Strength of Beams with Laminae Located According to Stiffness

By

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SOUTHERN PINE BOLTWOOD is in abundant supply, but it contains high proportions of juvenile wood, and hence utilization for structural purposes is difficult when conventional means of conversion are employed. As a different approach, it is proposed that heart-center cants be cut from boltwood and then sliced into thick veneers for assembly into beams. The veneers can be expected to exhibit a considerable range in stiffness. It is hypothesized that stiff veneers are stronger in tension and compression than less stiff veneers, and that this attribute can be used to advantage by locating the stiffest veneers in the outermost portions of laminated beams.

Procedure

Sliced veneer was simulated by sawing heart-center cants into green lumber which was planed to 7/16-inch thickness prior to drying. Sufficient cants measuring 4-, 6-, 8-, 10-, and 12-inches square were first produced and then sawn through to obtain 120 veneers of each width, 600 veneers in all. The 120 veneers of each width were sequentially dealt into five sorts that were randomly assigned to drying treatments: (A) air dried; (B) in a lumber kiln on a mild schedule; (C) in a jet dryer for 60 minutes at 300° F.; (D) by conventional roller veneer dryer for 90 minutes at

300° F.; and (E) for 23 minutes in a hot-plate press equipped with ventilated cauls and operating at 300° F. Each drying group contained 120 veneers, 24 in each of five widths.

The dry veneers were brought to an average equilibrium moisture content of 9 percent and then surfaced to precisely 1/3-inch thick and straight-line ripped to 1 inch less than nominal green width (3, 5, 7, 9, and 11 inches). The veneers were primarily loblolly pine with a sprinkling of shortleaf and longleaf pine. The bolts were picked at random out of a large deck of freshly cut pine.

Stiffness of Veneers

Figure 1 illustrates the apparatus used to segregate the veneers by stiffness. With the deflection value obtained with this setup, it was possible to calculate the modulus of elasticity for each veneer:

$$E = \frac{PL^3}{4ybd^3}$$

where E = modulus of elasticity, p.s.i.

L = length between supports, inches (in this case 96)

b = width of veneer, inches

y = deflection, inches

d = thickness of veneer, inches (in this case 1/3)

P = concentrated load in center of simple span, pounds (in this case P was held equal numerically to b)

The relationship was simplified to $E = 5,972,000/y$.

The maximum bending stress imposed by this loading system was 1,300 p.s.i. The end reactions at the support points make the formula not entirely accurate, but it was considered close enough for the purpose. Deflections ranged from less than 2 inches to more than 6 inches each way.

Lamination

From each set of 24 veneers of a particular width and drying treatment, three were discarded because they were either mismanufactured, broken, or most limber. For the sake of appearance, the two most nearly clear veneers of the remaining 21 were used as tension and compression skins, with the stiffer of the two placed on the tension side. With this exception, the veneers were located in each beam strictly according to stiffness.
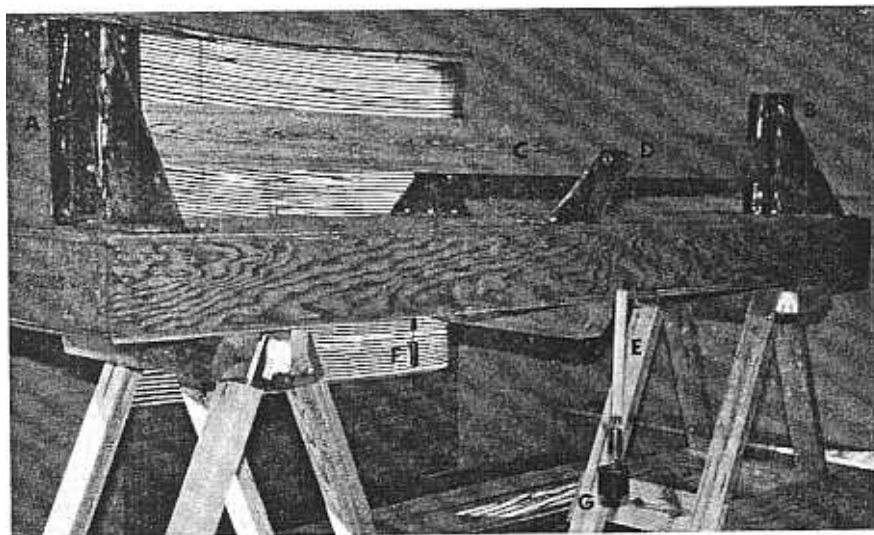
Figure 1.—Deflection apparatus for segregating veneers by stiffness. V-shaped vertical supports, at A and B, are 96 inches apart. Wires are attached by screw eyes to center point C on each side of veneer and arranged to run over ball bearing D to vertical scale E; one-pound weights F are hung on the end of each wire to eliminate slack in the system. Unbalanced weight G (1 pound per inch width of veneer) was placed first on one side and then on the other to cause deflection in both directions. Scale E read through transit (not shown) to obtain total deflection from one loaded condition to the other. One-half of this value is equal to average deflection under load. Readings corrected for stretch in wires.

