

EFFECT OF PRESTEAMING ON DRYING STRESSES OF RED OAK USING A COATING AND BENDING METHOD¹

Zuoxin Wang

Former Graduate Assistant

Elvin T. Choong

Professor

Louisiana Forest Products Laboratory
School of Forestry, Wildlife, and Fisheries
Louisiana State University Agricultural Center
Baton Rouge, LA 70803

and

Vijaya K. Gopu

Professor

Department of Civil Engineering
Louisiana State University
Baton Rouge, LA 70803

(Received May 1993)

ABSTRACT

This study was initiated to investigate the effect of presteaming on drying stresses of red oak (*Quercus* sp.) using the coating and bending method. Besides the presteaming effect, a directional effect on drying stresses was also tested. Four blocks were randomly selected. Each block was divided into two pairs (four samples). One pair was randomly assigned to steaming while the other was assigned to control. A statistical split-plot model was used to analyze the results. Presteaming increased drying stress by up to 36% and decreased drying time by 23% when red oak was dried at 75% relative humidity and 44 C from average moisture content of 80 to 16%. The maximum drying stress of the steamed samples occurred before that of the unsteamed samples due to faster moisture loss from the sample. This study indicated that the coating and bending method could be used to study drying stresses of red oak. The statistical model revealed the differences between steaming and control and between inner and outer directions. Drying stresses were different in two opposite directions (outward and inward), regardless of whether the wood was steamed or not.

Key Words: Coating and bending method, drying deflection, drying stress, modulus of elasticity, presteaming, slicing method.

INTRODUCTION

Presteaming and steaming of wood have been practiced in Europe since the middle of the

¹ This paper (No. 93-22-7152) is published with the approval of the Director of the Louisiana Experiment Station. The research was supported in part by the McIntire-Stennis Cooperative Forest Research Program. The authors gratefully acknowledge the contribution of Peter J. Fogg, Professor Emeritus of Forestry, during the course of this study.

18th century to prepare for drying, to sterilize wood, to darken some species, and to relieve drying stresses (Campbell 1961). They have been in use in Australia for 30 years, but in the United States these processes have not been commercially adopted. One reason is that in this country there is a greater concern for quality than for shorter drying time. Presteaming of wood has been reported to increase the drying rate of heartwood of many wood species

(Campbell 1961; Simpson 1975; Alexiou et al. 1990a, b). Campbell (1961) reported a reduction in drying time of 20–35% for *Eucalyptus obliqua*. Alexiou et al. (1990a) reported that presteaming increased the drying rate of *Eucalyptus pilularis* by 7–16%.

The reason that presteaming can reduce drying time is not completely clear. Some researchers (Haslett and Kininmonth 1986; Choong and Achmadi 1989) postulated that steaming changes the nature of polyphenolic extractives that line cell walls, lumina, and pit areas. Before steaming, these extractives form a continuous layer. After steaming, the layer appears cracked, blistered, and generally discontinuous; therefore, the cell walls become more accessible to water, and moisture movement is enhanced. Alexiou et al. (1990a) thought that the increase in drying rate is due to the mobilization and partial removal of heartwood extractives, which allow greater access of water molecules to the cell walls. Microscopic investigation (Kubinsky 1971) of steamed northern red oak showed a reduced fiber lumen size, indicating an increased internal swelling that is caused by disruption of the warty layer that lines the lumen walls. The resultant effect is an increase in accessibility of the cell wall to moisture. Transmission electron micrographs of pit membranes of the steamed wood indicate hydrolysis of the membranes, which weakens both the membrane and the bond between the torus and the border, resulting in despiration of the pits (Siau 1984). Extraction by hot water and chemical solvents tends to have the same effects on permeability as steaming in softwoods (Fogg 1969) and in tropical woods (Choong and Achmadi 1989).

