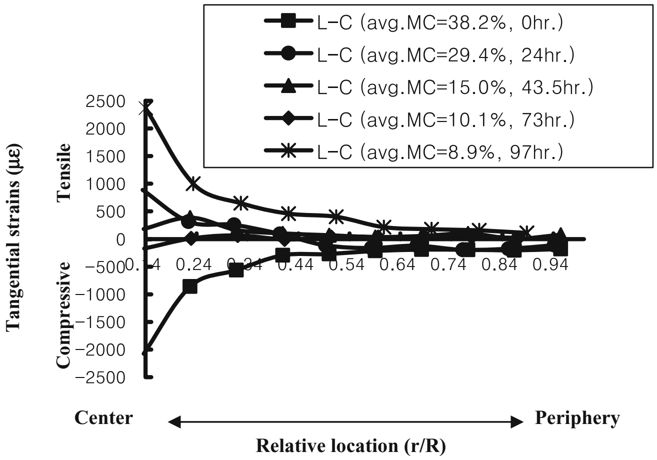

Fig. 3. A history of the tangential strains from *r*/*R* = 0.14 to 0.94 of an L-C specimen at different stages of drying

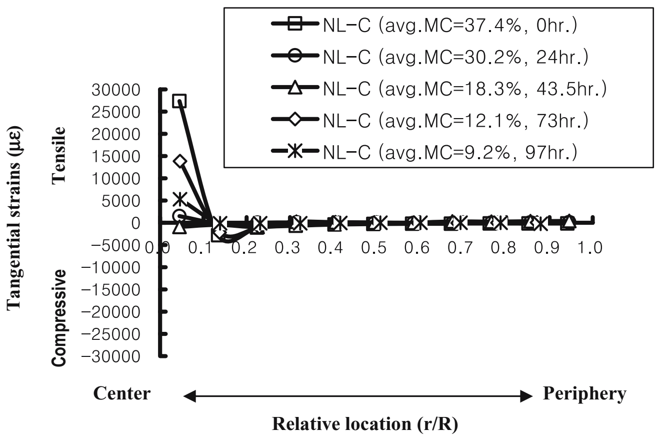

Fig. 4. A history of the tangential strains from the center to the bark of a load-free control (*NL-C*) specimen at different stages of drying

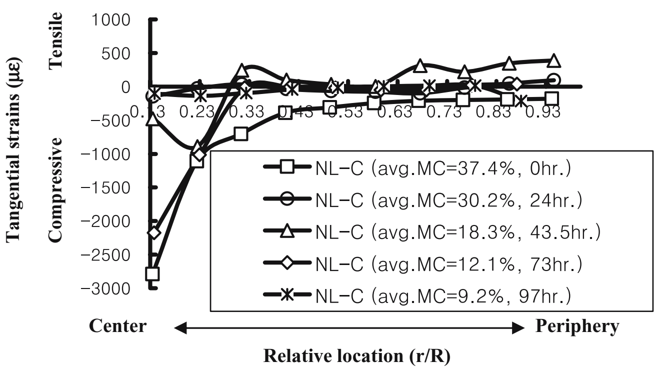

Fig. 5. A history of the tangential strains from *r*/*R* = 0.13 to 0.93 r for an NL-C specimen at different stages of drying

Table 1. Moisture contents of two treatment specimens during drying in relation to distance from cross section center

Treatment	r/R										Drying time (h)
	0.04	0.13	0.22	0.31	0.40	0.49	0.58	0.67	0.76	0.85	
L-C	35.4	26.2	15.6	33.6	31.8	34.3	34.9	34.6	34.4	44.0	0
NL-C	37.4	28.1	14.7	31.9	31.4	33.0	33.0	33.1	33.4	42.0	
L-C	23.7	24.2	18.3	32.4	31.9	31.7	32.5	31.5	31.4	31.0	24
NL-C	23.0	18.3	15.2	31.5	34.7	35.0	35.1	33.8	32.5	33.1	
L-C	12.3	13.3	8.2	16.6	16.7	16.5	16.5	16.3	16.0	16.2	43.5
NL-C	19.2	12.7	8.7	20.1	20.3	20.7	20.4	20.0	19.8	19.9	
L-C	10.9	8.8	5.5	10.7	11.1	10.8	10.7	10.7	10.7	11.2	73
NL-C	12.4	10.4	3.9	13.6	13.8	13.5	13.4	13.2	13.2	13.4	
L-C	5.0	9.1	5.5	11.6	9.6	9.5	9.4	9.5	9.5	9.9	97
NL-C	9.5	9.3	5.9	10.6	10.7	10.4	10.2	10.1	10.1	10.5	