All beams were laminated in a simple press made from 18 rocker-head clamps equally spaced over the 100-inch length of the press. Movable steel angles provided side restraint and prevented misalignment of the veneers. Screw pressure was applied with a hand wrench to achieve fairly uniform glue squeeze-out. A phenol-resorcinol adhesive was spread manually at a rate of 60 pounds per 1,000 square feet of glue line. This amount was divided equally between mating surfaces. A temperature of 70° F. or over was maintained in the press room and beams were allowed to cure approximately 24 hours in the clamps. No bond failures were observed during subsequent strength testing. Figure 2 illustrates a typical cross section through a beam and Figure 3 shows the veneers that went into the same beam.

Strength of Beams

Bending tests were made on twenty-five 100-inch beams, each with twenty-one 1/3-inch-thick laminations.

Prior to the test, each beam was scraped free of squeezed-out adhesive, jointed on one side, and finally parallel-planed on the other side to the maximum thickness that would clean up. The strength of each beam was evaluated with the apparatus described in Figure 4. Deflections between supports were measured to the nearest 0.01 inch with a taut wire and scale. The wire was stretched between nails located at mid-depth of the beam above the supports, and the scale was at mid-length of the beam. The scale was read with a telescope.

Abstract

This is the third paper of a series of four describing a system for converting southern pine boltwood into laminated beams of uniformly high strength.

Southern pine veneers 1/3-inch thick were assembled into beams containing 21 laminae located with the stiffest on the outside and the most limber in the center. Modulus of elasticity of the veneers averaged 1,700,000 p.s.i., and ranged from 740,000 to 3,370,000 p.s.i. The beams had an average modulus of rupture of 9,900 p.s.i. and a modulus of elasticity (corrected for shear) of 1,820,000 p.s.i. Ninety-five percent of the population represented by the 25-beam sample could be expected to have an MOR in excess of 8,060 p.s.i. With beams made by this system, allowable design stress apparently is equivalent to the maximum allowable stresses now in use for high-grade lumber randomly assembled into beams.

If the laminae contain properly spaced finger joints, the average MOR should not fall below 7,300 p.s.i. (with a 95-percent exclusion limit of 5,250 p.s.i.).

After each beam failed, a 1-inch-long cross-sectional slice was cut approximately 12 inches from one end and oven-dried to determine moisture
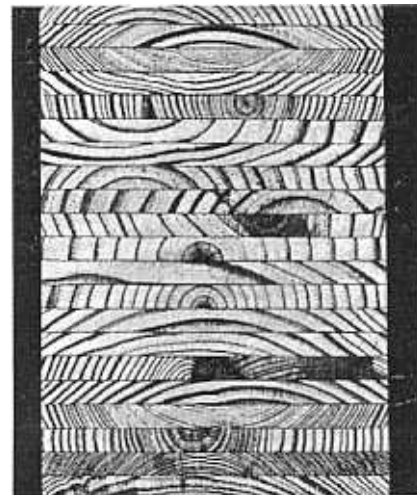

Figure 2.—Typical beam cross section. All beams contained 21 laminations, each ⅓-inch thick. This beam has a net width of 5 inches, with the tension side on the bottom. Each veneer is approximately symmetrical about the pith. Placing the stiffest veneers toward the outside accomplished a certain gradation by ring width and percent of latewood. These particular veneers were cut from several 6- by 6-inch heart-center cants. The beam (6-D) had a modulus of rupture of 11,490 p.s.i., and a modulus of elasticity (corrected for shear) of 2,020,000 p.s.i.

content. This moisture content was assumed to represent the average of the beam.

