Steam-Bending Properties of Southern Pine

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Abstract

Southern pine wood can be successfully steam-bent if the bending jig incorporates a flexible metal bending strap together with a mechanism to apply a uniform end-compression load during the bending operation. With clear, 1/2- and 1-inch-thick southern pine at 17-percent moisture content, highest bending ratings were obtained with fast-grown, vertical-grain, low-density wood free of cross grain. With this optimum stock (cross grain—as measured by the maximum angle that resin canals on either edge made with face of stock—averaged 3.5°) bent to a radius of 12 times thickness, 75 percent of the 1-inch specimens and 80 percent of the 1/2-inch specimens had bending ratings of 8 or above on a scale that ran from 0 (worst) to 10 (best). With optimum stock bent to a radius of 12 times thickness plus 3 inches, 85 percent of the half-inch and 68 percent of the 1-inch specimens rated 9 or 10. To obtain 75-percent yield of near perfect pieces, a bending radius of about 16 times thickness was required. A steaming time of 20 minutes per inch of thickness was adequate. Placement of pith side of specimen—toward or away from concavity—had no significant effect on the bending ratings. When restraint was removed from specimens previously bent 180° over a semicircular form and dried under restraint, immediate increase in diameter averaged 0.5 inch. If then stored unrestrained in a water-saturated atmosphere, they further increased substantially in diameter (average of 2.5-inch increase after 4 weeks' exposure). If stored unrestrained in a dry atmosphere for 4 weeks, however, specimens contracted slightly (0.2 inch). Best stability was obtained with vertical-grain wood steamed 20 minutes (compared to 10 minutes) per inch of thickness. One-half-inch stock bent to a 6-inch radius was more stable than if bent to a 9-inch radius; it was also more stable than 1-inch stock bent to a 15-inch radius.

For many purposes, bending wood over a curved mold is preferable to machining it. Bending processes are quick and simple, require little power, and do not waste wood as chips or shavings. The resulting bent wood is generally stronger and stiffer than wood machined to the same contour. Major disadvantages are loss of wood by breakage and a tendency of the bent stock to lose some of its curvature when exposed to humid conditions.

The concave surface of a bent stick is shorter than the convex surface. Solid wood therefore can be permanently bent only when plastic enough to take and retain the proper amount of compressive deformation. Exposure to heat and moisture is an effective plasticizing treatment.

The most complete discussion of the bending process appears to be that of Stevens and Turner (1948). Less extensive reviews include those by Wangaard (1952), Kubler (1957), Jorgensen (1965), and Kollmann and Cote (1968). Stress distributions during bending are discussed by Peck (1968, pp. 31-37). Peck also notes (p. 4) that hardwoods can be steam-bent more successfully than coniferous woods. He lists 25 hardwoods in descending order of bending quality; the top half of the list includes hackberry (*Celtis* spp.), white and red oaks (*Quercus* spp.), chestnut oak (*Quercus prinus* L.), magnolia (*Magnolia grandiflora* L.), pecan (*Carya illinoensis* (Wangenh.) K. Koch), black walnut (*Juglans nigra* L.), hickory (*Carya* spp.), beech (*Fagus grandifolia* Ehrh.), American elm (*Ulmus americana* L.), willow (*Salix* spp.), yellow birch (*Betula alleghaniensis* Britton), and white ash (*Fraxinus americana* L.).

Stevens and Turner (1948) list the minimum radius of curvature to which various species can be formed without breaking more than 5 percent of the pieces. They give the radii listed below as applicable to air-dry, 1-inch-thick wood of good bending quality—steamed at atmospheric pressure and bent with a tension strap:

	Minimum radius of curvature
	Inches
Hardwoods	
Dutch elm (*Ulmus hollandica* var. *major*)	0.4
White oak	1.0
Yellow birch	3.0
European beech (*Fagus sylvatica*)	4.0
American ash	4.5
Softwoods	
Caribbean pine (*Pinus caribaea* Morelet)	14.0
European spruce (*Picea abies*)	30.0

The research reported in this article was limited to determining the kind of southern pine wood that can be most successfully steam-bent. Some relationships affecting the percentage of specimens surviving the bending operation were observed, and changes in radius of unrestrained bent specimens were related to changes in service humidity conditions.

Strength properties were not measured, but research on hardwoods has indicated that specimens steam-bent to small radii have substantially less strength in flexure than matched straight specimens (Wangaard 1952), and less flexural strength and stiffness than wood laminated from thin strips into a bend of equal radius (Luxford and Krone 1962). According to Luxford and Krone (1962), however, steam-bent oak boat frames will absorb several times more impact energy than similar laminated frames.

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Preliminary Experimentation and Factors Selected

Preliminary experimentation with 1/2- and 1-inch stock indicated that the probability of a successful bend was greatest when the specimen had been first conditioned to about 17-percent moisture content and then steamed for a short time. Steaming times of 10 minutes and 20 minutes per inch of thickness appeared to be sufficient; longer times generally resulted in an excess of both tension and compression failures.

Pre-bending treatments rejected as less desirable than steaming included soaking the specimen in water until saturated (with or without subsequent steaming) and boiling in water (starting from a 10-percent moisture content or from a saturated condition). Steaming under pressure was not attempted, since the literature indicates it is less effective than atmospheric steaming.

Specimen thicknesses of 1/2 and 1 inch were selected because these thicknesses can be readily bent with simple hand equipment.

Bending radii were chosen, after preliminary trials, so that most (but not all) of the specimens would survive when formed to the largest radius, and would break when bent to the smallest radius.

