MECHANISM OF CROOK DEVELOPMENT IN LUMBER DURING DRYING

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ABSTRACT

Crook can cause yield and grade loss in lumber. In this study the mechanism of crook was studied so that a better understanding might lead to methods for minimizing its development. Crook was observed to begin at an average moisture content of about 50%, and then to increase linearly as moisture content decreases. Differential longitudinal shrinkage on opposite edges of boards is shown to be the cause of crook. A model was developed to predict crook from differential longitudinal shrinkage, and experimental results agree with model predictions. The model was extended so that estimates can be made of the restraining force necessary to prevent crook.

Keywords: Drying, warp, crook, bow, oak, drying stresses, longitudinal shrinkage.

INTRODUCTION

Crook and other forms of warp that develop in lumber during drying can cause significant losses due to reductions in grade and yield. The purpose of this investigation was to observe some of the basic phenomena associated with crook development during drying red oak lumber and develop an analytical model to predict crook and the forces necessary to restrain it. Such basic information should prove useful in further research in warp restraint or in the design of restraint systems.

Hsu and Tang (1974) categorize stresses and distortion from moisture changes as resulting from three causes: (1) inhomogeneity of the properties of wood, (2) nonuniform distribution of moisture content, and (3) cylindrical anisotropy of wood. For example, if longitudinal shrinkage is greater on one edge or face of a board, then crook, bow, or twist may develop. If one face of a board loses moisture faster than the opposite face, cup may develop. Growth ring curvature can also cause cup, particularly in wide boards or boards cut from small diameter trees where the radius of curvature of growth rings is small. Four general approaches have been used in attempts to reduce warp: (1) restrain lumber from warping during drying, (2) saw lumber enough oversize so that warp can be machined out after drying, (3) modify drying schedules, and (4) straighten warped lumber after drying.

The first approach above is relevant to the subject of this paper and has received the most research attention. Considerable practical research has been conducted on the use of restraints to control warp, and is reviewed by Simpson (1982). Restraint methods include proper stacking, uniform board thickness, weights on

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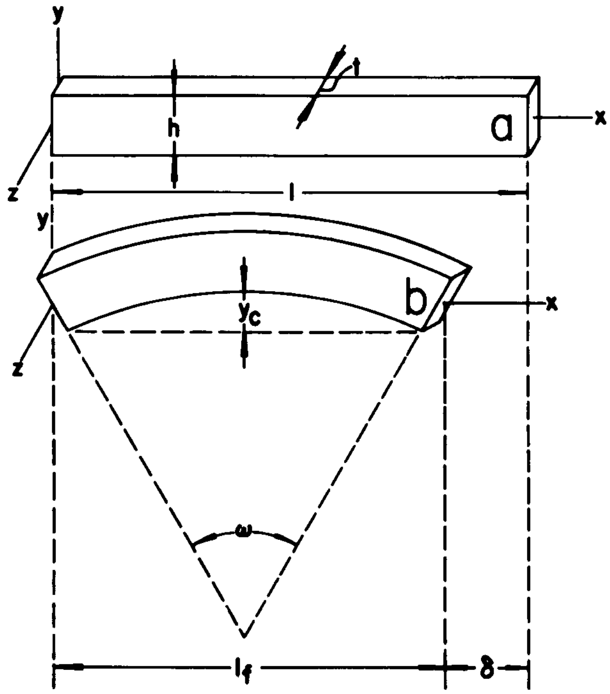

FIG. 1. Geometry of board in (a) undeformed (green) state, (b) distorted (dried) state.

top of lumber, special restraining stickers, and various spring or hydraulic clamping devices. However, relatively little research has been reported on the more basic aspects of warp development, particularly such basic considerations as estimation of the forces that would be necessary to restrain warp. Hsu and Tang (1975) developed an analytical model to estimate the force required to prevent cupping. The model is based on simple beam theory and consideration of differential radial-tangential shrinkage and growth ring curvature. The model predicts that cup (and thus necessary restraining force) increases with an increase in differential radial-tangential shrinkage and also with proximity to the pith where radius of curvature of growth rings is small.

