HIGH-TEMPERATURE DRYING AND EQUALIZING: EFFECTS ON STRESS RELIEF IN YELLOW-POPLAR LUMBER[1]

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ABSTRACT

Warp caused by longitudinal growth stress has limited the use of hardwoods for some products such as structural lumber. This study evaluates the effects of high-temperature drying and equalizing times on relief of longitudinal growth stress. Small-diameter yellow-poplar logs were sawn into flitches for evaluation of total stress levels in green flitches and final stress levels in dried flitches.

High temperatures evaluated were 200 F (93 C), 240 F (116 C), 260 F (127 C) and 290 F (143 C). Equalizing times were 10, 20, 40, and 100 hours at 10% equilibrium moisture content.

Average adjusted absolute stresses for center flitches in the green conditions were about 525 psi (362 MPa). Average absolute stresses were 210 psi (145 MPa) for all high-temperature dried materials without equalizing, and 154 psi (106 MPa) for all equalized materials.

There were no well-correlated relationships of stress between the individual high-temperature or equalizing treatments and controls or green flitches. Possible causes for lack of correlation and suggestions for further research are discussed.

Keywords: Kiln-drying, growth stresses, lignin plasticization.

INTRODUCTION

A major problem in using hardwoods for structural and other small-dimension lumber is warp. Warp is the result of stresses, both natural and induced. Sources of these stresses may be reaction wood, drying conditions, and growth conditions. The primary stress of concern in hardwoods is longitudinal growth stress. Longitudinal growth stresses, the product of physical and mechanical causes (Boyd 1950; Boyd and Schuster 1972; Dinwoodie 1966) are a continuum of changing stresses from high compression at the pith to high tension at the bark (Fig. 1).

Lumber of small dimensions, such as 2 × 4 stud[3] (38 × 89 mm), will often warp when sawed from a green log, as imbalanced longitudinal growth stresses are released (Koch and Rousis 1977). The wood under compression stress lengthens on release and that in tension shrinks (Fig. 2). The release of stress (strain) results in three types of warp of concern in studs: crook, bow, and twist.

The objective of this study is to empirically evaluate the effects of drying temperature and/or equalizing time on longitudinal growth stress relief in yellow-poplar (*Liriodendron tulipifera* L.) lumber.

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[2] The Laboratory is maintained by the U.S. Department of Agriculture, Forest Service, at Madison, Wis., in cooperation with the University of Wisconsin.

[3] A nominal 2 × 4 is actually 1.5 × 3.5 inches in cross section.

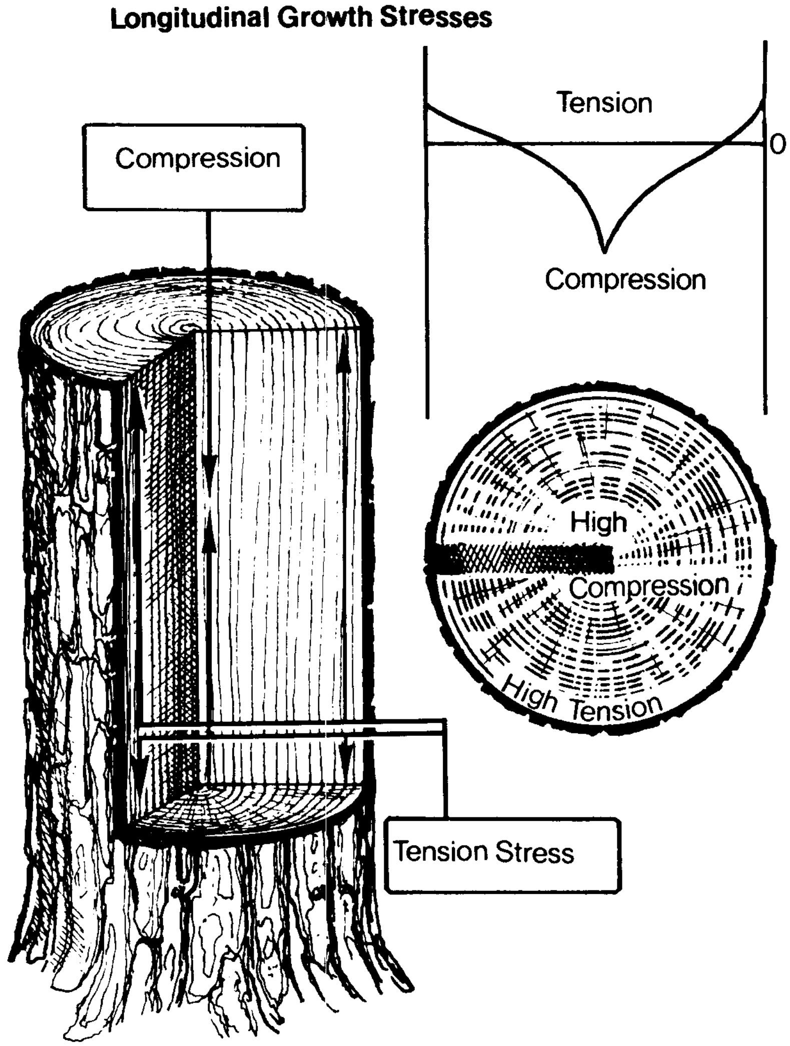

FIG. 1. Longitudinal growth stress distribution in trees and logs.

