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Beam Strength as Affected by Placement of Laminae

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Abstract

Beams glued up from southern pine veneers were strongest and stiffest when assembled with the stiffest laminae in the outer portions and the most limber in the center.

The beams, 100 inches long, were laminated from 21 1/3-inch thick S4S veneers, 3 inches wide. The veneers were sawn from heartcenter cants cut from 26-year-old plantation-grown slash pines.

Five methods of assembly were tested, here listed in descending order of strength and stiffness of the resulting beams:

1) Stiffest veneers were placed in outer laminae and limber veneers in inner laminae. Compression and tension faces reinforced with high-strength aluminum alloy sheets 0.05-inch thick. These beams carried a 31-percent greater maximum load and were 25 percent stiffer than the similar, but unreinforced, beams in arrangement 2. Variability was reduced.

2) This was the same as 1, but there was no metal reinforcing. Average modulus of rupture was 10,200 p.s.i. Of the beam population represented by the sample, 95 percent could be expected to have an MOR of 7,140 p.s.i. or higher. Average modulus of elasticity was 2, 130,000 p.s.i. (Table 2, col. 10).

3) Clearest veneers were in outer laminae, knottiest in inner. MOR was 9,590 p.s.i. (95-percent exclusion limit of 5,960 p.s.i.), and MOE was 1,930,000 p.s.i.

4) Veneers of high specific gravity were in outer laminae and veneers of low specific gravity in inner laminae. MOR was 8,390 p.s.i. (95-percent exclusion limit of 4,790 p.s.i.), and MOE was 1,910,000 p.s.i.

5) Veneers were randomly placed. MOR was 6,630 p.s.i. (95-percent exclusion limit of 2,890 p.s.i.), and MOE was 1,620,000 p.s.i.

Solid-sawn, heart-center beams similar to the laminated beams in dimension and moisture content were cut from the same slash pine plantation. MOR was 9,540 p.s.i. (95-percent exclusion limit of 3,720 p.s.i.), and MOE was 2,000,000 p.s.i. Specific gravity of all beams averaged 0.56 (ovendry weight and volume at test moisture content of 9.4 percent).

Log-run veneers withstood substantially higher stress in a laminated beam than when loaded individually in pure tension; tensile strengths of such veneers were more accurately indicated by MOE (in bending) than by specific gravity.

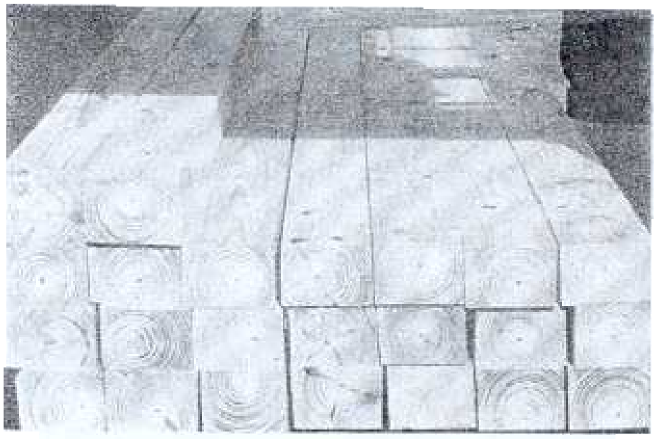

Figure 1.—Thick veneers were sawn from these 100-inch-long heart-center cants cut from slash pine bolts.

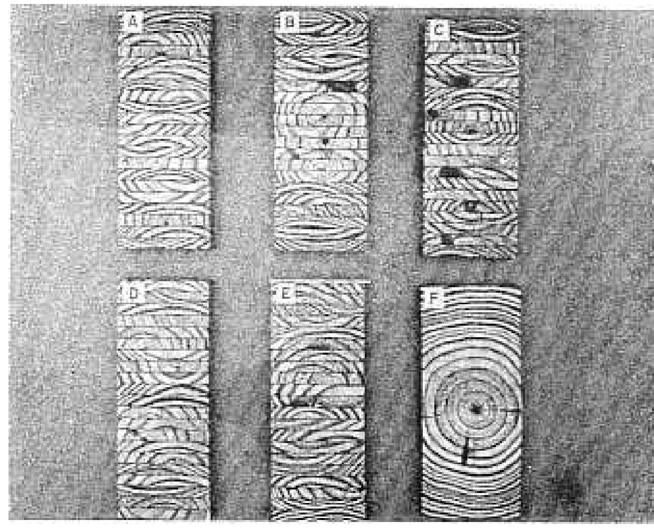

Figure 2.—Typical cross sections of beams from each group: A—densest veneers in outer laminae; B—stiffest in outer laminae; C—clearest in outer laminae; D—random assembly; E—stiffest in outer laminae, plus aluminum faces; F—solid wood. Beams are about 3 inches wide and 7 inches deep; laminae are ⅓-inch thick. Tension side at bottom.

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PREVIOUS RESEARCH[2] has shown that beams of relatively uniform high strength can be made from southern pine veneers if the stiffest veneers are placed in the outermost portion of the beam and the most limber near the neutral axis. Segregation by stiffness was chosen in the initial research because it was hypothesized that stiff veneers would prove strong in tension and compression. The study reported here compared this arrangement with alternative ones. Practical machines for rapidly segregating lumber by stiffness have recently been developed.

