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ORIGINAL ARTICLE

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# Effect of end-taping and removal of sapwood on radial distribution of moisture content and tangential strains during radio-frequency/vacuum drying of *Cedrela sinsensis* log cross sections

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**Abstract** This study was carried out to investigate the effects of end-taping of sapwood (ETS) and removal of sapwood (ROS) treatments of log cross sections on the radial distributions of moisture content (MC) and tangential strain, according to the circumferential slicing method (CSM), during radio-frequency/vacuum (RF/V) drying of log cross sections. The MC of control and ETS samples showed an even distribution around the center but decreased closer to the periphery side. In ROS samples, the MC decreased closer to the periphery side when above the hygroscopic range but showed an even distribution at the late stage of drying. Tangential strain in ETS samples showed slight compressive stress or tensile stress through the entire area of the cross section during the initial stage of drying, although the periphery side was in tensile stress from an area starting at a relative radius of 0.7. ROS samples showed tensile stress in the heartwood around the center and the heartwood of the periphery side and showed no stress or slight compressive stress in the middle area at the initial stage of drying, after which it showed an even distribution of tensile stress throughout the entire end surface. About 90% of the total checks contained in ETS and ROS samples were observed on the periphery side starting from a relative radius of 0.7.

**Key words** Circumferential slicing method · Periphery side · Tensile stress · Compressive stress · Checks

## Introduction

Chinese mahogany (*Cedrela sinensis*) has been favored as a raw material for furniture or crafts because of its high density and appealing color. When it is cut as log cross sections, the variation in wood color from the red heartwood to the lighter sapwood offers artistic beauty that is not seen in conventional sawn lumber. In addition, good yields can be obtained during cross cutting, even from small-diameter logs.

Unfortunately, when this species is processed into log cross sections and dried, heart checks and V-shaped cracks frequently occur during drying as in other species of wood due to growth stress, cross-cut stress, hygrothermal recovery stress, and differential shrinkage stress.[1–7] In particular, checks can occur frequently in the border between the heartwood and sapwood due to differences in green moisture content (MC) or permeability between the heartwood and sapwood. After investigating the radial distribution of moisture content in Chinese mahogany log cross sections during oven drying, Lee et al.[8] reported that the MC was slightly lower in the sapwood in the bark side compared with the heartwood in the pith when the log sections were in the green state. They reported that checks were likely to develop in the region between two areas when tensile stress or compressive stress between the two adjacent areas developed because of areas of wood both below and above the fiber saturation point (FSP). Although it is desirable to lower the drying rate in the sapwood so that the FSP is reached at almost the same time in the heartwood and sapwood, caution would be needed for excess treatment inducing the heartwood to reach the FSP first. However, it would be difficult to find the optimal treatments because differences exist in not only the permeability between heartwood and sapwood but also in the shrinkage between mature and juvenile wood. Therefore, the previous studies claimed that circumferential band-sawing would be necessary before drying to remove the sapwood in species with low percentages of sapwood.[8–10]

After 30-mm-thick *Cedrela sinensis* log cross sections were treated with end-taping of sapwood (ETS) and removal of sapwood (ROS), the radial distributions of MC and tangential strain were investigated according to the circumferential slicing method (CSM) during radio-frequency/vacuum (RF/V) drying in each stage. This investigation provides useful data for optimal pretreatment con-

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**Table 1.** Numbers, diameter, initial moisture content (MC), and specific gravity based on green volume of log cross section for the radio-frequency/vacuum (RF/V) drying test

| Treatment | Number (pieces) | Diameter (cm) | Initial MC (%) | Sp Gr | |
|---|---|---|---|---|---|
| | | | | Sapwood | Heartwood |
| Control | 36 | 27.4 | 69.4 | 0.51 | 0.60 |
| ETS | 36 | 27.5 | 69.4 | 0.51 | 0.60 |
| ROS | 36 | 23.0 | 67.6 | 0.51 | 0.60 |

Sp Gr, specific gravity based on green volume; ETS, end-taping of sapwood; ROS, removal of sapwood

ditions and in setting optimal drying conditions during RF/V drying.