Drying stresses in wood are closely related to drying rate and they affect drying quality. Several papers (Schniewind 1960, 1963; Kuebler 1960) have described in detail the nature of these stresses. The technique often used to detect the stress in wood is the slicing method (McMillen 1955, 1968; Simpson 1975; Rice 1988), which requires cutting a drying sample into slices. There is a change in dimensions soon after cutting, i.e., an elastic strain in the

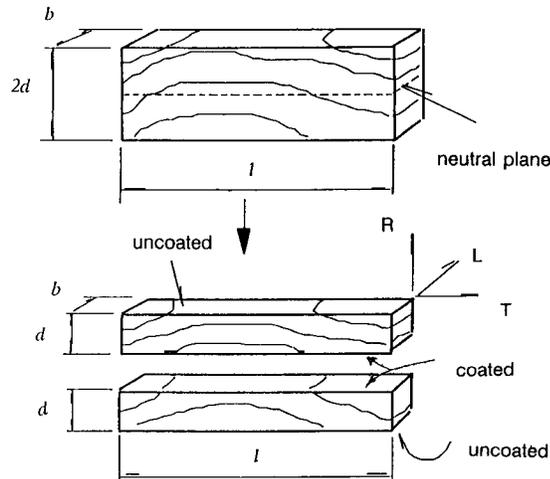


FIG. 1. Sample preparation and dimensions.

sample is indicated. This strain causes stress in the wood and results in honeycombs and checks if the stress is greater than the strength of the sample. This phenomenon can also be found if the sample is cut along the neutral plane (Fig. 1).

The slicing method to analyze drying stress was first used by McMillen (1955). Youngs and Norris (1958, 1959) further refined this method to calculate the internal stress in drying wood. The information derived by their technique gives a clear insight into the stress behavior during drying of wood, although the stress values apply to only one stage of drying of one sample under one set of drying conditions. This method, however, is difficult to use. When wood is sliced, the slices are affected by either a knife or a saw, and by temperature and relative humidity at the slicing site, which cause large variations in the data. Also, attention must be given to the techniques used for gathering data on strain recovery of the slices. McMillen (1968) reported irregular distributions of surface checks in some specimens and this phenomenon discourages any attempt to analyze all of the specimens for actual drying stresses. Rice (1988) reported that because of limitations in the slicing technique, the stresses that occur at the surface cannot be predicted.

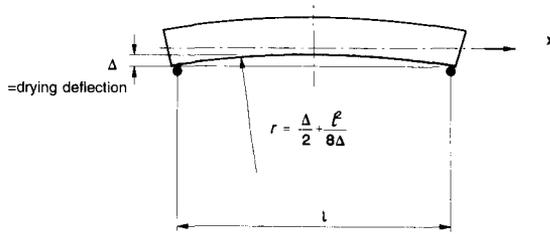
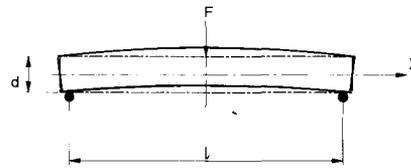


FIG. 2. Deflected shape of sample during drying.

Alexiou et al. (1990b) stated that direct measurement of internal stresses in wood is not possible; but drying stresses can be estimated by measuring the strains. Because information on the mechanical properties of blackbutt (*Eucalyptus pilularis*) across the grain is lacking, Alexiou et al. (1990b) could use instantaneous strain recovery only as an indicator of stress development. Also due to the highly variable magnitudes, the trends were not statistically significant. In addition, it is not possible to get the exact strain at the time of checking. Therefore, this slicing method can be used only during the first several days of drying. For these reasons, a new method needs to be developed to test and analyze drying stress.

EXPERIMENTAL AND ANALYTICAL METHOD

The main objective of this study was to develop a new method to determine the effect of presteaming on drying time and occurrence of drying stresses in wood. In order to accomplish the research objective, a coating and bending method was developed to replace the slicing method. Simplified assumptions for this method were: (1) water in wood between two opposite surfaces moves to the nearest surface, i.e., if a neutral plane is assumed between the two opposite surfaces, then water would not traverse the neutral plane; (2) drying stresses and strains vary linearly from the surface of the wood to the neutral plane; (3) strain and stress distributions are symmetrical with respect to the neutral plane; (4) slicing the wood into two halves along the neutral plane will not affect the moisture movement if the cut surface is coated. It is pertinent to point out that a sliced sample would develop a bend that is

FIG. 3. Mid-span loading to determine the modulus of elasticity E of the sample.

concave to the uncoated surface (Fig. 1) during the first phase of drying because the uncoated surface shrinks first.