Preliminary trials also showed that a tension strap is an essential part of the bending jig (Fig. 1). Steaming greatly increases compressibility of wood parallel to the grain but not its ability to elongate under tension. The tension strap, by uniformly applying an end load during the bending operation, reduces breakage by decreasing tension stress in the convex side of the specimen. To insure that pre-stress compression force was applied principally to the convex side, both ends of specimens were beveled to midthickness (Fig. 1).

A stratified random sample of 1-1/2-inch-wide S4S southern pine wood was collected from sawmills and retail yards in central Louisiana. Most specimens were probably loblolly pine, but some shortleaf, longleaf, and slash pine wood was included. Study variables were:

1) Thickness: 1/2-inch and 1 inch.
2) Rings per inch: either less than six or more than six, determined by averaging the count on each end; both ends of each specimen had to show less (or more) than six rings per inch to qualify for the fast (or slow) growth class.
3) Specific gravity (ovendry volume and weight): either less or more than 0.58.
4) Orientation of annual rings: flat grain or edge grain. Flat-grain pieces had annual rings that made an angle averaging 40° or less with the face of the specimen; edge grain called for a 50° or greater angle.

5) Radius of curvature, inches: 12t − 3 inches, 12t, and 12t + 3 inches; where t = specimen thickness in inches.
6) Time steamed at atmospheric pressure before bending: 10 and 20 minutes per inch of specimen thickness.
7) Replications of factors: two.
8) Replications of specimens within each factor replication: ten.

Thus, the experiment required 1,920 specimens: (2 thicknesses) (2 growth rates) (2 specific gravities) (2 orientations of rings) (3 radii of curvature) (2 steaming times) (2 replications of factors) (10 replications of specimens).

Only knot-free, sound, and straight-grained specimens were selected. Specimens were cut just long enough to permit end-clamping and bending around a semicircle of the selected radius.

While not a primary factor in the experiment, the maximum angle between resin canals exposed on the edge of each specimen and the face (resin canal angle) was observed as an indicator of cross grain. Both edges were measured, and the largest angle was recorded.

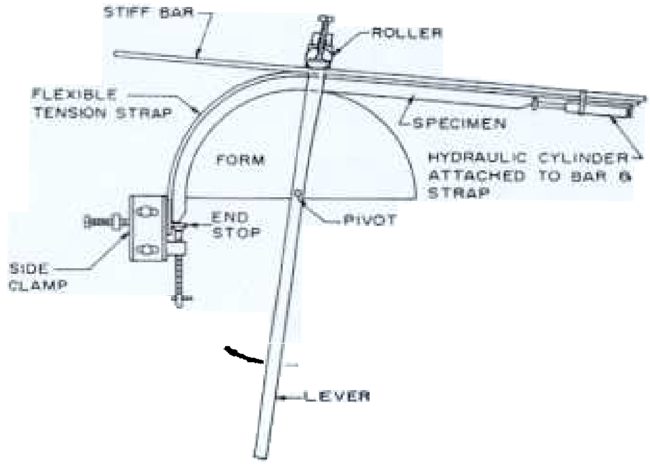

Figure 1. — End load applied through a flexible metal tension strap preloads the specimen in compression as it is being bent, thus reducing tensile stress on the convex side.