BACKGROUND

In recent research on the SDR (Saw, Dry, and Rip) method of manufacturing studs (Maeglin 1978; Maeglin and Boone 1980, 1983), it was shown that livesawing flitches and drying them before ripping into studs resulted in substantial warp reduction as compared to conventionally manufactured studs. When the flitches were dried at high temperature (>212 F, 100 C), even greater warp reduction resulted.

We believe that the extra width of the flitches, plus a somewhat balanced stress distribution in the flitches, restrains the tendency to warp while drying. It is felt, too, that drying stresses may partially compensate for growth stresses.

Additionally, we hypothesize that drying at temperatures above about 194 F (90 C) results in stress relaxation via lignin plasticization. Lignin, the natural

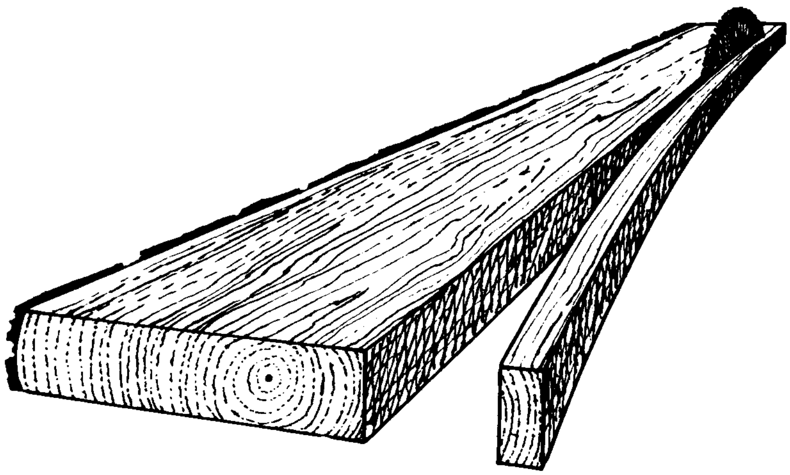

FIG. 2. Longitudinal growth stresses being released in form of warp (bow) in lumber.

adhesive between fibers, is thermoplastic in nature—i.e., it becomes plastic at higher temperatures (Skolmen 1967). Goring (1971) shows that extracted softwood lignin plasticizes at various temperatures depending on moisture content. A composite curve using Goring's data shows extracted softwood lignin and temperature combinations (Fig. 3). Because Goring's work was done on isolated softwood lignin, the results may not exactly apply to hardwoods, but they are believed to be similar. Whole wood may also respond in a manner different from that of isolated lignin.

At high temperatures, as the lignin plasticizes, we believe the fibers slip from

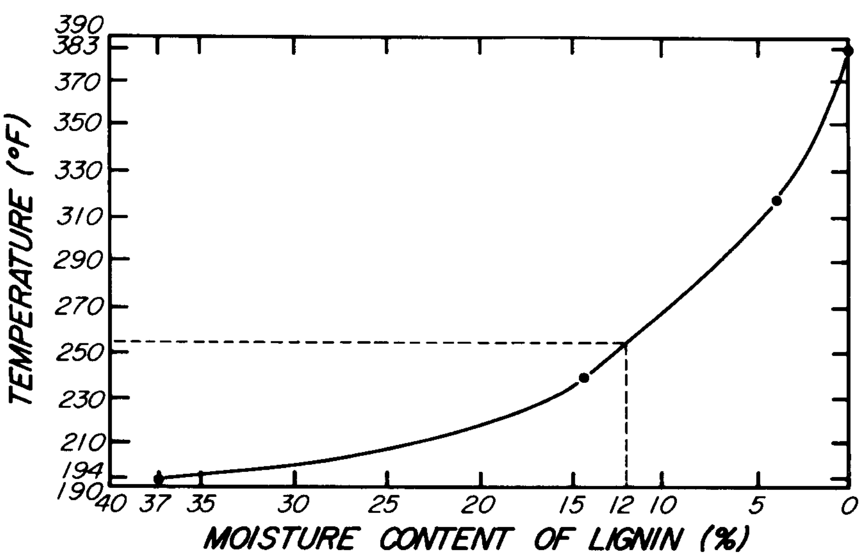

FIG. 3. Relationship of moisture content and temperature to peak (maximum) lignin plasticization (after Goring (1971)).