AN ANALYTICAL MODEL FOR SHRINKAGE-INDUCED DEFORMATIONS

Problem definition

Consider an undeformed board of length ℓ, width h, and thickness t with a corresponding (x,y,z) coordinate system as shown in Fig. 1a. Define the linear shrinkage coefficient S by

$$S = \frac{\epsilon}{\Delta M} \tag{1}$$

where ϵ is engineering normal strain and ΔM is moisture content change in percent. Equation (1) is applicable only for unrestrained contraction or expansion. It can be used to determine S for a particular board location by cutting a thin strip of

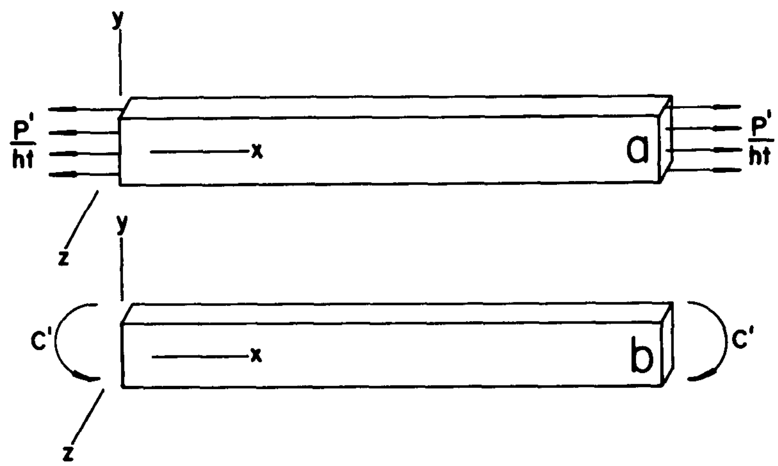

FIG. 2. Auxiliary problems for thermoelastic reciprocal theorem: (a) uniform tension, (b) uniform bending moment.

wood and measuring changes in strain as the moisture content is varied. Although the actual variation of S with board width is unknown, a linear model will be assumed to approximate the actual distribution. Therefore

$$S = (S_2 - S_1)\frac{y}{h} + (S_2 + S_1)\frac{1}{2} \tag{2}$$

where S_2 and S_1 are the shrinkage coefficients on the top ($y = h/2$) and bottom ($y = -h/2$) board faces, respectively. Only a variation of S with y will be considered in the model to be presented since this variation leads to crook deformation. However, the method presented can be directly extended to model z (bow deformation) and x variation (twist deformation) of S.

The initial moisture content of the green board, M_g, will be assumed to be constant across board width. The moisture content after drying, M_f, will be assumed to vary parabolically with y in a symmetric manner (Stamm 1964).

$$M_f = 4(M_e - M_c)\left(\frac{y}{h}\right)^2 + M_c \tag{3}$$

where M_e and M_c are local moisture contents for the dried board on the edges ($y = \pm h/2$) and center ($y = 0$), respectively. The change in moisture content resulting from drying is

$$\Delta M = M_f - M_g \tag{4}$$

The final assumption made will be to neglect the variation of Young's Modulus, E, with y during drying. Since E is related to the moisture content, the variation should be symmetric about the y axis. This effect would seem to contribute little to crook deformation. The validity of this assumption, as well as those made in Eqs. (1), (2), and (3), will be ascertained by comparison of the predicted crook with the experimentally measured crook.

Expressions for mean changes in length and end rotation

Using Eq. (1) in conjunction with Eqs. (2) and (4) will not describe the correct state of strain in the board after drying since it is valid only for unconstrained shrinkage of a thin strip of wood. The method presented in this section uses a theorem from elasticity theory to compute deformations induced by drying. By substituting α (thermal expansion coefficient) for S and T (temperature) for M, the problem defined in the previous section becomes identical to an elasticity thermostress problem. Thus, the thermoelastic reciprocal theorem (Timoshenko and Goodier 1970) can be applied. The theorem is derived rigorously from the governing differential equations of elasticity theory and it is able to compute deformations of members under arbitrary temperature loads. Application of the theorem requires consideration of the identical member under a simple (non-thermal) loading condition that produces a known state of stress in the member. Quantities associated with this auxiliary problem are denoted by being primed. The theorem states that

$$W' = \iiint (\theta' \alpha T)\, dV \tag{5}$$

where W′ is the work done by forces applied to the auxiliary problem on the actual displacements of the thermoelastic problem and θ' is the sum of the normal stresses acting in the auxiliary member, i.e., $\theta' = \sigma'_x + \sigma'_y + \sigma'_z$.