Effect of End Joints

Because laminated beams are commonly manufactured and used in lengths up to 60 feet or more, it was necessary to assess the effect of end joints in individual laminae.

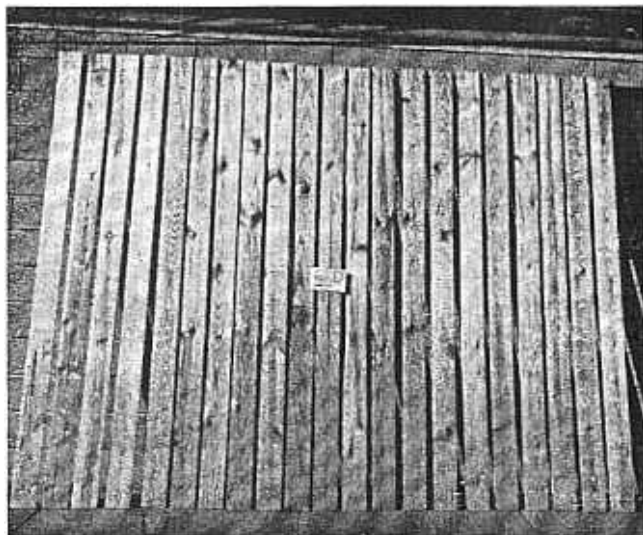Figures 5 and 6 illustrate a beam used to test the effect of the end joints

Figure 3.—These 100-inch-long veneers comprise beam illustrated in Figure 2, arranged in order of assembly. The stiffest clear veneer (on the extreme left) was used for a tension skin and the next stiffest (extreme right) for a compression skin. With these exceptions the veneers are in order of stiffness from outside to center without regard to visible defect.
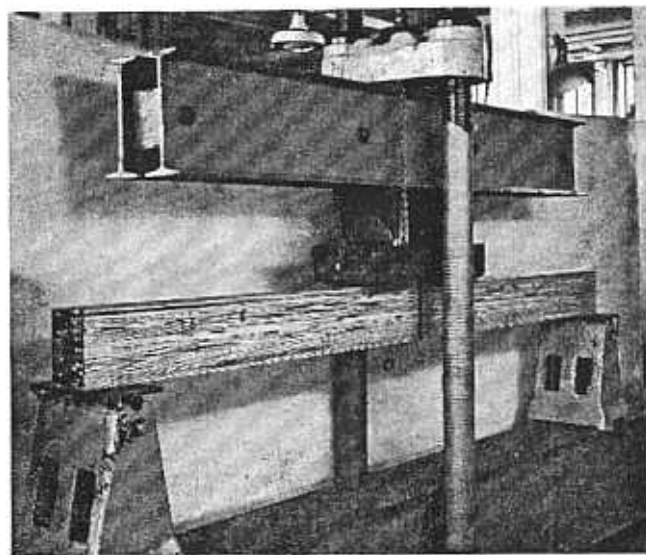
Figure 4.—Setup of testing machine (200,000-pound capacity) for evaluating beams on 94-inch span with two-point loading. Load points were 14 inches apart at midspan. Rocker-type end supports were used, and roller nests were placed under one head to insure that loading was vertical. Rate of vertical movement of the loading heads was 0.137 inch per minute. The apparatus and speed of loading follow recommendations in ASTM D 198—27, Static Tests of Timbers.
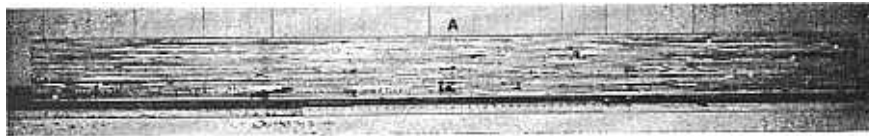
Figure 5.—In this beam each of the 19 interior laminae contains a single butt joint (marked by a white thumbtack). The tension and compression skins contain no end joints. Each butt joint is 100/19 or 5¼ inches (measured along the length of the beam) from the joint on either side. In effect the butt joints form a staggered finger joint with ⅓-inch tip thickness and zero slope on the fingers. Butt joint at point A is at midspan of the second lamination on the tension side. All beams (Table 2) failed at this point.

in the individual laminae. Note in Figure 5 that the butt joints in the interior laminations were staggered in relation to the joints in adjacent laminations, so that the joints would have the least possible weakening effect on the beam as a whole. It was reasoned that results of tests to failure of the most damaging 100-inch configuration of these joints would constitute evidence of the maximum possible damage caused by any kind of an end joint distributed on the same pattern. Tests were therefore conducted accordingly.