Procedure

Bolts with a minimum top diameter of 8 inches (inside bark) and a length of 104 inches were cut from a 26-year-old slash pine *(Pinus elliottii* Engelm.) plantation near Alexandria, La. Of 129 bolts, 124 were reduced to S4S heart-center cants measuring 4 by approximately 5½ inches and were double-end trimmed to 100 inches in length (Figure 1).

The other 5 bolts were sawn into green, heart-center S4S cants measuring 4 by 8 by 100 inches. These cants were piled on sticks in a heated room controlled to 50-percent relative humidity (± 5 percent) and were left to dry for approximately 50 days. They were then planed to a net S4S size of 3 by 7 inches (Figure 2, Beam F) and returned to the controlled humidity room for 100 days before they were loaded in bending to failure.

The 124 cants were immediately resawn into 626 veneers approximately 7/16-inch thick by 4 inches wide. The first 600 veneers were sequentially numbered as they came from the resaw, and the final 26 were sequentially tagged *A* to *Z*. The veneers from 1 to 600 were used to make laminated beams for the main test. Those marked *A* to *Z* were allocated to a correlative experiment in which the full-length veneers were tested to failure in tension.

Drying and Specific Gravity

The veneers were loaded in a single kiln charge and ovendried on a 5-day schedule: 24 hours at 165° F. dry bulb and 150° F. wet bulb; 48 hours at 180° F. dry bulb and 156° F. wet bulb; and, finally, 48 hours at 215° F. dry bulb.

They were then weighed individually and put back in the kiln for conditioning at 115° F. dry bulb and 98° F. wet bulb to cause an approximate EMC of 8.9 percent. After 24 days of conditioning, each was weighed and measured for volume. Thus, the specific gravity of each veneer in its entirety could be calculated from oven-dry weight and volume at EMC.

All 626 veneers were then planed to ⅓-inch thickness S2S, straight-line jointed, and ripped to 3-inch width. Subsequently, they were stored in a room controlled to 50-percent relative humidity (± 5 percent).

Stiffness of Veneers

The stiffness of each veneer (numbered and lettered) was determined and recorded along with the specific gravity. The apparatus used to segregate the veneers by stiffness was the same as that used in the previous research[2]. With the deflection obtained

[1] Acknowledgement is due Dr. W. Hopkins, Louisiana State University, Dr. R. F. Blomquist, U.S. Forest Products Laboratory, and M. Roessler, Southern Forest Experiment Station.

[2] Koch, Peter. 1964. Strength of beams with laminae located according to stiffness. For. Prod. Jour. 14(10):456–60.

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by this setup, it was possible to calculate the modulus of elasticity of every veneer:

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

where E = modulus of elasticity, p.s.i.
L = length between supports, inches (in this case 96)
y = deflection, inches
b = width of veneer, inches (in this case 3)
d = thickness of veneer, inches (in this case 1/8)
P = concentrated load in center of simple span, pounds (in this case 2)

The relationship was simplified to:

$$E = 3{,}981{,}000/y$$

The maximum bending stress imposed by this system was 864 p.s.i.

Lamination

The veneers numbered from 1 to 600 were randomly divided into five major groups, each group containing five randomly selected lesser sets of 24. Each of the lesser sets provided veneers for a single beam.

Group A: Specific Gravity: Each of the five sets of 24 veneers was arranged according to specific gravity. Veneers with the highest specific gravity were placed outermost; those with the lowest were placed innermost in the beam. The densest veneer was placed on the tension face, the next most dense on the compression face, and so on. Thus the veneer of lowest specific gravity was centrally placed (Figure 3). As only 21 veneers were utilized in each beam, three were rejected from each set of 24. Scant pieces were discarded first, then broken pieces, and then the pieces of lowest specific gravity.

Group B: Stiffness: The procedure was identical to that for Group A except that placement was by stiffness instead of by specific gravity (Figure 4).

Group C: Appearance: The procedure was identical to that for Group A except that the most knot-free veneer was placed on the tension face, and the second most knot-free veneer on the compression face, and so on until the acceptable veneer with the most knot area was centrally located (Figures 5 and 6).

Group D: Random Selection: After scant or broken pieces were rejected, 21 of the remaining veneers in each set were randomly selected and randomly placed in each beam.

Group E: Stiffness with Aluminum Reinforcement on Tension and Compression Faces: The procedure was identical to that for Group B except that 7075T6 clad aluminum strips 3 inches wide and 0.05-inch thick were