Consider the deformed shape of the board after drying as depicted in Fig. 1b. To estimate the mean length change of the board, δ, consider the board loaded in uniform tension as shown in Fig. 2a. The state of stress for this auxiliary problem is simply

$$\sigma'_x = \frac{P'}{ht}, \qquad \sigma'_y = \sigma'_z = 0 \tag{6}$$

and Eq. (5) becomes

$$P'\delta = \int_0^{\ell} \int_0^{t} \int_{-h/2}^{h/2} \frac{P'}{ht} S\Delta M\, dy\, dz\, dx \tag{7}$$

Substituting Eqs. (2) and (4) into Eq. (7) and then integrating yields

$$\delta = -\frac{\ell}{2}(S_1 + S_2)\left(M_g - \frac{2}{3}M_c - \frac{1}{3}M_e\right) \tag{8}$$

The negative sign indicates that a drop in moisture content will be associated with a decrease in board length.

In general, the dried board will also deform in a bending mode as shown in Fig. 1b. To calculate ω, the rotation of one end of the beam relative to the other, consider an auxiliary loading of the board under constant bending moment C′ as shown in Fig. 2b. For this problem (Timoshenko and Goodier 1970)

$$\sigma'_x = \frac{C'y}{I}, \qquad \sigma'_y = \sigma'_z = 0 \tag{9}$$

where I is the second area moment about the z axis. Application of the thermoelastic reciprocal theorem requires that

TABLE 1. *Constant temperature kiln schedules for drying* $^5/_4$ *oak.*

Moisture content %	Dry-bulb temperature F	Wet-bulb temperature F	Relative humidity %	EMC[a] %
		Schedule A		
Above 50	110	106	87	17.5
50–40	110	105	84	16.2
40–35	110	102	75	13.3
35–30	110	96	60	9.9
30–25	110	85	36	6.3
25–8	110	74	17	3.5
		Schedule B		
Above 50	140	136	89	16.9
50–40	140	135	87	15.8
40–35	140	132	79	13.2
35–30	140	126	66	10.0
30–25	140	113	45	6.4
25–20	140	100	25	4.1
20–8	140	95	19	3.4
		Schedule C		
Above 50	180	177	94	17.3
50–40	180	176	91	15.5
40–35	180	174	87	13.3
35–30	180	168	75	10.1
30–25	180	154	52	6.4
25–20	180	135	30	3.8
20–8	180	130	26	3.3

[a] Equilibrium moisture content.

$$C'\omega = \int_0^{\ell} \int_0^{t} \int_{-h/2}^{h/2} \frac{C'y}{I} S\Delta M \, dy \, dz \, dx \tag{10}$$

Substitution of Eqs. (2) and (4) into Eq. (7) yields after integration

$$\omega = \frac{\ell}{h}(S_1 - S_2)\left(M_g - \frac{2}{5}M_c - \frac{3}{5}M_e\right) \tag{11}$$

From Eqs. (8) and (11), it is clear that length change is proportional to ($S_1 + S_2$) while bending deformation is proportional to ($S_1 - S_2$). Thus, the model predicts that a board with shrinkage coefficients that are constant across the width (i.e., $S_1 = S_2$) will change length but not bend. It should also be noted that the method presented can be applied when more accurate expressions are available for the distributions of S and M_f with y. For instance, by experimentally determining the value of S at $y = 0$ in addition to $y = \pm h/2$, a parabolic approximation could be used for S instead of the linear one used in Eq. (2). A more precise expression for the variation of M_f with y can be obtained using the finite element method as done by Thomas et al. (1980).