Five beams were fabricated by identical procedure; each contained twenty-one 1/3-inch-thick veneers measuring approximately 100 inches long by 3 inches wide. The laminae were ripped from extra veneers from all drying treatments and arranged in order of stiffness as for the main test. Just prior to assembly, interior veneers were cut through to create the pattern of butt joints shown in Figures 5 and 6. These five beams were then loaded to failure on the test apparatus.

Results and Discussion

Stiffness of Veneers

The average lot going into any one beam contained veneers that ranged from 2.35 to 5.19 inches in deflection. These deflections correspond approximately to moduli of elasticity of 2,540,000 and 1,150,000 p.s.i. Average deflection of all veneers was 3.51 inches, which corresponds to a modulus of elasticity of 1,700,000 p.s.i. The stiffest veneer deflected only 1.77 inches ($E = 3,370,000$ p.s.i.), while the most limber veneer deflected 8.09 inches ($E = 740,000$ p.s.i.).

Drying treatments did not significantly affect stiffness (see Table 1 of preceding paper in the September Journal). Figure 7 illustrates the location of veneers in the beams according to stiffness. It is evident that the clearest veneers used for tension and compression skins were not necessarily the stiffest.

Locating each veneer according to its stiffness produced a degree of arrangement by specific gravity (Figure 8). A significant relationship between deflection and specific gravity was observed. For the range tested,

this relationship can be expressed as

$$\hat{y} = 6.60 - (5.82)\ (x)$$

where x = specific gravity (oven-dry weight and volume at equilibrium moisture content)

$\hat{y}$ = deflection of veneer, inches

Average specific gravity for all veneers was 0.531.

Strength of Beams

Table 1 shows the results of the bending tests. The beam numbers identify the drying treatment and the nominal width of each beam. Average moisture content of all beams at the time of test was 11.8 percent, while average specific gravity was 0.53, with

Table 1.   RESULTS OF BENDING TESTS OF 25 SOUTHERN PINE LAMINATED BEAMS

Beam No.	Height	Width	Mois-ture content	Specific gravity [1]	Stress at proportional limit	Modulus of rupture	Modulus of elasticity Between supports	Modulus of elasticity Corrected for shear	Type and sequence of failure [2]
(1)	(2)	(3)	(4)	(5)	(6)		(8) 1,000	(9) 1,000	(10)
	Inch	Inch	Percent		P.s.i.		P.s.i.	P.s.i.	
					Air Drying				
A-4	7.20	2.74	10.7	0.56	5,920	9,300	1,840	2,020	T
A-6	7.19	4.95	11.9	.52	5,640	10,720	1,610	1,770	C-T
A-8	7.12	6.95	12.2	.50	5,110	9,420	1,540	1,690	T
A-10	7.11	8.93	12.1	.53	5,320	8,780	1,670	1,830	T
A-12	7.21	10.92	12.3	.52	6,340	9,860	1,700	1,870	T
Av.			11.8	.53	5,670	9,620	1,670	1,840	
					Lumber Kiln Drying				
B-4	7.21	2.96	12.3	.55	5,850	11,800	1,820	2,010	T
B-6	7.19	4.96	12.0	.53	5,150	8,980	1,580	1,740	T
B-8	7.12	6.94	12.4	.53	5,800	10,170	1,560	1,710	C-T
B-10	7.08	8.93	12.0	.53	5,100	8,700	1,470	1,610	T
B-12	7.18	10.92	13.0	.51	5,120	8,180	1,580	1,730	T
Av.			12.3	.53	5,400	9,570	1,600	1,760	
					Jet Veneer Drying				
C-4	7.21	2.96	11.8	.53	5,850	10,570	1,720	1,890	T
C-6	7.19	4.96	11.7	.52	5,150	8,520	1,640	1,800	T
C-8	7.11	6.94	11.7	.52	4,790	9,120	1,530	1,670	T
C-10	7.10	8.92	11.5	.53	5,080	8,440	1,500	1,640	T
C-12	7.18	10.93	11.9	.50	5,540	9,380	1,620	1,780	T
Av.			11.7	.52	5,280	9,210	1,600	1,760	
					Roller Veneer Drying				
D-4	7.21	2.96	10.8	.53	5,850	10,500	1,790	1,970	C-T
D-6	7.22	4.96	10.6	.52	6,500	11,490	1,840	2,020	C-T
D-8	7.13	6.94	10.8	.55	5,100	9,320	1,530	1,680	T
D-10	7.12	8.94	10.8	.54	5,300	11,220	1,580	1,730	T
D-12	7.22	10.92	11.1	.51	6,750	9,820	1,680	1,840	T
Av.			10.8	.53	5,900	10,470	1,680	1,850	
					Hot-Plate Press Drying				
E-4	7.19	2.96	11.9	.55	6,280	11,680	1,940	2,130	C-T
E-6	7.20	4.96	12.1	.56	5,610	11,140	1,680	1,850	C-T
E-8	7.12	6.94	13.0	.52	5,800	9,960	1,680	1,850	C-T
E-10	7.13	8.94	12.2	.54	5,820	10,000	1,710	1,880	T
E-12	7.19	10.93	13.0	.52	5,960	10,390	1,680	1,840	C-T
Av.			12.4	.54	5,890	10,630	1,740	1,910	
Overall av.			11.8	.53	5,630	9,900	1,660	1,820	

