Super-Strength Beams Laminated from Rotary-Cut Southern Pine Veneer

By

Peter Koch[1]

Southern Forest Experiment Station
Alexandria, La.

Abstract

Very strong beams were made by arranging 42 laminae of 1/6-inch rotary-cut southern pine veneer so that the stiffest veneers were on the tension and compression flanges and the most limber in the center. Beams thus fabricated to a 3-inch width and a 100-inch length averaged 13,280 p.s.i. stress in the outer laminae when failed in flexure. Modulus of elasticity averaged 2,330,000 p.s.i.

Similarly arranged beams were further strengthened by having the outer 6 veneers on both tension and compression sides impregnated with polymethylmethacrylate and then irradiated. These beams withstood 15,030 p.s.i. stress and had an MOE of 2,570,000.

Comparable beams strengthened by having the outer 6 laminae on both sides densified by heat and pressure averaged 22,090 p.s.i. stress in the outer laminae at failure; MOE was 3,040,000.

When laminae were arranged by stiffness, but not densified or impregnated, 2-inch-wide beams were stronger per inch of width than 3-inch beams; they also were less variable. The reason probably is that the narrowness of the laminae increases the probability of finding very strong pieces. There appear to be possibilities in assembling wide beams from narrow beams of 2 inches or some other standard width. Further tests of these narrow beams might justify an allowable stress of 4,000 p.s.i.

Ultimate horizontal shear stress (transformed section) of the stiffness-arranged beams averaged in excess of 550 p.s.i. While this is a very respectable value for wood beams, it does become a design limitation on these exceptionally strong, stiff beams.

DRY, THIN BOARDS sawn from young southern pine trees exhibit modulus of elasticity (MOE) values of 1,000,000 to 3,000,000 p.s.i. Beams of relatively uniform high strength can be laminated from this material if the boards are arranged so that the stiffest are on the outside of the beam and the most limber in the center.[2,3] Thick slicing of veneer is one possibility for commercial production of the laminae.

A second possibility — one that employs existing technology — is the use of thick rotary-cut veneer, kiln-dried and subsequently ripped to width:

1. Veneer rotary-cut from a bolt has higher specific gravity, fewer knots, and hence higher strength than wood sliced from a cant squared from the same bolt.
2. It may be removed in continuous ribbons from bolts of various sizes, dried, and ripped or clipped to width with minimum edging loss from crook. In contrast, sliced veneer must be cut from cants of the proper width (including a 1-inch crook and edging allowance) for the desired beam dimension.
3. Finally, yield is greater in rotary cutting. For example, a 4-foot bolt 8 1/2 inches in diameter will yield a 6-by-6-inch cant that can be sliced into 72 square feet of 1/6-inch green laminae. The same bolt can be rotary-peeled to a 3 1/2-inch core to yield 94 square feet of 1/6-inch laminae — a 30 percent increase.

It must be observed, however, that if long veneers of maximum thickness are required, slicing may have more promise than rotary peeling. It is extremely difficult to peel veneer over 5/16-inch thick from small 8-foot-long bolts, especially if the bolt must be turned to a core diameter of 3 1/2 inches. Increases in bolt length aggravate the difficulty.

The research reported here explored the possibility of using rotary-cut veneers 1/6-inch thick.

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[2]Koch, P. 1964. Strength of beams with laminae located according to stiffness. For. Prod. Jour. 14 (10): 456-460.

[3]Koch, P., and B. Bohannan. 1965. Beam strength as affected by placement of laminae. For. Prod. Jour. 15(7): 289-295.

