FLEXURAL PROPERTIES OF GLUED-LAMINATED SOUTHERN PINE BEAMS WITH LAMINATIONS POSITIONED BY VISUAL-STIFFNESS CRITERIA

U.S.D.A. FOREST SERVICE
RESEARCH PAPER
FPL 127
JANUARY 1970

U. S. Department of Agriculture
Forest Service
Forest Products Laboratory
Madison, Wis.

ABSTRACT

To establish the effect of using modulus of elasticity in addition to visual grade as criteria for the positioning of laminations in glued-laminated beams, an experimental study on southern pine members was conducted. The beams were manufactured in accordance with current specifications for glued-laminated southern pine timber, except that (a) minimum-quality tension laminations meeting AITC 301-67 were used and (b) restrictions were placed on the modulus of elasticity of all laminations. Current specifications require that boards lie positioned in glued-laminated members on the basis of their visual grades. The use of modulus of plasticity in addition to visual grading in selecting quality laminations for highly stressed areas should provide for better assessment of lamination quality and result in stronger and stiffer laminated timber members.

Five glued-laminated southern pine beams, 5-1/4 inches wide, 24-3/8 inches deep, and 40 feet long, were manufactured using the dual criteria for positioning of laminations. Results of bending tests were compared to data reported in USDA Forest Service Research Paper FPL 113 for comparable beams made using only visual grading requirements. In both sets of beams, the tension laminations were selected to represent near minimum visual quality for the AITC 301-67 grade.

The average modulus of elasticity of the beams manufactured using both visual and stiffness criteria was 12 percent higher than that for beams using only the visual criteria. This agreed with the theoretically expected increase in modulus of elasticity. The average modulus of rupture of the visual-stiffness beams was 14 percent higher than that for the visual-only beams. However, the minimum strength for each group was approximately equal.

FLEXURAL PROPERTIES OF GLUED-LAMINATED SOUTHERN PINE BEAMS WITH LAMINATIONS POSITIONED BY VISUAL-STIFFNESS CRITERIA[1]

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INTRODUCTION

Glued–laminated members are designed to meet both strength requirements and deflection limitations. Since deflection limitations often govern the design, the development of stiffer laminated timber beams could result in reduced size and lower manufacturing costs. If, for example, the present design modulus of elasticity of laminated timber beams could be increased from 1.8×10^6 p.s.i. to 2.2×10^6 p.s.i., it would then be possible to reduce the depth of beams, where depth is controlled by deflection limitations, by 7 percent and yet maintain the same beam stiffness.

The basic principle of glued–laminated construction is to place selected grades of lumber in each member so as to best utilize the material supply. The higher quality material is placed in areas of the member that are most highly stressed under load, and lesser grades are placed in lower stressed areas. The lumber presently used in laminated beams is graded by visual methods, with no consideration being given lo the modulus of elasticity. Using modulus of elasticity as an added measure of quality to visual grading should permit more accurate assessment of the quality of the laminations, and using the stiffest laminations in the outer areas of a beam could produce both stiffer and stronger beams.

BACKGROUND

The principle of using modulus of elasticity to locate laminations within a beam has been investigated by Koch et al (5,6,7,8).[3] In each of these studies, thin (1/6–1/3 in. thick) southern pine veneers were used to fabricate beams from 7 to 18 inches deep. Veneers were so arranged that the stiffest veneers were near the outer faces of the beam and veneer stiffness was gradually decreased toward the neutral axis.

In a study by Koch and Woodson (8), butt-jointed southern pine veneers were located by stiffness and fabricated into beams. The beams, which were 2 inches wide, 18 inches deep, and

[1] This research was conducted in cooperation with the American Institute of Timber Construction.
[2] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.
[3] Underlined numbers in parentheses refer to Literature Cited at the end of this research paper.

25 feet long, had an average modulus of elasticity of 2.1 x 10^6 p.s.i., which is considerably more than the value of 1.8 x 10^6 p.s.i. now used in the design of southern pine members. Average modulus of rupture was 9,020 p.s.i. with a 95 percent exclusion limit of 7,650 p.s.i.

Koch and Bohannan (7) evaluated laminated beams in which the veneer laminations were arranged by four different methods: Specific gravity, stiffness, appearance, and random. They found that the modulus of elasticity of small beams which had their laminae arranged by stiffness averaged 31 percent higher than those which had their laminae arranged randomly. The accompanying increase in average modulus of rupture was from 6,300 p.s.i. to 10,200 p.s.i., a 54 percent increase.

Current specifications require that laminated beams be manufactured using structural grades which are based on visual grading. Thus, present practice would probably more nearly approximate an appearance-type layup than a random one. The five beams tested by Koch and Bohannan (7), which were assembled by appearance, were considerably stronger and stiffer than those randomly laid up, but they were not as strong and stiff as those laid up using stiffness as the criterion. This research indicates that small beams with thin laminae arranged by stiffness were stronger and stiffer than beams assembled by other means.

Results of the above research on beams with thin laminations may not directly apply to structural glued laminated timbers because of possible effects of lamination thickness. However, using modulus of elasticity as an indicator of board quality warrants further investigation as a method of improving both the strength and stiffness of large structural glued-laminated timber beams with nominal 1- and 2-inch-thick laminations.

OBJECTIVE AND SCOPE

The objective of this study was to evaluate the flexural properties of large glued-laminated southern pine beams manufactured according to current AITC and lumber association specifications for structural glued-laminated timbers, except that restrictions were placed on the modulus of elasticity of the laminations.

A total of five beams were tested. These data were compared with data from five beams previously reported (4) in which modulus of elasticity was not used to locate their laminations during manufacture.

RESEARCH MATERIAL AND BEAM MANUFACTURE

Description of Beams

The beams were 5-1/4 inches wide, 24-3/8 inches deep, and 40 feet long and consisted of fifteen 1-5/8-inch-thick laminations. They were prepared according to combination A-2, a 2,600-p.s.i. stress grade combination, as given in the current specification for southern pine (9), except restrictions were placed on the modulus of elasticity of each lamination throughout the beam. This is discussed in the "Method of Beam Layup" section. Also, the outer tension lamination of each beam was replaced with one of minimum quality graded according to AITC 301-67 (2).

Selection and Nondestructive Evaluation of Material

A supply of nominal 2- by 6-inch southern pine lumber, which represented enough material to lay up about 20 beams, was accumulated from five different shipments received at a commercial laminating plant. This was the same lumber supply from which the 40-foot-long southern pine beams previously evaluated (4) were manufactured. The boards, which were 12, 14, or 16 feet long, were consecutively numbered, and the odd-numbered boards were selected for making the ten 40-foot-long southern pine beams discussed in (4). Part of the remaining even-numbered boards, which represented enough material for nearly 10 additional beams, was used for the five beams for this study.

All lumber was regraded by a Southern Pine Inspection Bureau inspector to assure that it was of the correct visual grade. The modulus of elasticity of each board was determined using a vibration technique.[4] During the vibration evaluation the board was supported at its ends as a simple beam and the reaction at one end was

[4] Equipment described in product information of Irvington Machine Works, Inc., Portland, Oreg.

recorded. This was assumed to be one-half of the board weight in subsequent specific gravity calculations. Moisture content was measured at three locations along the length of each board with a power-loss type moisture meter.

Method of Beam Layup

The beams were laid up with the stiffest laminations in the most highly stressed or outer laminations of the beams. A survey of the available lumber supply indicated that the following minimum modulus of elasticity could be imposed upon boards used for the 15 individual laminations of each beam (lamination 1 is the tension side and 15 is the compression side):

Lamination No.	Minimum modulus of elasticity 10^6 p.s.i.
1, 15	2.2
2, 14	1.9
3, 13	1.8
4, 12	1.6
5, 11	1.6
6, 10	1.4
7, 9	1.2
8	1.0

These requirements provided for full utilization of the available lumber supply.

In addition to the above minimum stiffness requirements, the visual grading requirements of the A-2 grade combination (9) were used, as in beam Nos. 11-15 in (4) The outer tension laminations were the minimum quality meeting the AITC 301-67 visual specifications (2). The range of modulus of elasticity and the visual grade of each lamination are as shown in figure 1.

