Structural Lumber Laminated From 1/4-Inch Rotary-Peeled Southern Pine Veneer

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Abstract

By the lamination process evaluated, 60 percent of total log volume ended as kiln-dry, end-trimmed, sized, salable 2 by 4's—approximately 50 percent more than that achieved by conventional bandsawing of matched logs. Moreover, modulus of elasticity of the laminated 2 by 4's (adjusted to 12 percent moisture content) averaged 1,950,000 psi compared to 1,790,000 for the sawn 2 by 4's. Allowable fiber stress in edgewise bending was 2,660 psi for the laminated 2 by 4's, more than twice the value obtained (1,270 psi) for the sawn 2 by 4's. A manufacturing procedure for 6-ply lumber is described that calls for no major innovation in equipment. When the price per MBF of structural lumber is 50 percent greater than the price per M sq. ft. of 1/2-inch sheathing plywood, it should be more profitable to manufacture laminated lumber than plywood.

The possibility of laminating lumber from sliced or rotary-cut veneer has interested researchers and industrialists for many years because of the potential for increased yield and uniformity of strength. Quantitative evaluations of laminated lumber have been sparingly reported, however. Lutz et al. (1962) found that knife checks in thick-sliced chestnut oak veneer (slicewood) caused a reduction in tensile strength measured perpendicular to the grain; modulus of rupture (MOR) in bending also appeared to be slightly lower than in sawn wood. Modulus of elasticity (MOE), however, did not differ between slicewood and sawed controls.

Murphey et al. (1967) made small vertically laminated beams from sliced yellow-poplar veneer. They found that MOE was substantially lower, and that maximum fiber stress in bending was higher, than in sawed controls.

Bohlen (1972) described a process for converting Douglas-fir into 1/4-inch rotary-cut veneer and subsequently parallel-laminating it into lumber; by comparison with conventional sawing methods, gains in yield ranged up to 47 percent. Bohlen tested two of his fabricated planks as joists; they had an average MOR of 6,790 psi.

Echols and Currier (1973) tested 4/4 Douglas-fir boards parallel-laminated from 1/6-inch and 1/10-inch rotary-cut veneer. In flatwise bending (i.e., loaded as planks and not as joists), the 20 fabricated boards compared favorably in MOE and MOR with vertical-grain sawed boards. The laminates had less resistance to cleavage than solid wood, chiefly because of lathe checks in the veneer. MOR of the laminated boards ranged from 9,270 to 11,400 psi; and MOE ranged from 2,112,000 to 2,248,000 psi.

In tests of small clear beams made from vertically laminated 1/2-inch rotary-cut southern pine veneers, Moody and Peters (1972) found that average bending strength was 82 percent of that for matched solid-sawn specimens; MOE was 95 percent of that for solid wood. Shear strength in the tangential plane was 67 percent of the value for sawn wood; in the radial plane lathe checks reduced it to 59 percent.

Schaffer et al. (1972) laminated 1/4- and 1/2-inch rotary-cut southern pine veneers into beams 1.5 inches thick, 4.5 inches deep, and 8 feet long. Two of the laminae in each beam were clear. Joists of 1/4-inch veneer averaged substantially higher in MOR and MOE than those from 1/2-inch laminae and were less variable in strength. MOE and MOR in the joists made from 1/4-inch veneers averaged 1,710,000 and 6,470 psi when tested at 12.6 percent moisture content in edgewise bending; corresponding standard deviations for the 15 beams were 96,000 psi and 671 psi. Yield of product was about 60 percent of log volume.

Jokerst (1972) described a system of utilizing residual heat from press drying to fabricate joists vertically laminated from thick veneer.

The author is Chief Wood Scientist, Southern Forest Expt. Sta., USDA Forest Service, Pineville, La. This paper was presented December 6, 1972, in Pensacola, Fla., at the Forest Products Research Society's Fall Meeting of its Southeastern Section. The Tremont Lumber Company, Joyce, La., made substantial contributions of material, manpower, and mill time during the study reported here. This paper was received for publication in December 1972.

My series of experiments, which began in 1963, evaluated methods of laminating southern pine into beams. Results were summarized in a paper presented at the 1967 IUFRO meeting in Munich and later published by the Southern Forest Experiment Station (Koch 1967). This publication presented experimental data on four subjects that are central to the current study.

First, it was demonstrated that parallel-laminated rotary-cut veneer could be glued without difficulty into uniformly strong beams. Second, butt joints did not seriously weaken the beams if laminae were thin and the joints were staggered (see also Koch and Woodson 1968; Koch 1971). Third, in joists or beams with gluelines vertically arranged, MOE was about average for the species when low- and high-grade laminae were mixed and placed randomly. Fourth, the 95-percent exclusion limit for MOR averaged higher if laminae were 1/2-inch or less in thickness—rather than 1 inch thick.

From this research it was evident that there are substantial advantages to be gained from making southern pine structural lumber by parallel lamination of wide sheets of rotary-cut veneer into 1-1/2-inch-thick slabs that could then be smooth-ripped to desired net width and sold without planing.