[1] Calculated from size of beam at time of test and weight of beam at time of test corrected to oven-dry weight with moisture content in column 4.

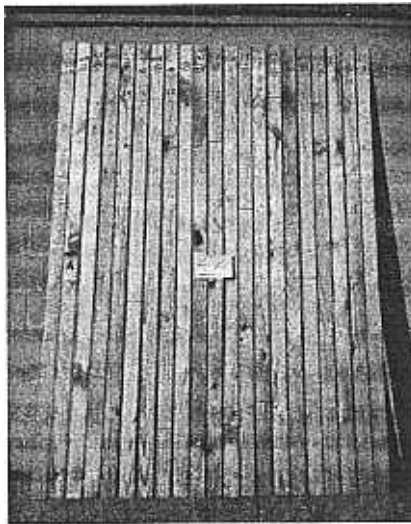[2] T means tension failure and C-T means compression failure followed by tension failure.

Figure 6.—One-hundred-inch-long veneers comprising beam in Figure 5. Veneers are arranged in order of assembly with solid tension skin to the left and solid compression skin to the right. Horizontal lines on the 19 interior laminae locate saw cuts made before the beam was assembled. This beam had a modulus of rupture of 8,220 p.s.i., in spite of the 19 butt joints. Note butt joint at midspan of second tension lamination (point A).

Table 2. — RESULTS OF BENDING TESTS OF FIVE SOUTHERN PINE BEAMS HAVING BUTT JOINTS IN ALL INTERIOR LAMINAE

Beam No.	Height	Width	Moisture content	Specific gravity [1]	Stress at proportional limit	Modulus of rupture	Modulus of elasticity Between supports	Corrected for shear	Type and sequence of failure [2]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(9)	(9)	(10)
	In.	In.	Percent		P.s.i.	P.s.i.		1,000 P.s.i.	
4-V	7.16	2.95		0.55				1,780	T
4-W	7.20	2.95		.55				1,860	T
4-X	7.18	2.95		.57				1,970	T
4-Y	7.18	2.95		.52				1,900	T
4-Z	7.20	2.96		.56				1,670	T
Av.				.55				1,840	

[1] Calculated from size of beam at time of test and weight of beam at time of test corrected to oven-dry weight with moisture content in column 4.
[2] T means tension failure. All five beams failed in tension through the butt joint located at midspan in the second lamination on the tension side.

no significant differences by drying treatment.

Stress at proportional limit did not vary significantly between drying treatments. The average was 5,630 p.s.i. and the range was from 4,790 to 6,750 p.s.i.

Modulus of rupture averaged 9,900 p.s.i. and ranged from 8,180 to 11,800 p.s.i. Beams from veneers dried on a mild schedule were not significantly stronger than those from veneers dried on an accelerated schedule. Ninety-five percent of the population represented by this 25-beam sample can be expected to have a modulus of rupture in excess of 8,060 p.s.i.