Each of the five outer tension laminations consisted of three boards: A midlength board and two end boards finger-jointed to it. Boards for the middle portion of the tension laminations were selected so that they contained at least one near-maximum strength-reducing characteristic permitted by the following AITC 301-67 requirements (2):

1. Growth rate requirements shall apply to the full length and pieces of exceptionally light weight shall be excluded.
2. Knots shall not occupy more than one-quarter of the cross section.
3. The general slope of grain shall not exceed 1 in 16 except where more restrictive slope of grain is required by the standard laminating specification.
4. Areas of local grain deviation steeper than 1 in 16 shall not occupy more than one-third the cross section.
5. Knots shall not occur within two knot diameters of the finger joints.

These boards therefore represent the low line of material that would meet the tension lamination grading requirements. The boards used on both ends of this midlength board were also graded according to AITC 301; however, they were not necessarily minimum quality.

The even-numbered boards from the lumber supply were sorted into grade and stiffness groups, and boards were randomly chosen from the proper group for end-jointing into full-length laminations. Full-length laminations from each group were then randomly assigned to a beam.

After the boards were finger-jointed into full-length laminations, the width and location of each knot in the middle one-half length of the laminations were determined. Except for the tension laminations, the width of knots was measured only on the face of the laminations away from the neutral axis of the beam. The width of knots and associated grain deviation steeper than 1:16 was measured on both faces of the tension lamination. These measurements included grain deviations across the wide face and estimates of grain deviation through the thickness of the boards. Any knot whose associated grain deviation opened on a narrow edge of the board was considered an edge knot.

Manufacture of Beams

All five beams were manufactured at a commercial laminating plant in August 1968 to conform to the requirements given in U.S. Commercial Standard CS 253-63 for Structural Glued-Laminated Timber (10). Commercial production finger-type end joints which met requirements of the AITC qualification tests (1) were used to produce each lamination. The end joints in the tension laminations were at least 5 feet from midlength of the beams. This was at least 1 foot outside of the area of maximum bending moment of beams under test. Since the primary objective of this study was to evaluate the effect of the modulus of elasticity restrictions on the strength and stiffness of the beams, the end joints were purposely placed outside of the most highly stressed region.

After gluing with a phenol–resorcinol adhesive, the beams were surfaced to a 5–1/4–inch width, cut to the proper length, and shipped to Madison, Wis. The beams were identified as beams 31 through 35.

RESEARCH METHODS

Test Equipment and Procedure

The beams were tested using the same equipment and procedure previously used for 40–foot–long beams (4). The test method conformed to the requirements of ASTM D 198 (3). Load was applied at two points, each 4 feet from the midlength of the beam which was supported on a 38–foot span (fig. 2). Each beam was laterally supported to prevent buckling at each end support and 40 inches each side of midlength. An overall view of the beam during test is shown in figure 3.

A preload of 2,000 pounds was first applied to the beams to assure proper alinement of the test equipment; then loading was continuous to failure at a rate of 1.00 inch per minute.

Data Obtained

The dimensions, weight, and moisture content of the beams were determined prior to test. Average dimensions were obtained near the midlength of each beam. Moisture content readings were taken at random positions on the beam at every 5–foot interval along the length with a power–loss–type moisture meter. These values were averaged to obtain the moisture content data.

Data taken during tests included maximum load, centerline deflections between supports, and centerline deflections of the beam over a 7–foot span between load points. Deflections between load points were measured on one side

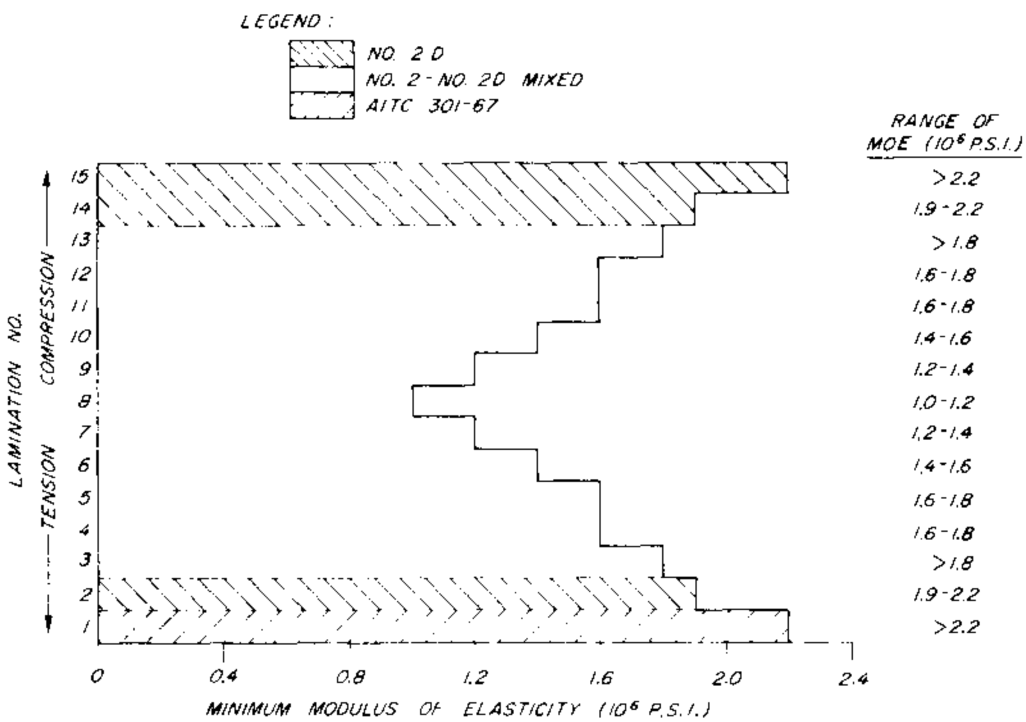

Figure 1.––Modulus of elasticity and visual grades of boards used in the 15 laminations of beams made using both visual and stiffness criteria.
M 136 859

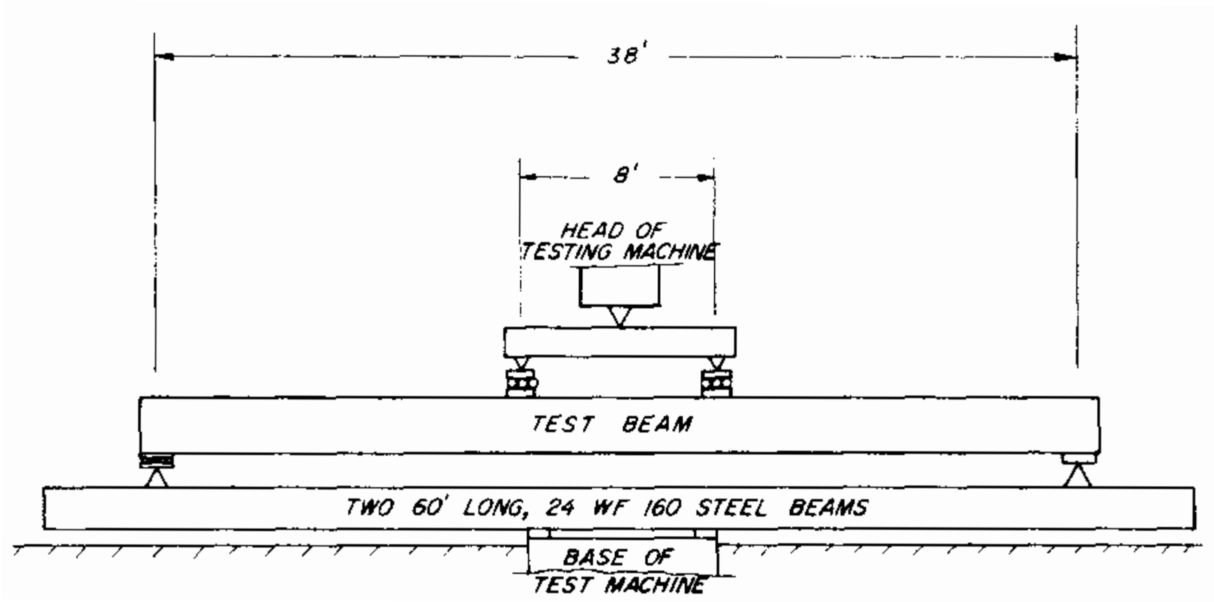

Figure 2.--Schematic diagram of method of testing 40-foot-long glued-laminated wood beams.
M 136 733