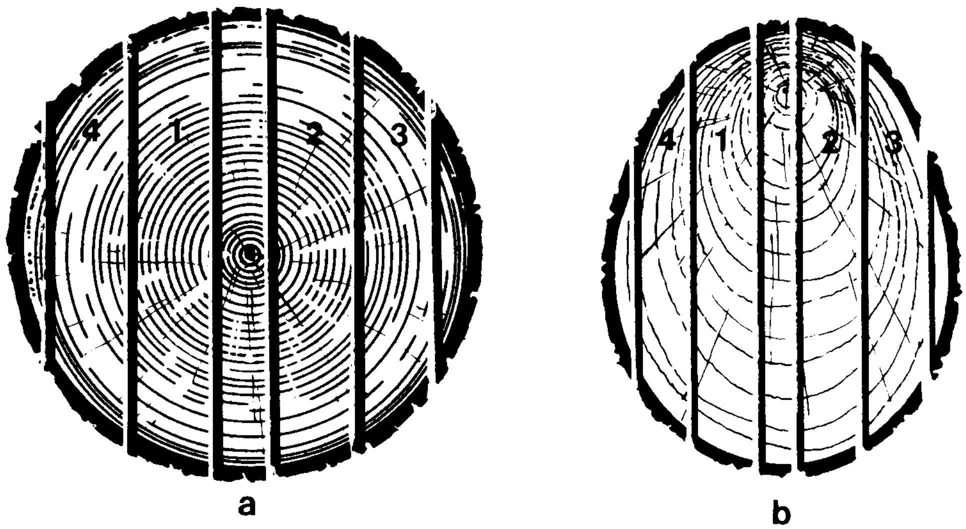

FIG. 4. Cutting patterns for flitches from round and eccentric logs. Flitches 1 and 3 were treated; flitches 2 and 4 were controls.

a stressed state to a more nearly stress-free state. As drying proceeds, the temperature of lignin plasticization increases, so the stress-relieved fibers are once again bonded tightly by the lignin.

Finally, a possibility exists that fairly long equalizing time may result in some stress relief, perhaps by balancing the MC differentials in the pieces.

In this study the effects of four high-temperature drying treatments and four equalizing treatments are compared with controls and green center flitches for longitudinal growth stress reduction. The study may lead to an understanding of the factors that cause warp in hardwood lumber and may suggest conditions to prevent warp. Ultimately the research will benefit both manufacturers and consumers by production of higher quality lumber products at lower cost.

MATERIALS AND METHODS

Using a modification of Jacobs' (1938, 1945) strip method for analyzing longitudinal growth stresses, we sawed yellow-poplar logs into flitches and the flitches into strips. Jacobs used only center flitches. In a similar study, Post et al. (1980) used both center and side flitches. We used center and side flitches but, unlike Post et al., we dried side flitches and only measured strains between flitch and strip, and not between log and flitch.

Materials

Yellow-poplar logs chosen were 5 to 10 inches (12.7–25.4 cm) diameter inside bark, small end, and 8.5 feet (2.6 m) long, from Tennessee, Virginia, and West Virginia. Eighty logs were equally distributed, by small-end diameter, into eight groups of ten logs each. Each log group was assigned to a separate drying treatment. Each group was sawn and dried separately, half of the flitches dried at treatment conditions and half at control conditions. The volume of each half batch was approximately 100 board feet of lumber.

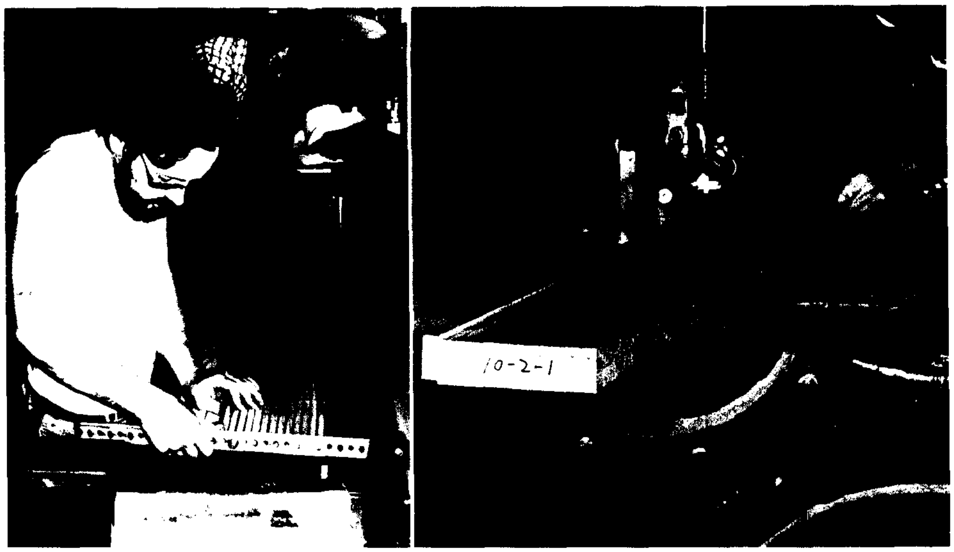

FIG. 5. Preparation of strips for measuring strain. Left: The measuring jig with a flitch being measured before cutting. Right: Flitch end showing escutcheon pins, markings, and the cutting of strips against the round-nose fence.