In 1965 I manufactured a number of very strong, stiff, eight-ply, 12-inch joists in this manner (Fig. 1). These joists demonstrated that the proposed lamination system has a number of advantages that are particularly, but by no means exclusively, applicable to southern pine:

- A significant proportion of logs from southern pine plantations are 10 feet and shorter. Such logs, if 8 inches or larger in diameter, can be peeled advantageously; if conventionally sawn, however, the resultant short lumber has low value.
- Southern pine logs have a 4- to 6-inch juvenile core of weak wood; rotary peeling utilizes the strong wood from the outside and leaves the weak wood in the core. In contrast, conventional sawing must yield boards and planks containing juvenile wood.
- Crop trees in southern pine plantations tend to develop clear boles through natural pruning. Peeling permits recovery of clear veneers from the knot-free periphery of such boles. These veneers can be used to face the planks and joists.
- The process of randomly laying up parallel-bonded, 8-foot lengths of veneer into wide endless slabs with staggered butt joints placed in a controlled pattern, and then gang ripping to obtain planks of the desired width, will yield joists having fairly uniform MOE approximately equal to the average for outer wood of the species. Thus the extreme variation in MOE between corewood and outer wood will be avoided. Moreover, in planks loaded as joists, distribution of defects within the several plies will be random; MOR therefore will vary less from piece to piece than in similar-size joists sawn from solid wood.
- With this system, product yield per cubic foot of log will be substantially increased, as peeling wastes less wood than sawing.
- Finally, rafters and joists of any width and length can be made from short logs of fairly small diameter.

The present study was executed to help establish data on yields and working stresses of structural lumber laminated by the proposed method.

Procedure

Twelve southern pine logs from 11 to 17 inches in butt diameter (inside bark) were randomly selected from the log pile of Tremont Lumber Company, Joyce, Louisiana, in such manner that a range of grades and sizes was represented (Table 1).

Each 17-foot stem section (Fig. 2) was crosscut to yield three 1-inch disks (taken from each end and at mid-length) for evaluation of specific gravity. The central disk was removed at such a point as to leave one peeler log and one sawlog, each about 8-1/2 feet long. Large

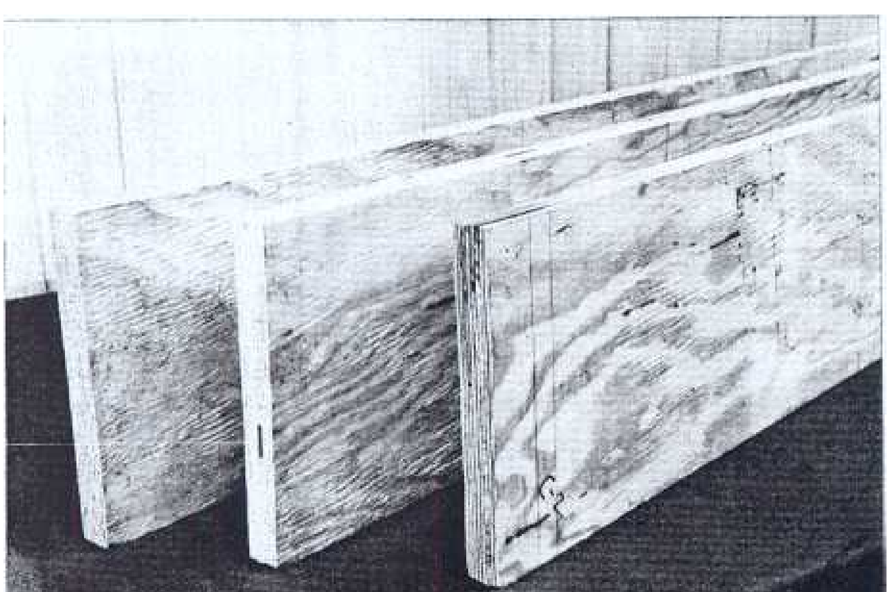

Figure 1. — Prototype joists 12 inches deep fabricated in 1965 from eight parallel plies of 1/6-inch rotary-peeled southern pine veneer.

Table 1. — VOLUME, GRADE, AND DENSITY OF MATCHED SAWLOGS AND VENEER BOLTS, WITH YIELDS OF SOLID-SAWN AND LAMINATED LUMBER.

Log number[1]	Volume	Specific gravity[2]	Log diameter[3] Small end	Log diameter[3] Large end	Rings per inch	Log grade[4]	Log scale[5]	Product yield[6] Bd. ft.[7]	Product yield[6] Cu. ft.[8]	Product yield[6] %[9]
			- - -	In.			Bd. ft.	Bd. ft.[7]	Cu. ft.[8]	%[9]
3S		0.50	12.5	16.4	3½	1	47	54.7	3.10	32.6
3V		.48	11.5	12.5	4	2	40	72.9	3.80	58.3
4S		.48	10.2	10.3	14	3	30	30.7	1.73	36.2
4V		.51	10.3	12.2	14		31	55.9	2.85	49.6
5S		.53	12.3	12.7	9	1	46	53.3	2.98	42.1
5V		.50	11.6	12.3	8½	2	41	74.3	3.93	60.8
6S		.53	11.1	11.3	10	1	36	48.0	2.54	44.8
6V		.54	11.3	12.3	10½	1	38	79.4	4.17	65.8
7S		.46	9.9	12.5	6	3	27	34.0	3.23	56.9
7V		.42	12.5	12.7	6	2	47	72.9	3.85	53.4
8S		.52	12.0	12.9	11	1	44	57.3	3.19	45.1
8V		.54	12.9	15.2	11½	1	52	89.9	4.71	52.3
9S		.55	13.2	15.0	12½	1	55	53.3	2.96	32.8
9V		.52	12.6	13.2	11	1	48	92.7	4.84	64.2
11S		.49	14.1	14.5	13	2	63	72.0	4.09	44.2
11V		.46	13.6	14.1	12½	2	58	111.9	5.91	68.1
12S		.52	13.0	17.3	4	1	52	65.3	3.65	35.0
12V		.48	12.1	13.0	4	1	45	87.1	4.57	63.9
Avg. S		.51	12.0	13.6	9	1.6	44.4	52.1	3.05	41.1
Avg. V		.49	12.0	13.0	9	1.4	44.4	81.9	4.29	59.6
Avg.		.50	12.0	13.3	9	1.5	44.4	67.0	3.67	50.3

[1]Logs 3S and 3V, etc., were cut from the same 17-1/2-foot log; suffix S means sawlog, V means veneer bolt. All sawlogs were trimmed to a length of 100 inches, and all veneer bolts to 102 inches; log cubic volumes are based on these lengths.