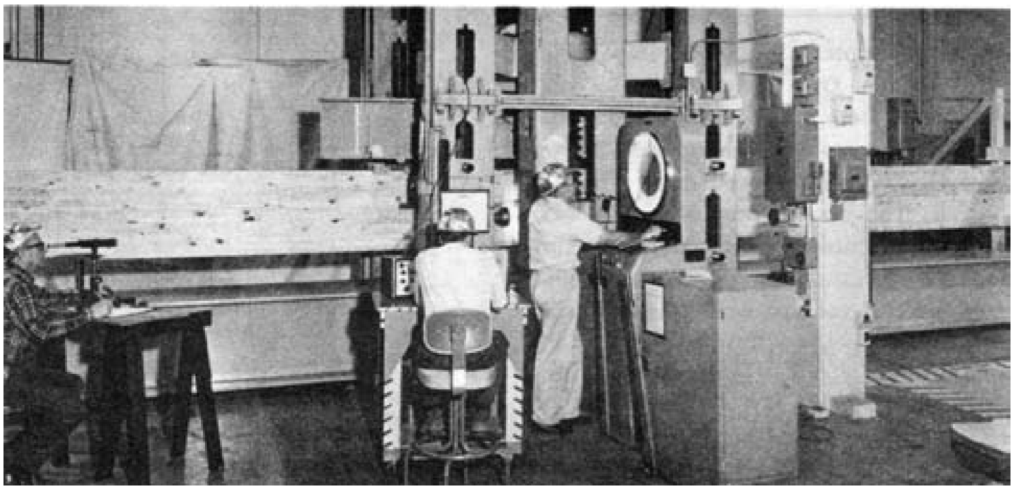

Figure 3.--General view of beam during test. The 10-foot-long base of the million-pound capacity testing macnine was extended with two 60-foot-long steel beams. A steel loading beam was used to apply loads 4 feet each side of the midlength of the 40-foot-long beams and 5 feet each side of midlength of the 50-foot-long beams.

of the beam with a yoke deflectometer, as described in ASTM D 198 (3). Dial readings were taken at 2,000-pound increments of load up to 18,000 pounds total load. At this load the yoke was removed. Centerline deflections between supports were measured using a wire deflectometer, as described in ASTM D 198. Deflection readings were taken at 2,000-pound increments of load to failure.

Failure details in each beam were sketched, and each failed beam was photographed. When failure was attributable to a specific area of the beam, this area was cut from the beam for further inspection.

Minor Tests

Immediately after failure of each beam, a section about 1 foot long was cut from within the center 8 feet of each beam. Clear specimens about 4 by 4 by 1-1/2 inches were then cut from each lamination to determine their specific gravity and moisture content. Specific gravity was based on volume at time of test and ovendry weight. Moisture content was calculated from the weight loss during ovendrying and the ovendry weight.

PRESENTATION AND DISCUSSION OF RESULTS

Results are presented for two comparable groups of five beams. One group of beams was manufactured using both visual grades and stiffness criteria for positioning laminations. These beams will hereafter be referred to as visual-stiffness beams. The other group of beams was manufactured with laminations positioned by the visual grades given in current specifications (9). These beams will hereafter be referred to as visual-only beams.

Lumber Stiffness

Because the results depended in a large measure on the stiffness properties of the lumber supply, it was important that these were well defined. Results of modulus of elasticity determinations made on the lumber supply from which the five visual stiffness beams were manufactured are summarized in figure 4. Average modulus of elasticity values for the No. 1 Dense, No. 2 Dense, and No. 2 grades of boards were 2.0, 1.8, and 1.4 million p.s.i., respectively. The tension laminations were selected from the No. 1 Dense material. The No. 2 Dense material was used for the outer two compression laminations and the second lamination on the tension side of the beam. The mixture of No. 2 Dense and No. 2 material used for the interior laminations had an average modulus of elasticity of 1.6 million p.s.i.

Tension Laminations

Results of the nondestructive tests on the boards used for the center portion of the tension lamination for the beams are given in table 1. The major strength-reducing characteristics which occurred in the center 10 feet of each tension lamination are summarized in table 2.

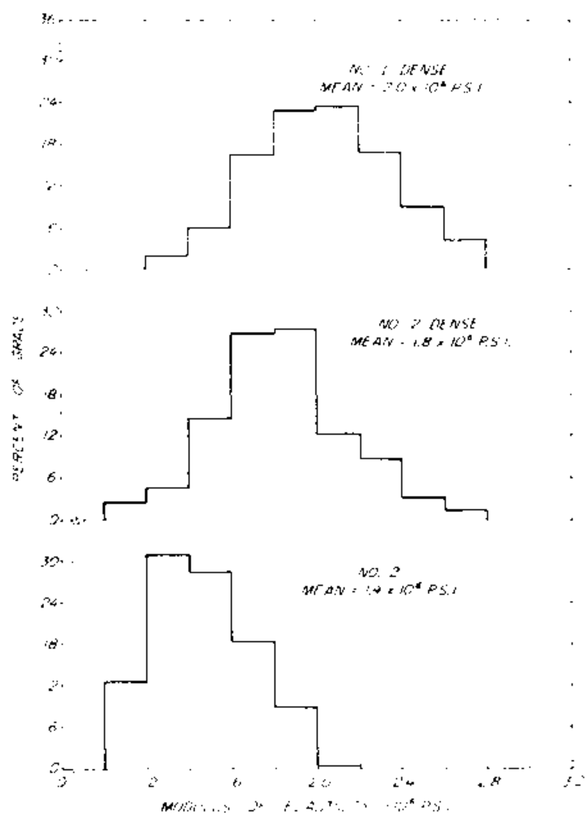

Figure 4.--Frequency distribution of modulus of elasticity in southern pine lumber supply used for visual-stiffness beams. Modulus of elasticity of each board was determined by a vibration technique. M 136 861

Table 1.--Specific gravity and modulus of elasticity of selected southern pine boards used for midlength portion of tension laminations

Beam No.	Board identification	Nominal length	Specific gravity[1] Specimen	Specific gravity[1] Board	Moisture content[2]	Vibration modulus of elasticity
(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Ft.			Pct.	1,000 p.s.i.
LAMINATIONS POSITIONED BY VISUAL-CRITERIA ONLY						
11	T59	14	0.51	0.50	11	2,020
12	T43	16	.53	.53	12	2,340
13	T39	16	.52	.50	14	1,650
14	T20	12	.45	.48	10	1,730
15	T22	12	.48	.49	10	2,100
Av.			.50	.50	11	1,970
LAMINATIONS POSITIONED BY VISUAL-STIFFNESS CRITERIA						
31	914	16	.61	.58	14	2,420
32	818	16	.52	.56	13	2,290
33	816	16	.6[illegible]	.58	14	2,500
34	T51	16	.61	.60	14	2,540
35	134	16	.50	.54	17	2,240
Av.			.57	.57	14	2,400

[1] Values in col. 4 are based on volume at time of test and ovendry weight of small specimens cut from near the midlength of the boards. Values in col. 5 are based on volume and weight of complete board corrected to ovendry weight using moisture content in col. 6.

[2] Moisture content determined using power-loss type moisture meter at same time the vibration modulus of elasticity measurements were made.

Modulus of elasticity.--The average stiffness (MOE) of the boards used near midlength of the tension laminations for the visual-only beams was 1.97 x 10^6 p.s.i., while that of the visual-stiffness beams (which had a minimum MOE requirement of 2.20 x 10^6 p.s.i.) averaged 2.40 x 10^6 p.s.i. The tension laminations used for the visual-only beams were representative of the stiffness of the No. 1 Dense material from which they were selected. The minimum modulus of elasticity of the tension laminations for the visual-stiffness beam (2.2 x 10^6 p.s.i.) limited the supply of No. 1 Dense material from which they could be selected to the stiffest 30 percent of that grade (fig. 4). Of the five boards used for the middle portion of the tension lamination of the visual-only beams, only the one used for beam 12 would have met the minimum MOE requirement of the visual-stiffness beams.