Methods

Sawing and sample preparation. Each log was stencilled on the small end to indicate a balanced sawing pattern using a pith-centered flitch (Fig. 4a); logs with off-center pith were rotated to center the pith for sawing (Fig. 4b). Flitches were used both as a source of strips to measure stress and to duplicate the conditions used in the SDR process. The logs were livesawn with all cuts parallel to the opening face. The center flitch was cut 1 inch (25.4 mm) thick. The side flitches were 1.5 inches (38 mm) thick to simulate SDR-type flitches. Flitches were edged on each side for a clean rectangular cross section, and precision end trimmed to 8 feet (2.4 m), which was the measuring length.

Center flitches were measured in the green condition to evaluate initial stress conditions in the log. Stress data from these flitches were later adjusted (ASTM 1983) to dry conditions to facilitate comparison with side flitches. Center flitches were maintained in the green condition by regular spraying with water and covering with plastic during processing.

Side flitch pairs, starting on either side of the center flitch, were numbered alternately for control and treatment (Fig. 4). By alternating sides, any bias due to lean or cardinal direction was minimized between drying treatment and control flitches.

Flitches were marked for ripping into 0.5-inch (12.7-mm) strips; center flitches were marked green; and side flitches were marked after drying (Fig. 5). Marking was from the board edges toward the center. Brass escutcheon pins were driven into the end grain center of each strip as measuring points for length. Each 0.5-inch (12.7-mm) strip, marked and pinned, was measured in the flitch for total length. A measuring jig with calibrated dial gage was used to determine the strip

TABLE 1. *Study design for treatment of flitches to evaluate drying and equalizing effects on longitudinal growth stresses in yellow-poplar.*

Treatment no.	Drying conditions to 12 ± 3% MC	Equalizing conditions
	GREEN CENTERS	
	None. Maintained in green condition by spraying with water and covering with plastic.	None
	HIGH-TEMPERATURE DRYING	
1	200 F (93 C) DB/190 F (88 C) WB,[1] 40 h, EMC 10%	None
2	240 F (116 C) DB/190 F WB, 28 h, EMC 3.1%	None
3	260 F (127 C) DB/190 F WB, 18 h, EMC 2.0%	None
4	295 F (143 C) DB/190 F WB, 10 h, EMC 0.5%	None
	DRYING CONTROLS	
1–4	FPL Schedule T11-D4[2]	None
	EQUALIZING	
5	Not high-temperature dried.	200 F DB/190 F WB, 100 h, EMC 10%
6	240 F (116 C) DB/190 F WB, 28 h, EMC 3.1%	200 F DB/190 F WB, 10 h, EMC 10%
7	240 F DB/190 F WB, 28 h, EMC 3.1%	200 F DB/190 F WB, 20 h, EMC 10%
8	240 F DB/190 F WB, 28 h, EMC 3.1%	200 F DB/190 F WB, 40 h, EMC 10%
	EQUALIZING CONTROLS	
5–8	240 F DB/190 F WB, 28 h	None

[1] DB = dry bulb; WB = wet bulb.
[2] See Appendix 1.

lengths. The strips were then ripped free from alternate sides of the flitch, using a band saw and round-nose fence to maintain constant strip thickness.

Prior to actual strip-length measurement, a trial flitch was cut into strips and each strip was measured immediately after cutting. The strips were then measured at 1-min intervals for 20 min, then at 1-h intervals for 5 h, and finally after 24 h. The measurable strain maximized after 15 min, consistent with the results of Boyd and Schuster (1972).

The strips, after being sawed free, were allowed 15 min to equilibrate for length. They were straightened before measuring for length (being thin, they were very flexible and easily held straight for measuring). The gage was calibrated frequently, using a steel bar of 96.000 inches (2.44 m) at 75 F (24 C). Measurement was to the nearest $1/_{1,000}$ inch (0.0254 mm).

High-temperature drying. Variable drying times for each of four temperatures (Table 1) were used in an effort to have all material dried to approximately the same levels for each treatment. The desired MC was 12 ± 3%. The various drying temperatures (200 F (93 C), 240 F (116 C), 260 F (127 C), and 290 F (143 C)) were chosen to provide a best solution to stress relief (Table 1).