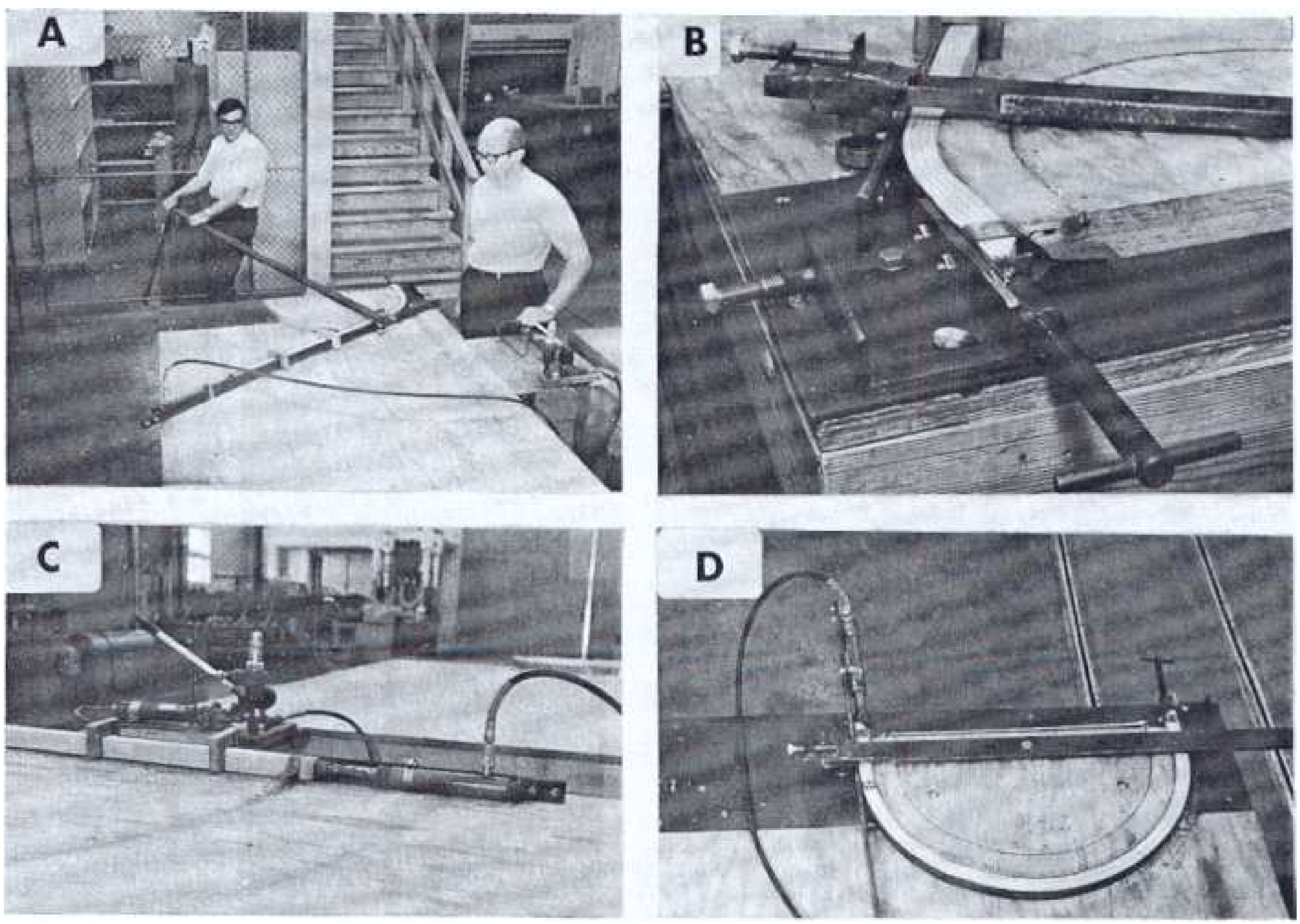

Figure 2. — Bending jig with 1-inch-thick specimen in place. (A) As the lever bar is moved around its pivot, a constant end load is maintained by means of a hydraulic cylinder. Two removable plywood clips to prevent specimen bow are visible. (B) End clamp. The thin metal band running around convex side of specimen is attached to the hydraulic cylinder. Pivoted lever bar with ball-bearing pressure point is shown rolling over the thick steel bar also attached to the hydraulic cylinder. (C) Hydraulic pump, cylinder, and pressure controlled by-pass valve for application of controlled force to reduce tension in convex side of specimen. (D) Specimen bent in full semicircle and ready for removal. Retaining rod is secured to metal end clips visible in Figures 2B and C.

Bending direction (toward the pith or toward the bark) was at random, and was recorded after bending. While most readily determined on flat-grain pieces, it was also recorded on those classified as edge grain, because none had precisely vertical grain.

Procedure

Specimens, equilibrated to 10-percent moisture content, were cut to length, end-beveled, and placed in cool water until they picked up sufficient weight for 17-percent moisture content. They were then stored in polyethylene bags (at least 24 hours for 1/2-inch specimens and 48 hours for 1-inch specimens) to permit the moisture to diffuse into each piece.

Each was steamed over vigorously boiling water for the specified time in a vertical chamber vented through a fan at the top. The steady flow of steam appeared ample to prepare wood for bending.

Following steaming, the beveled-end specimen was quickly transferred to the bending jig shown in Figures 1 and 2. One end was firmly clamped with the screw shown on the lower left side of Figures 1 and 2B; and the ball-bearing pressure point was made "finger-tight" with the screw shown in the upper left corner of Figure 2B. Then a steady end load was applied with a hydraulic cylinder (Fig. 2C) so that the outside, or convex side, of the specimen was preloaded in compression against the screw-adjusted end stop shown in the lower right of Figure 2B. The 1/2-inch-thick pieces were given a 500-pound preload on a bearing surface of 0.375 square inch, while a 1,000-pound load was applied to the 0.750-square-inch bearing surface of the 1-inch-thick specimens. Wooden clips visible in Figures 2A, B, and C prevented bowing in the specimen.

Figure 2D shows the thin, flexible, and continuous metal tension strap that was arranged on the convex side; the strap was anchored by a clamp at one end and attached to the hydraulic cylinder on the other. One end of a thicker bar was attached to the base of the hydraulic cylinder (and the tension strap); its other end was free. A lever pivoted at the center of the semicircle rolled the pressure point over the surface of the bar, bending the strap and specimen into semicircular form (Fig. 2D). When the bend was completed, a wire retaining rod was secured to the two sheetmetal clips shown in Figure 2B and 2C; the specimen was then lifted from the jig, secured with glass filament tape so the retaining rod could be removed, and allowed to reach equilibrium in an atmosphere held at 72°F. and 50-percent relative humidity.

Twenty-four hours after removal from the bending jig, each specimen was matched against a previously selected set of 10 pieces and evaluated on a scale ranging from 0 to 10; 0 indicated total failure and 10 complete success. Rating was by a single observer, and consisted of a visual assessment of the amount of compression and tension failure. In general, only specimens rated 8 or above would be serviceable for any purpose, and a rating of 10 would be required for most applications where appearance is a ruling factor (Fig. 3).

When all bent wood had come to equilibrium at 50-percent relative humidity and 72°F., certain specimens were studied for changes in radius when subjected to different humidities.

Procedure was as follows. From the bent specimens in three categories (1/2-inch thick bent to 12-inch diameter, 1/2-inch thick bent to 18-inch diameter, and 1-inch thick bent to 30-inch diameter), it was possible to select from every factorial combination six pieces that rated 8 or better. A diameter line was drawn across each specimen while it was still restrained by the glass tape, and the inside diameter was measured. Next the restraining tape was cut and the inside diameter again measured after an elaspsed time of 10 seconds. The specimen was then weighed. Two of each set of six were then left in the laboratory at about 50-percent relative humidity, two were placed in a sealed polyethylene bag along with a water-soaked sponge, and two were sealed in a polyethylene bag together with a substantial quantity of desiccant; all were held at a dry-bulb temperature of 72°F. Diameter measurements were made weekly for 4 weeks. Finally, specimens were ovendried at 212°F., weighed, and measured for diameter. Moisture contents were calculated for each observation time.