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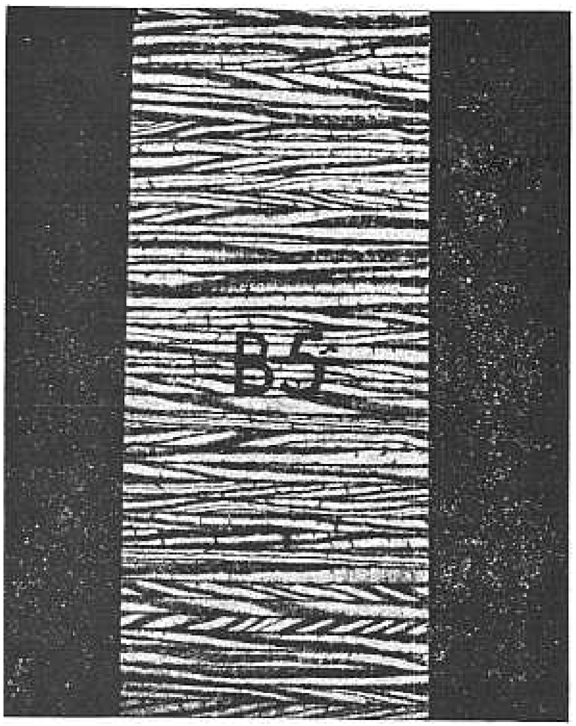

Figure 1. — Typical beam cross section. All beams contained 42 rotary-cut laminae, each 1/6-inch thick and arranged with the tight side outermost. Lathe checks are visible. This beam is 3 inches wide, with tension side on the bottom. It had a modulus of rupture calculated from the transformed section of 13,970 p.s.i. and a modulus of elasticity of 2,210,000 p.s.i.

Also considered was the possibility of improving the strength properties of the outermost laminae by 1) densification through heat and pressure and 2) impregnation with polymethylmethacrylate followed by irradiation. Effect of laminae width was also explored for the special case of beams having laminae placed by elastic modulus.

Procedure

Sixteen 8-foot bolts, principally loblolly and shortleaf pine from east Texas, were selected for symmetrical pith location and an estimated minimum of 50 percent latewood. The bolts averaged 13.1 inches in diameter, ranging from 12 to 14 1/2 inches. Growth rate averaged 7 rings per inch.

After steaming at 160°F. for twelve hours, the bolts were peeled on a lathe equipped with a roller nosebar. The green veneer was clipped to yield 328 sheets 0.172 inch thick by 27 inches wide by 102 inches along the grain.

The intent was to dry the sheets in a jet dryer for 12 minutes at 400°F., but time control was confused and the moisture content of the emerging veneer varied from oven-dry to more than 15 percent. On many pieces, considerable scorching was evident. The dried veneer was 1/6-inch thick and exhibited 6.6 lathe checks per inch averaging 0.13 inch deep.

In the absence of a suitable clipper, the sheets were sawn into strips on a roll-feed gang ripsaw. A maximum of eight strips — four 3 3/8 inches wide and four 2 11/32 inches wide — were ripped from each sheet. Only broken or splintered veneers were discarded. Yield was approximately 1,134 wide veneers and 936 narrow.

All of the wide veneers and approximately 300 of the narrow were stacked on sticks for one month in an atmosphere controlled at approximately 50 percent relative humidity and 72°F.

Grouping of Veneers

As the veneers were taken off sticks, they were randomly assigned to beams in each of five categories designated as follows (veneers in groups A through D were 3 3/8 inches wide):

A. Randomly arranged beams — laminae placed at random.
B. Arranged by stiffness — stiffest laminae at flanges, most limber in center.
C. Arranged by stiffness and with flanges densified.
D. Arranged by stiffness and with flanges impregnated and irradiated.
E. Narrow and arranged by stiffness. Same as B, except that veneers were 2 11/32 inches wide.

There were 5 beams in each category, 25 in all, and 48 veneers were drawn for each beam.

Evaluation for Stiffness

Just prior to stiffness testing, all veneers were trimmed to 100 inches and weighed. The residual end was weighed, oven-dried, and weighed again. Moisture content and specific gravity of each veneer were calculated from these data.

Veneers in groups A, C, and D were tested for stiffness (MOE) in flatwise bending over a simple span of 96 inches with a net center-point load of 142 grams. The test apparatus and procedure have been previously described.[2] Deflection measurements were replicated twelve times — one half in each direction — and averaged.

Because of their extreme flexibility and the presence of some cup, the veneers were difficult to evaluate by this system. Veneers for beams B and E were therefore tested for central-portion stiffness over a 48-inch fixed-end span. The central-point load was 2 pounds for B veneers and 1.39 for E. Measurements were replicated 8 times.

Placing Laminae Within Beams

Group A veneers: After broken or split veneers had been rejected, 42 were randomly selected from the remainder of those allocated to each beam and randomly placed within beams.