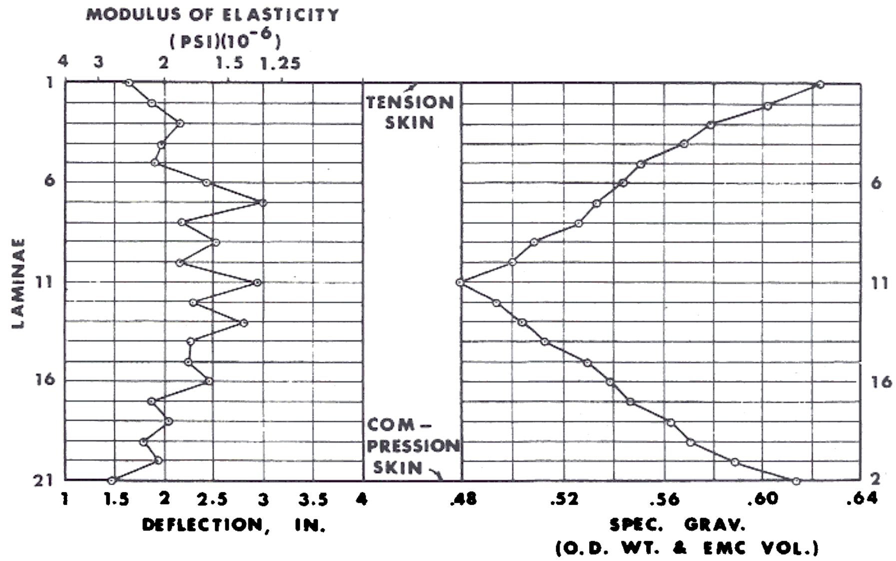

Figure 3.—Group A beams, with laminae arranged by specific gravity. Each value is the average for five veneers—one from each of the five beams in the group.

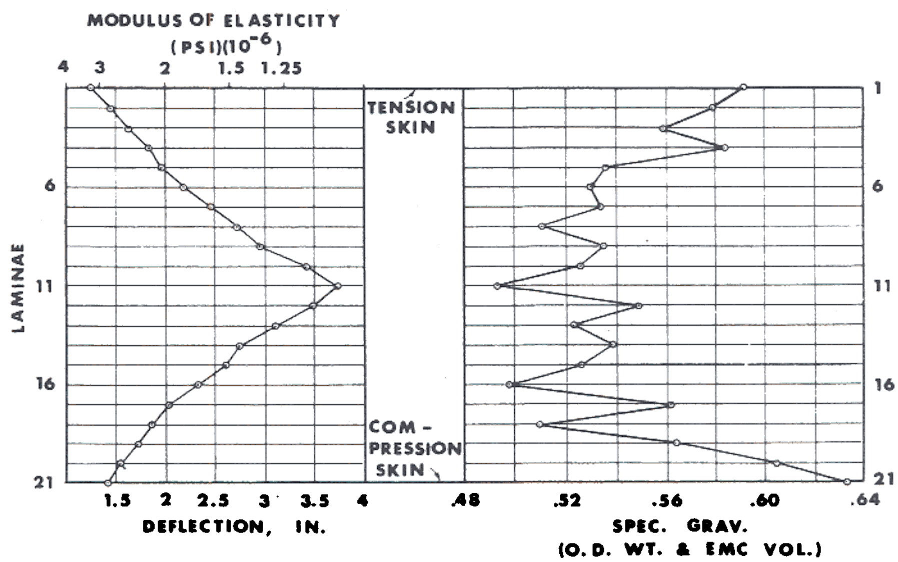

Figure 4.—Group B beams, with laminae arranged by stiffness. Each value is the average for five veneers.

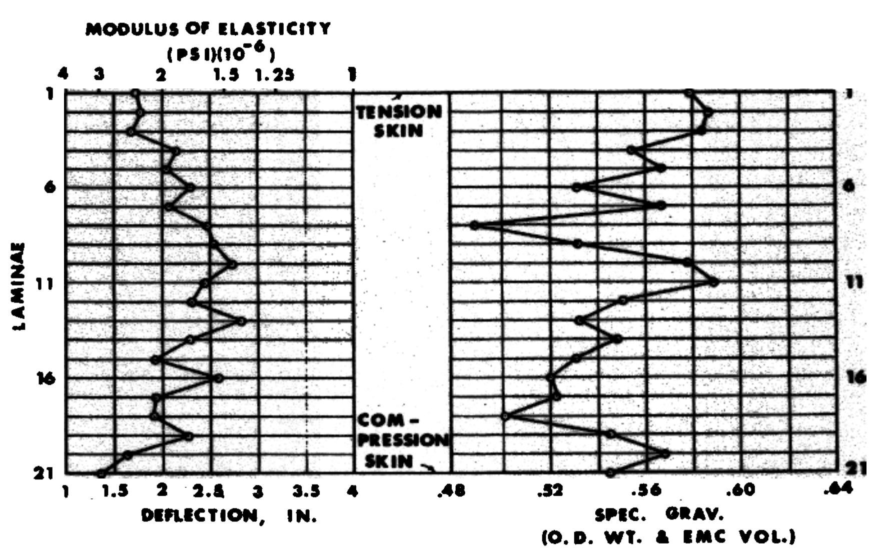

Figure 5.—Group C beams, with laminae arranged according to knot area. Each value is the average for five veneers.

Figure 6.—Veneers illustrative of the quality of material comprising all 25 laminated beams. These particular veneers comprise beam C-1 (illustrated in Figure 2). The piece with the least knot area (on the extreme left) was used for a tension skin and the next clearest (extreme right) for a compression skin. All veneers are arranged from clearest at the outside to knottiest at the center.

glued to the tension and compression faces with an epoxy resin in a secondary gluing operation. Prior to this secondary operation, the Group E beams were jointed and surfaced to a width of approximately 2¾ inches. Thus the aluminum overhung the wood by about ⅛-inch on each side.