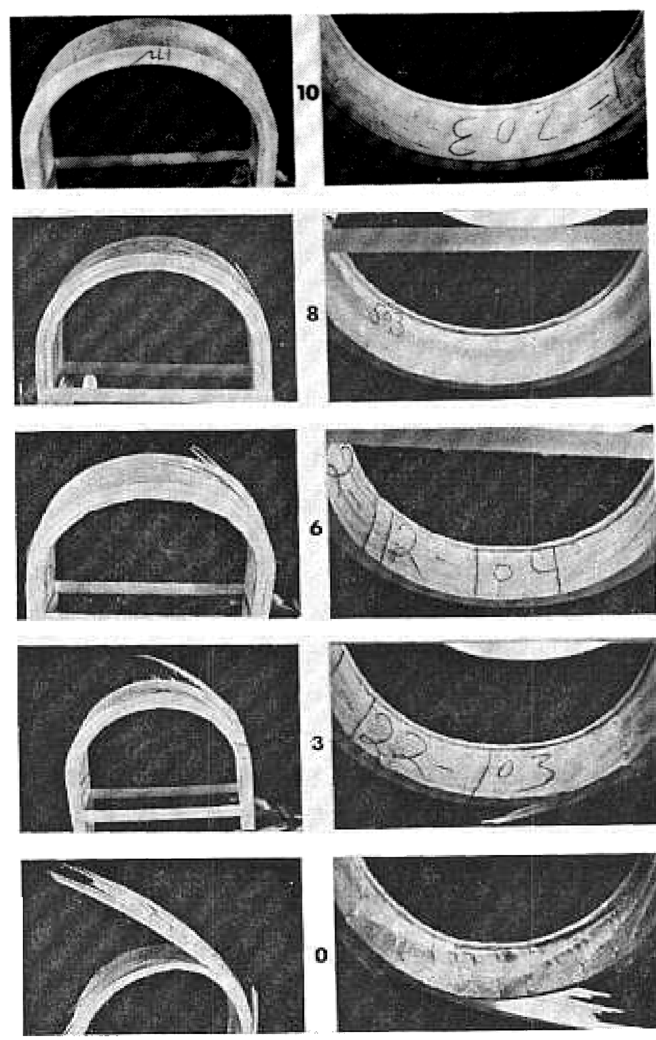

Figure 3. — Representative ratings of steam-bent southern pine. The rating scale ran from 0 (worst) to 10 (best). The ledge visible on the concave side of each specimen was caused by a too narrow form, i.e., the form should have been wider than the specimen.

Results

Average Rating

Relationships influencing the average bending rating are evident in five two-factor interactions shown to be significant by analysis of variance (Table 1, col. 2). Steaming time was not significant—alone or in combination with other factors. Specimen thickness entered into three interactions; growth rate, specific gravity, and radius of curvature each entered into two. Grain type interacted only with radius of curvature. All of these interactions are described by the following four tabulations.

Factor	Specimen thickness 1/2-inch	1 inch
Rings per inch		
Less than 6	7.1	6.5
More than 6	6.8	4.9
Specific gravity		
Under 0.58	7.1	6.4
More than 0.58	6.9	5.1
Radius of curvature		
12t − 3	4.9	4.6
12t	7.2	5.7
12t + 3	8.8	6.9

Rings per inch	Specific gravity Less than 0.58	More than 0.58
	- - - Rating -	
Less than 6	7.0	6.7
More than 6	6.5	5.3

Radius of curvature	Grain description Flat	Edge
Inches	- - - - - Rating - - - - -	
12t − 3	4.6	4.9
12t	5.6	7.4
12t + 3	7.4	8.3

These data indicate that the stock bent best if edge-grained, fast-grown, and low in specific gravity. Highest ratings were achieved with thin stock bent to large radii. Thus, low-gravity, edge-grain, fast-grown specimens gave average ratings as follows when data from both steaming times were pooled:

Specimen thickness and bending radius	Rating
Inches	
1/2-inch	
3	4.7
6	7.7
9	8.8
1 inch	
9	5.7
12	8.1
15	8.4

The interactions show that low ratings were achieved with specimens that were slow grown and thick, or dense and thick, or slow grown and dense. When bent to small radii, flat-grain specimens—or thick specimens—had particularly low average ratings.

Regression analyses, separately by each thickness, showed that no single factor—or combination of two factors—was closely correlated with average bending rating. Only the factors listed below had an r value of 0.20 or greater.

Factor correlated with bending rating	r value 1/2-inch	1 inch
Radius of curvature	0.49	0.25
Radius of curvature ÷ grain angle	.34	
Resin canal angle	− .21	
Resin canal angle squared	− .20	
Rings per inch		− .20
(rings per inch) (specific gravity)		− .26

Had thickness been tested over a greater range than 1/2 to 1 inch, it would probably have been significantly correlated.

While success in explaining the total variability in bending ratings was not notable, a multiple regression expression was selected for each thickness through use of the Rex Program (Grosenbaugh 1967). According to the equations, bending rating (average for 1/2- and 1-inch specimens was 7.0 and 5.7, respectively) can be predicted by summing the products of the coefficients and independent variables shown in Table 2. The equation for 1/2-inch-thick stock accounted for 32 percent of the variation, with standard error of the estimate of 2.8; comparable figures for the equation applicable to 1-inch specimens were 25 percent and 3.2.