Group B, C, D, and E veneers: Broken, split, or scant veneers were rejected. The stiffest 42 per beam were then selected from the remainder and organized with the most stiff on the tension face, the next most stiff on the compression face, the third most stiff adjacent to the tension face, the fourth most stiff adjacent to the compression face, and so on until the most limber veneers were in the center.

Fabricating Beams

All beams were laminated in a screw-operated cold press. A phenol resorcinol adhesive was applied with a glue spreader at an approximate rate of 75 pounds per 1000 square feet of glue line. This amount was divided equally between mating surfaces. Figure 1 illustrates a typical cross section through a beam, and Figure 2 shows the veneers that went into the same beam. The tight side of each veneer was placed outermost; thus only glue line 21-22 was loose-to-loose.

All beams except those in group A (random placement of laminae) were fabricated with two dry glue lines so located that the tension and compression flanges, each comprised of six veneers, were separable from the core of the beam.

The flanges from beams B, C, and D were jointed on the two edges to barely clean up the glue squeeze-out and misalignment of veneers. After specific gravity had been determined, MOE was measured by deflecting (flatwise) each flange over a 96-inch simple span with a net center-point load of 20 pounds. Deflection measurements were replicated eight times — half in each direction. The narrower flanges from group E beams were similarly evaluated but with a proportionately reduced load.

Modifying Strength Properties of Flanges

Flanges for group C beams were densified to an average specific gravity of 1.18 (based on weight and volume on emergence). The hot press schedule was:

Phase	Time	Pressure P.s.i.	Temperature Deg. F.
Heating prior to densification	25	200	230
During densification	5	1,200	230
After densification	10	750	330
Cooled to room temperature	15	750	transition
TOTAL	55		

Flanges from group D beams were impregnated with polymethylmethacrylate and subjected to gamma radiation from a cobalt 60 source to achieve a total dose of 2.5 megarads. This procedure increased flange weight by 68 percent.

Following treatment, flanges from groups C and D were machined to the maximum width that would clean up and re-evaluated for stiffness.

All flanges were then glued to their respective cores. To reduce squeeze-out, some pecan shell flour was added to the adhesive mix applied to the densified and the irradiated flanges. All beams were then jointed on one side and parallel-planed on the other to the maximum thickness that would clean up.

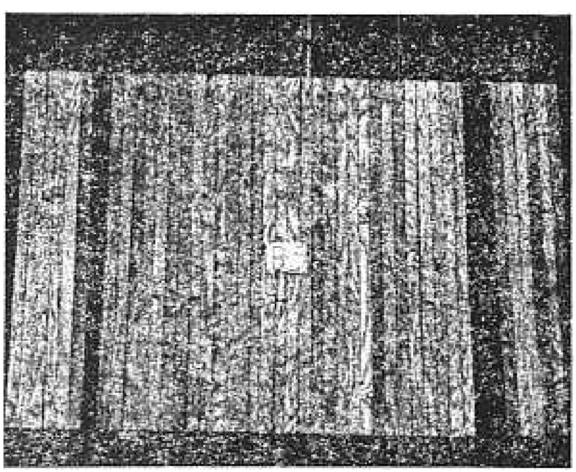

Figure 2. — These 100-inch-long veneers comprise the beam illustrated in Figure 1. They are arranged in order of assembly. The stiffest veneer (on the extreme left) was used as a tension skin. The veneers are in order of stiffness from outside to center without regard to visible defect. Six outermost laminae on each side were glued up as separate flanges, tested for stiffness, and assembled to the beam core in a secondary gluing operation.

Evaluating Strength of Beams

The strength of each beam was evaluated with the apparatus shown in Figure 3. Deflections were measured to the nearest 0.01 inch with a taut wire and scale.

From those beams that failed in tension or compression, a 1-inch cross-sectional slice was promptly cut 12 inches from one end, measured for volume, and oven-dried to determine MC and specific gravity based on oven-dry weight and volume at time of test. These values were assumed to represent the average of the beam.

From beams that failed in horizontal shear leaving the flange apparently intact (B-1, C-1, C-2, C-3, D-1, D-4, and E-2), similar cross-sectional slices were removed approximately one inch from an end. The two halves of each split beam were then resurfaced on the core side to remove all damaged wood and to balance the two pieces; they were then relaminated to form a new 94-inch balanced beam of less depth. The new beams were planed and loaded to failure as before.