All 25 beams were laminated in a simple press made from 18 rocker-head clamps equally spaced over the 100-inch length of the press. Steel angles provided side restraint and prevented misalignment of the veneers. A phenol-resorcinol adhesive was spread manually at the rate of 60 pounds per 1,000 square feet of glueline. This amount was divided equally between mating surfaces. Screw pressure was applied with a hand wrench to achieve fairly uniform squeeze-out. The press room was at 70° F. or over, and the beams were cured 24 hours in the clamps. No wood-to-wood gluelines were observed to fail during subsequent strength testing. Figure 6 illustrates typical veneers going into a single beam.

Before application, the aluminum strips from Group E beams were pickled for 2 hours at ambient temperature in a solution containing 10 pounds of concentrated sulphuric acid (specific gravity 1.84), 1 pound of technical grade sodium dichromate, and 30 pounds of water. After the surfaces had been flushed with water and dried with clean cloths, the strips were glued to the tension and compression faces. Mixed epoxy adhesive was used at the rate of 60 pounds per 1,000 square feet of glueline—one-half applied to each mating surface with a small paint brush. The press and press times were the same as for the primary laminating operation.

Strength Tests

The 25 laminated and five solid-sawn beams were tested in bending to destruction. The poorest faces of the solid-sawn beams were loaded in tension.

Prior to test, each laminated beam was scraped free of squeezed-out adhesive, jointed on one side, and finally parallel-planed on the other side to maximum thickness that would clean up. Strength was evaluated with the apparatus used in the previous research[2]. Deflections between supports were measured to the nearest 0.01 inch.

After each beam failed, a 1-inch-long, cross-sectional slice was cut approximately 12 inches from one end and ovendried to determine moisture content. This moisture content was assumed to represent the average of the beam.

The 100-inch-long veneers labelled *A* to *Z* were evaluated in full-length tension parallel to the grain[3]. Flared grips were used. Rate of vertical movement on the loading head was 0.15 inch per minute. Strain measurements were made over a 60-inch gage length with dial gages placed on each side of the specimen. If the piece failed more than 22 inches from its center, the middle 44 inches was cut out and retested. After each veneer failed, a 1-foot length was cut 18 inches from one end and ovendried to determine the moisture content.

Specific Gravity and Stiffness of Veneers

The veneers in each group did not differ significantly (0.05) from each other in specific gravity. The average specific gravity was 0.55. Groups A and B were 0.547, Groups C and D were 0.549, and Group E was 0.555. The range among individual veneers was from 0.439 to 0.718.

[3] Bohannan, Billy. 1965. Exploratory development of tension test methods for structural size lumber. U.S. FS Res. Note FPL-0102, Madison, Wis.

Deflections of veneers used in the beams ranged from 1.1 to 5.0 inches each way. These deflections correspond to MOE values of 3,600,000 and 800,000 p.s.i.

For reasons not clear, Duncan's multiple range test disclosed that some groups differed significantly (0.05) in stiffness from other groups. The notation below records average deflection on the veneers (inches) according to group; any two means not underscored by the same line are significantly different, and any two means underscored by the same line are not significantly different.

E	*C*	*A*	*B*	*D*
2.08	2.14	2.20	2.30	2.39

The average deflection was 2.22 inches, corresponding to an MOE of 1,790,000 p.s.i.

Figure 7 indicates that there was a significant, but weak, correlation between specific gravity and MOE (as indicated by deflection) of the veneers used in the test beams. The stiffness of an individual veneer could not be predicted from its specific gravity.

Strength and Stiffness of Beams

Table 1 compares the MOR and MOE for each group of beams. The beams with veneers arranged by stiffness appeared to be stronger and stiffer than those made by any other arrangement. Beams with randomly arranged laminae (Group D) were significantly (0.05) weaker and less stiff than the rest. Those with laminae arranged by specific gravity (Group A) had a significantly lower MOR than did the wood cores of the Group E beams.

Placement of laminae according to stiffness not only increases the average MOR but also decreases the variability between beams (see Table 2, Column 8). The tabulation of 95-percent exclusion limits confirms this observation.

The pertinent values of the beam groups, arranged by decreasing strength, are:

Group	Laminations arranged by--	Avg. MOR	Avg. MOE	95% exclusion limit, MOR
		P.s.i.	P.s.i.	P.s.i.
B	Elastic modulus	10,200	1,940,000	7,140
C	Appearance	9,590	1,760,000	5,960
F	Solid-sawn	9,540	1,830,000	3,720
A	Specific gravity	8,390	1,740,000	4,790
D	Random	6,630	1,480,000	2,890