Table 1. — EFFECTS OF PRIMARY VARIABLES ON BENDING RATINGS OF SOUTHERN PINE WOOD.[1]

Factor	Average rating	Percent of bent specimens with ratings of: 8,9,10	9,10	10
		- - - - Percent		
A. Replication[2]		....	....	
B. Rings per inch				
Less than 6	6.8	57	47	33
More than 6	5.9	43	34	19
C. Specific gravity[3]				
Under 0.58	6.7	55	46	28
Over 0.58	6.0	44	36	24
D. Steaming time per inch thickness				
10 minutes	6.3	49	40	26
20 minutes	6.5	51	41	26
E. Radius of curvature, inches				
12t − 3	4.7	23	17	
12t	6.5	53	42	24
12t + 3	7.9	74	63	44
F. Thickness				
1/2-inch	7.0	57	49	33
1 inch	5.7	43	33	19
G. Grain description				
Flat	5.9	42	32	17
Edge	6.9	58	50	36
Grand means	6.4	50	41	26
Significant interactions[4] (and significant factors where interactions did not involve them).			C	C
	BC	BC		
	BF	BF	BF	
	CF	CF		
	EF	EF	EF	
	EG	EG	EG	BDEFG

[1]Averages include data on all 1,920 observations; the only segregation is by the factors in column 1.

[2]Dummy factor.

[3]Basis of ovendry volume and weight.

[4]Significant at 0.01 level.

Table 2. — COEFFICIENTS AND INDEPENDENT VARIABLES IN REGRESSION EQUATIONS FOR PREDICTION OF AVERAGE BENDING RATINGS OF 1/2- AND 1-INCH-THICK SOUTHERN PINE.

Coefficient[1]		Independent variable	Average values[1]		Range
1/2-inch	1 inch		1/2-inch	1 inch	
— 3.007	1.650	(This coefficient is a constant.)			
— .2067	.0790	Rings per inch	7.130	6.980	1 - 32
.00782	.0191	Rings per inch squared	63.38	61.28	....
24.34	N.S.	Specific gravity, basis of OD vol. and wt.	0.5774	N.S.	0.35 - 0.83
—23.77	N.S.	Specific gravity squared	0.3381	N.S.	....
N.S.	—1.185	(rings per inch) (specific gravity)	N.S.	4.06	....
N.S.	.0321	Steaming time, minutes per inch of thickness	N.S.	15.0	10 - 20
.9341	.8439	Radius of curvature, inches	6.0	12.0	12t — 3 to 12t + 3
— .0323	— .0183	Radius of curvature squared	42.0	150.0	....
.0895	.0321	Grain angle (flat or edge), degrees	43.65	45.30	0 - 90
— .000870	— .000055	Grain angle squared	2813.8	2855.4	
.00239	N.S.	(radius of curvature) (grain angle)	262.47	N.S.	
— .5016	— .6284	Resin canal angle, degrees	3.394	3.592	0 - 14.1
.000650	.0166	Resin canal angle squared	15.17	16.36	
2.022	N.S.	Resin canal angle ÷ grain angle	0.1525	N.S.	

[1]N.S. means not selected by the REX process.

[2]t = specimen thickness, inch.

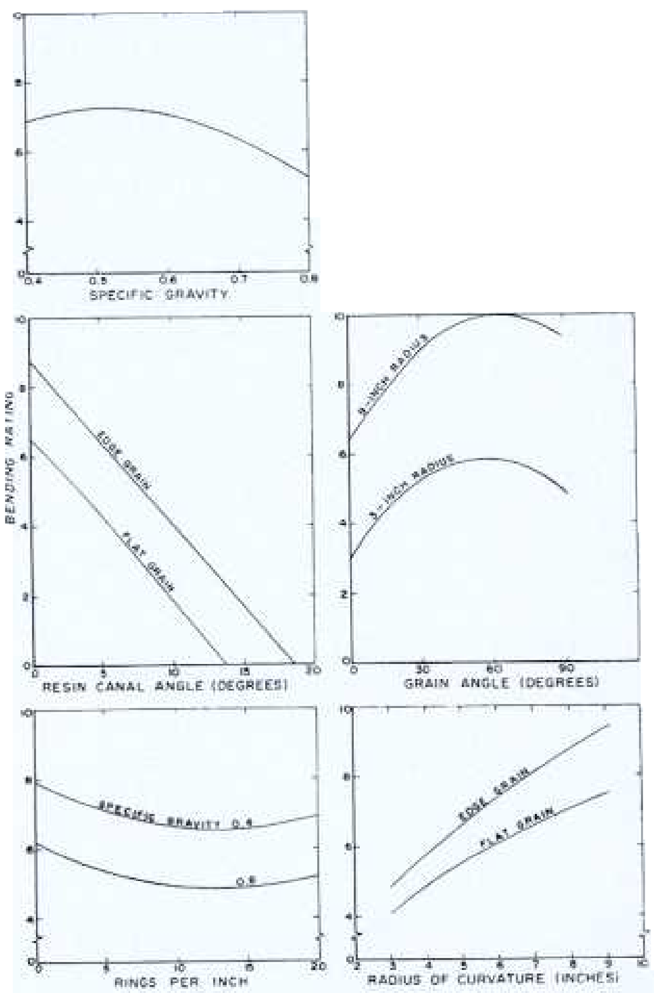

Figure 4. — Relationships, for 1/2-inch-thick southern pine specimens, between bending rating and primary factors. Curves were plotted from regression equation shown in Table 2 by holding all factors but the ones of interest at average value.