Table 2.--Description of major strength-reducing characteristics at midlength of "B11" tension laminations for 40-foot southern pine beams with laminations arranged by visual-only or visual-stiffness criteria

Beam No.	Strength-reducing characteristics	Location along length[1]	Knot: Top face: Size[2]	Knot: Top face: Percent of width[3]	Knot: Bottom face: Size[2]	Knot: Bottom face: Percent of width[3]	Knot: Combined percent of cross section[4]	Knot and grain deviation steeper than 1:16: Top face: Size[2]	Top face: Percent of width[3]	Bottom face: Size[2]	Bottom face: Percent of width[3]	Combined percent of cross section[4]	Clear straight-grained section[5]	Strength-reducing characteristics in columns 8 and 13 and beam failure: Principal causes	Involved	Location of beam failure[1]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
		Ft.	In.	Pct.	In.	Pct.	Pct.	In.	Pct.	In.	Pct.	Pct.	Pct.			
							LAMINATIONS ARRANGED BY VISUAL-ONLY CRITERIA									
11	Knot	18.8	1.12	20	1.25	23	22	1.88	34	2.00	36	35	65	No	No	End joint in tension lamination at 16.6 ft.
12	Knot	16.4	--	0	1.38	25	13	--	0	2.00	36	18		No	No	End joint in tension lamination at 11.6 ft.
	Knot	20.6	--	0	.88	16	8	.38	7	2.00	36	22	78	No	No	
	Knot	17.1	.38	7	.88	16	11	.50	9	1.25	23	16		No	No	
13	Two knots	18.7	.50	9	1.38	25	17	1.25	23	1.88	34	28	72	No	No	Edge knot at 16.4 ft. and end joint at 12.9 ft. in tension lamination
	Edge knot	16.4	.88	16	.62	11	14	1.38	25	1.38	25	25		Yes	Yes	
14	Edge knot	22.2	1.25	23	1.12	20	22	1.75	32	1.38	25	28	72	No	No	Edge knot in tension lamination and 1:7-1:10 cross grain in second lamination, both at 20.0 ft.
	Edge knot	20.0	.88	16	.50	9	13	1.38	25	.62	11	18		Yes	Yes	
15	Knot	20.3	1.50	27	1.12	20	24	1.50	27	1.88	34	31	69	No	No	Edge knot in tension lamination and 1:6 localized cross grain in second lamination, both 15.7 ft.
	Edge knot	15.7	.75	14	1.12	20	17	1.00	18	1.88	34	26		Yes	Yes	
Av.													72			
							LAMINATIONS ARRANGED BY VISUAL-STIFFNESS CRITERIA									
31	Knot	23.2	.75	14	1.00	18	16	1.00	18	1.25	23	20		No	No	Knot in tension lamination at 21.6 ft.
	Knot	21.6	--	0	.88	16	8	.62	11	2.25	41	26	74	Yes	Yes	
32	Spike knot	23.5	2.25	41	--	0	20	2.75	50	--	0	25	75	No	No	Edge knot in tension lamination at 20.9 ft.
	Edge knot	20.9	.50	9	1.38	25	17	.88	16	1.75	32	24		Yes	Yes	
	Knot	22.7	.50	9	1.00	18	14	.88	16	1.88	34	25		No	No	
33	Knot	17.0	.62	11	1.25	23	17	.88	16	2.25	41	28	77	No	No	Edge knot in tension lamination at 23.0 ft.
	Edge knot	23.0	--	0	1.88	34	17	--	0	2.50	45	23		Yes	Yes	
34	Edge knot and two small knots	20.0	--	0	2.00	36	18	--	0	3.12	57	28	72	Yes	Yes	Edge knot in tension lamination at 20.0 ft.
	Edge knot	21.2	--	0	1.00	18	9	--	0	1.00	18	9		No	No	
35	Edge knot	17.4	.62	11	1.50	27	19	.75	14	1.62	29	22		Yes	Yes	Edge knots in tension laminations at 17.4 and 19.1 ft. and edge knot in second lamination
	Edge knot	19.1	1.00	18	1.12	20	19	1.75	32	1.38	25	28	72	Yes	Yes	
Av.													73			

[1] Given with reference to zero end of beam in feet. Midlength of the beam was 20.0 ft. and the constant moment section was 16.0 to 24.0 ft.

[2] Dashed lines indicate that the knot did not appear on that face.

[3] (Width ÷ 5.50) x 100.

[4] Average of top and bottom faces.

[5] Percent of section with clear material having 1:16 or flatter slope of grain.

Specific gravity.--The average specific gravity of the boards used for the center portion of the tension lamination is given in columns 4 and 5 of table 1. A significantly higher average specific gravity (0.57) was obtained when both the visual and stiffness criteria were imposed as compared to the visual criteria only (0.50). This might be expected because the tension laminations were not selected to have minimum specific gravity as given in the AITC 301-67 requirements; rather the midlength tension laminations for the visual-only beams were selected to have specific gravities representative of the species, but exceptionally heavy or exceptionally lightweight boards were not used. Similarly for the visual-stiffness beams, the midlength tension laminations were selected to have specific gravities representative of the supply of material with modulus of elasticity values over 2.20×10^6 p.s.i.

Strength-reducing characteristics.--Rased on measurements (table 2, col. 8) made prior to beam manufacture, major knots were of comparable site in the tension laminations of both the visual-only and visual-stiffness beams. Clear straight-grained sections past these knots (table 2, col. 14) were also comparable. Three of the visual-only beams and four of the visual-stiffness beams had edge knots of significant size. Beam 35 had two large edge knots on opposite sides of the board and about 2 feet apart longituditially. Based on the knot data, approximately, equivalent visual grades of boards were used for the center portion of the tension lamination of both groups of beams.

Laminated Beam Properties

Data from the five beams whose laminations were located by the visual-stiffness criteria are given in table 3. Also given in table 3 are data for the five beams previously reported (4) whose laminations were located by visual-only criteria. Moduli of rupture and moduli of elasticity given in columns 8 to 10 of table 3 are for the moisture content conditions at time of test. Values adjusted to 12 percent moisture content using the following formulas (from 4) are given in columns 12 to 14:

$$MOR_{12} = MOR_M(1.020)^{M-12} \quad (1)$$

$$MOE_{12} = MOE_M(1.015)^{M-12} \quad (2)$$

where MOR_{12} = modulus of rupture adjusted to 12 percent moisture content

MOR_M = modulus of rupture from test

M = moisture content at test

MOE_{12} = modulus of elasticity adjusted to 12 percent moisture content

MOE_M = modulus of elasticity from test

The specific gravity of each beam is given in columns 6 and 7 of table 3. Average specific gravity of both groups of beams was 0.49, which is slightly less than the average clear wood value for southern pine (11). Specific gravity and moisture content data for each lamination near midlength of each beam are included in Appendix I.

Modulus of Elasticity.--The overall modulus of elasticity of laminated beams should be improved if lamination stiffness is used as a criterion of quality for selection and positioning laminations. Therefore, it is important to compare theoretical and actual improvements in beam modulus of elasticity that may be achieved.