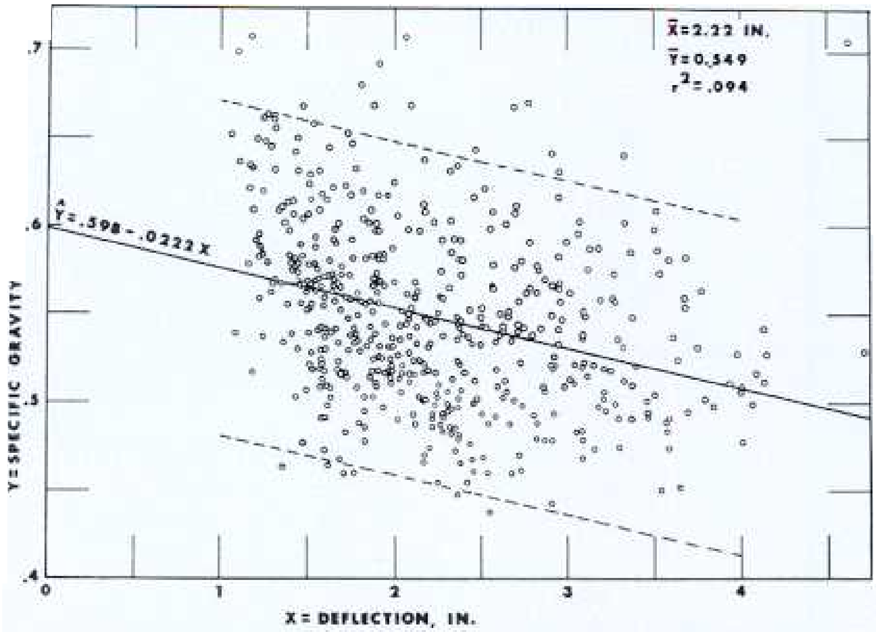

Figure 7.—Relationship between specific gravity of the veneers (ovendry weight and volume at EMC) and deflection under center-point loading. A deflection of 1 inch corresponds to an MOE of 4,000,000 p.s.i.; a deflection of 4 inches to an MOE of 1,000,000 p.s.i. Values are plotted for all 525 veneers used in the beams. Dotted lines define 95-percent confidence interval.

Table 1.—COMPARISON OF STRENGTH AND STIFFNESS OF BEAMS[1] HAVING LAMINAE LOCATED ACCORDING TO VARIOUS SYSTEMS: A, BY SPECIFIC GRAVITY; B, BY STIFFNESS; C, BY APPEARANCE; D, RANDOMLY; E, BY STIFFNESS WITH ALUMINUM ALLOY STRIPS GLUED TO TENSION AND COMPRESSION FACES. F-SERIES BEAMS WERE SOLID, HEART-CENTER CANTS

Levels[2] of performance: best at top, worst at bottom	Specific gravity of beams (ovendry weight/volume at test moisture content)	Moisture content of beams at time of test	Modulus of rupture of wood	Modulus of elasticity[3] of wood
(1)	(2)	(3)	(4)	(5)
		Percent		P.s.i.
First	E — 0.57 C — 0.57 A — 0.56 D — 0.56 B — 0.56 F — 0.54	E — 8.9 B — 9.0	E — 10,970[4]	E — 2,000,000 B — 1,940,000 F — 1,830,000 C — 1,760,000 A — 1,740,000
Second		C — 9.4 A — 9.4 D — 9.5		D — 1,480,000
Third		F — 10.0		

[1]Values are averages for the five beams of each series.
[2]Levels of performance differ significantly (0.05) by Duncan's multiple range test. Boxed values are not significantly different from each other, even though located on different levels.
[3]From Table 2, Column 9.
[4]Maximum stress in the wood core, calculated by theory of transformed cross section.

Detailed results of the bending tests are given in Table 2. The height and width values in Columns 2 and 3 are the average at approximately 1 foot from each end of the beam. The average specific gravity for all beams was 0.56, which is less than the average of 0.61 for slash pine at 12-percent moisture content (Wood Handbook[4], Table 12).

For all beams except Group E, stress at proportional limit and MOR were calculated from the standard flexure formula:

$$f = \frac{Mc}{I}$$

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 MOE's in Column 9 were calculated from the deflection formula:

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

and the values in Column 10 were from the formula:

$$\Delta = \frac{Pa}{48EI}(3L^2 - 4a^2) + \frac{3Pa}{5GA}$$

where Δ is midspan deflection, inches
- P = total load on beam, pounds
- a = distance from support to load point, inches
- E = MOE, p.s.i.
- I = moment of inertia of cross section, inches[4]
- L = span length, inches
- A = cross-sectional area, square inches
- G = modulus of rigidity or shear modulus, p.s.i.

The first of these equations is the usual one for midspan deflections of a simply supported beam under two equal concentrated loads symmetrically placed; deflection is assumed to be entirely due to bending stresses, and shear deflection is neglected. The second formula accounts for deflections caused by both bending and shear stresses. When MOE was calculated with the second formula, the shear modulus *(G)* was assumed to equal 1/16 the MOE (Wood Handbook, p. 78).

The stiffness *(EI)* values in Column 11 for Groups B and E were calculated by the first formula. The MOE values in Column 9 for Group E beams are for the wood core of each beam and were calculated from the formula:

$$EI = E_a I_a + E_w I_w$$

where EI = the value from test data in Column 11
- E_a = the MOE of the aluminum faces and was assumed to be 10,000 p.s.i.

[4] U.S.D.A. 1955. Wood handbook, Rev. Ed. Agriculture Handbook No. 72, For. Prod. Lab., Madison, Wis.

I_a = the moment of inertia of the aluminum faces, inches[4]

E_w = the MOE of the wood core, p.s.i.

I_w = the moment of inertia of the wood core, inches[4]

The MOR values in Column 8 for Group E beams were calculated from the formula:

$$f = \frac{Mc}{\frac{E_a}{E_w} I_a + I_w} = \frac{E_w Mc}{EI}$$

where E_w = the calculated MOE of the wood core

M = the maximum moment carried by the beam, inch-pounds

c = the distance from the neutral axis of the beam to the aluminum-to-wood glueline, inches.