As drying continues into the second phase, moisture close to the coated surface begins to shrink, and the bending will be convex with respect to the uncoated surface. The bending will release the drying stresses. If a force, F , is exerted on the sample (Fig. 2) to straighten it (bend backward), then the bending stress induced by this force is equal to the drying stress in the uncut sample. This force, F , can be obtained experimentally. Knowing F , the drying stress, σ , can be determined by elementary theory of bending as:

$$\sigma = \frac{M}{S} = \frac{Fl/4}{bd^2/6} = \frac{3}{2} \left(\frac{Fl}{bd^2} \right) \quad (1)$$

where M is the mid-span moment due to F and equal to $Fl/4$, l is the distance between two supports (Fig. 2), S is section modulus of the cross section with respect to the x axis, d (Fig. 1) is the distance from the coated surface to the uncoated surface (i.e., depth of sample), and b is the width of the sample.

A potential problem with this procedure is that when the force is applied to the sample, the sample may crack before it straightens. If too small a force is used, the sample will not straighten completely. To solve this problem, it is possible to use another approach by first determining the modulus of elasticity, E , and then calculating the drying stress from elementary bending theory as follows:

$$\sigma = \frac{E(d/2)}{r} \quad (2)$$

where r is the radius of curvature of the sample,

and equal to

$$\left(\frac{\Delta}{2} + \frac{l^2}{8\Delta}\right) \quad (3)$$

in which Δ is the midspan deflection of the sample after drying (Fig. 2).

The modulus of elasticity, E , of the sample can be determined from the relationship:

$$\delta = \frac{Fl^3}{48EI} \quad (4)$$

where δ is the deflection due to a concentrated load, F , applied at mid-span (Fig. 3), and $I = bd^3/12$ is the moment of inertia of the cross section with respect to the x -axis. Substituting the value of E into Eq. 2, yields the drying stress, σ . Because $r/d > 10$, the straight bar formula for maximum stress is used here (Timoshenko 1955).

MATERIALS

A green red oak (*Quercus* sp.) heartwood board was randomly selected for this study. The original moisture content (MC) of the board was 80%. The dimensions were 5 cm thick, 20 cm wide, and 240 cm long. Four clear blocks were randomly selected from the board (Fig. 4). In order to decrease the variance of the wood, each block was divided into two pairs, of which one was assigned to the control group and the other to the steaming group. Then each pair was split into two samples according to their structural positions with respect to the tree stem. The inner part that was nearer to the pith was labeled "inner," while the outer part that was nearer to the bark was called "outer" wood. The dimensions of each sample were about 20 mm in the radial (R) direction, 23 mm in the longitudinal (L) direction, and 140 mm in the tangential (T) direction. The sample was cut so that the rings were symmetrically oriented with respect to the center of the l dimension (T direction).

PROCEDURE

Block numbers were properly marked on the randomly selected board, indicating four ran-

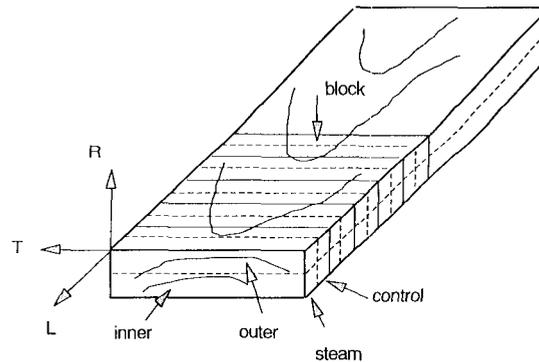


FIG. 4. Method of cutting sample blocks.

domly selected blocks. The blocks were cut as shown in Fig. 4. Then each block was cut into two pieces (a pair) (Figs. 1 and 4). The two pieces were randomly assigned to the control group and the steaming group. Each piece was marked by letters and numbers to identify its block, group, and positions-directions. Then each piece was cut into two samples of inner and outer positions.