The average modulus of elasticity, which was corrected for shear, was 1,820,000 p.s.i., with no significant variation between drying treatments. The range was from 1,612,000 to 2,130,000 p.s.i.

Stress at proportional limit and modulus of rupture were calculated from the standard flexure formula $f = Mc/I$, where f is the calculated stress, M is the applied moment, c is the distance from the neutral axis to the outer face of the beam, and I is the moment of inertia of the cross section.

The modulus of elasticity value without correction for shear was calculated by solving the deflection formula:

$$\Delta = \frac{Pa}{48EI}(3L^2 - 4a^2)$$

and the value corrected for shear was calculated:

$$\Delta = \frac{Pa}{48EI}(3L^2 - 4a^2) + \frac{24P}{GA}$$

where Δ is midspan deflection, inches

P is total load on beam, pounds

a is distance from support to load point, inches

E is modulus of elasticity, p.s.i.

I is moment of inertia of cross section, inches⁸ [inches^8]

L is distance between supports, inches

A is cross sectional area of beam, inches² [inches^2]

G is modulus of rigidity, or shear modulus, p.s.i.

A "modulus of elasticity" calculated with the first formula is not the actual modulus because the measured deflection is produced by shear as well as bending stresses. This formula however, is the one most often used in design of beams. Values of actual modulus in column 9 of Table 1 were calculated by the second equation, with the shear modulus (G) assumed equal to one-sixteenth of the modulus of elasticity (see Wood Handbook,[1] Table 13).

Values in column 8 are generally somewhat less than the average (with-

[1] U. S. Forest Products Laboratory. 1955. Wood Handbook, U. S. Department of Agriculture, Agriculture Handbook 72.

out correction for shear) for southern pine[1] but are within the range that might be expected. These beams contained much juvenile wood, which often has a low modulus of elasticity. Also, since the less stiff laminae were in the middle of the beams, shear deformation may have been greater than is normal in southern pine beams, and hence the assumed one-sixteenth ratio of shear modulus to modulus of elasticity may not be correct. Thus the values in column 9 may be too low.

In all beams, final failure was a very abrupt tension failure, but some compression failure was visible in a few beams before maximum load was reached.

Some cross grain was visible in the outer tension laminae, but cross grain was a factor in the failure of only one beam. The outer tension lamination of beam 6C failed because of 1-in-6 cross grain; failure occurred at 14,900 pounds, but the beam continued to sustain load to a maximum of 18,200 pounds.

Average modulus of rupture for the 25 beams was 9,900 p.s.i., and the range of values was relatively narrow.

The values are better than expected for such material. They may be due in part to the thin laminations, as well as to the method of assembly. Thickness of laminations is not usually considered to influence strength of beams, but it is possible that with 1/3-inch laminations there is less stress concentration and better randomization of strength-reducing features than with
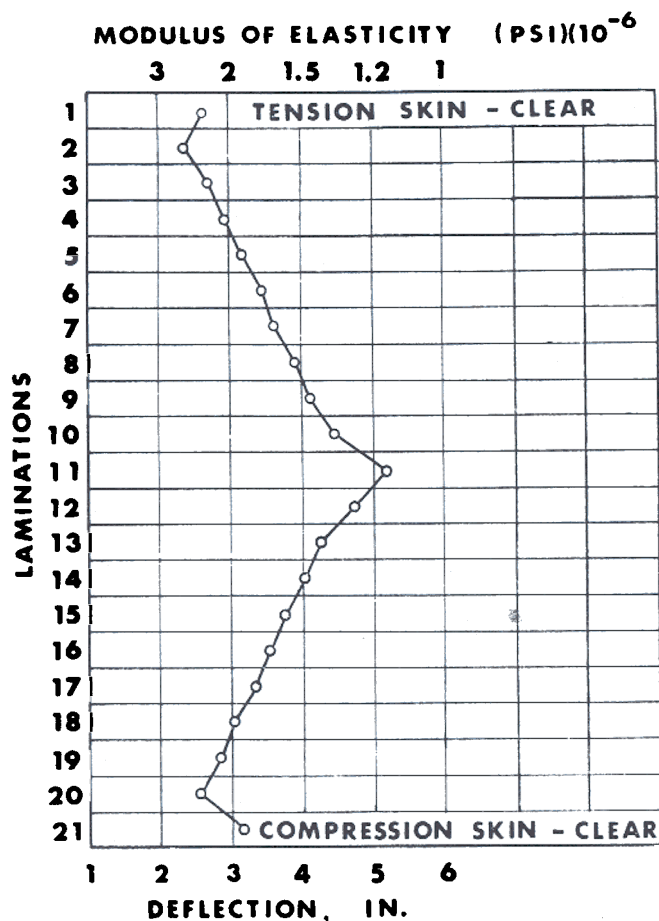
MODULUS OF ELASTICITY (PSI)(10⁻⁶)