Table 2.—RESULTS OF BENDING TESTS OF 30 SOUTHERN PINE BEAMS

Beam number					Stress at proportional limit	Maximum load	Modulus of rupture	Modulus of elasticity: Between supports	Modulus of elasticity: Corrected for shear	Stiffness (EI)	Type and sequence of failure [2]
					(6)	(7)	(8)	(9)	(10)		
		Inches									
Laminations arranged by specific gravity											
A-1	7.16	2.81	9.0	0.55	6,660	10,100	8,420	1,860	2,040	—	T
A-2	7.12	2.81	9.4	.57	5,480	6,920	5,830	1,520	1,660	—	T
A-3	7.08	2.80	9.5	.56	7,280	11,000	9,440	1,780	1,950	—	T
A-4	7.13	2.77	9.6	.57	7,250	9,990	8,500	1,740	1,910	—	T
A-5	7.13	2.79	9.7	.57	7,200	11,500	9,740	1,800	1,970	—	C-T
Average			9.4	.56	6,770	9,900	8,390	1,740	1,910		
Laminations arranged by elastic modulus											
B-1	7.10	2.80	8.9	.55	8,080	12,500	10,600	1,920	2,110	162	T
B-2	7.15	2.77	9.0	.55	6,780	9,890	8,390	1,600	1,760	137	T
B-3	7.16	2.80	9.0	.57	7,940	12,800	10,600	2,060	2,270	174	C-T
B-4	7.18	2.81	9.0	.56	8,280	14,200	11,800	2,040	2,240	176	C-T
B-5	7.16	2.78	9.1	.57	8,010	11,200	9,440	2,080	2,290	176	T
Average			9.0	.56	7,820	12,100	10,200	1,940	2,130	165	
Laminations arranged by appearance											
C-1	7.10	2.80	9.3	.56	7,660	11,700	9,980	1,860	2,040	—	T
C-2	7.11	2.80	9.3	.58	6,780	11,500	9,760	1,800	1,970	—	T
C-3	7.09	2.80	9.1	.56	6,830	10,600	9,090	1,610	1,770	—	T
C-4	7.14	2.80	9.6	.57	7,990	13,900	11,700	2,020	2,210	—	T
C-5	7.18	2.80	9.5	.56	5,820	8,910	7,410	1,510	1,660	—	T
Average			9.4	.57	7,020	11,400	9,590	1,760	1,930		
Random arrangement of laminations											
D-1	7.12	2.80	9.4	.56	6,340	7,680	6,500	1,480	1,620	—	T
D-2	7.07	2.80	9.9	.56	5,140	6,000	5,140	1,560	1,710	—	T
D-3	7.20	2.77	9.4	.56	7,110	10,400	8,730	1,480	1,620	—	T
D-4	7.26	2.76	9.3	.57	6,180	9,360	7,720	1,540	1,690	—	T
D-5	7.19	2.80	9.3	.56	4,560	6,120	5,070	1,340	1,480	—	T
Average			9.5	.56	5,870	7,910	6,630	1,480	1,620		
Laminations arranged by elastic modulus, beams faced with aluminum											
E-1	7.23 [3]	2.72 [4]	9.1	.57	—	17,500	12,600 [5]	2,270 [6]		226	B-C-S
E-2	7.27 [3]	2.78 [4]	9.1	.58	—	15,300	10,500 [5]	2,030 [6]		212	B-C-T
E-3	7.19 [3]	2.76 [4]	9.1	.53	—	14,400	9,860 [5]	1,770 [6]		184	B-C-T
E-4	7.27 [3]	2.75 [4]	8.7	.58	—	16,000	11,000 [5]	1,970 [6]		206	B-C-T
E-5	7.26 [3]	2.77 [4]	8.6	.59	—	15,900	10,900 [5]	1,970 [6]		206	B-C-T
Average			8.9	.57	—	15,800	11,000	2,000		207	
Solid-sawn beams											
F-1	6.92	2.95	10.0	.43	6,370	11,400	9,680	1,590	1,740	—	C-S
F-2	6.91	2.95	10.6	.55	5,960	11,000	9,330	1,680	1,840	—	C-S
F-3	6.93	2.95	9.9	.55	4,960	6,600	5,590	1,620	1,770	—	T at knot
F-4	6.92	2.98	9.9	.60	7,980	12,800	10,800	2,150	2,350	—	C-T
F-5	6.93	2.94	9.6	.56	8,500	14,400	12,300	2,120	2,310	—	T at knot
Average			10.0	.54	6,750	11,200	9,540	1,830	2,000		

[1]For Groups A to D, calculated from size and weight of beam at time of test, corrected to ovendry weight using moisture content in Column 4. For Group E, calculated from size and weight of wood core only.
[2]C = compression; T = tension; S = shear; and B = buckling of top aluminum face.
[3]Total height of beam including 0.05-inch-thick aluminum faces.
[4]Width of wood core. Aluminum faces were 3.01 inches wide.
[5]Calculated by theory of transformed cross section.
[6]Calculated values for wood core.

This MOR represents the maximum stress in the wood core at failure. In calculating it, the full cross section of the beam was assumed effective to failure, but in all cases the top aluminum face buckled and peeled off near the load points before maximum load was reached (Figure 8). Both aluminum faces were effective in increasing stiffness, but it is possible that only the bottom face increased strength. Therefore, it is difficult to calculate a meaningful MOR for these beams. The effect of the ⅛-inch overhang of the aluminum faces is unknown. This overhang represents about 1.6 percent of the effective moment of inertia of the transformed cross section.