## Materials and methods

### Preparation of log cross sections

Several 240-cm-long green logs of *Cedrela sinensis* were purchased from the market. Two logs were used for RF/V drying and the rest were used as controls. All logs were cross cut into 30-mm-thick cross sections after removing about 30 cm of material from each end. The log cross sections obtained with matching ends were divided into control, ETS-treated, and ROS-treated groups. The initial MC and specific gravity based on green volume were investigated in 1-cm-thick cross sections obtained from each end-match series. At this time, only the heartwood removed of sapwood was used to determine the initial MC from the ROS. For each treatment, the average initial MC of each log cross section was calculated from the initial MCs of each end-match series. The specific gravity based on green volume was calculated according to the immersion method by distinguishing the sapwood and heartwood. Table 1 shows the number, diameter, specific gravity based on green volume, and initial MC in each treatment group.

### ETS and ROS treatments

Two sheets of traditional Korean paper were taped to the end surface of the sapwood of log cross sections for ETS treatment. ROS treatment was performed by coating the tangential surface with several coats of water-proof urethane paint to prevent moisture evaporation from the tangential surface, after complete removal of the sapwood by circumferential band-sawing. All log cross sections for control and ETS were not debarked.

### RF/V drying test

#### *RF/V dryer*

The RF/V dryer used in this experiment was composed of a vacuum tank in a polygonal cylinder 274 × 102 × 40 cm (L × W × H) and a radio frequency generator.[10] The maximum output of the radio frequency generator was 7 kW. The frequency was set at approximately 13 MHz, and the generator was operated in a cycle of 8 min on and 2 min off.

**Table 2.** Drying schedule for the RF/V drying test

| Drying period (h) | Wood temperature (°C) |
|---|---|
| 0–24 | 40 |
| 24–48 | 43 |
| 48–72 | 45 |
| 72–108 | 49 |
| 108–122 | 54 |
| 122–128 | Cooling |

#### *Stacking and drying conditions*

Log cross sections for each treatment were stacked in four layers of the sample log cross sections on top and dummy log cross sections in the bottom of the charge plate within the vacuum tank. The sample log cross sections were stacked so that each stacking layer would be side matched. The log cross section for controlling wood temperature was placed in the second layer from the bottom charge plate after selecting one log cross section among the dummy log cross sections. A teflon-coated platinum 100-Ω sensor was inserted toward the pith down to the heartwood of the log cross section for controlling wood temperature on the tangential surface. The location of the sensor was the center line thickness of the log cross section, and the sensor was sealed with silicon. After noise was filtered, it was attached to the temperature controller to control wood temperature.

Wood temperature was increased from 40°C at the initial stage of drying to a maximum of 54°C at the end of drying in an appropriate time interval (Table 2). This drying schedule was selected after pre-experimentation. The pressure used in the vacuum drying was maintained between 6.7 and 13.3 kPa.

### Determination of radial distributions of MC and tangential strain during drying and check formation

The weight of all log cross sections was determined every 12 h during the 108 h after drying started to calculate the MC and the drying rate. Each log cross section for control, ETS, and ROS was then selected at appropriate stages in

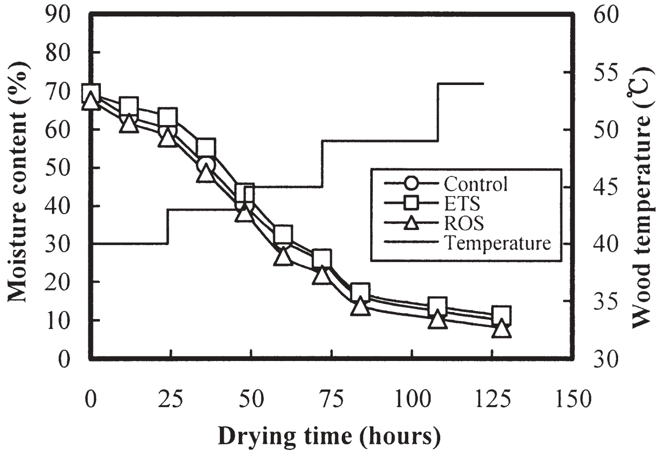

**Fig. 1.** Drying curves for control, end-taping of sapwood (ETS), and removal of sapwood (ROS) samples during radio-frequency/vacuum (RF/V) drying