Specific Gravity and Stiffness of Veneers and Flanges

The veneers in each group of beams did not differ significantly in specific gravity. The average (volume at 7 1/2 percent MC and oven-dry weight) was 0.54. The range in individual veneers was 0.41 to 0.70. In the 20 beams arranged by stiffness, specific gravity of the 2 center veneers averaged 0.51, while the outermost tension and compression veneers averaged 0.57.

After they had been glued up and equilibrated, the 6-ply tension and compression flanges averaged

0.63 specific gravity (volume at 7 1/2 percent MC and OD weight and including adhesive). Impregnation and irradiation of group D flanges increased the specific gravity to 1.07. The C flanges averaged 1.18 at volume and weight following densification, i.e., nearly oven-dry.

MOE of the core veneers for beams B, C, and D averaged 1,760,000 p.s.i. and MOE of the veneers on the tension and compression faces was 3,110,000 p.s.i. for a ratio of 1:1.77 (Figure 4). The narrower group E veneers (average of 5 beams) ranged from 2,580,000 p.s.i. at the core to 3,600,000 at the faces, for a ratio of 1:1.40.

MOE of the final 6 laminae (measured as a glued-up flange) for both tension and compression sides averaged as follows:

Beam group	Before treatment, p.s.i.	After treatment, p.s.i.
B — Arranged by stiffness	2,590,000	
C — Arranged by stiffness and densified	2,510,000	4,560,000
D — Arranged by stiffness and irradiated	2,520,000	2,870,000
E — Narrow and arranged by stiffness	2,680,000	
AVERAGE	2,560,000	

Densification by heat and pressure stiffened the flanges more effectively than densification by impregnation and irradiation. Figures 5 and 6 illustrate the structure of beams C and D.

It also appears that the narrow laminae of group E made stiffer flanges than the wider group B laminae. The average MOE of the outermost tension lamina was 3,600,000 p.s.i. in group E beams and 2,700,000 in group B beams.

Typical cross sections of beams from all five groups are shown in Figure 7.

Strength and Stiffness of Beams

Detailed results of the bending tests are given in Table 1. The average specific gravity (volume at MC in column 4 and oven-dry weight) for untreated beams A, B, and E was 0.61; values for densified beams C and irradiated beams D were 0.69 and 0.75 respectively.

Beams C — arranged by stiffness and densified — had significantly[4] highest MOR and MOE (columns 9 and 14). Beams D were stiffer than beams E, B, and A, while beams E were stiffer than beams B and A. Beams D were stronger than beams B and A, but not stronger than beams E. The relationship is tabulated below; by Duncan's test, values in the same box do not differ significantly from each other.

[4]The term "significant" as used in this paper indicates the 0.05 level.

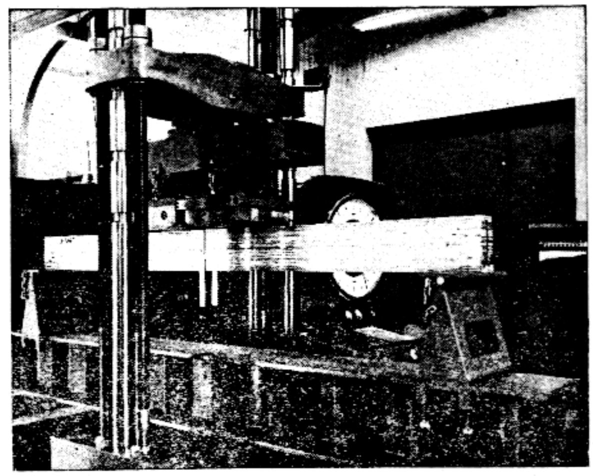

Figure 3. — Set-up of testing machine (120,000-pound capacity) for evaluating beams on 94-inch span with two-point loading. Load points were 14 inches apart at mid-span. Rocker-type end supports were used, and roller nests were placed under one head to insure that loading was vertical. Rate of vertical movement of the loading heads was 0.137 inch per minute. The apparatus and speed of loading follow recommendations in ASTM D198-27, Static Tests of Timber. The group D beam in the machine is arranged by stiffness and has irradiated flanges.