After cutting, the samples of the presteaming group were put inside a steamer for 2 h at atmospheric pressure and 100 C. Presteaming, however, causes some water to come out of the sample. In order for steamed samples to have the same moisture content as that in the control group, the presteamed samples were put into water in a flask, and the flask was vacuumed for 20 min every 6 h during 24 h. Then all the samples, in both control and presteaming groups, were coated as shown in Fig. 1. All the surfaces, except the top surface of the outer sample and the bottom surface of the inner sample, were coated with saran resin diluted in methyl ethyl ketone. Each sample was coated three times. Thus the inner and outer samples dried in the inward and outward direction, respectively.

In order to calculate the bending stress, the modulus of elasticity, E , was experimentally evaluated at 12 h and at the end of drying (about 800 h) on an Instron universal testing machine. All samples were placed inside a Blue M environmental chamber to dry, at a dry bulb

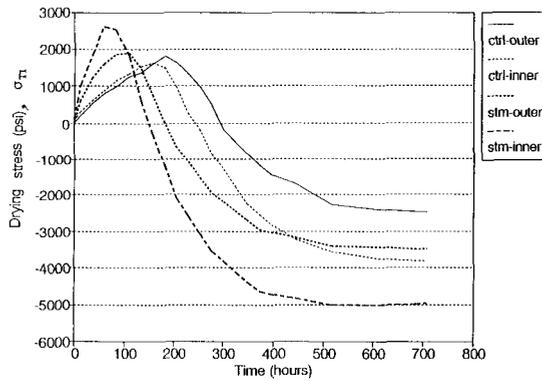


FIG. 5. Relationship between stress and drying time.

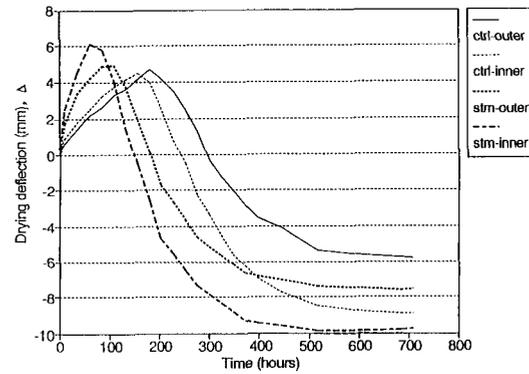


FIG. 6. Relationship between deflection and drying time.

temperature of 44 C, and a wet bulb temperature of 39.5 C (nominal 75% RH). The first measurement was made after 12 h, then subsequent measurements were made every 24 h. After 132 h, the measurement intervals were increased to 72 h or more. At each observation, five variables were measured: namely, the three dimensions of a sample, the weight, and the drying deflection. The drying deflection caused bending of the tangential (L-T) face (Fig. 1). The bending was assumed to be uniform for a sample, and the tangential face formed an arch. The chord length was measured and the radius of the arch was then calculated using the chord length, l , and the drying deflection, Δ (the height of the arch) in Eq. 3.

The MC profile was measured with extra samples in both the steaming and the control groups. One sample was cut into four slices along the tangential direction. The average MC of the slice was measured. These data were used to determine the MC at the mid-point of the slice. The four measuring points in the sample were at 2.5 mm, 7.5 mm, 12.5 mm, and 17.5 mm from the uncoated surface. Because of symmetry, these data were also used to estimate the MC of the paired sample.

From the data, the maximum stresses, the maximum deflections, the times corresponding to these stresses and deflections, and the times at MC of 30% and 16% were determined. In the first phase of drying, the surface layer

TABLE 1. Summary of experimental results comparing treatment and control.