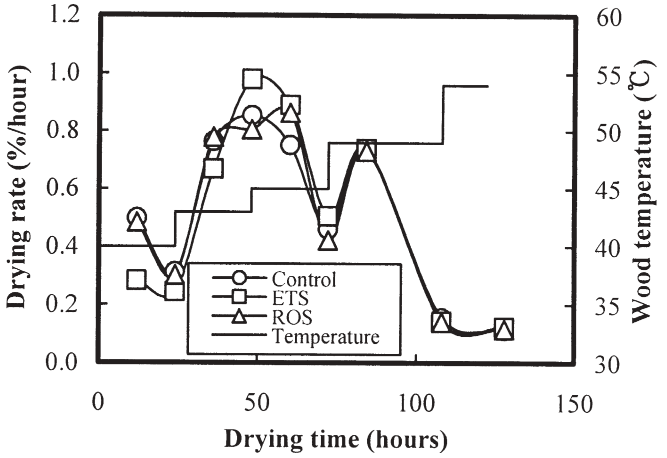

**Fig. 2.** Drying rates as a function of RF/V drying times for control, ETS, and ROS samples

changing of the MC to determine the radial distributions of MC and tangential strain by the CSM.[11]

After completion of drying, frequency of check formation was observed in all ETS and ROS sections that were not circumferentially sliced. The numbers of V-shaped cracks and heart checks passing through the pith were excluded from the observation.

## Results and discussion

### Drying curves and drying rates

Figure 1 shows the drying curve of each log cross section during RF/V drying. Control, ETS, and ROS samples were dried from green to 10.0% MC, 11.2% MC, and 8.0% MC, respectively, in a total drying time of 128h. ROS, despite the removal of its low-MC sapwood, showed a lower green MC than the control by 1.8%, and this lower MC continued until the completion of drying. ETS showed the same initial MC as the control log cross section but showed a higher value immediately after drying started. However, this difference was very slight after drying was half complete. This suggests that the effect of moisture evaporation through the sapwood at high MC above the FSP is significant on the average MC in the overall log cross section.

The drying rate curves during RF/V drying are illustrated in Fig. 2 as a function of drying time. The drying rate during the first 12h of the RF/V dryer run was 0.28%/h in ETS samples, which was very slow compared with 0.50%/h and 0.48%/h in the control and ROS samples, respectively. However, this trend reversed after 48h into the run, at which time the drying rate was highest in ETS samples. This is probably closely related to equilibration of the pressure between the internal and external portions of the log cross section during the drying run after a difference in absolute pressure was established along the longitudinal direction during the initial stage of RF/V drying.[12] In other words, even if the driving force for movement of water due to the difference in absolute pressure developed during the initial stage of drying, moisture evaporation through the sapwood with good permeability was probably limited in ETS samples, showing that ETS treatment was effective in delaying the initial drying rate, but was not effective at low MC. On the other hand, the drying rate increased in all groups when the wood temperature was increased to 43°C. The high drying rate of 0.8%/h was maintained up to 60h into the drying run when the temperature was increased to 45°C. This result was probably due to the increased internal absolute vapor pressure according to the application of temperature above the boiling point of water under the conditions of reduced pressure. The drying rate decreased drastically afterward because diffusion became the main driving force of internal water movement below FSP.[13]