Beam group	Avg. MOR of rectangular section	Avg. MOE	95 percent exclusion limit for MOR of rectangular section
	P.s.i.	P.s.i.	
C — Arranged by stiffness and densified	16,560	3,040,000	13,300
D — Arranged by stiffness and irradiated	14,180	2,570,000	10,440
E — Narrow and arranged by stiffness	13,060	2,460,000	11,340
B — Arranged by stiffness	12,260	2,330,000	10,480
A — Randomly arranged	11,670	2,240,000	8,850

The 95 percent exclusion limits for MOR (i.e., of the beam population represented by the sample, 95 percent could be expected to have this MOR or higher) were calculated by following assumptions outlined on page 47 of Steele and Torrie (1960). These very high values might justify relatively high allowable working stresses.

For reasons not clear, the MOR of beams D — arranged by stiffness and irradiated — was somewhat more variable (range 3,736 psi) than the MOR of the other beams. Non-uniform penetration of the polymethylmethacrylate probably was the cause. Beams E — narrow and arranged by stiffness — displayed least range in MOR (2,030 psi) and least range in MOE (100,000 psi), very likely because the narrowness of the laminae increased the probability of finding (by stiffness segregation) really superior wood for the highly stressed portions of each beam.

Because rotary-cut veneer contains the strongest wood in the tree, beams A — randomly arranged — were much stronger and stiffer than any beams previously made from laminae cut from pith center cants.[2,3] As in the earlier research, variability of MOR in the randomly arranged beams caused a relatively low 95 percent exclusion limit.

For all beams, stress at proportional limit (column 7) and MOR (column 9) 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 MOE's in column 13 were calculated from the deflection formula, $\Delta = (Pa/48EI)(3L^2 - 4a^2)$, and the values in column 14 were from the formula $\Delta = (Pa/48EI)(3L^2 - 4a^2) + (3Pa/5GA)$, where Δ