TABLE 2. *Average green center flitch stress levels by replicate.*

Stress type	Stress[1]								
	Replicate								Average of replicates
	1	2	3	4	5	6	7	8	
	psi								
Tension	−495	−446	−430	−574	−543	−512	−584	−540	−518
	(61)	(45)	(41)	(44)	(37)	(52)	(63)	(41)	(384)
Compression	698	470	429	563	466	595	527	521	533
	(35)	(44)	(40)	(59)	(48)	(57)	(60)	(41)	(384)

[1] Stress values adjusted to dry basis according to ASTM Standard D 245, Table 11 (Current Issue). Averages are based on all strips in each flitch; numbers in parentheses are numbers of strips in average.

Equalizing.—Equalizing is a stage in the drying sequence in which equilibrium moisture conditions in the kiln are slightly lower than the desired end-point moisture content, to bring the lumber to a nearly uniform target moisture content. Various equalizing times (100 h of equalizing conditions only, and 10, 20, and 40 h after high-temperature drying) were selected to reveal a best equalizing time for stress relief (Table 1).

Stress-strain evaluation.—Strain was calculated using the equation:

$$\text{Strain} = \Delta L/L$$

where ΔL is the deformation (change in length) and L is the total length of the strip before ripping. Stress was calculated using the equation:

$$\text{Stress} = E \times \Delta L/L$$

where E is the modulus of elasticity for the strip and $\Delta L/L$ is the strain for the strip. The modulus of elasticity of each strip was determined using an E computer (an electronic device that computes modulus of elasticity (E) based on transverse wave propagation).

Data presentation.—The stress values calculated from the measurements are intended as comparative values. Because of edging and saw kerf removal, stress values were reduced from maximum. The values should, however, be relevant for comparisons between controls and treatments. The data are presented graphically and tabularly without statistical analysis.

RESULTS AND DISCUSSION

General trends

The overall averages of stresses, calculated from strain and "E" measurements for strips ripped from the green center flitches were 517 psi (357 MPa) in tension and 533 psi (368 MPa) in compression (Table 2). (The data on green center flitches were adjusted to a 15% MC (ASTM 1983) basis for better comparability with the dried material.) The averages are both based on 384 sample strips. The stress levels for the green center flitches are considerably higher than for the controls and treatments, which averaged 260 psi (180 MPa) and 180 psi (124 MPa), respectively. This is so for several reasons:

1. The green center flitches are complete diameters through pith, while the con-

trols and treatments are tangential cuts away from the highest levels of compression.

2. The green center flitches were not dried and thus did not receive the stress-reducing influence of drying.
3. The squaring of the flitches to rectangular form was less severe for the green center flitches than for either controls or treatments, thus having less effect on stress reduction.

For controls and treatments, actual measurements indicated higher levels of tension stress than compression stress and more strips in tension than in compression. While it would be possible to have more strips in either one or the other stress type, the average stress values must be in balance, excluding sampling error. The average green center stresses reflect this near balance (Table 2).

After examining the stress data, we decided that drying had not been uniform enough for treatments and controls. The measured differences in tension and compression were, for example, 235 psi (162 MPa) in tension and 128 psi (88 MPa) in compression for controls of the high-temperature trials. The number of sample strips was 262 in tension and 63 in compression. The other dried controls and treatments were similar in magnitude. Longitudinal shrinkage after sawing of strips may be responsible for the calculated imbalance in stresses, as any longitudinal shrinkage will appear as relieved tension stress (strain).

Longitudinal shrinkage of normal wood averages 0.2% (Rasmussen 1961) and may vary from 0.01 to 1.0% (Hann 1969; Kubler 1980). Much greater longitudinal shrinkage (1% or more) will occur when juvenile wood or tensionwood are present (Haygreen and Bowyer 1982; Kubler 1980; Panshin and de Zeeuw 1980). Even though the flitches were dried to an average of 12% MC, the interior strips may have been greater than 12%, while the exterior strips may have been dry enough to not shrink further. Because of the delay between processing and data analysis, empirical data could not be obtained. The strips when sawed were exposed to the heat of sawing and to equilibrium moisture conditions of about 8%. The small cross section and relatively great length of the strips provided a large surface area for rapid drying and subsequent shrinkage.

The stress formula can be used to calculate the shrinkage (ΔL) necessary to cause the imbalance between tension and the compression stresses:

$$\Delta L = SL/E$$

where

S = difference in weighted tension and compression stress—e.g., [(262 × 235 psi) − (63 × 128 psi)] ÷ 325 = 165 psi (114 MPa).
L = 96.000 inches (2.4 m), the measuring length for the study.
E = 1.78×10^6 psi (1.23×10^6 MPa), the average E for the kiln-dried study strips (this value is corroborated by Gerhards (1983)).

The calculated ΔL for the controls in the high-temperature drying phase is 0.009 inches (0.23 mm). This value is well within the realm of normal longitudinal shrinkage for drying yellow-poplar from 15% to 12% MC.