Using the transformed-section approach, the minimum expected modulus of elasticity for each beam may be calculated from the following formula:

$$MOE_b = \frac{\sum MOE_i I_i}{I_b} \quad (3)$$

where MOE_b = MOE of beam

I_b = moment of inertia of beam

MOE_i = MOE of the i^{th} lamination

I_i = moment of inertia of the i^{th} lamination

Using the minimum values given in figure 1, the minimum expected modulus of elasticity of the visual-stiffness beams would be 1.91×10^6 p.s.i. If the average of each MOE group of lami-

Table 3.--Results of bending tests of 40-foot southern pine laminated beams with laminations positioned by visual-only or visual-stiffness criteria

Beam No.	Dimensions[1]: Width	Dimensions[1]: Depth	Moisture content[2]: Oven drying	Moisture content[2]: Meter	Specific gravity[3]: Lamination	Specific gravity[3]: Beam	Unadjusted data: Modulus of rupture	Unadjusted data: Modulus of elasticity: Full span	Unadjusted data: Modulus of elasticity: Constant moment section	Shear stress	Data adjusted to 12 percent moisture content[4]: Modulus of rupture	Data adjusted to 12 percent moisture content[4]: Modulus of elasticity: Full span	Data adjusted to 12 percent moisture content[4]: Modulus of elasticity: Constant moment section	Comments on failure
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
	In.	In.	P.ct.	P.ct.			P.s.i.	1,000 p.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.	1,000 p.s.i.	1,000 p.s.i.	
LAMINATIONS POSITIONED BY VISUAL-ONLY CRITERIA														
[illegible]	[illegible]	24.[illegible]	11.4	13.6	.48	.50	4,610	1,730	1,7[illegible]	157	4,900	1,750	1,820	Tension lamination at end joint containing pith associated wood [illegible] ft. from midlength
[illegible]	[illegible]	24.[illegible]	11.6	12.5	.49	.53	6,260	1,740	1,900	206	6,250	1,800	1,950	Tension lamination at end joint containing pith associated wood [illegible] ft. from midlength. Second lamination above end joint has three small knots and has pith [illegible]
[illegible]	[illegible]	24.[illegible]	11.5	12.7	.49	.46	4,770	1,690	1,610	162	4,920	1,730	1,670	Tension lamination at edge knot and associated grain deviation [illegible] cross section 3.6 ft. from midlength. Propagated to end joint in [illegible] containing pith associated wood [illegible] ft. from midlength
[illegible]	[illegible]	24.[illegible]	[illegible]	[illegible]	.47	.52	3,880	1,630	1,640	133	3,950	1,650	1,660	Tension lamination at edge knot and associated grain deviation over 2[illegible] pct. of cross section at midlength. Second lamination has 1.[illegible] to 1.2[illegible] slope [illegible] across [illegible] width near midlength
[illegible]	[illegible]	24.[illegible]	12.1	12.0	.48	.48	4,840	1,620	1,710	165	4,910	1,640	1,710	Tension lamination at edge knot and associated grain deviation over [illegible] pct. of cross section and second lamination to [illegible] localized slope of grain over [illegible] pct. of cross section, both 4.1 ft. from midlength
Av.			13.4	[illegible]	.48	.49	4,830	1,680	1,730	164	4,970	1,710	1,770	
LAMINATIONS POSITIONED BY VISUAL-STIFFNESS CRITERIA														
[illegible]	[illegible]	24.34	[illegible]	[illegible]	.49	.52	5,900	1,840	1,850	200	6,160	1,900	1,920	Tension lamination at knot and associated grain deviation over 2[illegible] pct. of cross section 1.6 ft. from midlength
[illegible]	[illegible]	24.39	[illegible]	12.4	.49	.48	6,040	1,900	1,870	204	6,120	1,970	1,940	Tension lamination at edge knot and associated grain deviation over [illegible] pct. of cross section 0.9 ft. from midlength
[illegible]	[illegible]	24.37	[illegible]	[illegible]	.50	.48	5,830	1,870	1,990	198	6,070	1,930	2,050	Tension lamination at edge knot and associated grain deviation over 2[illegible] pct. of cross section 1.0 ft. from midlength
[illegible]	[illegible]	24.[illegible]	[illegible]	12.8	.49	.50	5,860	1,820	1,860	199	6,000	1,860	1,890	Tension lamination at edge knot and associated grain deviation over 2[illegible] pct. of cross section at midlength
[illegible]	[illegible]	24.[illegible]	11.6	[illegible]	.48	.49	5,710	1,840	1,780	126	1,830	1,880	1,830	Tension lamination at edge knots and associated grain deviation over [illegible] and 2[illegible] pct. of cross section 2.6 ft. and 0.9 ft. from midlength, respectively, and at edge knot and associated grain deviation over 27 pct. of cross section in second lamination 0.9 ft. from midlength
Av.			13.4	14.1	.49	[illegible]	5,470	1,860	1,870	185	5,680	1,910	1,910	

[1] Dimensions are averages of measurements made 5 ft. both sides of the midlength of each beam.

[2] Data in col. 4 were determined by averaging the moisture content of each lamination, which was obtained by ovendrying small specimens cut from the center 8 ft. of each beam. Data in col. 5 were obtained by averaging readings taken at each 5-ft. section along beam with a power-loss type moisture meter.

[3] Data in col. 6 are the average of the specific gravity of each lamination which was determined from ovendry weight and volume at time of tests of small specimens cut from the center 8 ft. of each beam. Data in col. 7 were determined from volume of complete beam at time of test and weight at time of test corrected to ovendry weight using moisture content in col. 5.

[4] Based on moisture content in col. 4.

nations was 100,000 p.s.i. higher than the minimum, or approximately, the average within each group, then an MOE of 2.01×10^6 p.s.i. would be expected as an average value. The calculated average MOE for the visual-only beams, using equation (3), was previously found to lie 1.8×10^6 p.s.i. (4). Therefore, the expected increase in MOE for the visual-stiffness beams would be from 1.8×10^6 to about 2.0×10^6 p.s.i., or an 11 percent increase in stiffness, over the visual-only beams.

Actual average full-span MOE values given in column 9 of table 3 were 7 percent less than calculated both for the visual-only and visual-stiffness beams. If the full-span MOE were corrected for the contribution of shear deflection, which is about 4 percent, the two would check closely. The visual-stiffness beams were 12 percent stiffer than the visual-only beams based on the full-span data adjusted to 12 percent moisture content as given in column 13 of table 3. This compares closely with a theoretical difference of 11 percent.

Beam failures.--Failure of three of the five visual-only beams involved edge knots in the tension lamination. (The specific gravity of one midlength tension lamination (beam 14) at the failure location, was 0.45 and, at that particular location, could be considered lightweight for the species.) The two beams that had no significant edge knots in the center portion of the tension lamination failed in the region of end joints. At least one of the boards in each of the latter two beams had pith-associated wood (wide-ringed, nondense wood near the pith) in the end joints.

Four of the five visual-stiffness beams also had failures which involved edge knots in the tension lamination. The other beam (No. 31), which had no significant edge knots, failed through a centerline knot in the tension laminations. Each of the beams in both groups which had edge knots and associated grain deviation of significant size in the tension lamination, as indicated in column 2 of table 2, failed through these knots.

Failure sections from each tension lamination of the five visual-stiffness beams are shown in figure 5. Failure of visual-stiffness beams 32 and 35 is shown in figures 6 and 7. These two beams failed at edge knots in the tension lamination, as did beams 33 and 34. Examination of the failure regions indicated that localized grain deviation associated with the edge knots at 20.9 feet on beam 32 and 19.1 feet on beam 35 was more than measured prior to beam manufacture. At these locations, grain deviation through the thickness of the tension lamination was found to occupy about 50 percent of the width of the bottom of the beam.

As previously noted, two visual-only beams failed at end joint regions which had pith-associated wood in one of the boards. No failures of the visual-stiffness beams were attributable to end joints. Imposing a minimum MOE of 2.2×10^6 p.s.i. on all boards in the tension lamination tended to eliminate pith-associated boards, apparently resulting in stronger end joints. As noted in column 15 of table 3, the second lamination may have influenced the failure of three of the visual-only beams. Failure of one of the five visual-stiffness beams, No. 35, was associated with a major strength-reducing characteristic in the second lamination.

The face of the tension lamination of beam 35 is shown in figure 5 and shows failure through two edge knots about 2 feet apart and on opposite edges of the beam. Tension tests conducted on structural lumber at the Forest Products Laboratory have indicated that two such edge knots on opposite edges of the board, although they may be spaced quite a distance apart, severely reduce the tensile strength of structural lumber. Beam 35, in addition to having these two edge knots in the tension lamination, also had an edge knot with local grain deviation in the second lamination directly above one of these edge knots. Figure 7 shows that the failure followed this grain deviation through the thickness of the second lamination. Therefore, beam 35 had three knots that may have combined to cause failure.