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

No.	Ht.	Width	M.C.	Sp. gr.[1]	Max. load	Stress at proportional limit		Modulus of rupture		Horizontal shear		Modulus of elasticity		Defl. at max load	EI per inch beam width[2]	Max. load per inch width	Type of failure[3]
						Rect. sect.	Trans. sect.	Rect. sect.	Trans. sect.	Rect. sect.	Trans. sect.	Uncorr. for shear	Corr. for shear				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
	In.	In.	Pct.		Lbs.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	P.s.i.	1000 P.s.i.	1000 P.s.i.	In.	1000 Lb.-in.[2]	Lbs.	
Laminae randomly arrangea																	
A-1	6.78	2.84	8.87	0.60	11,940	9,470		10,980		470		1,970	2,140	1.39	51,060	4,200	T
A-2	6.75	2.98	8.60	.63	14,500	10,160		12,820		540		2,070	2,250	1.60	53,000	4,870	T
A-3	6.83	2.84	9.38	.62	10,950	9,060		9,920		420		2,120	2,300	1.16	56,180	3,860	T
A-4	6.72	2.92	8.75	.62	13,830	10,120		12,590		530		2,070	2,250	1.57	52,300	4,740	T-S
A-5	6.79	2.94	9.62	.61	13,580	8,940		12,020		510		2,080	2,270	1.47	54,320	4,620	[illegible]
Avg.	6.77	2.90	9.04	.62	12,960	9,550		11,670		490		2,060	2,240	1.44	53,370	4,460	
Laminae arranged by elastic modulus																	
B-1	6.75		8.51	.60	15,320	10,330	11,190	13,190	14,290	560	540	2,120	2,300	1.61	54,310	5,010	S
B-2	6.81		9.71	.63	13,700	10,830	11,740	12,020	13,020	510	500	2,260	2,460	1.31	59,460	4,640	T
B-3	6.75		9.64	.62	13,180	10,750	11,650	11,810	12,790	500	480	2,240	2,440	1.27	57,490	4,480	T
B-4	6.75		9.66	.60	12,860	9,280	10,060	11,370	12,320	480	470	2,080	2,260	1.36	53,180	4,320	T
B-5	6.77		9.40	.60	14,475	9,350	10,130	12,890	13,970	550	530	2,030	2,210	1.53	52,500	4,920	T
Avg.	6.77	2.97	9.38	.61	13,907	10,110	10,950	12,260	13,280	520	500	2,150	2,330	1.42	55,390	4,670	
Laminae arranged by elastic modulus with flanges pressure densified																	
C-1	6.03	2.88	8.22	.67	14,970	11,900	16,190	17,160	23,350	650	590	2,770	2,970	1.94	50,540	5,200	S
C-2	5.99	2.97	8.44	.70	15,620	11,600	15,440	17,790	23,410	660	600	2,820	3,010	1.96	50,520	5,260	S
C-3	6.01	2.89	8.35	.70	15,400	10,810	14,380	17,700	23,560	660	600	3,010	3,220	1.85	54,510	5,330	S
C-4	5.99	2.92	9.31	.70	13,430	12,480	16,640	15,380	20,500	580	520	2,750	2,940	1.59	49,250	4,600	T
C-5	5.98	2.90	9.29	.70	12,760	14,350	19,050	14,770	19,610	550	500	2,870	3,070	1.67	51,180	4,400	T
Avg.	6.00	2.91	8.72	.69	14,436	12,230	16,340	16,560	22,090	620	560	2,840	3,040	1.80	51,200	4,960	
aminae arranged by elastic modulus with flanges impregnated and irradiated																	
D-1	6.86	2.80	7.18	.75	13,920	10,380	11,020	12,680	13,460	540	520	2,240	2,450	1.41	60,360	4,970	S
D-2	6.88	2.97	7.32	.74	15,500	11,520	12,230	13,230	14,040	570	540	2,380	2,590	1.36	64,570	5,220	T
D-3	6.80	2.91	7.56	.74	17,180	9,100	9,660	15,320	16,260	650	630	2,440	2,650	1.69	63,820	5,900	T
D-4	6.79	2.95	6.99	.75	15,030	11,120	11,790	13,260	14,070	560	540	2,410	2,620	1.38	62,800	5,090	S
D-5	6.88	2.87	7.64	.75	18,580	9,820	10,350	16,410	17,300	710	680	2,320	2,530	1.95	63,050	6,470	T
Avg.	6.84	2.90	7.34	.75	16,042	10,390	11,010	14,180	15,030	610	580	2,360	2,570	1.56	62,920	5,530	
Narrow laminae arranged by elastic modulus																	
E-1	6.80	1.99	8.69	.60	9,970	8,870	9,540	13,000	13,990	550	540	2,230	2,430	1.52	58,430	5,010	T-S
E-2	6.79	2.01	8.26	.60	10,780	9,320	10,030	13,960	15,010	590	580	2,230	2,430	1.72	58,290	5,360	C-S
E-3	6.78	2.04	7.85	.63	10,220	9,850	10,600	13,080	14,070	550	540	2,260	2,450	1.50	58,560	5,010	T
E-4	6.79	1.96	7.91	.62	10,030	9,430	10,580	13,320	14,940	560	550	2,280	2,480	1.56	59,510	5,120	T
E-5	6.68	1.98	7.98	.62	8,780	6,790	7,310	11,930	12,830	500	480	2,330	2,530	1.33	57,980	4,430	-
Avg.	6.77	2.00	8.14	.61	9,956	8,850	9,610	13,060	14,170	550	540	2,270	2,460	1.53	58,550	4,990	

[1]Based on volume at test M.C. (column 4) and oven-dry weight.

[2](MOE from column 13) (moment of inertia per inch of beam width).

[3]C = compression; T = tension; S = horizontal shear. Sequence indicated, when failure was multiple

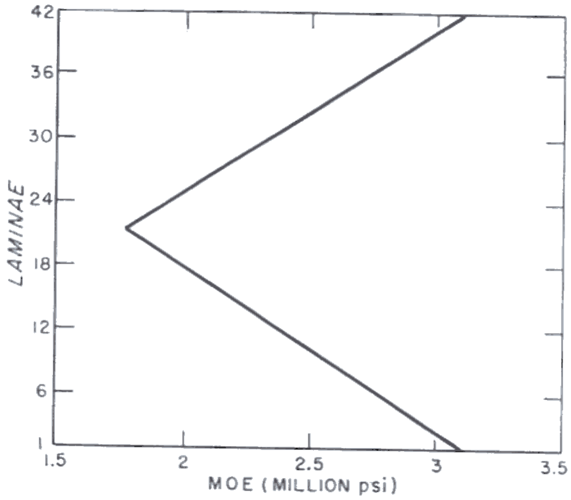

Figure 4. — Approximation of average MOE values for individual laminae comprising beams in groups B, C, and D.