We believe that the outermost strips were sufficiently dry in the flitch so as to not shrink when ripped from the flitch. The stress values for these outermost

TABLE 3. *Residual stress levels for outermost strips of green center flitches and dried side flitches.*

Treatment	Stress[1] Replicate 1	2	3	4	Average	Treatment	Stress[1] Replicate 5	6	7	8	Average
	psi						psi				
Green center[2]	955	755	673	823	801	Green center[2]	775	846	793	935	837
Control	217	397	295	327	309	Control	265	94	284	242	221
High-temperature	272	145	239	214	218	Equalizing	151	137	89	176	138

[1] Average stress regardless of sign (compression +, tension −) for outermost strips.
[2] Green center stress values adjusted to dry basis according to ASTM Standard D245, Table 11 (Current Issue).

strips can be taken as maximum and the ones for which internal stresses must be balanced.

Table 3 shows averages of longitudinal stress values for the outermost strips from green center, control, and treatment flitches. Green center stress values in Table 3 are considerably higher than in Table 2 because Table 3 averages only stress values for the outermost strips, whereas all strip values are included in Table 2 averages.

The highest individual stresses in the outermost strips were 1,351 psi (932 MPa) in green center 4; 1,333 psi (920 MPa) in control 2; 921 psi (635 MPa) in control 5; 928 psi (640 MPa) in high-temperature 3; and 430 psi (297 MPa) in equalizing 8.

Strain measurements suggest that numerous strips (36 of 75) of the high-temperature treatments were in compression. The high-temperature treatments, especially treatments 2, 3, and 4, showed extreme casehardening, a condition due to drying stress that results in the shell of the flitch being in compression stress. Controls 5 through 8 were dried the same as high-temperature 1 and had 22 of 75 strips in compression. Equalizing and/or conditioning was used to remove casehardening stresses (Rasmussen 1961). The equalizing treatments reflect drying stress removal where only 13 of 75 strips showed compression stress.

Effects of treatment

It is possible to get only one complete center flitch from each log. Because it was decided that each center flitch should be evaluated without drying, a complete evaluation of the stress-reducing effects of high temperature and equalizing treatments was not possible. The reduction of initial compression stress levels for controls and treatments by selection of more tangential flitches limits the conclusions that can be drawn. In spite of the deficiencies, some effect of treatments may still be seen in the comparisons presented.

High-temperature drying.—Figure 6 shows the stress relationships between green center flitches, controls, and treatments based on outermost strip stress averages. The average stress for all four high-temperature treatments is quite variable, 145 to 272 psi (100 to 188 MPa) but lower in overall average stress than the controls 1 through 4. There is no trend in stress with increasing temperature, and initial green stress values are not correlated with the final high-temperature stress levels.

High-temperature 1 showed the least stress reduction. It also was a temperature

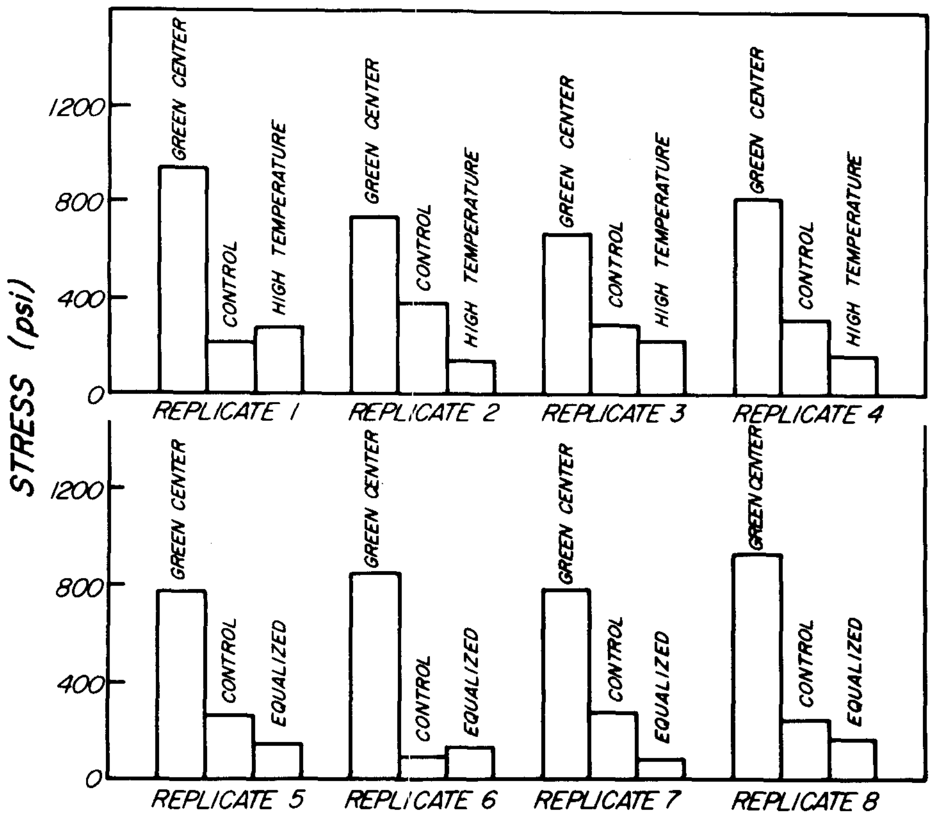

FIG. 6. Comparisons of average stresses for green centers, controls, and treatments.

that by general definition is not considered "high-temperature."[4] It is believed that some lignin plasticization does occur at this temperature, however. The stress for green center 1 was the highest of replicates 1 through 4 at 955 psi (659 MPa).