Variable	Number of samples	Control		Steaming		F value	Pr > F
		Mean ¹	SD	Mean ¹	SD		
σ_{T_1} (psi)	8	1,748.5	178.9	2,321.3	549.6	19.74	0.0212
σ_{C_3} (psi)	8	-3,106.7	789.9	-4,212.5	1,171.1	33.92	0.0101
Δ_1 (in.)	8	0.184	0.019	0.222	0.035	28.74	0.0127
Δ_3 (in.)	8	-0.291	0.088	-0.345	0.061	9.21	0.0561
t_1 (h)	8	168.0	18.1	81.0	20.0	841.00	0.0001
θ_{11-2} (h)	8	98.6	22.2	83.6	8.7	4.66	0.1197
t_2 (h)	8	266.6	37.1	164.6	22.7	112.73	0.0018
θ_{12-3} (h)	8	333.4	57.0	345.4	49.7	0.28	0.6359
t_3 (h)	8	600.0	61.5	510.0	65.1	10.07	0.0503
t_4 (h)	8	596.8	127.1	490.5	44.3	8.35	0.0630
t_5 (h)	8	244.3	30.7	188.4	25.0	40.36	0.0079
E (psi)	8	80,757.4	11,975.3	86,403.9	11,010.1	0.97	0.3972
R (psi)	6	1,713.0	143.8	1,721.3	116.0	0.02	0.9108

¹ Average of inner and outer samples.

TABLE 2. Summary of experimental results comparing directions of moisture movement.

Variable	Number of samples	Inner		Outer		F value	Pr > F
		Mean ¹	SD	Mean ¹	SD		
σ_{T_1} (psi)	8	2,209.2	620.3	1,860.6	260.1	3.77	0.1002
σ_{C_1} (psi)	8	-4,354.0	789.9	-2,965.2	983.9	12.90	0.0115
Δ_1 (in.)	8	0.216	0.041	0.190	0.020	4.19	0.0867
Δ_3 (in.)	8	-0.372	0.032	-0.265	0.073	27.10	0.0020
t_1 (h)	8	111.0	50.4	138.0	45.8	22.09	0.0033
θ_{t_1-2} (h)	8	82.1	13.8	100.1	17.9	7.15	0.0369
t_2 (h)	8	193.1	53.5	238.1	61.8	19.04	0.0048
θ_{t_2-3} (h)	8	340.9	46.1	337.9	60.6	0.01	0.9187
t_3 (h)	8	534.0	80.9	576.0	71.4	1.43	0.2773
t_4 (h)	8	506.8	58.4	580.5	134.4	3.23	0.1225
t_5 (h)	8	199.0	30.6	233.6	41.5	10.04	0.0193
E (psi)	8	83,919.7	10,362.2	83,241.6	13,236.7	0.01	0.9126
R (psi)	6	1,740.2	111.9	1,694.0	142.8	0.36	0.5812

¹ Average of control and steaming samples.

(uncoated surface) was stretched, i.e., under maximum tension stress σ_{T_1} , and the core (coated surface) was under maximum compressive stress σ_{C_1} . Corresponding to σ_{T_1} are the drying deflection Δ_1 , and time t_1 (Phase 1). At time t_2 , the sample became straight, i.e., there was no drying deflection. Further drying (Phase 2) resulted in a reversal of curvature, and at time t_3 , the maximum compressive stress σ_{C_3} , occurred on the uncoated surface and the corresponding drying deflection was Δ_3 . Times t_4 and t_5 occurred when the average MC reached 30% and 16%, respectively. The time interval θ_{t_1-2} was the difference between t_2 and t_1 ; and θ_{t_2-3} was the difference between t_3 and t_2 . The purpose of determining these two time intervals was to establish whether steaming had an affect on drying time at the maximum tension stress σ_{T_1} .

When the drying was completed, all samples were again tested on the Instron machine to determine the modulus of elasticity, E, followed by a bending strength test. Finally, all samples were oven-dried at 104 C for three days, and then weighed. The data were used to calculate the MC's during the drying period.