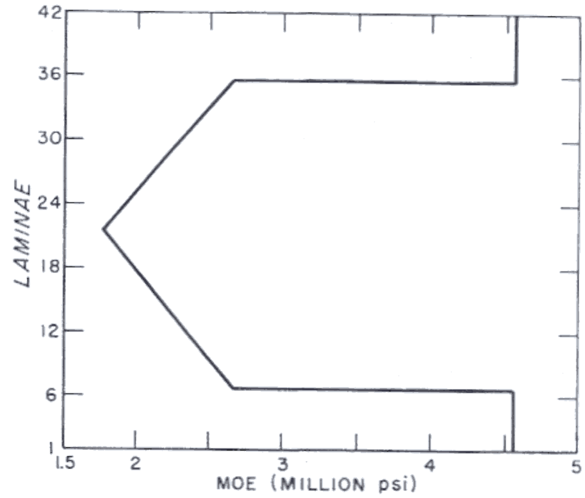

Figure 5. — Approximation of distribution of MOE values within group C beams after the densified flanges were assembled with the untreated cores.

is midspan deflection, inches

P = total load on beam, pounds
a = distance from support to load point, inches
E = MOE, psi
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, psi

The first of these equations is the usual one for midspan deflection of a simple 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 16 were calculated by the first formula.

A comparison of maximum loads (col. 17) and EI values (col. 16) was illuminating because all beams had the same number of laminae:

Beam group	Average maximum load per inch of beam width	Average EI per inch of beam width
	Pounds	Pound-inches^2
D — Arranged by stiffness and irradiated	5,530	62,920,000
E — Narrow and arranged by stiffness	4,990	58,550,000
C — Arranged by stiffness and densified	4,960	51,200,000
B — Arranged by stiffness	4,670	55,390,000
A — Randomly arranged	4,460	53,370,000

Beams D — arranged by stiffness and irradiated — performed best, with beams E — narrow and arranged by stiffness — next best. Treatment E is easier to accomplish than densification C or irradiation D, and hence is of considerable interest. It would appear that wide beams of unusual strength, stiffness, and uniformity could be assembled from a number of group E beams.

The depth reduction caused by densifying the flanges of group C beams caused loss of stiffness. The effect would be less pronounced on deeper beams, provided that the number of laminae densified remained constant.

The proportional limit (PL) and MOR values in columns 8 and 10 of Table 1 were calculated by transforming the cross section to a one-material beam with an MOE equal to the MOE of the flange material (Figures 4, 5, and 6). A separate transformation was made for each beam.

Column 11 tabulates the maximum horizontal shear stress (S_s) as calculated from the actual rectangular cross section of the beam by the usual formula, $S_s = V\bar{y}A'/Ib$,

where S_s = horizontal shear stress, p.s.i.
V = vertical shear, lbs.
b = width of rectangular beam, inches
I = moment of inertia of rectangular section about the neutral axis, inches^4
A' = area of cross section above the plane in which stress is in question, inches^2
$\bar{y}$ = distance from neutral axis to center of gravity of area A′, inches

Because direct application of the equation ignores the variation in stiffness of laminae, cross sections were transformed to a one-material beam with an MOE equal to the MOE of the two central laminae (Figures 4, 5, and 6). The equation was then used to calculate the horizontal shear values (column 12) from the transformed section.