Expression for crook

To estimate the amount of crook developed during drying, an assumption must be made about the characteristic shape of the deformed board. Under the standard assumptions of beam theory, the deflection v of the beam centerline (y = 0) can be determined from

$$\frac{d^2v}{dx^2} = \frac{-C(x)}{EI} \tag{12}$$

where C(x) is the resultant bending moment about the z axis at a given x. In modeling the oak board, both the shrinkage coefficient and moisture content have been assumed to vary with width (y) but to be independent of length (x). Thus, it is consistent to assume that the deformed shape of the board can be approximated by Eq. (12) with the bending moment C independent of x (constant). Integration of Eq. (12) twice and use of the following boundary conditions yield an equation for v in terms of ω. The boundary conditions are

$$\begin{aligned} v &= 0 \quad &&\text{at} \quad x = 0 \quad \text{and} \quad x = \ell \\ \frac{dv}{dx} &= \frac{\omega}{2} \quad &&\text{at} \quad x = 0 \\ \frac{dv}{dx} &= \frac{-\omega}{2} \quad &&\text{at} \quad x = \ell \end{aligned} \tag{13}$$

which leads to

$$v = \frac{\omega}{2\ell}(x\ell - x^2) \tag{14}$$

The maximum centerline deflection occurs at $x = \ell/2$ and it differs negligibly from the crook, y_c, as measured on the bottom board face as shown in Fig. 1b. Therefore

$$y_c = \frac{\omega \ell}{8} \tag{15}$$

Substitution of Eq. (11) into Eq. (15) yields the desired relation

$$y_c = (S_1 - S_2)\left(M_g - \frac{2}{5}M_c - \frac{3}{5}M_e\right)\frac{\ell^2}{8h} \tag{16}$$

For the special case when the moisture gradient can be neglected in the dried board, i.e., $M_f = M_c = M_e$ Eq. (16) becomes

$$y_c = (S_1 - S_2)\left(M_g - M_f\right)\frac{\ell^2}{8h} \tag{17}$$

EXPERIMENTAL

The experiment measured crook and corresponding average moisture content in lumber at periodic intervals during drying at three temperatures, modulus of elasticity (MOE) in bending and cross-sectional dimensions (at two temperatures) at the same periodic intervals, and the longitudinal shrinkage coefficients of strips cut from opposite edges of the boards.

The experimental material consisted of 40 pieces of green 5/4 oak (mixed red and white) 3 inches wide by 8½ feet long. The boards were divided into three groups for kiln-drying at the three constant-temperature schedules (110, 140, 180 F) shown in Table 1. Each board was end trimmed and moisture sections were taken,

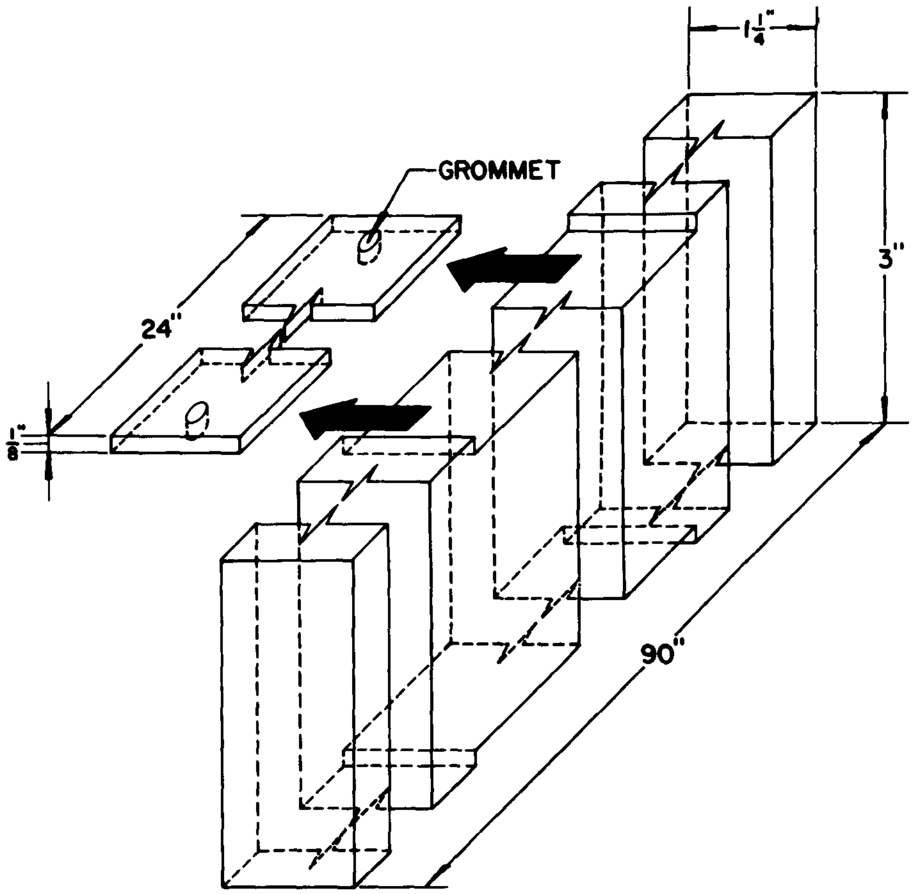

FIG. 3. Schematic showing preparation of strips for measurement of longitudinal shrinkage.