Modulus of elasticity, specific gravity, and moisture content of boards in the failure regions of the visual-only and visual-stiffness beams are given in Appendix II.

Modulus of rupture.--The strength of visual-stiffness beams 31 through 34 was quite consistent with MOR values (adjusted to 12 pct. moisture content), varying between 6,000 and 6,400 p.s.i. Beam 35, however, had a much lower modulus of rupture, 3,830 p.s.i. The mode of failure of this beam gives an indication of the cause of its low strength.

In comparison to the beams made using visual-only criteria, the visual-stiffness beams averaged 14 percent higher in strength. However, the

Table 4.--Summary of maximum I_K/I_G values for southern pine beams with laminations positioned by visual-stiffness criteria

Beam No.	Center half of beam		Constant moment section		At location of failure	
	I_K/I_G	Location[1]	I_K/I_G	Location[1]	I_K/I_G[2]	Location[1]
		Ft.		Ft.		Ft.
LAMINATION POSITIONED BY VISUAL-ONLY CRITERIA						
11	0.108	12.4	0.107	21.8	0.025	14.6
12	.153	17.2	.153	17.2	.117	13.6
13	.179	20.8	.179	20.8	.118	16.4
14	.205	17.8	.205	17.8	.157	20.0
15	.215	18.2	.215	18.2	.093	15.7
Av..	.172	....	.172	....	.102	......
LAMINATIONS POSITIONED BY VISUAL-STIFFNESS CRITERIA						
31	.161	17.8	.161	17.8	.094	21.6
32	.155	22.6	.155	22.8	.100	20.9
33	.206	26.0	.118	16.0	.068	23.0
34	.138	12.4	.137	20.8	.107	20.0
35	.173	19.0	.173	19.0	.173	19.0
Av..	.167	....	.149	....	.108	......

[1]Location measured from zero end of beam.
[2]Maximum value of I_K/I_G at a 12-in.-long section at failure.

design of beams cannoty be based on average values; rather it must be based on values somewhat lower than the average. The minimum strength beam in each group, beams 14 and 35, had nearly equal moduli of rupture of about 3,900 p.s.i.

I_K/I_G ratios.--The effect of knots on the bending strength of laminated wood beams is based on the I_K/I_G concept developed by Wilson and Cottingham (12). According to this concept, strength is expressed as a function of the maximum ratio of the moment of inertia of knots (I_K) to the moment of inertia of the entire beam (I_G).

A maximum I_K/I_G ratio for each beam in this study was determined using the method proposed by Wilson and Cottingham (12). Knots within a 1-foot length were considered as occurring at the same section. Values were calculated for each 0.2-foot increament of length along the mid-one-half of each beam, and results are given in table 4.

Maximum I_K/I_G ratios for the center half of the beams for both the visual-only and visual-stiffness groups were comparable and would indicate that the visual grades of the two groups of beams were nearly equal. According to knot surveys which form the basis of the present laminating standards, the maximum I_K/I_G ratio expected for the beams would be 0.19. Nos. 14 and 15 of the visual-only beams and No. 33 of the visual-stiffness beams had maximum I_K/I_G values which exceeded 0.19.

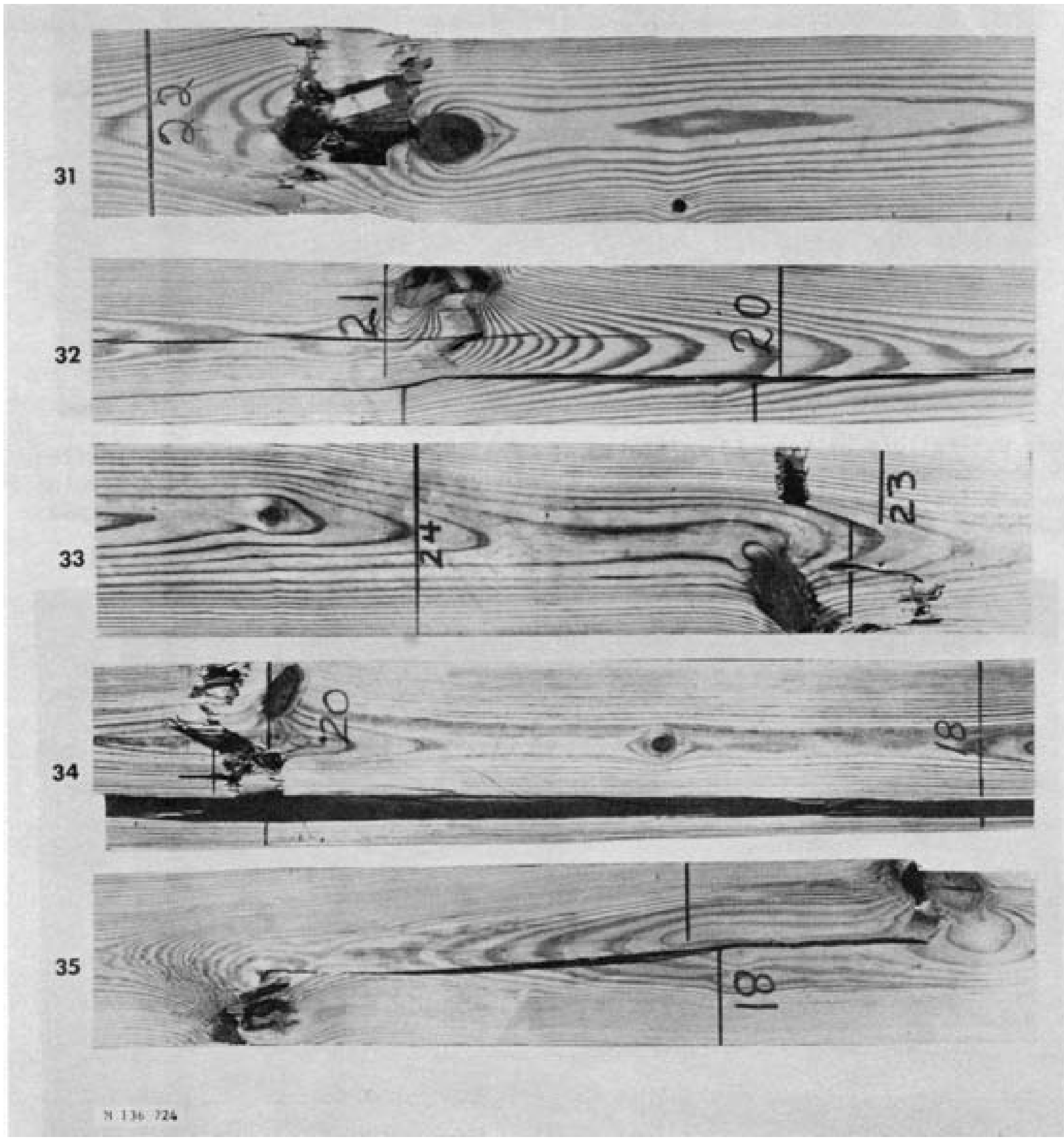

Figure 5.--Failure sections showing bottom of tension lamination of five visual-stiffness beams. Beam 31 failed at a knot near the center of the width of the beam, while the other four failed at the knots and associated grain deviation on the edge of the tension laminations.