Trends indicated by the equations are plotted in Figures 4 and 5. For both thicknesses, the equations show that bending ratings were highest for specimens with specific gravity (ovendry volume and weight basis) of 0.4 to 0.5, 0° resin canal angle, and 1 to 5 growth rings per inch. While steaming time was not a significant factor for the 1/2-inch thickness, the 1-inch specimens yielded higher bending ratings when steamed 20

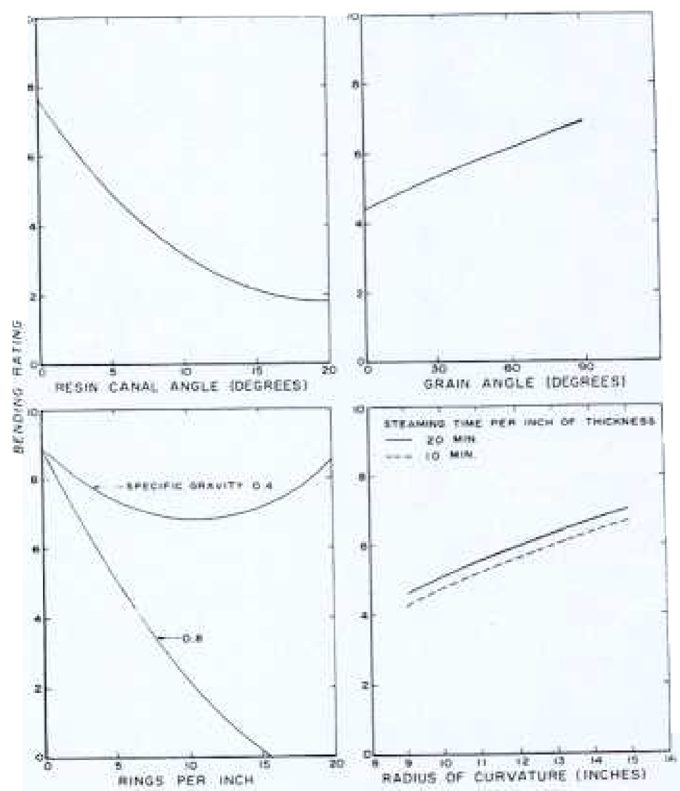

Figure 5. — Relationships, for 1-inch-thick southern pine specimens, between bending rating and primary factors. Curves were plotted from regression equation shown in Table 2 by holding all factors but the ones of interest at average value.

Table 3. — INTERACTION OF GROWTH RATE, STEAMING TIME, RADIUS OF CURVATURE, THICKNESS, AND GRAIN TYPE ON PERCENTAGE OF SPECIMENS YIELDING A BENDING RATING OF 10.

Growth rate	Steaming time	Grain type	1/2-inch thickness 3-inch radius	1/2-inch thickness 6-inch radius	1/2-inch thickness 9-inch radius	1-inch thickness 9-inch radius	1-inch thickness 12-inch radius	1-inch thickness 15-inch radius
	Min./in.		- - Percent yielding bending rating of 10 - -					
Fast	10	Flat	18	20	67	13	30	25
		Edge	15	45	60	28	30	50
	20	Flat	10	25	48	10	5	33
		Edge	18	43	78	25	48	55
Slow	10	Flat	5	5	30	0	0	8
		Edge	3	48	80	0	20	25
	20	Flat	0	3	50	0	8	0
		Edge	5	50	73	3	8	25

minutes per inch of thickness. With 1-inch specimens, high-gravity, slow-grown wood yielded very low ratings.

In summation, these data suggest that fast-grown, edge-grain, low-gravity wood without cross grain is probably the best selection for steam bending 1/2-inch and 1-inch southern pine. A steaming time of 20 minutes per inch of thickness appears to be adequate.

Porportion of Specimens Rated 8, 9, and 10

The factors that influenced the percentage of specimens rated 8, 9, and 10 were evident in five two-factor interactions shown significant by analysis of vari-

Table 4. — CHARACTERISTICS OF SOUTHERN PINE WOOD AND STEAMING TIME FOR MAXIMUM RECOVERY OF 10-RATED PIECES AFTER BENDING.

Radius of bend	Optimum characteristics and steaming time	Percent bent with rating of 10
Inches		Percent
	One-half-inch-thick specimens	
3	Fast grown, edge grain, low gravity, steamed 20 minutes per inch of thickness	25
6	Slow grown, edge grain, low gravity; steaming time not critical	48
9[1]	Slow grown, edge grain, low gravity; steaming time not critical	75
	One-inch-thick specimens	
9	Fast grown, edge grain, low gravity; steaming time not critical	30
12[2]	Fast grown, edge grain, low gravity, steamed 20 minutes per inch of thickness	40
15	Fast grown, edge grain, low gravity, steamed 20 minutes per inch of thickness	75

[1]When 1/2-inch stock was bent to a 9-inch radius, 85 percent of the edge-grain, high-gravity stock was rated 10; growth rate and steaming time were not critical. The reason for the good results with high-gravity wood at the 9-inch radius is not clear.

[2]When 1-inch stock was bent to a 12-inch radius, 55 percent of the fast-grown, edge-grain, high-gravity stock, which was steamed 20 minutes per inch of thickness, was rated 10. The reason for the relatively good performance of the high-gravity wood at this radius is not clear.

Table 5. — CHANGES IN DIAMETER OF BENT SPECIMENS AFTER EXPOSURE TO VARIOUS ATMOSPHERES.