leaving 7½-foot-long boards. Before kiln-drying, each board was weighed, the cross-sectional dimensions were measured, and initial crook was measured. Crook was measured with wedge gages on a flat table made especially for warp measurement. These measurements were repeated periodically during drying to approximately 7% moisture content. In addition, periodic estimates were made of the MOE in bending on four boards at both 110 and 140 F. The boards were loaded on edge (with a 20-lb weight) as simply supported beams with center-point loading (78-in. span). Deflection was measured to the nearest 0.001 inch. Because of difficulties in making these measurements at 180 F, modulus was estimated at 110 and 140 F only. After kiln-drying, each board was oven-dried for exact moisture-content calculations.

Because differential longitudinal shrinkage is suspected to be a major cause of crook, measurements were made of longitudinal shrinkage of the opposite edges of the boards. After the boards had been oven-dried, strips 24 inches long by ⅛ inch thick were cut from the concave and convex edges of the boards (Fig. 3). In each strip two grommets were inserted 20 inches apart for placement of a gage

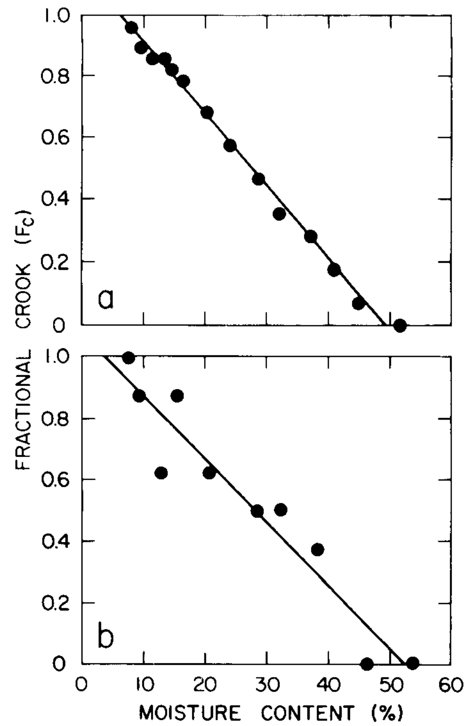

FIG. 4. Examples of linear relationship between crook and moisture content: (a) good correlation ($F_c = 1.141 - 0.02335MC$, correlation coefficient = −0.995), (b) poorer correlation ($F_c = 1.078 - 0.02088MC$, correlation coefficient = −0.957).

to measure distance between grommets. The strips were equilibrated at first 90 and then 30% relative humidity at 80 F and finally oven-dried. Weight and distance between grommets were determined at each equilibration condition.

RESULTS

When plots of crook versus moisture content were made, it became apparent that the relationship could be adequately described as a linear function. Fig. 4 shows typical plots—one of the best relationships (correlation coefficient = −0.995) and one of the poorest relationships (correlation coefficient = −0.957)—of crook versus average moisture content. The average correlation coefficient was −0.980. Crook is described in fractional terms as follows so that the varying amounts of crook in different boards could be put on a common basis:

$$F_c = \frac{C}{C_f} \qquad (18)$$

where

F_c = fractional crook
C = crook
C_f = final (total) crook.

TABLE 2. *Individual values of total crook observed in drying oak boards.*

	Temperature		
	110 F Total	140 F Total	180 F Total
	In.		
	1.094	0.313	0.438
	0.625	0.250	0.844
	0.875	0.594	0.344
	0.250	0.594	0.688
	0.250	0.125	0.250
	0.344	1.531	0.219
	0.344	0.500	0.844
	0.250	0.188	0.563
	0.188	0.438	0.750
	0.281	0.313	0.156
	0.375	0.531	1.344
	0.250	0.219	0.375
	0.250	0.906	—
	0.719	0.688	—
Average	0.435	0.513	0.568

The three intercepts 50.2, 50.4, and 54.5% moisture content represent the moisture contents at which crook began to develop at the three experimental temperatures. The values are very close together and are not significantly different statistically, so drying temperature apparently does not affect the moisture content at which crook begins to develop.