[2]Basis of green volume and ovendry weight; average for entire log.

[3]Inside bark.

[4]USDA Forest Service grades for sawlogs (Schroeder et al. 1968).

[5]International 1/4-inch scale.

[6]Values for veneer bolts include the board foot and cubic foot volume from 2 by 4's cut from veneer cores.

[7]Lumber scale based on nominal sizes, e.g., 2 by 4 inches in 96-inch lengths for sawn lumber, and 102 inches for laminated lumber.

[8]Net cubic feet kiln-dry, end-trimmed, sized product (based on measured dimensions); sawn 2 by 4's were computed at 96-inch length and laminated 2 by 4's at 102-inch length.

[9]Percent of gross cubic log volume recovered as kiln-dry, end-trimmed, sized product (based on measured dimension of each board).

Figure 2. — Bark-free, 17-foot-long southern pine logs prior to crosscutting into matched pairs of logs for rotary-peeling and sawing.

and small ends of original logs were randomly allocated. Ends of logs were marked to identify the matched pairs. All logs were graded according to USDA Forest Service rules (Schroeder et al. 1968).

One log from each of the 12 pairs was sawed, the other rotary-peeled. Logs 1 and 2 were miscut in the sawmill and log 10 spun out in the veneer mill. Nine pairs thus were left for the study. Of these 18 logs, 11 were graded No. 1, five were No. 2, and two were No. 3.

Specific gravity (green volume and ovendry weight), diameter, and number of rings were determined on the disks, and results averaged to yield data for each short log.

Log Data

Sawlogs averaged 1.6 in grade, 7.61 cubic feet in gross volume, and 0.51 in specific gravity. They measured 12.0 inches in diameter at the small end, with a large-end average of 13.6 inches. The veneer logs also were 12.0 inches in small-end diameter but averaged 13.0 inches at the large end, and they therefore had slightly less volume (7.18 cubic feet). Slightly lower specific gravity of the veneer logs (0.49) was offset by grade, which averaged slightly better (1.4) than that of the sawlogs. Since none of these differences proved statistically significant (0.05 level), the sawlogs and matched peeler logs were closely comparable (Table 1).

Procedure with Sawlogs

The logs were sawn on a band headrig (with chipping head) and band linebar resaw to yield studs and wider 8/4 lumber. One-inch sideboards were removed if they could edge out to at least 3-inch width and 6-foot length. The 8/4 lumber was sawn about 1-13/16 inches thick and full nominal width. Planks and boards from each log were labelled to correspond with the log from which sawn, and then kiln-dried to 10 percent moisture content. After drying, planks and boards were planed to standard dimension (1-1/2 or 3/4 inches thick by 3-1/2, 5-1/2, 7-1/4, 9-1/4, or 11-1/4 inches wide) and end-trimmed to standard length (6 feet and 8 feet only). Net cubic volume of the dry, planed, trimmed planks and boards recovered from each log was measured.

At this point, all of the 8/4 planks 8 feet long were remanufactured into S4S 2 by 4's of standard dimension, i.e., 2 by 6's were planed back to 2 by 4, 2 by 8's were center-ripped and replaned into 2 by 4's, 2 by 10's were ripped and planed to yield 2 by 4's plus a waste strip, and 2 by 12's were ripped and planed to yield three 2 by 4's. Identity of these 2 by 4's was maintained by log, and all were equilibrated at 72°F and 50 percent relative humidity (Fig. 3). After rejection of wood with wane or evidence of rot, 57 sawn 2 by 4's were selected for evaluation of bending strength.

Procedure for Peeler Logs

Peeler logs were heated in water vats for about 5 hours, and then peeled on the Tremont Lumber Company's lathe to yield 1/4-inch veneer (when dry) and 5-1/4-inch cores. The nine cores were sawn into eighteen 2 by 4's on the mill's equipment, and the identity of the pieces was maintained by log.

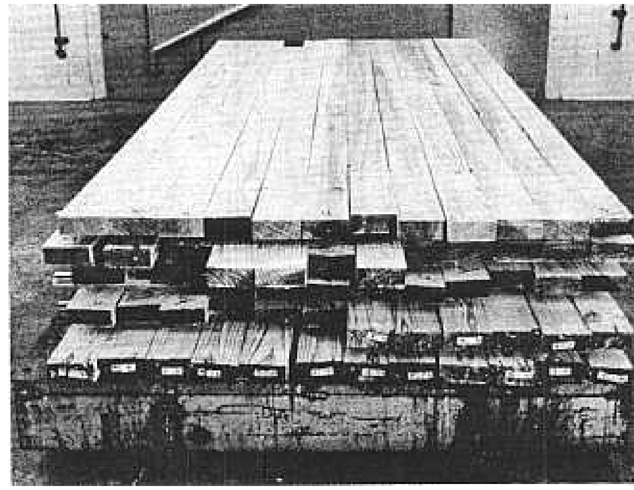

Figure 3. — Sawn log-run 2 by 4's (top of pile), when kiln-dry and planed, measured 1.5 by 3.5 inches. Those on bottom (marked with metal tags), sawn from veneer cores, also measured 1.5 by 3.5 inches when planed.