Figure 7.—Average deflection and modulus of elasticity for veneers comprising laminae of the 25 test beams; each value is the average for 25 veneers.
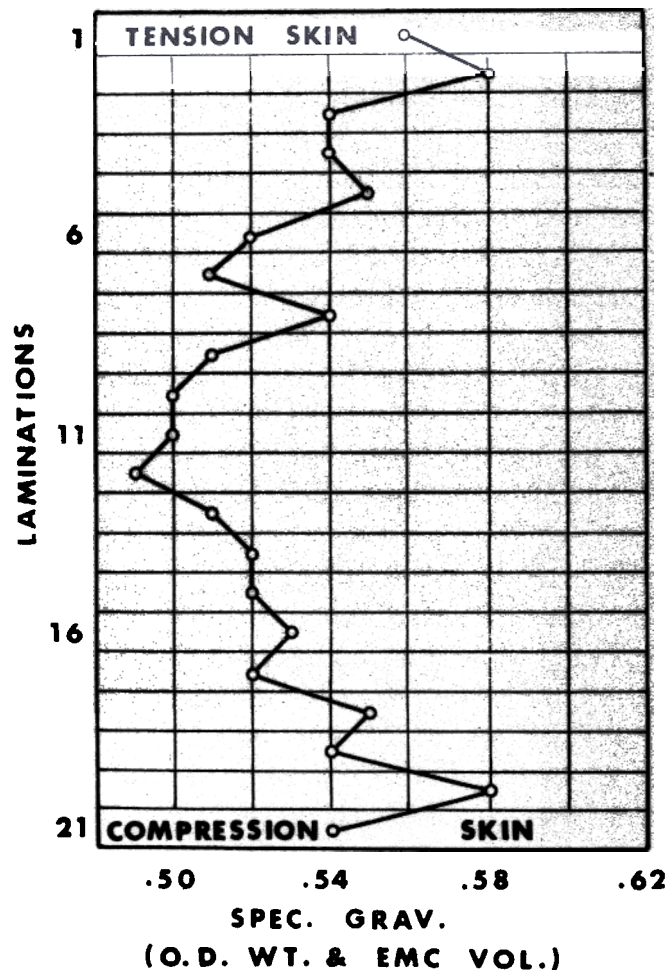

Figure 8.—Average specific gravity for veneers comprising the laminations of the 25 test beams.

nominal 1- and 2-inch laminations. The high modulus of rupture obtained by this system should justify an allowable design stress equivalent to the maximum allowables now in use with high-grade lumber randomly assembled into beams. It should be noted that the laminae in these 25 beams had no end joints of any kind.

Table 2 shows results of the bending tests on beams having butt joints in the interior laminae. The average modulus of rupture for these five beams was 7,300 p.s.i. Ninety-five percent of the population represented by this sample can be expected to have an MOR in excess of 5,250 p.s.i.

It is not proposed that beams be manufactured with butt joints. It is reasoned, however, that beams similar to those tested but having finger joints properly placed in all laminae would equal or better the performance indicated in Table 2.

An MOR of 7,300 p.s.i. is 74 percent of the average for beams without butt joints (Table 1). The reduction of section modulus due to the single butt joint at the midspan of the second tension lamination is theoretically only 14 percent. Thus it appears that considerable stress concentration is caused by this critical butt joint—a fact observed by other investigators as well.

Peter Koch

In next month's issue of the Journal, Dr. Koch will report on the economic and production aspects of converting southern pine boltwood into long laminated beams of uniform high strength. Previous parts of this four-part series have discussed the problems involved in cutting square cants from round bolts (August) and techniques for drying thick southern pine veneer (September).