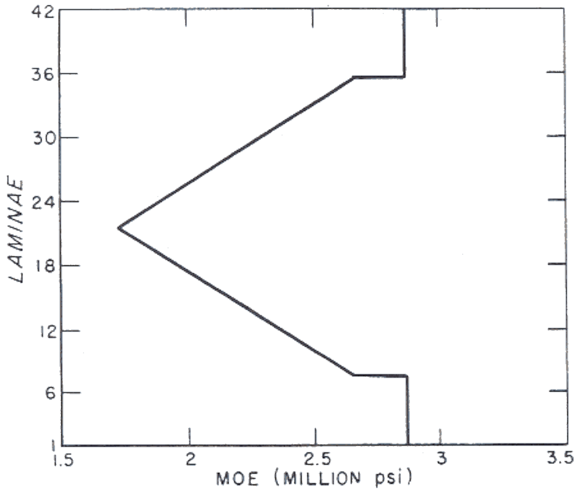

Figure 6. — Approximation of distribution of MOE values within group D beams after the irradiated flanges were assembled with the untreated cores.

Average values of PL, MOR, and S_s from columns 8, 10, and 12 are summarized below:

Beam group	Calculated from transformed sections		
	MOR	PL	S_s
		P.s.i.	P.s.i.
C — Arranged by stiffness and densified	22,090	16,340	560
D — Arranged by stiffness and irradiated	15,030	11,010	580
E — Narrow and arranged by stiffness	14,170	9,610	540
B — Arranged by stiffness	13,280	10,950	500

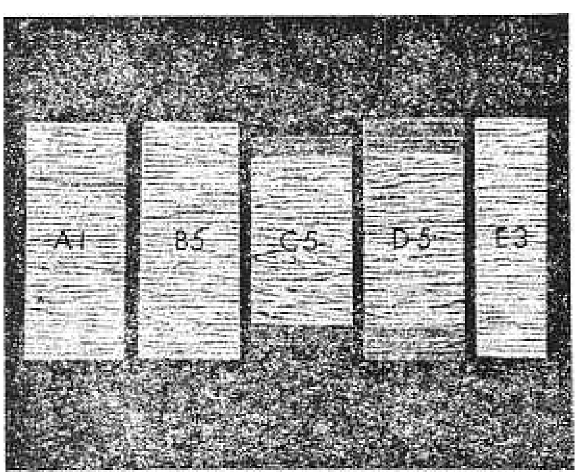

Figure 7. — Typical cross sections of beams from each group: A — laminae randomly arranged; B — stiffest in outer laminae; C — stiffest in outer laminae with final six veneers on top and bottom densified with heat and pressure; D — stiffest in outer laminae with final six veneers on top and bottom impregnated with polymethylmethacrylate and irradiated; and E — narrow veneers, stiffest in outer laminae. Tension side at bottom on all beams.

Group D beams had lower MOR values than group C beams; impregnation and irradiation did little to improve strength in the tension flange, where most failures occurred.

Seven of the 25 beams failed in horizontal shear — one each in groups B and E, two in D, and three in C. Obviously these methods of fabrication greatly increase MOR but leave S_s values unimproved. When the 7 beams were refabricated to a lesser depth and retested to failure, the MOR values did not significantly alter the averages in columns 9 and 10 of Table 1. Rebuilt beam C-1, with densified flanges, had an MOR calculated from the transformed section of 24,010 p.s.i., an extraordinary value.

The laminae in beams B and E decreased in MOE from the outer faces to the neutral axis (Figure 4). If the decrease is assumed linear, by basic mechanics the stiffness 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 laminations at the neutral axis

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

The gradient in beams B (Figure 4) was approximately linear, and E_{max}/E_{min} approximately equaled 1.77, and thus: $EI = 1.6E_{min}(bd^3/12)$. Now, if the laminations in group B beams had been placed randomly, the average stiffness would be:

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

If

$$\frac{E_{max}}{E_{min}} \quad 1.77,$$

then

$$(EI)_{avg} \quad 1.4E_{min}\frac{bd^3}{12}$$

Theoretically, therefore, the increase in stiffness achieved by arranging laminae according to elastic modulus instead of randomly is in the ratio of 1.6/1.4, that is, a 13-percent increase. Beams B-arranged by stiffness — were actually only 4 percent stiffer than randomly arranged group A. Achievement of less than the theoretical difference was probably due to the difficulty in accurately measuring the MOE of the individual thin, somewhat cupped, rotary-cut veneers, and hence difficulty in accurately placing the laminae as intended. Previous research[3] with thicker sawn laminae showed closer agreement with theory, the advantage achieved being greater than predicted.

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