### Radial distribution of MC

The radial distributions of MC in control, ETS, and ROS samples during RF/V drying are shown in Figs. 3–5. At an average MC of 65.4%, the MC was as high as 70%–75% for relative radii less than 0.64 but decreased toward the periphery to 52.0% MC in the sapwood of the control. Thus, a difference of about 24% was present from the highest MC in the center to the lowest MC at the periphery. Despite the range of relative radii of 0.64–0.91 being within the heartwood area, the MC decreased toward the periphery. This distribution continued until the average MC reached 48.9%, probably due to the physical characteristics of transition wood between the sapwood and heartwood. Thus, this result suggests that it would not be appropriate to distinguish the end surfaces of a log cross section into heartwood and sapwood when log cross sections are treated for the prevention of border checking during drying. Lee et al.,[6] Lee and Hayashi,[7] and Kang et al.[10] reported that it would be desirable to delay the drying rate in the sapwood so that the FSP would be reached in the heartwood and sapwood

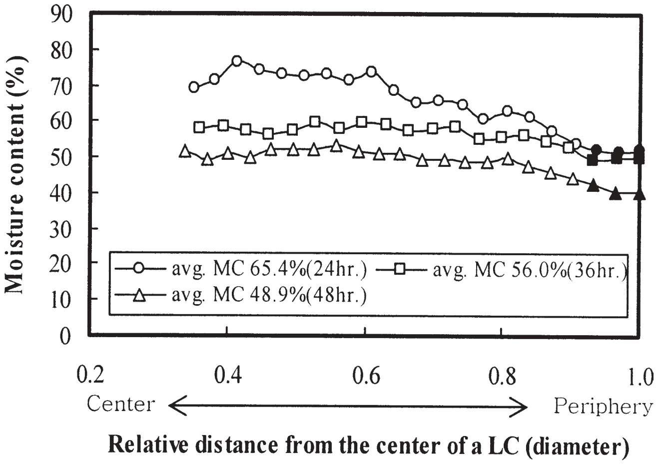

**Fig. 3.** The radial distribution of moisture content within a log cross section (*LC*) for control samples during RF/V drying. *Closed marks* represent the slices with mixed sapwood and heartwood

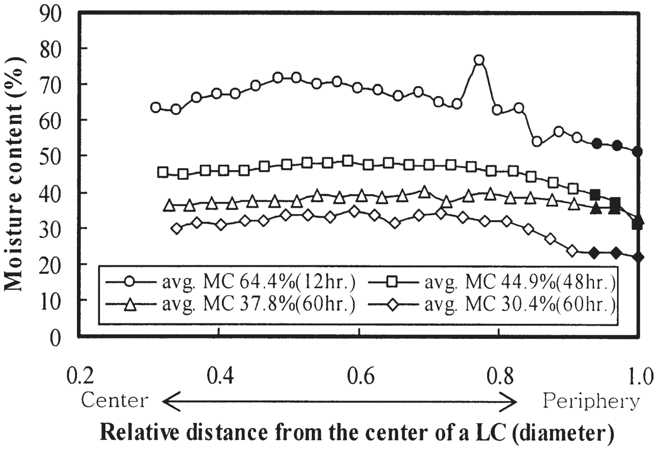

**Fig. 4.** The radial distribution of moisture content within a log cross section (*LC*) for ETS samples during RF/V drying. *Closed marks* represent the slices with mixed sapwood and heartwood

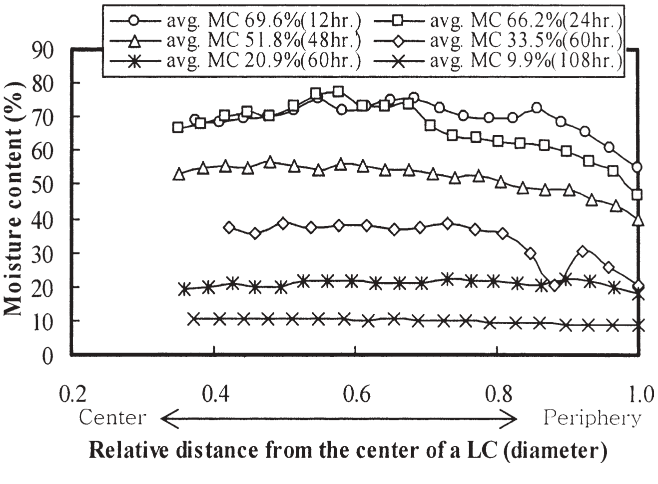

**Fig. 5.** The radial distribution of moisture content within a log cross section (*LC*) for ROS samples during RF/V drying