Condition	Change in diameter from restrained condition: 1-inch thick 30-inch diameter	1/2-inch thick 18-inch diameter	1/2-inch thick 12-inch diameter
	- - - - - Inches	- - - - -	
Restrained	0.00	0.00	0.00
On release of restraint			
Those to be put in desiccator	.60	.58	.26
Those to be kept at 50-percent R.H.	.63	.67	.23
Those to be put in saturated air	.60	.68	.23
After 4 weeks of exposure			
In desiccator	.30	.52	.11
At 50-percent R.H.	.76	.96	.35
In saturated air	3.14	3.47	2.51
After then ovendrying			
Those that were in desiccator	.03	.71	.10
Those that were in 50-percent R.H.	.50	.94	.00
Those that were in saturated air	1.67	2.19	1.59

ance (Table 1, col. 3); the interacting factors were the same as those influencing average ratings.

The data indicated that, to obtain a high proportion of specimens rated 8, 9, and 10, southern pine bending stock should be edge grain, fast grown, and of low density. Obviously, greatest success will be achieved with thin stock bent to a large radius. Steaming time—considered by itself or in interactions—proved to be not significant. Among specimens with the above characteristics, ratings after bending were as follows:

Specimen thickness and bending radius	Pieces rated 8, 9, and 10
Inches	Percent
One-half inch	
3	20
6	80
9	88
One inch	
9	45
12	75
15	80

Slow-grown dense, slow-grown thick, or dense thick stock was poor; flat-grain wood, when bent to small radii, yielded few pieces rated 8, 9, and 10.

Proportion of Specimens Rated 9 and 10

Analysis of variance showed that low-gravity wood yielded more specimens rated 9 and 10 than high-gravity wood (46 percent compared to 36 percent). Three two-factor interactions revealed the influence of growth rate, thickness, and grain orientation on the proportion of specimens rated 9 or 10. The first of these involved thickness and growth rate:

Thickness	Rings per inch: Less than 6	More than 6
Inch	Percent yielding bending ratings 9 and 10	
1/2	53	45
	42	23

The remaining two significant interactions both involved radius of curvature—one with thickness, the other with grain type:

Factor	Radius of curvature 12t − 3	12t	12t + 3
	Percent yielding bending ratings of 9 and 10		
Thickness			
1/2-inch	16	51	79
1 inch	18	33	48
Grain description			
Flat	13	26	58
Edge	21	58	69

From these interactions it is concluded that the highest percentage of 9- and 10-rated specimens were bent from low-gravity, fast-grown, edge-grain wood. Steaming time was not a significant factor. With these restrictions, yield of 9- and 10-rated specimens was as follows:

Specimen thickness and bending radius	Proportion bent with a rating of 9 or 10
Inches	Percent
One-half inch	
3	20
6	70
9	85
One inch	
9	38
12	63
15	68

The interactions also show that flat-grained wood yielded few 9- and 10-rated specimens if bent to small radii. Also, slow-grown, thick specimens yielded few 9- and 10-ratings.

Proportion of Specimens Rated 10

Analysis of variance indicated that low-gravity wood yielded more 10-rated specimens than high-gravity wood (28 percent compared to 24 percent). Interactions involving growth rate, steaming time, radius of curvature, thickness, and grain type made generalization difficult, but certain patterns could be discerned (Table 3). With these patterns as the criterion, Table 4 was devised to describe the stock that yielded the highest percentage of 10-rated pieces. As the footnotes to the table indicate, high-gravity wood did not always perform badly in comparison to low-gravity wood.

Pith Vs. Bark Side Placed Toward Concavity

It was thought possible that bending ratings might be improved if the side of the specimen nearest the pith was always placed on the concave side of the bend; however, analysis of variance showed no significant effect. With all data pooled, average rating of specimens with the pith on the concave side was 6.5; with pith on the convex side, the average rating was 6.3.

Change in Diameter with Time and Exposure Condition

As described in the procedure section, specimens in three categories were studied for changes in diameter when subjected to different humidities.

The moisture content at the time the restraining tapes were cut averaged 8.7 percent and ranged from 7.5 to 10.9. After 4 weeks, moisture contents were as follows:

Condition	Average	Range
	Percent	
In laboratory at about 50-percent R.H.	8.2	7.1 to 9.0
In bags with desiccant	7.3	6.1 to 9.5
In bags with water-soaked sponge	13.6	11.3 to 15.7

No significant differences in moisture content were found between categories of wood or pretreatment.

When the restraining tapes were cut, diameter of the average specimen increased 0.50 inch. In general, diameter change on release was least in vertical-grain wood that had been steamed 20 minutes per inch; also, the change was least in the 1/2-inch specimens bent to a 12-inch diameter.