RESULTS

Maximum stresses

The maximum surface stresses differed significantly between the steamed and control

samples. In the first phase, the maximum tension stress σ_{T_1} of the control group was about $\frac{3}{4}$ of that of the steaming group ($P = 0.02$). The difference between stresses due to directions was not significant ($P = 0.10$). If the blocks were divided into four parts, the stress for the inner direction in the steaming group was about 1.5 times as large as that of other groups (Figs. 5 and 6). Tension stress σ_{T_1} of the inner sample was less than that of the outer sample in the control group, but in the steaming group they were reversed.

Significant differences in compressive stress σ_{C_3} on the uncoated surface during the second drying phase were found for both methods (control and steaming) and directions (inner and outer wood), as shown in Tables 1 and 2. The steamed stress was about 4,213 psi and the unsteamed 3,107 psi, while the outer stress was 2,965 psi and the inner stress 4,354 psi.

Maximum deflections

The deflections Δ_1 for steaming and control, shown in Table 1, were significantly different ($P = 0.0127$) during the first phase; but in the second phase, the P value for Δ_3 was 0.0561 (Table 1), which was slightly over the critical value 0.05. From the SAS data, the steamed-inner Δ_1 (Fig. 6) was the highest, which indicated a trend similar to that observed for σ_{T_1} . The deflection of steamed-outer (Fig. 6) was

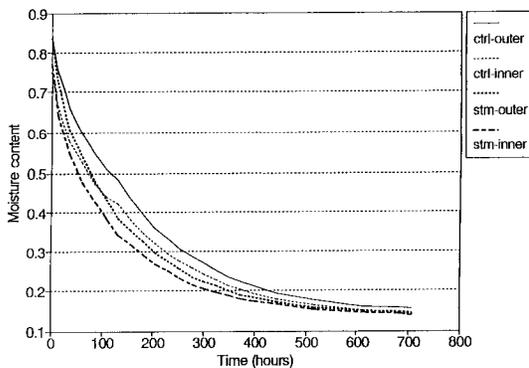


FIG. 7. Relationship between moisture content and drying time.

the second highest, while the outer and inner in the control group were almost the same in the first period.

Times and intervals

Time was recorded in hours from the beginning of the drying. Time t_1 was significantly different for both methods and directions (Tables 1 and 2). The steamed samples took 81 h, and the control samples 168 h to reach t_1 . The inner samples took an average of 111 h, and outer samples 138 h. Time t_2 had the same trend as Time t_1 . The steamed samples took 165 h, and the control samples 267 h; while the inner samples took 193 h, and the outer samples 238 h. Time t_3 for the control samples was approximately 20% higher than that for the steamed samples. However, the difference in t_3 between the inner and outer samples was only 8%.

The intervals θ_{t_1-2} and θ_{t_2-3} were not significant between steaming and control samples (Table 1). The interval, θ_{t_1-2} , was different for inner and outer samples but θ_{t_2-3} was not (Table 2). The θ_{t_1-2} for inner and outer samples was 82 h and 100 h, respectively, while θ_{t_2-3} for these samples was 341 h and 338 h, respectively.

The relationship between time and average MC is shown in Fig. 6. Time t_4 , which was the time at which the average MC reached 30%, shows no significant difference between the control and steaming samples (Table 1), and

between outer and inner samples (Table 2). However, time t_5 , at which the average MC was 16%, shows a significant difference between steaming and control samples and between outer and inner samples.

Others

The modulus of elasticity and the bending strength showed no significant difference between the various types of samples, i.e., the test method and the sample location had no influence.

DISCUSSION

Steaming increased drying stress by up to 36%, while drying time decreased by 23% in red oak dried at 75% RH and 44 C from an average MC of 80% to 16%. Since moisture moved outward from the interior, the surface dried below the fiber saturation point (FSP), but was restrained from shrinking due to the adjacent interior which was still above FSP. As a result of this phenomenon, the wood on the surface layers was stretched, i.e., under tension, whereas the inner core was under compression. The moisture content of the steamed samples dropped faster than for the unsteamed samples; therefore the surface of the steamed samples shrank faster than the unsteamed. The greater the shrinkage difference between the surface and the interior of wood, the larger the stress. Casehardening occurs when the interior of the wood loses moisture as drying progresses, which begins to shrink when the moisture content gets below the FSP, causing a stress reversal if the surface layer has "set."