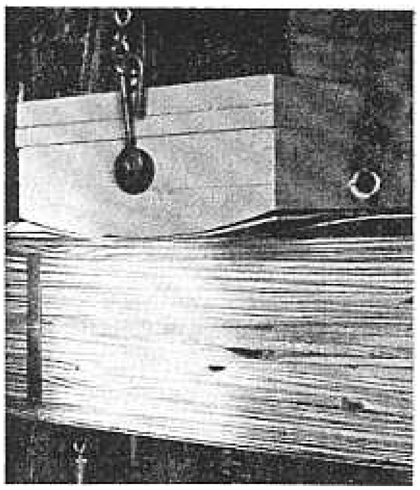

Figure 8.—Typical buckling failure of aluminum compression skin on beam from Group E.

No unusual type or sequence of failure was observed for any of the beams (Table 2, Column 12). A small split in cross grain at one edge of the bottom lamination of B-5 was observed before the beam was tested, but final failure did not occur through this section. The sequence in Group E was first a buckling of the aluminum compression face, then slight compression in wood, and finally, shear failure for beam E-1 and tension failure in the wood of the other four beams. When the wood failed in tension, the aluminum tension face peeled off. The peeling failure was partly in the wood and partly in the epoxy adhesive. Two of the solid-sawn beams failed in shear, probably because they were badly checked.

The Group B beams, whose laminations were arranged by elastic modulus (Figures 2B and 4), had the highest average strength and stiffness of all unreinforced beams. Their average MOR was 10,200 p.s.i., and their average MOE was 1,940,000 p.s.i. The average values for slash pine (12-percent moisture content and 0.61 specific gravity), as determined by standard strength tests on small, clear specimens, are 15,900 p.s.i. and 2,-060,000 p.s.i. respectively (Wood Handbook, Table 12).

The laminations in Group B beams decreased in elastic modulus from the outer faces to the neutral axis (Figure 4). If the MOE is assumed to decrease in a linear gradient from the outer faces to the neutral axis, by basic mechanics the stiffness of such a beam should be:

$$EI = E_{min} \frac{bd^3}{12} \left[1 + \frac{3}{4} \left(\frac{E_{max}}{E_{min}} - 1 \right) \right]$$

where E_{min} = MOE of the lamination at the neutral axis

E_{max} = MOE of the lamination at the outer faces

The gradient in Group B beams (Figure 4) was approximately linear and E_{max}/E_{min} approximately equaled 3, and thus:

$$EI \quad 2.5\, E_{min} \frac{bd^3}{12}$$

Now, if the laminations in Group B beams had been placed randomly, the average stiffness would be:

$$(EI)_{avg} = \frac{bd^3}{12} \frac{E_{min}}{2} \left(1 + \frac{E_{max}}{E_{min}} \right)$$

or

$$(EI)_{avg} = 2E_{min} \frac{bd^3}{12} \text{ if } \frac{E_{max}}{E_{min}} = 3$$

Theoretically, therefore, the increase in stiffness achieved by arranging laminae according to elastic modulus instead of randomly is equal to 2.5/2, that is, 25 percent. This agrees reasonably well with the 31-percent difference in stiffness between Group B beams (elastic modulus arrangement) and Group D beams (random arrangement).

The values for the solid-sawn beams are comparable to those for Groups B (Figure 4) and C (Figure 5). The beams were sawn so that stiff, dense wood was near the outer faces, and the pith was near the center (Figure 2F). If sawn in such a way, good solid beams can be produced from small trees. They are limited in size, however, and their quality is governed by the quality of the trees and the amount of degrade incurred during drying. The solid-sawn beams varied more in strength than the beams with selectively placed laminae, and thus might need to be assigned lower allowable stresses.

Group A beams, with laminations arranged by specific gravity (Figure 3), had an average MOR of 8,390 p.s.i., substantially less than that for Group B beams, whose laminae were arranged by stiffness. Specific gravity by itself is a good indicator of strength in clear, straight-grained wood, but not in pieces having knots and other strength-reducing characteristics.

The average measured stiffness *(EI)* of Group B beams was 165 x 10^6 pound-inches^2, and the average for the aluminum-faced Group E beams was 207 x 10^6 pound-inches^2. While this represents a 25-percent increase, the same gain could have been achieved by adding ½ inch to the height of the wood beam. Calculated by the theory of a transformed cross section, the average MOE of the wood core of Group E beams was 2,000,000 p.s.i., or very near the average of 1,940,000 p.s.i. for Group B.

Average maximum load was 12,100 pounds for Group B beams and 15,-800 pounds for Group E. The difference represents a 31-percent increase in strength. The loads at which the aluminum compression faces buckled on Group E beams were: E-1, 11,700 pounds; E-2, 13,900 pounds; E-3, 13,-400 pounds; E-4, 15,700 pounds; and E-5, 15,100 pounds. The average was 14,000 pounds.

The load that caused buckling might be considered the failing load, rather than the maximum load sustained. On this premise, the aluminum-faced beams had 16 percent more strength than the unreinforced, but otherwise similar, beams in Group B.