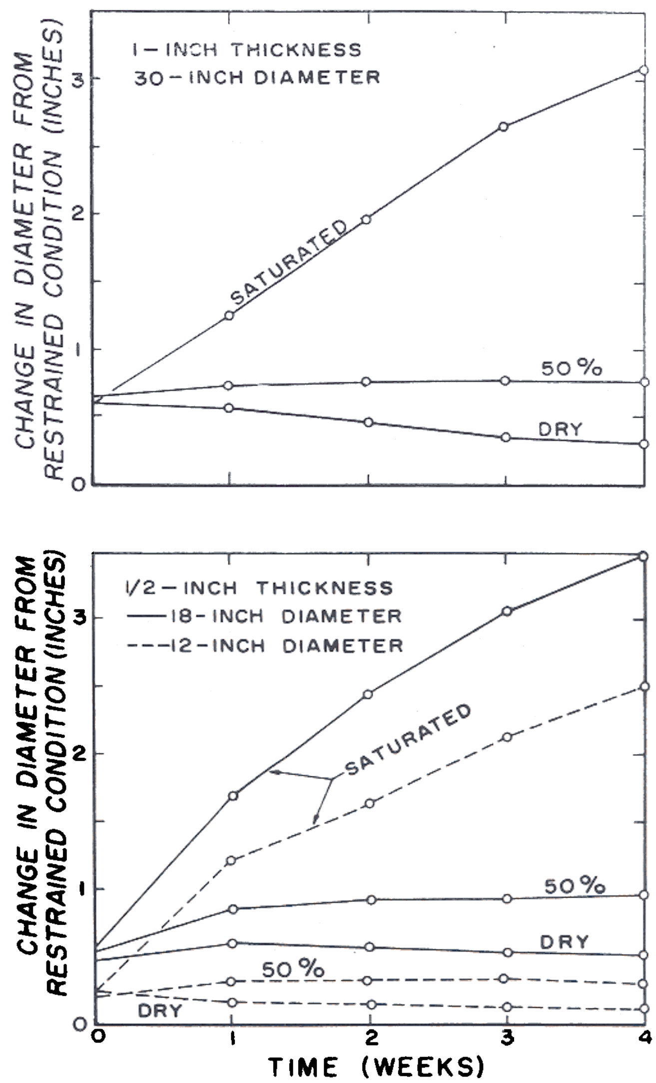

Figure 6. — Change in diameter, from the restrained condition, during 4 weeks of exposure to air which was saturated, at 50-percent relative humidity, or desiccated. The 0-week points show the changes in diameter that occurred when the restraining tapes were cut. Each curve based on data averaged from 32 specimens.

Factor and level	Change in diameter when restraining tapes cut
	Inch
Grain angle	
Flat grain	0.54
Vertical grain	.45
Pretreatment (steaming time)	
10 minutes per inch of thickness	.52
20 minutes per inch of thickness	.48
Thickness and diameter	
1/2-inch thickness, 12-inch diameter	.24
1/2-inch thickness, 18-inch diameter	.64
1-inch thickness, 30-inch diameter	.61

Specific gravity and growth rate of the wood did not significantly affect the change in diameter when the restraining tapes were cut.

After 4 weeks of exposure, the specimens in the humid atmosphere had increased in diameter most (from the restrained dimension), and those in the desiccators least; specimens held at about 50-percent relative humidity were intermediate. In general, change was least in edge-grain wood steamed 20 minutes per inch of thickness; the 1/2-inch-thick specimens bent to 12-inch diameter changed least; 1/2-inch specimens bent to 18-inch diameter changed most.

Factor and level	Increase in diameter from restrained diameter to unrestrained diameter after 4 weeks of exposure
	inches
Post treatment	
In laboratory at 50-percent R.H.	0.69
In bags with desiccant	.31
In bags with water-soaked sponge	3.04
Grain angle	
Flat grain	1.45
Vertical grain	1.24
Pretreatment (steaming time)	
10 minutes per inch of thickness	1.43
20 minutes per inch of thickness	1.26
Thickness and diameter	
1/2-inch thickness, 12-inch diameter	.99
1/2-inch thickness, 18-inch diameter	1.65
1-inch thickness, 30-inch diameter	1.40

Specific gravity and rings per inch of the wood had no significant effect on change in diameter. Figure 6 and Table 5 show diameter changes for each of the three specimen categories as a function of time and exposure condition.

When the specimens were ovendried they were reduced somewhat in diameter (except for the 1/2-inch-thick, 18-inch-diameter pieces previously held in bags with desiccant); after ovendrying, all had diameters larger than the diameters measured when they were under restraint by the glass tape. Vertical-grain specimens that had been steamed 20 minutes per inch of thickness more nearly contracted to their original restrained diameters than did flat-grain wood or wood steamed 10 minutes per inch of thickness. Also, the 1/2-inch specimens bent to 12-inch diameter and stored in bags containing a desiccant, when subsequently ovendried, approached most closely to their original restrained diameter; the 1/2-inch specimens bent to 18-inch diameter and stored in water-saturated air contracted least.

Table 6. — CHANGES IN FORMED DIAMETER OF 1/2- AND 1-INCH-THICK, STEAM-BENT SOUTHERN PINE SPECIMENS RELATED TO EXPOSURE CONDITIONS AND EXPERIMENTAL FACTORS.[1,2]

Factor and level	Increase in diameter when restraint removed	Change in diameter after 4 weeks of exposure	Change in diameter after then oven-drying
A. Replication (dummy factor)			
B. Post treatment		**	
In laboratory at 50-percent R.H.		0.69	0.48
In bags with desiccant		.31	.36
In bags with water-soaked sponge		3.04	1.68
C. Growth rate, rings per inch			
Less than 6	0.49	1.35	.74
More than 6	.51	1.35	.94
D. Specific gravity (basis of O.D. vol. and wt.)			
Less than 0.58	.49	1.36	.94
More than 0.58	.50	1.34	.74
E. Grain angle	**	**	**
Flat grain	.54	1.45	.96
Vertical grain	.45	1.24	.72
F. Pretreatment, steaming time	**	**	**
10 minutes/inch of thickness	.52	1.43	.96
20 minutes/inch of thickness	.48	1.26	.72
G. Thickness and nominal diameter	**	**	**
1/2-inch thickness, 12-inch diam.	.24	.99	.43
1/2-inch thickness, 18-inch diam.	.64	1.65	1.28
1-inch thickness, 30-inch diameter	.61	1.40	.81

[1]Changes in diameter are increases from the restrained diameter. Each value listed is an average, with data on all factors pooled.

[2]Values tabulated below two asterisks differ significantly at the 0.01 level.

All of these diameter changes are summarized in Table 6.

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