M 136 724

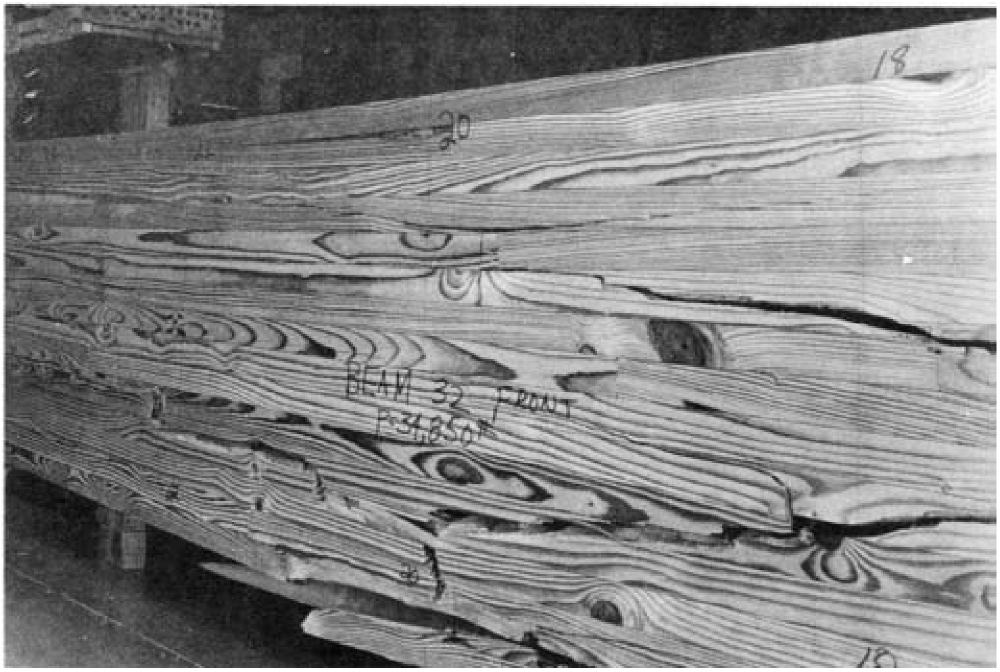

Figure 6.--Failure of beam 32 initiated at an edge knot in the tension lamination (lower center) and propagated through remainder of beam. Beam 32 had a modulus of rupture (adjusted to 12 pct. moisture content) of 6,320 p.s.i. and full-span modulus of elasticity of 1.97 x 10^6 p.s.i. M 135 713

Figure 7.--Failure of beam 35 was attributable to knots rear the edge of the beam in the tension lamination and an edge knot and associated grain deviation in the second lamination. Not shown is a knot in the tension lamination near the opposite edge and about 2 feet to the left of the other knots (see fig. 5). The low modulus of rupture of this beam (3,830 p.s.i.) was attributed to the combined effect of these three edge knots. M 135 719

CONCLUSIONS

The following conclusions are based on bending tests of five glued-lamilinted southern pine beams made using a combination of visual and stiffness criteria for positioning boards within the beams. Results were compared to tests of five other beams previously reported (4) which were manufactured using only visual criteria for positioning laminations.

(1) Beams made using both visual and stiffness criteria for positioning laminations were significantly stiffer than those using visual criteria only. The average full-span modulus of elasticity of the five visual-stiffness beams was 1.91×10^6 p.s.i. or 12 percent higher than that of' the visual-only beams, which was 1.71×10^6 p.s.i. This difference agrees closely with the theoretically expected difference.

(2) Average modulus of rupture of the visual-stiffness beams was 14 percent higher than the average for the visual-only beams. However, the minimum values within each group were nearly equal.

(3) Although using the visual-stiffness criteria improved the average strength of beams, better criteria than were used in this study must be used to insure consistently high strength glued-laminated timbers.

(4) Both the low strength visual-stiffness beam and the low strength visual-only beam failed due to a possible combination of two or more strength-reducing characteristics in the tension lamination and in the second lamination. These characteristics--grain deviation in board thickness, edge knots, two knots near each other but on opposite edges of the board, and regions of lightweight material--should be considered in developing criteria for and grading of tension laminations.

(5) Two of the five visual-only beams failed at end-joint areas in the tension lamination which contained pith-associated wood, but none of the visual-stiffness beams failed at end-joint areas. The difference was attributable to the tendency to eliminate boards containing pith-associated wood when a minimum modulus of elasticity of 2.2 x: 10^6 p.s.i. was imposed on the outer tension lamination.

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APPENDIX I

The specific gravity and moisture content of small sections cut from each lamination near midlength of each beam are given in tables I-1 and I–2. Laminations were numbered from the tension face; No. 1 is the tension lamination. The specific gravity was determined from volume at time of test and ovendry weight.

Table I–1.––Specific gravity and moisture content of each lamination of 40–foot southern pine beams laid up by visual criteria only[1]

Lamination No.[2]	Beam No. 11 Specific gravity	Beam No. 11 Moisture content	Beam No. 12 Specific gravity	Beam No. 12 Moisture content	Beam No. 13 Specific gravity	Beam No. 13 Moisture content	Beam No. 14 Specific gravity	Beam No. 14 Moisture content	Beam No. 15 Specific gravity	Beam No. 15 Moisture content	Average specific gravity for each lamination
		Pct.		Pct.		Pct.		Pct.		Pct.	
1	0.51	10.9	0.53	10.8	0.52	14.6	0.45	12.4	0.48	11.8	0.50
2	.50	14.7	.52	15.1	.52	12.1	.54	10.8	.51	13.9	.52
3	.49	10.9	.45	12.0	.59	14.7	.54	13.6	.48	10.6	.51
4	.49	14.2	.44	12.5	.42	14.5	.42	11.4	.47	11.4	.45
5	.43	15.8	.44	14.2	.47	15.4	.36	14.4	.45	11.0	.43
6	.47	14.7	.44	14.0	.49	12.0	.43	11.5	.47	13.2	.46
7	.41	14.0	.62	14.6	.44	15.4	.47	12.2	.52	15.5	.49
8	.42	16.2	.48	13.8	.49	16.0	.45	13.9	.49	11.6	.47
9	.47	15.1	.47	14.0	.47	14.7	.44	11.8	.44	11.5	.46
10	.49	13.5	.49	14.6	.33	14.8	.45	12.8	.42	13.8	.44
11	.58	15.8	.42	14.6	.60	10.7	.53	13.9	.43	13.9	.51
12	.46	14.1	.47	13.4	.42	14.3	.46	15.1	.40	13.5	.44
13	.49	14.4	.44	11.0	.54	12.4	.52	10.9	.47	13.4	.49
14	.45	13.3	.52	14.7	.56	13.4	.53	14.6	.61	13.9	.53
15	.47	13.5	.56	14.9	.50	11.1	.50	13.8	.58	14.6	.52
Av.	.48	14.1	.49	13.6	.49	13.7	.47	12.9	.48	12.9	

[1]Specific gravity determined from volume at time of test and ovendry weight of small specimens cut from each lamination near midlength of the beam.

[2]Laminations numbered from tension face of beam; No. 1 is tension lamination.

Table 1-2.--Specific gravity and moisture content of each lamination of 40-foot southern pine beams laid up by visual and stiffness criteria[1]

Lamination No.[2]	Beam No. 31		Beam No. 32		Beam No. 33		Beam No. 34		Beam No. 35		Average specific gravity for each lamination
	Specific gravity	Moisture content	Specific gravity	Moisture content	Specific gravity	Moisture content	Specific gravity	Moisture content	Specific gravity	Moisture content	
		Pct.		Pct.		Pct.		Pct.		Pct.	
1	0.61	14.6	0.52	14.0	0.61	13.7	0.61	14.4	0.50	14.4	0.57
2	.52	14.5	.63	14.5	.57	14.8	.41	13.5	.45	14.3	.52
3	.51	14.5	.48	14.2	.51	15.5	.50	13.9	.50	12.1	.50
4	.52	14.2	.47	15.1	.44	15.2	.48	11.0	.55	14.4	.49
5	.46	13.3	.47	14.5	.44	15.4	.48	14.1	.46	15.0	.46
6	.47	12.4	.45	13.7	.44	12.6	.43	11.1	.42	14.0	.44
7	.48	14.0	.38	13.6	.47	14.2	.39	13.3	.46	14.1	.44
8	.36	14.8	.43	12.6	.37	13.4	.42	13.3	.42	13.6	.40
9	.37	14.8	.47	16.2	.58	16.0	.54	13.0	.40	14.9	.47
10	.45	15.0	.48	14.6	.44	14.1	.47	14.5	.43	14.6	.45
11	.44	14.0	.44	15.1	.49	12.0	.50	11.3	.50	11.6	.47
12	.53	14.2	.49	15.2	.44	14.8	.48	13.4	.48	11.9	.48
13	.55	14.1	.53	14.8	.51	13.1	.55	14.1	.48	13.8	.52
14	.59	14.4	.52	15.3	.56	10.5	.52	13.1	.57	14.8	.55
15	.47	14.0	.56	13.4	.58	13.4	.54	14.3	.57	9.8	.54
Av..	.49	14.2	.49	14.4	.50	13.9	.49	13.2	.48	13.6	

[1] Specific gravity determined from volume at time of test and ovendry weight of small specimens cut from each lamination near midlength of the beam.