High-temperature 2 resulted in the lowest average stress of the high-temperature treatments. The corresponding green center stress was intermediate among green centers and the corresponding control was highest of controls 1 through 4. No clear evidence is present that this is the best stress-reducing temperature. Controls 5 through 8 were all dried at the same time and temperature schedule and vary considerably in stress between one another and from replicate 2. This basic schedule has been proven, though, in the SDR tests as being a suitable drying schedule when combined with equalizing.

High-temperature treatments 3 and 4 resulted in stress levels that were intermediate among the high-temperature treatments and not related to either the green center stresses or the control stresses.

The overall average stress for high-temperature was nearly 100 psi (69 MPa) less than controls 1 through 4 and nearly 600 psi (414 MPa) less than green centers 1 through 4 (Table 3), indicating a substantial reduction in stress.

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[4] High-temperature is generally defined as being at or above 212 F (100 C).

Equalizing.—The equalizing treatments resulted in the lowest average stress of all treatments. It is difficult to tell if there is really a trend in reduced stress due to increasing equalizing time. Treatments 5 through 7 show decreasing stress levels but treatment 8, with the longest equalizing time, has the highest level of stress. The green center 8 stress is also the highest for green centers 5 through 8, but the others are not correlated to the equalized treatments. There is also no correlation with control stress levels.

The overall averages (Table 3) indicate about 100 psi (69 MPa) less stress for equalized treatments compared to controls 5 through 8, and about 700 psi (483 MPa) less compared to the green centers. The equalized treatments were also nearly 100 psi (69 MPa) less in stress than the high-temperature treatments, and 200 psi (138 MPa) less than controls 1 through 4, which were dried at a maximum temperature of 180 F (82 C).

It was hoped, at the beginning of this research, that definite, correlated effects of temperature and equalizing time on stress would be found. This has not been done. It appears that drying between 200 F (93 C) and 295 F (143 C) results in substantial stress reduction with yellow-poplar. It also appears that some degree of equalizing, beyond high-temperature drying, or complete drying at equalizing conditions, further reduces stress.

Implications.—In this study we have verified the evidence of longitudinal growth stress relief reported by Maeglin and Boone (1983) based on warp allowance in STUD-grade structural lumber (Northern Hardwood and Pine Assoc. 1978).

The question may be asked: What level of stress is required to cause an 8-foot (2.4 m)-long, STUD grade, nominal 2 × 4 to warp the allowable amount (¼ in. (6.4 mm) in crook and ¾ in. (19 mm) in bow)?

If one assumes that a stud, warping due to growth stress relief, is similar in its reaction to a 2 × 4 loaded uniformly throughout, an answer may be obtained by using the formula:

$$S = \frac{24\ Eh\sigma}{5\,\ell^2}$$

where

S = stress (psi)
E = modulus of elasticity (psi)
h = depth of the piece in the direction of test (in.)
σ = deflection (in.)—i.e., ¼ in. in crook, ¾ in. in bow
l = length of piece (in.)

For an 8-foot (2.4-m) 2 × 4 with a modulus of elasticity (E) of 1.78 million psi (1.23 million MPa), the average for study strips, the stress needed to warp the piece ¼ in. in crook would be 811 psi (559 MPa). In bow, the stress needed to warp the piece ¾ in. would be 1,043 psi (719 MPa).

In a distribution of outermost strips by stress level, only 2% of controls 1 through 4 have stresses higher than 800 psi (552 MPa). Controls 5 through 8 have only 1% of the strips above 800 psi. High-temperature treatments 1 through 4 have 3% of the strips stressed above 800 psi and equalized treatments 5 through 8 have no strips above 800 psi (Fig. 7).