Normally, the maximum tension strength of southern red oak is about 480–510 psi (U.S. Forest Products Laboratory 1974). If the stress is greater than this amount, checks will occur. Figure 5 indicates that drying stresses of some samples were over 500 psi in the first 12 h, which was why some checks occurred on the surfaces of the samples.

The data show that casehardening occurred due to the loss of moisture on the surface of the wood. When a sample was placed inside

the drying chamber, its coated and uncoated surfaces were at the same temperature. Case-hardening occurred only on the uncoated surfaces, due to drastic change in moisture below 30% MC. It occurred during the first interval (from the beginning to t_1), when the uncoated surface was under tension stress. During the second period, casehardening restrained the inner wood from shrinking, thus giving a tension stress to the inner wood. A higher tension stress on the surface caused greater casehardening, as a result of which tension stress developed in the inner wood. For this reason, the compressive stress was about 4,213 psi in the steamed wood and 3,107 psi in the unsteamed. The stress values obtained here should be somewhat less than the actual values. In fact, under constant stress, creep develops, which may decrease the stress. If stress is over a critical value (i.e., the maximum tensile strength perpendicular to the grain), the wood will crack. Therefore, the coating and bending method gives an indication that the wood may be destroyed if the value calculated from the data is large enough.

Bending stress is expressed in terms of E and r (Eq. 2). The statistical analysis indicated that there was a significant difference in drying deflection, but no significant difference in E between the control and the steaming groups. This means that the drying deflection can be used to indicate whether there is significant difference in drying stress. Figures 5 and 6 indicate parallel trends in the stress and deflection of the samples.

The two maximum stresses in the steamed samples occurred earlier than in the unsteamed samples. The first maximum stress of the inner direction occurred earlier than that of the outer. However, the time t_3 associated with the maximum compressive stress σ_{C3} was not significant. In addition, there was no difference for the interval θ_{t1-2} and θ_{t2-3} among the groups. This means that the time interval between the two maximum stresses was almost the same for the steamed and control samples, and for the inner and outer samples. The faster moisture loss at the beginning of the drying

was a key factor for the development of drying stresses (Fig. 7).

This study shows that the coating and bending method may be used to study drying stresses. With this method, the effect of presteaming on drying stresses can be analyzed. Also, the drying stresses in inner and outer samples can be distinguished. Furthermore, this method can be used to analyze drying stresses at various drying conditions in different wood species. The advantages of the method presented here are: (1) the entire stress development within a sample can be observed and the drying stress can be determined whenever necessary; (2) the variances caused by cutting, which affect moisture distribution in the sample and result in deformation of the sample, can be eliminated; (3) the effect of environment in the testing room is avoided; and (4) measuring times are shortened. For further study, other methods may be used to determine the E values without requiring force application on the sample. The curved beam model may be used to determine the maximum stress during the first phase of the drying to obtain more accurate results. A method that utilizes image analysis to measure and analyze the drying checks and to relate checks to stresses may be used to improve this method.

CONCLUSIONS

Presteamer increased drying stress and decreased drying time in red oak when dried at 75% RH and 44 C from an average MC of 80% to 16%. The maximum drying stress of the steamed samples occurred earlier than that of the unsteamed samples due to faster moisture loss. Casehardening occurred on the surface due to a sharp change of moisture content when it was dried below the FSP. Steaming could be used to decrease drying time if drying stress, as well as the other accompanying defects such as checks, are of no consequence. Drying stresses were different in two directions (outer and inner), whether wood was steamed or not.

This study indicated that the coating and bending method was convenient to use for evaluating drying stresses in red oak. With this

method and a split-plot statistical model, the differences between steaming and control and between outer and inner two directions can be readily distinguished.

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