Specific Gravity and Stiffness of Individual Veneers as Indicators of Strength in Tension

Tension properties of the 26 veneers labelled *A* to *Z*, as related to their specific gravity and stiffness, are shown in Table 3. The tensile strengths in Columns 7 and 8 are surprisingly low in comparison to the MOR values in Column 8, Table 2, for beams fabricated from similar material. These data show the need for a better understanding of the correlation between the tensile strength of wood when loaded in pure tension and the strength when loaded in tension in a bending member. In a laminated beam, each lamina is restrained both laterally and longitudinally by adjacent laminae. Thus the laminae are believed to be more uniformly strained in a beam than when loaded individually in pure tension. It is known that, if a veneer or board has good tensile strength, it will perform equally well as the tension lamina in a laminated member. When knots and local grain deviations are present, however, the stress-strain distribution in a highly stressed tensile lamina is not understood. The benefits of adjacent laminae may be accentuated in beams having thin laminae.

Table 3.—DATA FROM TENSION TESTS OF 26 SOUTHERN PINE VENEERS

Specimen designation	Thickness	Width	Moisture content	Specific gravity [1]	Deflection [2]	Tensile strength [3]— of full length piece	Tensile strength [3]— of middle 44 inches	Modulus [4] of elasticity	Where failed
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			Percent				P.s.i.	1,000 p.s.i.	Inches
A			9.6	0.50			7,220	1,860	1T, 25T
B			9.8	.51			3,310	2,070	2T
C			9.2	.48			2,530	1,270	5T
D			8.8	.49			1,730	773	9, 36T
E			7.7	.50			1,780	712	4T, 26T
F			9.0	.47			2,900	1,100	6, 40
G			9.5	.49			4,570	1,570	6, 24T
H			9.8	.54			12,600	2,370	10T, 40T
I			8.9	.58			7,450	2,800	0, 32
J			8.5	.49			4,180	877	0, 30
K			8.6	.48			760	616	19T
L			8.6	.49			1,060	1,920	13
M			9.2	.51			700	1,100	12
N			9.8	.52			2,560	1,890	11
O			9.7	.49			6,080	1,730	3, 30T
P			9.2	.47			4,500		4, 37T
Q			8.5	.45			1,670	760	3, 26T
R			9.0	.46			730	659	4
S			9.0	.46			2,550	1,040	4, 30
T			8.7	.48			2,780	1,220	4, 31
U			9.7	.54			3,250	1,700	4, 31
V			9.4	.53			3,180	2,090	17T
W			9.2	.48			4,310	1,810	0
X			9.5	.43			2,640	1,310	18T
Y			9.2	.47			2,260	984	0, 29
Z			9.5	.49			440	650	0
Average			9.1	.49			3,370	1,400	

[1]Calculated from volume and weight at time of test. Weight was corrected to ovendry weight on basis of moisture content in Column 4.
[2]Deflection in flatwise bending with center load of 1.66 pounds on a 96-inch span.
[3]Tension test made on 100-inch-long specimen. If specimen failed at either end, the middle 44 inches was cut out and retested.
[4]Modulus of elasticity in tension parallel to grain. Gage length was 60 inches.
[5]Distance from middle of specimen. Where two values are given, piece was tested full length and retested over middle 44 inches. T after number indicates that failure was toward marked end of specimen.

Defects diminish the strength of a member in pure tension. A very severe defect may, for all practical purposes, reduce the tensile strength of a full-length veneer to zero.

In a recent test[2], all interior laminae were located according to stiffness and then cross cut before lamination to achieve a carefully controlled pattern of butt joints. Only tension and compression skins did not contain butt joints. The beams had an average MOR of 7,300 p.s.i.—74 percent of the average for similar beams without butt joints. Of the population represented by the sample, 95 percent could be expected to have an MOR in excess of 5,250 p.s.i.

No significant linear association was found between the specific gravity of the entire veneer and the tensile strength of the 100-inch, full-length veneer.

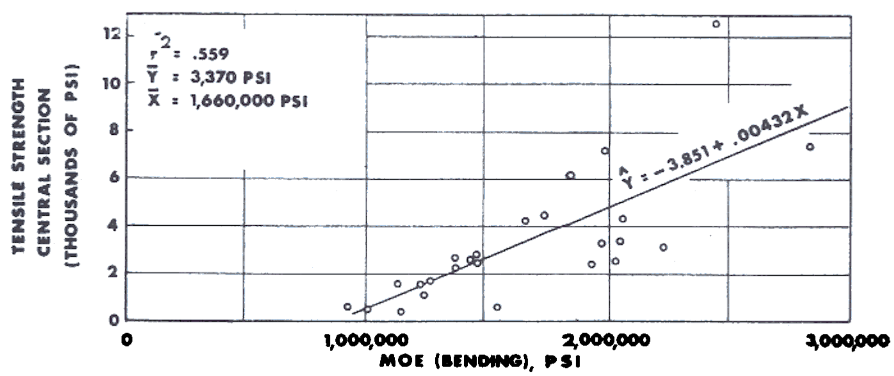

Figure 9.—Regression of MOE (bending) of veneer on pure tensile strength of 44-inch central portion of full-length veneer. Data from Columns 6 and 8, Table 3. (Veneer P not plotted.)

Figure 9 illustrates the association between stiffness (evaluated from deflection under center-point loading as recorded in Column 6 of Table 3) and ultimate tensile strength of the 44-inch-long central portion of each veneer. Although the coefficient of determination, r^2, is only 0.56, the correlation is significant at the 1-percent level.