The veneer was color-coded by log, clipped in the greatest possible widths, and air-dried to 10 percent moisture content. All veneer was saved.

The dry veneer was then ripped to widths of 15-1/8 inches, if possible, or to any multiples that would yield 15-1/8 inches when aligned side by side. This width was selected because four 3.5-inch widths can be ripped from it with minimum waste.

Ripped veneers from each log were then laid up 6 layers deep and 15-1/8 inches wide, and with butt joints in adjacent layers staggered 17 inches apart (Fig. 4). The tight side was outermost on surface veneers; interior glue bonds were all tight-to-loose except that the center line was loose-to-loose (Fig. 5). Resorcinol glue was spread at about 60 pounds per 1,000 square feet of glueline (this

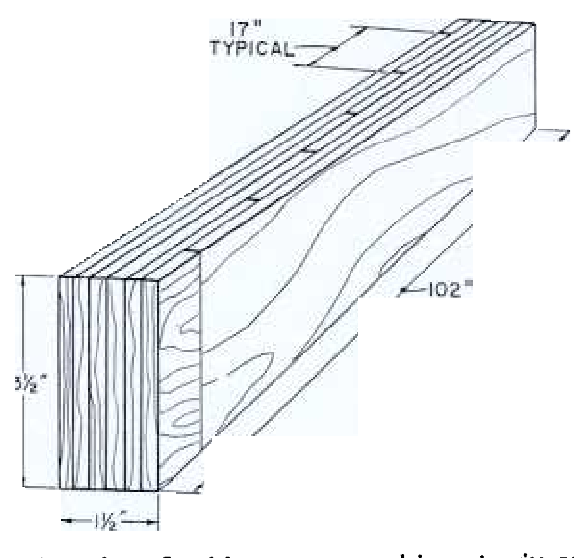

Figure 4. — Butt joints were arranged in a stepwise pattern designed to be repetitive every 102 inches should lumber be fabricated in long lengths.

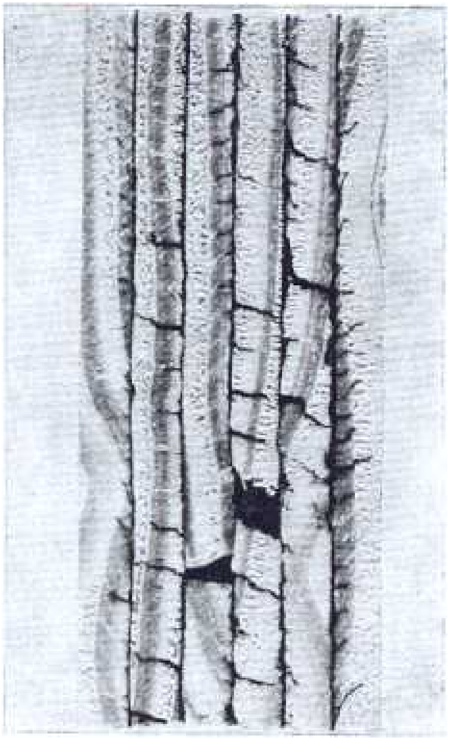

Figure 5. — End view of laminated 2 by 4 illustrating placement of tight side of veneers outermost.

amount was divided equally between mating surfaces), and the beams were pressed overnight in a mechanical cold press.

The resulting slabs, about 1-1/2 inches thick, were double-end trimmed to 102 inches. Slab widths of 15-1/8 inches afforded little waste when straight-line ripped with a planing saw to yield four 2 by 4's, each 3-1/2 inches wide (Fig. 6). Total net cubic volumes of these 2 by 4's (plus volume of remaining usable veneer pieces that would not make a full-width plank) were totalled for each log. On the assumption that the laminating process envisioned for industry would make more or less endless lumber, the full 102-inch length was credited in volume computations.

The 92 laminated 2 by 4's thus made were stored for 2 to 3 weeks at 72°F and 50 percent relative humidity.

Strength Tests

After equilibration, all 2 by 4's (sawn and from rotary-peeled veneer) were destructively evaluated for MOE, MOR, and proportional limit (PL) in edgewise bending. The 2 by 4's were evaluated on a 90-inch span with two-point loading (Fig. 7). Apparatus and speed of loading followed recommendations in ASTM D 198, Static Tests of Timbers. Deflections between supports were measured to the nearest 0.01 inch. Observed strength values of sawn and laminated 2 by 4's were adjusted to 12 percent moisture content.

Following failure, 1-inch, cross-sectional slices were removed from each end (near break) and ovendried to determine moisture content and specific gravity (ovendry weight and volume). Values from each pair of slices were averaged for each 2 by 4.

Results

Product Yield Data

On average, lumber from the sawlogs scaled 117 percent of log scale (International 1/4-inch rule). Forty-one percent of the cubic volume ended as kiln-dry, end-trimmed, sized product (Table 1).