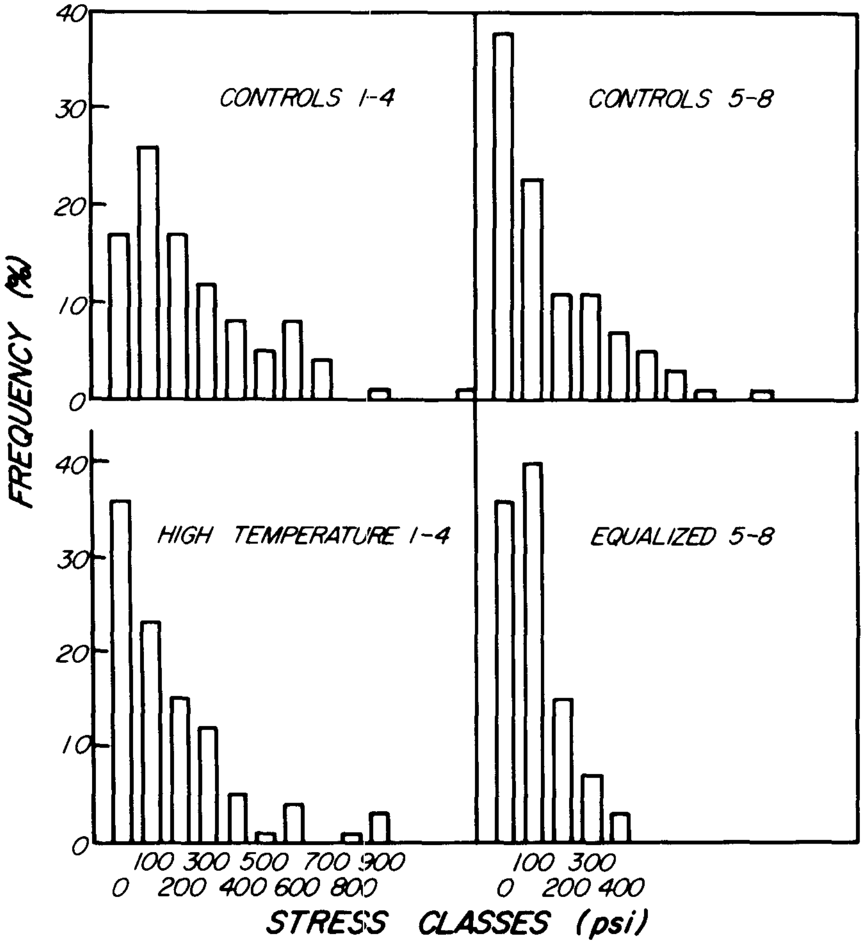

FIG. 7. Distribution of stresses by stress class for controls and treatments.

Maeglin and Boone (1983) showed that livesawn flitches dried at conventional temperatures (<180 F, 82 C) produced 2% rejects in 2 × 4's. The results of this study also suggest a potential 2% rejection rate. Maeglin and Boone also show no rejects for livesawn material dried at high-temperature and equalized. The results of this study, again, verify the previous work, for the equalized treatments 5 through 8 suggest a potential for no rejects.

SUMMARY AND CONCLUSIONS

This study was conducted to evaluate the effects of various drying conditions on stress relief in yellow-poplar. It was based on earlier work on the Saw-Dry-Rip (SDR) process for making structural lumber from hardwoods.

Longitudinal growth stresses cause excessive warping in sawn hardwood lumber of smaller construction sizes—e.g., 2 × 4's. The SDR process has shown that these stresses can be minimized by livesawing flitches, drying the flitches, and then ripping studs. High-temperature drying and equalizing result in even more stress relief.

For this study, small logs were sawn into flitches for evaluation of total stress levels in the green condition and of dried stress levels. One group of logs was processed to evaluate the effects of four drying temperature levels. Another group of logs was processed to evaluate the effects of four equalizing times.

Stress levels of individual strips varied from 0 to 1,350 psi. The high average stresses were about 525 psi for green center flitches. The low averages were about 140 psi for the equalized treatments.

There were no well-correlated relationships between the various high-temperatures and final stress levels, nor were there well-correlated relationships between initial green stresses and final, dried stress levels.

High-temperature drying at 240 F (116 C) for 28 h followed by 20 h of equalizing produced the lowest stress levels. The equalizing trials were not consistent in results and not correlated with green center flitch stresses.

The anticipated results of clearly correlated relationships to show optimum temperatures and equalizing times were not realized. The results do verify the stress-reducing effects of high-temperature drying and the further stress-reducing effects of equalizing.

Further research may be advantageous to determine optimum conditions. Several items should be considered.

1. To reduce variation, logs should be of uniform diameter and age, from the same or similar sites, and from the same position in the tree.
2. All flitches should be of the same thickness.
3. All flitches should be randomly selected for green measurement and drying conditions.
4. Flitch length should be measured in the log before sawing, measured in the flitch before stripping, and finally measured in the strip.
5. Cant sawing or other non-livesawing techniques should be evaluated for their effects on residual stresses.
6. After drying trials, flitches should be conditioned to ensure uniform MC, and should be measured under controlled conditions of temperature and humidity.

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APPENDIX

FPL Schedule T11-D4 for Drying Yellow-Poplar

Moisture content (%)	Dry bulb (°F)	Wet bulb (°F)	Depression (°F)
50	150	143	7
	150	140	10
50–40	150	135	15
40–35	150	125	25
35–30	160	120	40
30–25	160	110	50
25–20	170	120	50
20–15	180	130	50
15–0			

Condition and equalize, as necessary.