Total values of crook at each drying temperature are listed in Table 2. Total crook (maximum) averaged 0.435, 0.513, and 0.568 inch, respectively, for 110, 140, and 180 F drying temperatures, which would indicate an increase in total crook with drying temperature. However, there is a wide variability in individual values of total crook (Table 2), and analysis of variance does not show a statistically significant effect of drying temperature on crook.

Comparison of model with experimental measurements

The distance between grommets on the strips cut for determination of longitudinal shrinkage coefficients was measured at approximately 18, 6, and 0% moisture content. These distances were fitted by least squares to a linear model with moisture content and then converted to strains using 30% moisture content (approximate fiber saturation point) as the original length. The resulting plots of compressive longitudinal strain versus moisture content are shown in Fig. 5. The strip shrinkage tests were not conducted at the temperatures used in the drying runs of the whole boards (180, 140, 110 F), so no temperature comparisons can be made. The data presented in Fig. 5 are the average shrinkage values of strips cut from boards dried at all three temperatures. Because shrinkage data for strips were not taken at the same temperatures as the boards were dried, no exact test of the crook model is possible. However, any effect of temperature on longitudinal shrinkage is expected to be very small, and an approximate test of the model is possible.

From Eq. (1) it is clear that the slopes of the two lines in Fig. 5 are the average

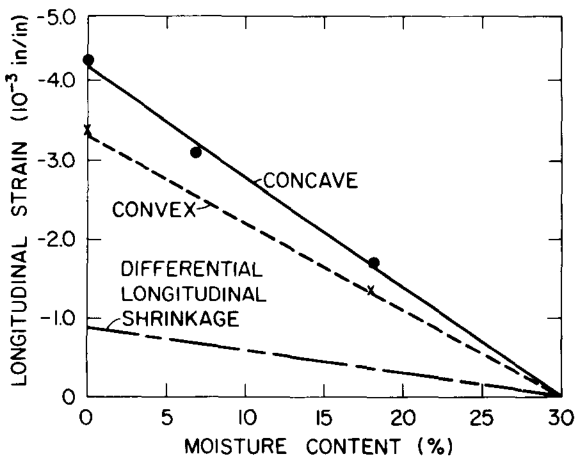

FIG. 5. Longitudinal shrinkage of strips cut from the concave and convex edges of boards with crook.

values of the shrinkage coefficients on the concave and convex edges of the boards. Thus

$$S_2 = 0.000111 \text{ in./in. per } \Delta M\ (\%)$$

$$S_1 = 0.000140 \text{ in./in. per } \Delta M\ (\%) \qquad (19)$$

To determine average crook, the moisture content will be assumed uniform for the dried board, i.e., Eq. (17) will be used. The average values for M_g and M_f from the tests are 51.7 and 7.0%, respectively. The value of h at the end of drying is 2.91 inches. Using these values, Eq. (17) predicts an average crook of 0.451 inch as compared to the experimental average (of values at 110, 140, and 180 F) of 0.505 inch. This agreement seems quite good especially considering the simplicity of the developed model.

It seems likely that the different drying schedules used in this study would promote different moisture profiles in the dried boards. Characterization of these profiles is possible through determination of the moisture content of the center (M_c) and edges (M_e) of the dried boards by experimental or numerical techniques. Using this information in Eq. (16) theoretically predicts the effect of drying schedule on crook development.

With the assumption that the model of Eqs. (16) and (17) can approximate crook, some generalizations can be made on the effect of board dimensions on crook development. This general effect is illustrated in Fig. 6, where crook is shown as a function of board width and length. As one would expect from practical experience, crook increases as length increases and width decreases. The predicted increase varies with the square of board length and the reciprocal of width.