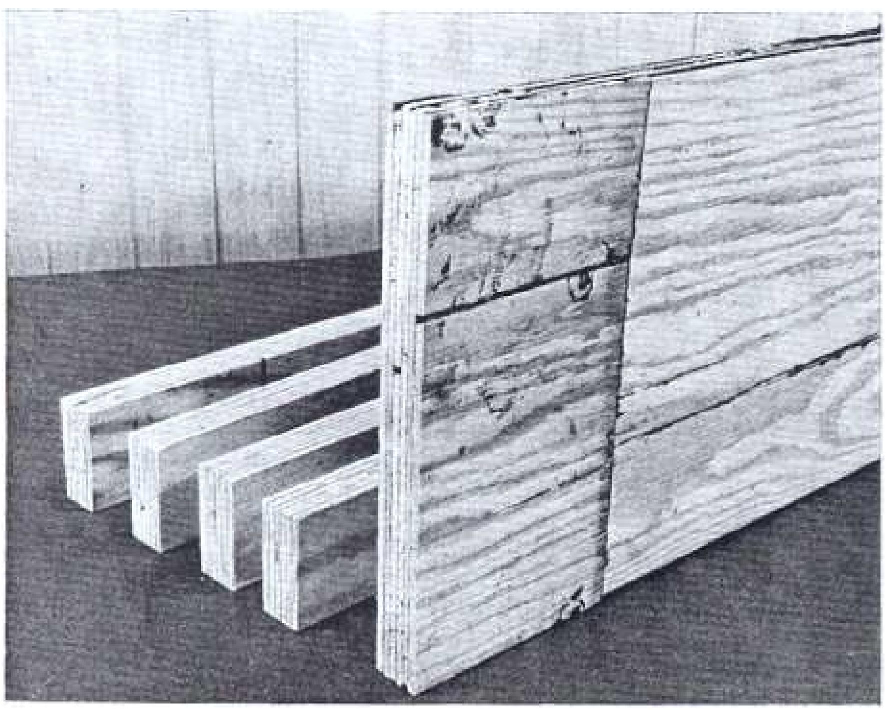

Figure 6. — Planks comprised of six parallel-bonded, 1/4-inch-thick, butt-jointed veneers were smooth-ripped to yield four pieces with net widths of 3.5 inches. Faces were neither sanded nor planed, and edges were left as ripped.

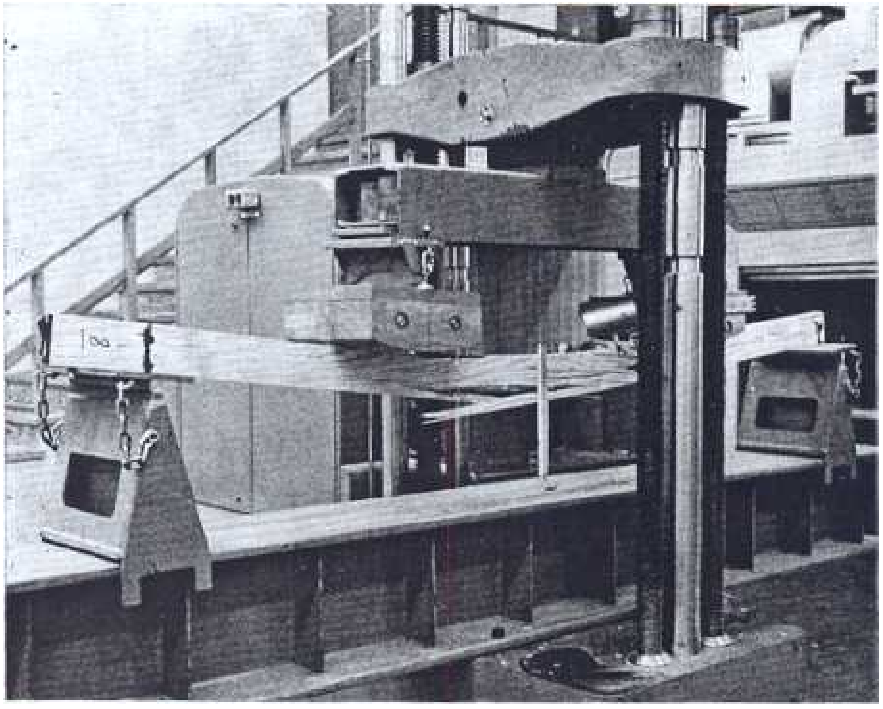

Figure 7. — Setup for testing 2 by 4's in edgewise bending over 90-inch span with two load points 40 inches apart at midspan. Tension failure of laminated 2 by 4's was typical.

Yield from the peeler logs, including the two studs cut from each core, was significantly higher, with lumber scale 185 percent of log scale[1]. Moreover, 60 percent of the cubic volume of each log ended as kiln-dry, end-trimmed, sized product. It is therefore evident that rotary-peeling and lamination yielded almost 50 percent more product than did sawing.

These yield data agree closely with those of Bohlen (1972) and Schaffer et al. (1972).

Specific Gravity, Strength, and Stiffness of 2 by 4's

Specific gravity for the 2 by 4's was as follows (basis of ovendry volume and weight):

Source	Average	Std. dev.	Range
Laminated from veneer (incl. glue)	0.62	0.050	0.53 - 0.72
Sawn from cores	.52	.072	.44 - .67
Sawn from sawlogs	.58	.060	.45 - .74

Since the laminated 2 by 4's were made from outer wood and contained glue, it is logical that they had the highest specific gravity.

Results of the bending tests, with log averages, are given in table 2. For all joists, stress at proportional limit and MOR were calculated from the standard flexure formula. MOE values were calculated from the deflection formula:

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

where
Δ 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
L = span length, inches
A = cross-sectional area, square inches
G = modulus of rigidity or shear modulus, psi

This formula accounts for deflections caused by both bending and shear stresses. The shear modulus (G) was assumed to equal 1/16 the MOE (USDA Forest Products Laboratory 1955, p. 78).