[2] Laminations numbered from tension face of beam: No. 1 is tension lamination.

APPENDIX II

The following two figures show the modulus of elasticity, specific gravity, and moisture content of the board in the failure regions of each beam. These were determined prior to beam manufacture. The modulus of elasticity was determined by a vibration technique in which the boards were supported at each of their ends. The reaction at one end was recorded and was assumed to represent one–half the weight of each board. Some inaccuracies are expected by this method due to the differences of specific gravities along the length of boards.

The average specific gravity for each board was calculated from assumed average board dimensions and weight of each board corrected to an ovendry weight using the moisture content which was determined with the power–loss type meter.

The numbers at the end of each figure represent the beam and lamination numbers. The vertical lines across each lamination are end–joint locations. A broken line indicates locations of failures.

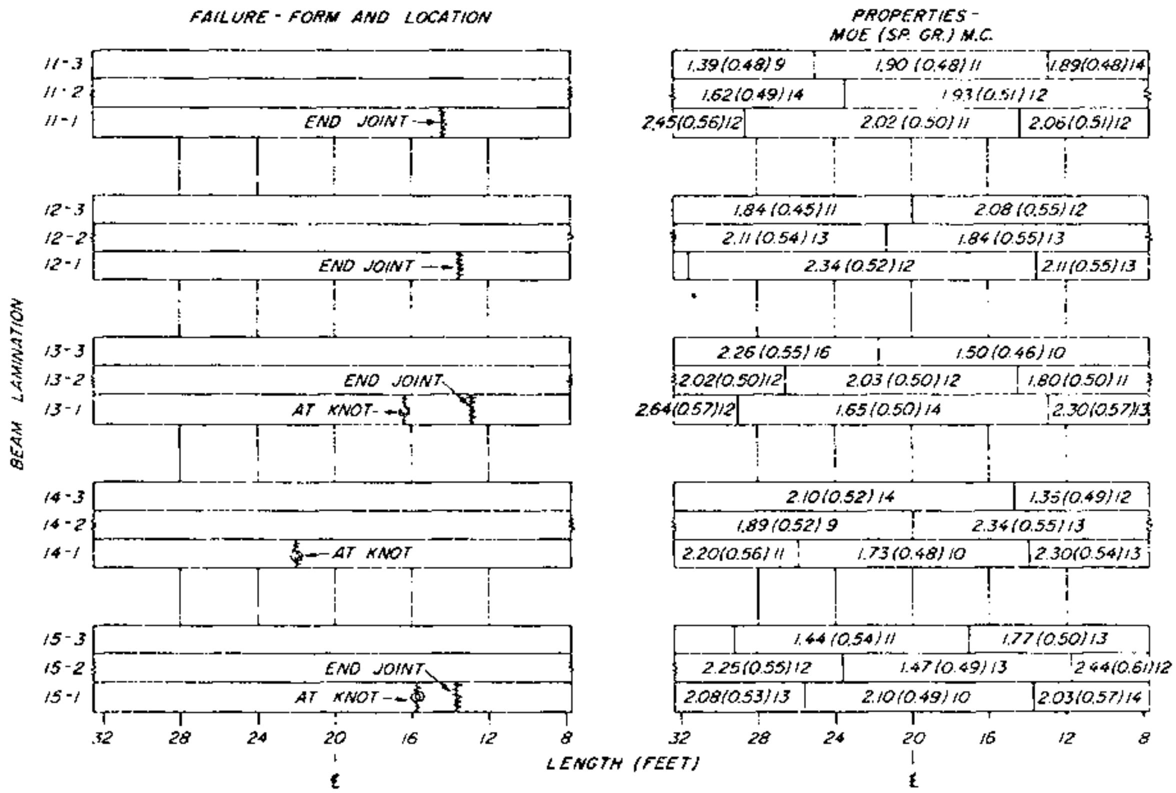

Figure II–1.––Modulus of elasticity, specific gravity, and moisture content of the three outer tension laminations near midlength of the 40–foot–long southern pine beams manufactured using visual criteria only. Failure location is also indicated.
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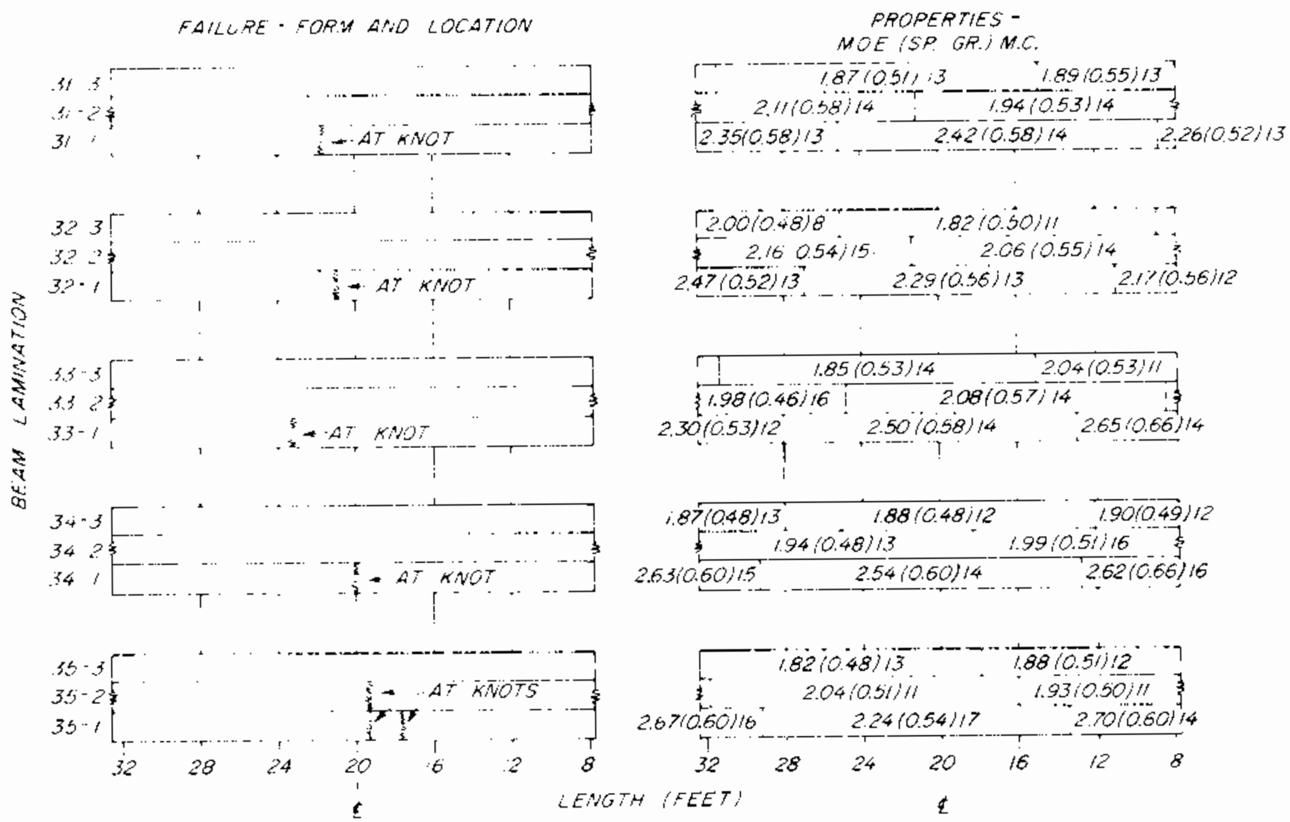

Figure II-2.--Modulus of elasticity, specific gravity, and moisture content of the three outer tension laminations near midlength of the 40-foot-long southern pine beams manufactured using visual and stiffness criteria. Failure location is also indicated.

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U. S. Government Printing Office: 1973-754-324/8