Moisture content data given as percentages
r/R, Relative measure of distance from cross section center where r is the radius of the slice of a cross section (from the cross section center) and R is the radius of the cross section sample; L-C, loaded treatment; NL-C, load-free treatment

were in agreement with Kubler's pattern.[2] Kubler's pattern is the tensile strain in the core and the compressive strain near the bark. However, the patterns in this experiment disagreed with Kubler's pattern at two points. One was that the zero strain or crossover point was $0.13R$ (R is the radius of the specimen) from the center of specimen, which was closer to the pith than Kubler's $0.368R$, because Kubler's model disregarded the Poisson effect of the longitudinal growth stresses on tangential strain.[2] The other is that the highest tensile strains measured in this experiment are $21\,741\,\mu\varepsilon$ for L-C and $27\,336\,\mu\varepsilon$ for NL-C, which are much higher than the highest value ($12\,600\,\mu\varepsilon$) found in the literature.[2,13]

As drying proceeded, some tendencies were shown quite clearly. In the zone from the center to $r/R = 0.13$ (r is the radius of the slice), the tangential tensile strains for NL-C treatment remained as tensile strains in spite of temporarily being compressive strains when the MCs of the specimens were 18.3%, while the tangential tensile strains for L-C treatment reversed to compressive strains when the MCs of the specimens were 29.4% (Figs. 2 and 4; Table 1).

In the zone toward the bark (r/R = 0.13 to 0.95), the tangential compressive strains for NL-C treatment reversed to tensile strains and grew to the maximum tensile strains when the MCs of the specimens were 18.3% and then approached zero strain, while the tangential compressive strains for L-C treatment reversed to tensile strains when the MCs of the specimens were 15.0% and then continuously increased to the maximum tensile strains at the last stage of drying (Figs. 3 and 5). The values of the tensile strains for L-C treatment were higher than those for NL-C treatment when the MCs of specimens were below 12.1% (Table 1).

Therefore, the possibility of developing heart checks is high for NL-C treatment in the core (from the center to r/R = 0.13) of the log cross section, while the possibility of developing cracks is high for L-C treatment in the zone toward the bark when the MCs of specimens are below 12.1%. These tendencies can be a result of the interaction of the various kinds of stresses. When a log is crosscut into log cross sections, the longitudinal growth stresses are released on the very end of the log cross section. This makes the primary transverse tensile strains near the pith higher because the tangential crosscut strains released from crosscutting are also highest near the pith. When an external load of 0.092 MPa is applied on the cross section of the L-C specimen, the load expands the specimen laterally.[2,6,14] Consequently the load reduces the original tangential compressive strains in the zone toward the bark and the tangential tensile strains in the core of the log cross section. This effect has a role in inducing cracking in the zone toward the bark, combining with other tensile strains. However, it also has a role in reducing or preventing the heart checks in the core. This also is a main factor that causes differences in the patterns of the strain distribution for the loaded and load-free specimens (Figs. 2–5).

During the early stage of drying, the vapor pressure gradients from the inside to the outside of the wood (rapid vapor generation inside wood produces significant total pressure gradients in addition to partial vapor pressure gradients),[15,16] and the hygrothermal recoveries up to the fiber saturation point (FSP) also generate additional tangential tensile strains. These cause the tangential compressive strains in the zone toward the bark to be further reduced and approach tensile strain. When the MCs of specimens are decreased below the FSP, the nonuniform shrinkage strains in the control treatment occur and neutralize the tangential tensile strains in the core and the tangential compressive strains near the bark to some extent because of their pattern of transverse tension near the bark and transverse compression in the core.[7] Ultimately, these strains make the tangential compressive strains in the zone toward the bark approach the tangential tensile strains.

As drying proceeds further, the tangential tensile strains in L-C treatment specimens become larger because the direction of the tensile strains is in the opposite direction of tangential shrinkage and the larger tensile strains increasingly restrain the tangential shrinkages. When these tensile strains are large enough, if the tensile stresses cannot be sufficiently relaxed, cracking inevitably occurs. When the tangential tensile strains in NL-C treatment specimens approach zero after reaching a certain level of tensile strains because the tangential shrinkages in NL-C treatment specimens are less restrained by tensile strains.

Conclusions

This study investigated the effect of a compressive load of 0.092 MPa on the history of tangential strains in the Japanese larch log cross sections subjected to external compressive load during RF/V drying. In the core of the log cross section, the tangential tensile strains for NL-C remained as tensile strain, while the tangential tensile strains for L-C treatment reversed to compressive strain.

In the zone toward the bark, the tangential compressive strain for NL-C treatment reversed to tensile strain and then approached to zero, while the tangential compressive strain for L-C treatment reversed to tensile strain and then increased to the maximum value at the last stage of drying. The values of the tensile strains for L-C treatment were higher than those for NL-C treatment when the MCs of the specimens were below 12.1%. Therefore, the possibility of developing heart checks in the core is high for NL-C treatments, and the possibility of developing the cracks in the zone toward the bark is high for L-C treatment when the MCs of specimens are below 12.1%.

A compressive load of 0.092 MPa has a role in inducing cracking in the zone toward the bark, combining with other tensile strains. However, it also has a role in reducing heart checks in the core when it is exerted on the cross section of log cross section.

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