Strength properties of each stud were adjusted to 12 percent moisture content by Wilson's equation (see p. 405 of Koch 1972).

In general, the sawn 2 by 4's failed in tension at knots or in regions of grain deviation. The laminates also generally failed in tension; the failures were generally traceable to a butt joint. None failed in horizontal shear.

Bending properties varied significantly (.05 level) among the three classes of 2 by 4's tested (Table 3). The laminated 2 by 4's not only averaged stronger and stiffer than the sawn, but they also had less variation. Lumber sawn from the cores was weaker than that cut from sawlogs but had less variation.

From Table 3, the following comparisons can be made of average values.

Source of joist	MOR	MOE: Corrected for shear	MOE: Not corrected for shear
	Psi	Psi	Psi
Laminated	9,310	1,950,000	1,910,000
Sawn from sawlogs	9,220	1,790,000	1,750,000
Sawn from cores	6,260	1,500,000	1,470,000

[1]This comparison of lumber overrun is somewhat biased because the sawn 2 by 4's averaged 1.47 inches thick after planing (range 1.45 to 1.53 with standard deviation of 0.016 inch), whereas the six 1/4-inch veneers comprising each laminated 2 by 4 compressed somewhat during the gluing operation to yield boards that averaged only 1.40 inches thick with range from 1.34 to 1.49 and standard deviation of 0.029 inch.

Table 2. — PROPERTIES OF 2 BY 4's MADE FROM NINE LOGS BY THREE METHODS.[1]

Log number and method[1]	Pieces tested	Specific gravity[2] Avg.		Specific gravity[2] Range	Modulus of rupture[3] Avg.		Modulus of rupture[3] Range	Proportional limit[3] Avg.		Proportional limit[3] Range	Modulus of elasticity[3,4] Avg.	Modulus of elasticity[3,4] Std. dev.	Modulus of elasticity[3,4] Range
	Number				- - - - - - - Psi		- - - - - - -	- - - - - - Psi		- - - - - - -	- - - Thousand psi		- - -
3V	8	0.62	0.018	0.59-0.64	7,970	1,185	6,070- 9,180	4,620	252	4,290- 4,990	1,500	101	1,280-1,590
3S	7	.58	.029	.51- .61	8,240	3,007	3,540-11,360	2,790	515	2,100- 3,370	1,020	256	730-1,490
3C	2	.46	—	—	6,270	—	—	2,520	—	—	1,050	—	—
4V	8	.66	.024	.62- .68	10,220	889	8,960-11,420	5,990	627	5,110- 6,790	2,230	64	2,140-2,300
4S	4	.53	.049	.47- .58	5,230	1,638	3,630- 7,500	3,730	1,291	2,920- 5,650	1,770	430	1,350-2,370
4C	2	.47	—	—	4,850	—	—	2,360	—	—	803	—	—
5V	8	.65	.020	.62- .68	9,210	970	7,810-10,050	5,890	589	5,200- 6,790	2,130	84	1,980-2,240
5S	8	.59	.056	.50- .66	8,880	3,050	5,560-13,830	5,760	2,513	3,600-11,250	2,050	329	1,560-2,470
5C	2	.48	—	—	4,700	—	—	3,070	—	—	1,370	—	—
6V	8	.69	.015	.66- .71	9,900	1,097	8,450-11,880	6,790	440	6,120- 7,440	2,510	64	2,380-2,600
6S	6	.61	.033	.57- .66	7,840	1,789	4,700- 9,180	4,870	736	3,880- 5,742	2,090	147	1,930-2,310
6C	2	.59	—	—	5,350	—	—	4,260	—	—	2,030	—	—
7V	8	.55	.014	.53- .57	6,740	871	5,670- 8,030	4,480	554	3,650- 5,300	1,420	48	1,320-1,480
7S	4	.46	.010	.45- .47	4,390	1,057	3,280- 5,530	3,090	478	2,420- 3,470	1,350	38	1,300-1,390
7C	2	.45	—	—	4,800	—	—	3,280	—	—	1,300	—	—
8V	12	.68	.019	.66- .72	12,410	769	10,790-13,950	6,860	725	6,100- 8,030	2,500	93	2,350-2,670
8S	9	.60	.015	.58- .62	11,170	3,378	6,100-14,600	7,590	1,899	5,680-10,490	2,470	327	1,910-2,900
8C	2	.66	—	—	9,190	—	—	7,890	—	—	2,230	—	—
9V	12	.65	.013	.63- .68	9,830	1,264	7,670-12,480	5,240	972	4,120- 6,720	2,060	141	1,790-2,350
9S	4	.70	.037	.66- .74	13,530	2,703	10,330-16,360	6,710	1,991	4,290- 9,110	2,380	364	1,850-2,620
9C	2	.50	—	—	7,100	—	—	4,530	—	—	1,580	—	—
11V	16	.57	.009	.55- .58	9,350	639	8,440-10,370	4,910	526	4,230- 6,030	1,790	48	1,670-1,870
11S	6	.54	.019	.53- .58	9,430	1,300	7,940-11,340	5,500	1,103	4,050- 7,430	1,870	144	1,680-2,080
11C	2	.58	—	—	7,150	—	—	3,780	—	—	1,820	—	—
12V	12	.60	.019	.57- .64	7,300	833	6,290- 9,410	4,340	411	3,710- 5,130	1,510	91	1,390-1,710
12S	9	.60	.027	.55- .63	11,120	1,338	9,410-13,210	3,150	520	2,570- 4,020	1,180	115	1,030-1,360
12C	2	.46	—	—	6,940	—	—	4,320	—	—	1,320	—	—

[1]Suffix V means laminated from rotary-peeled veneer; S means sawn from sawlogs; C means sawn from veneer cores. Since only two pieces were sawn from each veneer core, no standard deviations or ranges are tabulated for lumber from cores.