Force required to restrain crook

Before warp restraint systems can be designed, it is necessary to know the forces required to prevent warp. Suppose a board has a maximum crook deflection of y_c occurring at $x = x_0$ (see Fig. 1 for definition of coordinates). The force necessary

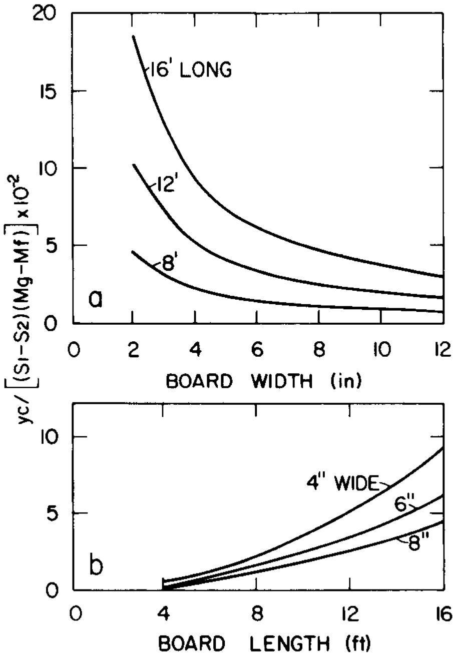

FIG. 6. Effect of board width (a) and board length (b) on crook.

to prevent crook can be estimated from beam mechanics by the following procedure. Assume that this force is the same as the force required to deform a simply supported straight board so that its maximum deflection equals y_c and occurs at $x = x_0$. Then, using this assumption and taking $x_0 = \ell/2$ as in the presented crook model, simple beam theory predicts the force P required to prevent crook to be

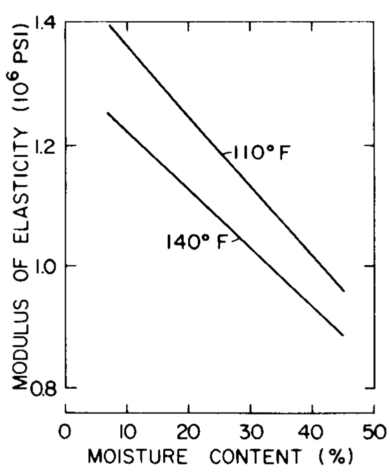

FIG. 7. Linear regression estimate of modulus of elasticity in bending of oak boards as a function of moisture content during drying.

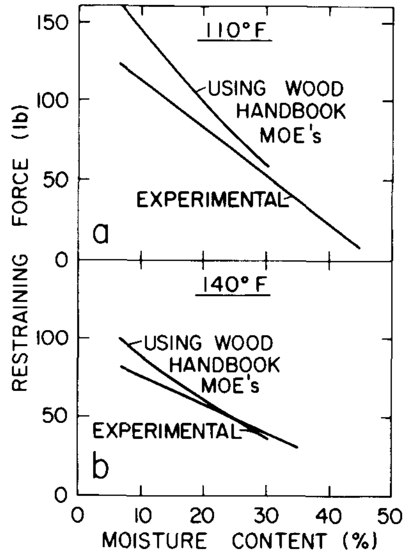

FIG. 8. Relationship between moisture content and force necessary to restrain crook in oak boards dried at constant temperatures of (a) 110 and (b) 140 F.

$$P = \frac{4Ey_c th^3}{\ell^3} \tag{20}$$

where

P = force (lb) applied at $x = \ell/2$
E = modulus of elasticity in bending (psi)
y_c = maximum crook deflection (in.)
t = beam thickness (in.)
h = beam width (in.)
ℓ = distance between supports (in.)

Although beyond the scope of the presented crook model, the authors also derived a more general equation which includes the case where maximum crook deflection, y_c, occurs at an arbitrary point, x_0, rather than the midpoint

$$P = \frac{3\sqrt{3}Ey_c th^3 \ell}{4a(\ell^2 - a^2)^{3/2}} \tag{21}$$

where

P = force (lb) applied at x = a

and

$$a = \sqrt{-2\ell^2 + 6x_0\ell - 3x_0^2}$$

The validity of Eq. (21) does depend upon x_0 being between 0.423ℓ and 0.577ℓ. If x_0 is not in this range, more than one force is required to attain a maximum