at the same time and claimed that it would be safe to remove the sapwood before drying in species with a very low percentage of sapwood.

Similar patterns were seen in the drying of ETS and control samples from the average MC of 64.4% until it reached 30.4%, suggesting that ETS treatment, i.e., taping two sheets of traditional Korean paper over both ends of the sapwood with a lower MC compared with that of the heartwood, did not significantly affect moisture evaporation, or that the drying rate in the heartwood was very poor. Nonetheless, sound ETS cross sections were found with MCs lower than controls, suggesting that ETS treatment contributed somewhat to the prevention of checking in the early stages of drying. Therefore, the drying rate should be delayed in the sapwood or increased in the heartwood around the pith in order to produce sound log cross sections containing the bark with superior natural beauty.

ROS samples also showed decreased MC toward the periphery above the hygroscopic range as in control and ETS samples despite the fact that the sapwood was removed and coating with paint was done to prevent moisture evaporation from the tangential surface. The maximum MC within the log cross section differed by 20.7% from the minimum MC with an average MC of 69.6%, showing a pattern similar to that of MC in ETS samples. This result confirmed our explanation that it would not be sufficient to distinguish the heartwood and sapwood at the end surfaces of a log cross section during drying. Thus, the physical characteristics of transition wood between the sapwood and heartwood should be investigated thoroughly and considered when drying log cross sections in species with low percentages of sapwood such as *Cedrela sinensis*. When the average MC was 33.5%, the MC was 20.4%, which was below the hygroscopic range, in the outermost slice, whereas the MC was higher than the FSP for relative radii up to 0.8. Lee et al.[8] and Kang et al.[10] reported that the possibility of check formation is high in the bordering region between two areas which may have are area with MC higher than the FSP and another with MC lower than the FSP. Therefore, ROS-treated log cross sections would be easily defected by checks when such a pattern of MC lasts for a long time according to the development of tensile stress in low MC areas of the periphery. The log cross section showed a very even MC distribution when the average MC was 20.9% and the average MC was 9.9% at the end of drying.

## Radial distribution of tangential strain

Figures 6–8 show the radial distributions of tangential strain in the control, ETS, and ROS samples during RF/V drying. In the control, some fluctuation from the average MC of 65.4% was observed at the early stage of drying. Tensile stress was apparent around the center and decreased toward the periphery and converted to compressive stress at a relative radius of about 0.7. Later, the periphery side showed slight tensile stress and the outermost slice showed high tensile stress. Although a close relationship would be

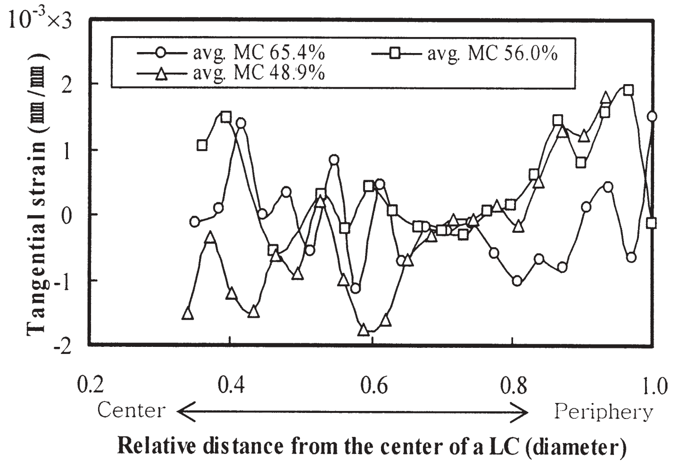

**Fig. 6.** The radial distribution of tangential strains within a log cross section (*LC*) for control samples during RF/V drying