[2]Basis of ovendry volume and weight; specific gravity of laminated lumber includes weight of glue.

[3]Adjusted to 12 percent moisture content.

[4]Corrected for shear.

The joists laminated from veneer had an average MOE equaling or exceeding the values published (Southern Pine Inspection Bureau 1970, pp. 64, 65) for all southern pine structural grades except "Dense select structural" and "No. 1 dense," which are given at 2,000,000 psi. MOE for the 2 by 4's from sawlogs was close to the species average (1,750,000 psi) commonly accepted for loblolly pine (Koch 1972, p. 408); probably most of the logs were from loblolly pine trees. The 2 by 4's from cores had an MOE (1,500,000 psi) about equal to that called for by SPIB rules applicable to studs (1,400,000 psi).

Interpretation of MOR values must take into account their variability, which is a factor in the establishment of allowable working stresses.

A recognized allowable bending stress for a specific population of joists can be calculated by breaking a random sample, computing the 95-percent exclusion limit for MOR, and multiplying this value by 0.476 (Hilbrand and Miller 1966). This factor is the product of three components: 9/16 for duration of load, 11/10 for normal loading, and 10/13 for factor of safety.

A conservative procedure for establishing the 95-percent exclusion limit of a population (assuming normality of distribution) requires the use of the tabulated K for one-sided statistical tolerance limits as given, for example, in Table A-7 of Natrella (1963). By this procedure, the probability is 95 percent that at least 95 percent of the MOR values in the distribution from which the sample was drawn will exceed the average MOR less K times the standard deviation, namely, $\bar{x} - Ks$. From Table 3, $\bar{x} = 9{,}310$ psi for MOR of laminated 2 by 4's, and the standard deviation (s) is 1,867 psi. The appropriate K (for $n = 92$) is 2.0. The lower 5-percent exclusion limit for MOR is therefore 5,576 psi, with an associated probability of 95 percent.

Application of this procedure to the 2 by 4's laminated from veneer resulted in an allowable bending stress of 2,660 psi, that is, 5,576/2.1. The significance of this

Table 3. SUMMARY OF RESULTS OF BENDING TESTS OF 167 KILN-DRY[1] 2 BY 4's.

Property and parameter	Laminated from rotary peeled veneer[2]	Sawn from veneer cores[3]	Sawn from sawlogs[4]
		psi —	
Modulus of rupture			
Average	9,310	6,260	9,220
Standard deviation	1,867	1,771	3,274
95% exclusion limit[5]	5,576	1,916	2,672
Range	5,670-13,950	2,890-10,540	3,280-16,360
Proportional limit			
Average	5,410	4,000	4,890
Standard deviation	1,081	1,782	2,183
95% exclusion limit[5]	3,248	0	524
Range	3,650-8,030	2,300-9,650	2,100-11,250
Modulus of elasticity[6]			
Average	1,950,000	1,500,000	1,790,000
Standard deviation	399,000	461,000	571,000
95% exclusion limit[5]	1,152,000	369,000	648,000
Range	1,280,000-2,670,000	730,000-2,450,000	730,000-2,900,000

[1]All strength values adjusted to 12-percent moisture content.

[2]92 pieces tested; average specific gravity was 0.62 (basis of oven-dry vol. and wt.)

[3]18 pieces tested; average specific gravity with 0.52 (basis of oven-dry vol. and wt.)

[4]57 pieces tested; average specific gravity was 0.58 (basis of ovendry vol. and wt.)

[5]Based on procedure of Natrella (1963).

[6]Corrected for shear.

experiment is apparent when one notes that the allowable bending stress, i.e., extreme fiber stress in bending, for the strongest structural grade of southern pine is 2,650 psi (Southern Pine Inspection Bureau 1970, p. 64).

Similar computations for the other two classes of 2 by 4's yielded the following comparison:

Source of lumber	K value from Natrella (1963)	Allowable fiber stress in bending
		Psi
Laminated from veneer	2.0	2,660
Sawn from sawlogs	2.0	1,270
Sawn from veneer cores	2.453	910

The value of 1,270 psi for allowable fiber stress in bending of lumber from sawlogs is about equal to that given by the Southern Pine Inspection Bureau for No. 2 Common (1,300 psi). That tabulated for 2 by 4's sawn from veneer cores is slightly higher than the SPIB value for Stud grade (875 psi).

Application

The conversion process outlined in the foregoing pages has obvious technical advantages, but is it practical? I think it is.

Bohlen (1972) diagrammed two approaches to the manufacturing procedure. One was continuous and utilized three moving-belt hot presses; the other was intermittent and called for three hot-platen presses in series. The USDA Forest Products Laboratory (1972) has proposed another system, in which the veneer is dried in a hot press; the heat stored in the veneer is then used to accelerate the lamination process.

I am suggesting a fourth alternative that calls for no major innovation in equipment; i.e., all components except the charger for the hot press have been proven in production. In brief, I propose to hot-press three-ply, 3/4-inch panels with conventional phenol-formaldehyde glues; pairs of these panels would then be cold-pressed into 1.5-inch-thick panels with single phenol-resorcinol gluelines.