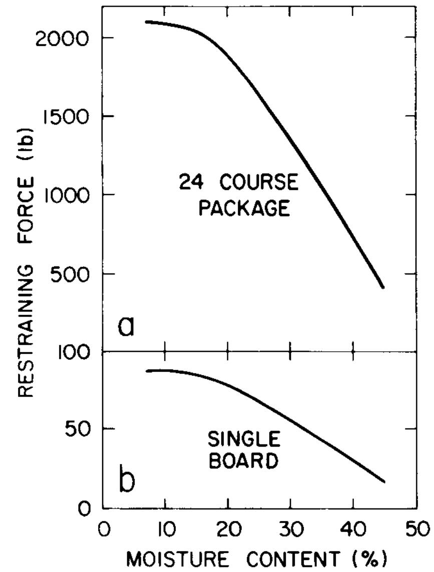

FIG. 9. Relationship between moisture content and force necessary to restrain crook in (a) a 24-course package of lumber dried by a conventional kiln schedule, T4-D2(111), and (b) a single oak board.

deflection of y_c at $x = x_0$. When $x_0 = \ell/2$, i.e., when maximum crook deflection is at the midpoint, Eq. (21) reduces to Eq. (20).

The MOE measured on the boards during drying is shown as a function of average moisture content in Fig. 7. The graphs represent the averages of all measured boards at each temperature. The relationship is linear, in contrast to the exponential relationship usually found between mechanical properties and equilibrated moisture content (USDA 1974). The effect of temperature on modulus is the same as that predicted by the adjustment graph of the Wood Handbook (USDA 1974). Both the Wood Handbook adjustment and the experimental results show that MOE at 140 F is approximately 90% of the value at 110 F. Similar results were found by Gerhards (1982).

Knowing MOE, maximum deflection (crook), beam dimensions, and how they vary with moisture content during drying, Eqs. (20) and (21) (in some boards maximum crook was not at midpoint) can be used to estimate the force required to restrain crook. Figure 8 shows the relationship between restraining force and average moisture content based on the drying temperatures, crook developed, MOE, and dimensions of the boards used in this study. Also included in Fig. 8 is the restraining force calculated using Wood Handbook values of MOE for oak and adjustments for moisture content and temperature. The values calculated from experimental MOE's and crook deflections vary linearly with moisture content. The forces calculated by substituting Wood Handbook values of MOE become increasingly greater than experimentally calculated values as moisture content decreases. Wood Handbook MOE's are based on equilibrated specimens, whereas the MOE's determined in this study are based on average moisture contents and include the effects of moisture gradients during drying. The results in Fig. 8 suggest that the core, which is at a higher moisture content than the average, and the shell, which is at a lower moisture content than the average, cause the MOE values to be different than what would be expected of material equilibrated to that average moisture content.

Because temperature influences MOE, the restraining forces determined at constant drying temperature (Fig. 8) do not apply to drying by a kiln schedule where temperature is changed a number of times during drying. Using the temperatures of a conventional kiln schedule for oak, MOE was adjusted appropriately. Restraining force was calculated and is shown in Fig. 9. The effect of the high final temperature of 180 F is shown by the leveling of the curve below 15% moisture content. Modulus of elasticity is reduced enough at 180 F that the restraining force no longer increases as moisture content decreases.

Equations (17) and (20) can be combined to derive an expression for restraining force in terms of the differential shrinkage, without knowing crook. The assumption is made that the moisture content is independent of y for the dried board, i.e., a uniform moisture content such as would occur after drying. By substituting Eq. (17) into Eq. (20), the resulting expression for restraining force is:

$$P = \frac{Eth^2}{2\ell}(S_1 - S_2)(M_g - M_f) \qquad (22)$$

SUMMARY AND CONCLUSIONS

Crook in oak lumber was investigated so that a better understanding might lead to methods for minimizing its development. Crook begins at an average moisture content of about 50% and increases linearly as moisture content decreases. Drying temperature does not affect the moisture content at which crook begins. There is some evidence that the total amount of crook increases with drying temperature, but the increase is not statistically significant. Differential longitudinal shrinkage on opposite edges of boards that developed crook is shown to be the cause of crook. A model was developed to predict crook from differential longitudinal shrinkage, and experimental results agree with the model predictions. The model was extended so that estimates can be made of the restraining force necessary to prevent crook from forming. Because of the dependence of modulus of elasticity on temperature and moisture content, the restraining force is also highly dependent on temperature and moisture content.

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