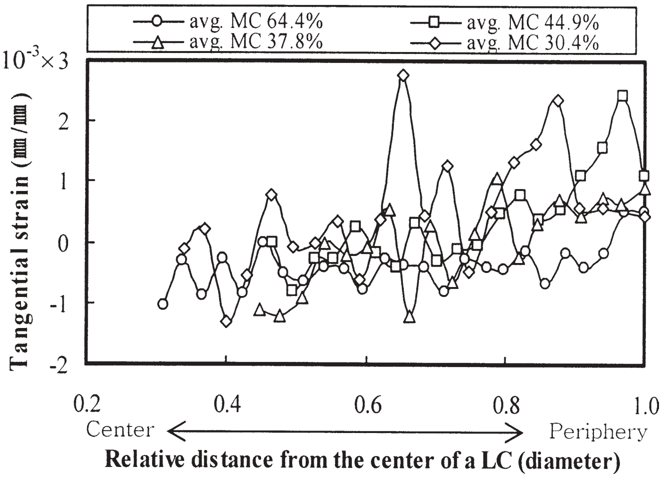

**Fig. 7.** The radial distribution of tangential strains within a log cross section (*LC*) for ETS samples during RF/V drying

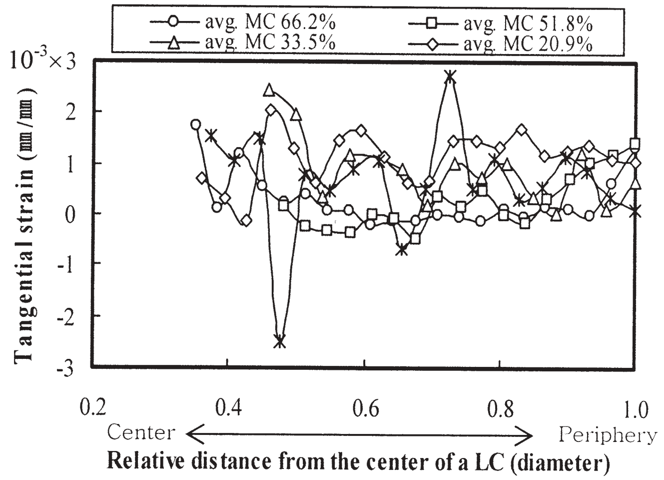

**Fig. 8.** The radial distribution of tangential strains within a log cross section (*LC*) for ROS samples during RF/V drying

present between tensile stress and growth stress distributions in the pith,[4] tensile stress near the periphery was probably due to uneven that shrinking during drying. The tensile stress developed more drastically near the periphery compared with at 0.8 relative radius, suggesting that the formation of checking could be very high at relative radii of 0.8–1.0, even at high moistures above the FSP. The fact that the lowest MC in the slices was relatively high compared with the MC where normal shrinking begins suggests that the high tensile stress near the periphery is probably due to abnormal shrinking at the early stage of drying, rather than due to the difference in MC in the sapwood and heartwood.

Unlike the control samples, compressive stress was seen in the entire section or slight tensile stress was shown near the periphery of ETS samples when the average MC was 64.4%, probably because ETS treatment delayed moisture evaporation from the sapwood at the early stage of drying and contributed to preventing tensile stress in the tangential direction of the periphery. However, tensile stress was present near the periphery starting at a relative radius of 0.7 with drying progressing. When the average MCs were 44.9% and 30.4%, a high tensile stress of $2 \times 10^{-3}$ mm/mm was built up in the area adjacent to the outermost, probably because shrinking of sapwood on the outside was restrained by the presence of the adjacent area with MC higher than the FSP (Fig. 4).[6,7,10] Therefore, ETS treatment would not be fully effective for preventing formation of checking in the border between the heartwood and sapwood.