Conventional equipment would be used to peel, clip, dry, and assemble 1/4-inch veneer into 4-foot-wide sheets of veneer measuring 8 feet along the grain; because of "fishtails," some of the 4-foot-wide sheets would be assembled in lengths of 4 and 6 feet. For first-step hot-pressing into 3/4-inch-thick 3-ply panels, glue applicators and phenolic adhesives would also be identical to those presently used.

Many hot presses currently in use by the southern pine plywood industry have 32 openings with platens that measure 4 by 8 feet. I visualize that step-one gluing of three 1/4-inch veneers into 3/4-inch laminates can be accomplished in a hot press of identical capacity but with eight openings having platens measuring 4 feet wide by 32 feet long.

The layup and charging mechanism for a 32-foot press would have to be specially designed to achieve the prescribed pattern of butt joints (Fig. 4). Short sheets of veneer resulting from fishtails would diminish distance between butt joints in adjacent plies from 17 inches where all 8-foot lengths are used to 12.75 inches for 6-foot lengths and 8.5 for 4-foot lengths. It is believed that occasional insertion of a pair of 4-foot lengths, or four 6-foot lengths, would not significantly reduce either MOE or MOR, but this assumption needs experimental validation.

Following the single hot press would be four single-opening cold presses, each with a little over 5 feet of daylight; each would accommodate forty panels measuring 1-1/2 inches thick by 4 feet wide by 32 feet long. Each 1-1/2-inch-thick panel would be comprised of a pair of 3/4-inch panels glued together with a single phenol-resorcinol glueline. The four cold presses would be charged in rotation during each shift and discharged 8 hours later by the next shift or 24 hours later in a single-shift operation. Thus a one-shift operation would turn out 2,560 cubic feet of product a day (40 panels x 1.5/12 x 4 ft. width x 32 ft. length x 4 presses). This cubic footage translates into about 45 thousand board feet of 8/4 dimension lumber (assuming 57 cubic feet of wood per MBF of 2 by 6, for example).

On discharge from the cold press, panels would pass through a cross-cutting saw to produce lumber lengths desired. The cross-cut panels would then be smooth-ripped to yield lumber of net standard widths.

Moisture content of the lumber at this stage would likely be 5 to 10 percent; preferably it should be as near 9 percent as possible.

The primary advantage of this system is its simplicity. Offsetting this simplicity are several disadvantages. First, cost of the central glueline is several times more than that of outer gluelines. Second, by laying up 32-foot-long panels there will be waste from trimming and squaring. Third, end veneers in each panel must be precut to length to avoid overhanging the 32-foot panel length. Finally, two glue systems are required, one for outer gluelines and a second for the central one.

Economics

The profitability of plywood plants as compared to sawmills is a relationship well understood by managers of southern pine mills. Since it is easier to relate the proposed laminating plant to a plywood plant than to a sawmill, the following discussion touches on some similarities and differences in costs and sales prices for laminated lumber and sheathing plywood.

Of the five gluelines required for the six-ply lumber construction contemplated, four would be made with the economical phenol-formaldehyde glues used by the southern pine plywood industry. The fifth glueline—the center one—would be of phenol-resorcinol, which costs about six times as much as phenol-formaldehyde. Glue costs therefore would likely be about $15 per thousand square feet of 1-1/2-inch-thick panel or about $7.00 per thousand board feet of lumber. This is somewhat higher than the glueline cost per thousand square feet of 1/2-inch, 4-ply sheathing (about $4.50).

A thousand board feet of sized, dry, dimension lumber (2 by 6, for example) contains about 57 cubic feet of wood; 1,000 square feet of 1/2-inch plywood contain only 42 cubic feet. If 1/2-inch sheathing-grade plywood is priced at $100/M square feet, the laminated dimension product would therefore have to sell for at least $136/M board feet to achieve equality in sales price per cubic foot (i.e., $100/42 = $136/57 = $2.38 per cubic foot).

Since the market price per MBF of favored lengths, widths, and grades of southern pine structural lumber is usually about 50 percent higher than the price per M sq. ft. of 1/2-inch sheathing plywood, it would appear that manufacture of laminated dimension lumber might be more profitable than manufacture of sheathing plywood.

Discussion and Conclusions

The MOR values obtained by Bohlen (1972) on two Douglas-fir joists (average 6,790 psi) cannot be compared directly with the values (9,270 to 11,400 psi) obtained by Echols and Currier (1973) on 20 Douglas-fir planks loaded in flatwise bending. Since published data on Douglas-fir are limited, it is not possible to draw conclusions about allowable fiber stress in edgewise bending.

The 15 southern pine joists made by Schaffer et al. (1972) from 1/4-inch rotary-cut veneer would appear to be fairly comparable to the 92 made in this study. For reasons not clear, MOR values from the Schaffer study averaged substantially lower (6,470 psi) but had less variation (standard deviation of 671 psi) than the values observed in this study (average 9,310 psi with standard deviation of 1,867 psi).

From these two experiments, it appears that southern pine joists laminated, in the manner described, from 1/4-inch rotary-peeled veneers should justify an allowable extreme fiber stress in bending approximately equal to the strongest structural grade now recognized by the Southern Pine Inspection Bureau. Moreover, MOE of these joists should be greater than the species average.

It also appears that production and marketing economics will often make it more profitable to manufacture southern pine veneer into joists rather than into plywood.

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