In case of ROS treatment, tensile stress was also shown in the heartwood around the center and the periphery when the average MCs were 66.2% and 51.8% at the early stage of drying, and no stress or slight compressive stress was shown in other middle areas, showing a U-shaped distribution. Tensile stress near the periphery was probably related to shrinking characteristics of transition wood as in the controls. Tensile stress was distributed relatively evenly throughout the entire end surfaces as drying progressed, although some fluctuation occurred when normal shrinking began. Considering the fact that the moisture gradient along the radial direction was gentle at this time (Fig. 5), this even distribution of tensile stress could be interpreted as differential shrinkage stress due to differences in shrinkage between the tangential and radial directions. Therefore, microchecks already present could expand further at the end of drying. It should also be noted that the risk of V-shaped crack formation increases during processing or use of the log cross section when this tensile stress is present as residual stress, even after drying is completed. Therefore, further studies are needed for the prevention of residual stress in log cross sections.

## Radial distribution of checks

Figure 9 illustrates the frequencies of checks according to the distance from the center of log cross sections in all ETS and ROS samples that were not circumferentially sliced. Checks were most prevalent at a relative radius of 0.8 in all ETS and ROS samples at the frequencies of 47.1% and

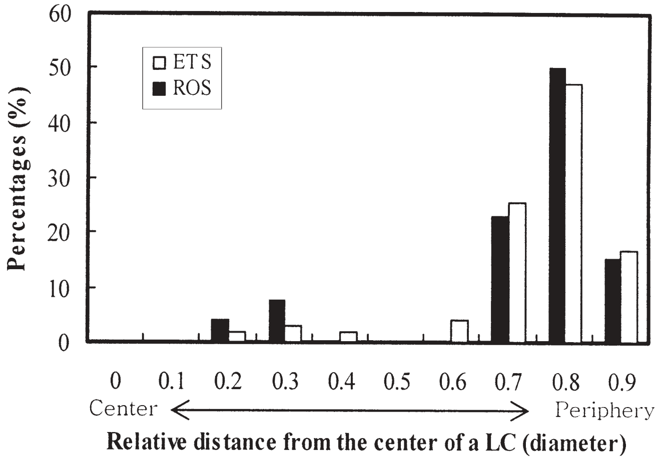

**Fig. 9.** The percentages of formation of checking after RF/V drying in relation to distance from the center of a log cross section (*LC*) in ETS and ROS samples

50.0%, respectively. About 90% of checks in both groups were observed on the periphery side within the relative radius range of 0.7–1.0, suggesting that the risk of checking is high in the border between the heartwood and sapwood or in the transition wood area. The risk of heart checking was low due to poor permeability in the heartwood. Attention should be paid to the fact that the distribution of checks in ROS samples with no sapwood area was similar to that in ETS samples. In other words, the mechanism of checking on the periphery side should not be approached simply by pairing the heartwood and sapwood[6–8,10] but should be done by fully considering the physical characteristics of transition wood, as well proven according to the radial distribution curves of MC and tangential strain. Therefore, in order to produce *Cedrela sinensis* log cross sections without defects by RF/V drying, the critical point should be set at a relative radius of 0.7.

## Conclusions

The MC of control and ETS samples showed an even distribution around the center but decreased closer to the periphery. In ROS samples, the MC decreased closer to the periphery when above the hygroscopic range but showed an even distribution at the late stage of drying.

Tangential strain in ETS samples showed slight compressive stress or tensile stress through the entire area of the cross section during the early stage of drying, although the periphery side was in tensile stress starting at a relative radius of 0.7. For ROS samples, tensile stress was observed in the heartwood around the center and the heartwood of the periphery side and no stress or slight compressive stress was observed in the middle area at the initial stage of drying. An even distribution of tensile stress was observed there after throughout the entire end surface. About 90% of checks contained in ETS and ROS samples were observed near the periphery, starting from a relative radius of 0.7.

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