LAMINATION OF CONNECTICUT RED OAK

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Nicholas V. Poletika

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LAMINATION OF CONNECTICUT RED OAK[1]

Nicholas V. Poletika

Red oak, *Quercus borealis maxima* (Marsh.) Ashe, and related species, *Quercus coccinea* Muenchh. and *Quercus velutina* Lamarck, constitute the predominant species group in the upland forests of Connecticut and adjacent states. The trees are relatively young and lumber recovered from them is usually of low quality. It seemed desirable, therefore, to determine whether this low grade material could be reduced to relatively defect-free laminae and subsequently reassembled by gluing into timbers of higher value.

Laminated wood[2] offers a number of advantages over solid wood. Boards one inch or less in thickness can be seasoned with less degrade than thicker material. Defects of various kinds can be eliminated or so localized in assembling that their effect on strength is minimized. Laminae can be placed so as to produce timbers of maximum strength, and stability of shape can be achieved through balanced construction. Structural members can be produced in dimensions that are limited by the capacity of the equipment available rather than by the size of trees, and curved shapes, previously considered impracticable in solid wood, can be fabricated.

This bulletin presents a comprehensive evaluation of the factors affecting the laminating of native red oak, including the yield of material suitable for laminating, the properties and characteristics of laminated lumber, and the development of recommendations for fabrication procedures. Consideration is given to such factors as strength, freedom from warp and glue joint durability; to the effect of wood variability upon these factors; and to methods of controlling the influence of this variability.

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[1] The research on which this paper is based was performed by the author while on the staff of the Connecticut Agricultural Experiment Station. The results of the work herein described were presented in expanded form as a dissertation for the degree of Doctor of Forestry in the Yale School of Forestry in June, 1948.

[2] For the purposes of this report the term "laminated wood" applies to a glued assembly so arranged that the grain direction of all layers is parallel.

HISTORICAL REVIEW

Laminated structural material has been used for interior and protected construction in Europe for more than 40 years (20). In the United States the first glued structural members, in the form of laminated wood arches, were built by the Forest Products Laboratory in 1935 (20). It was not, however, until the development of durable synthetic resin adhesives (about 1940) that laminated products could be made for use under any type of exposure conditions (8).

Current applications of laminated wood, fabricated principally of softwood lumber, include such structures as theaters, churches, gymnasiums, aircraft hangars, dairy barns, factories and bridges. In addition, laminated white oak has been used in marine work for keels, stern assemblies and frames of motor boats, torpedo boats, tugs, life-saving launches, and other small craft (8). Laminated wood is also used for such products as oars, hammer handles, shuttles, bowling pins, shoe lasts, tennis rackets and skis.

METHOD OF INVESTIGATION

Procurement of Material

All lumber used in this study was obtained from 20 red oak trees cut on the forest of the White Memorial Foundation located in Litchfield. This particular area is representative of native oak stands throughout Connecticut.

The plan of the study required that lumber with a wide range in specific gravity[1] be available. In order to obtain this spread in density,[1] the trees were selected from a series of sites, grading from bottom land to rocky ridges. Growth rate, measured on increment borings taken at breast height before the trees were felled, was used as an indicator of specific gravity. Correlation between growth rate and specific gravity was subsequently found to be rather low. Nevertheless, the lumber obtained from the logs had a quite satisfactory range and distribution of specific gravity classes.

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1. As used in this paper the term "specific gravity" means "bulk specific gravity", i.e., the specific gravity of the wood substance plus included voids. The density of a material is its weight per unit of volume. Since the specific gravity or relative density of a solid is the ratio of its density to the density of distilled water at 4°C. and since, in the centimeter-gram-second system, the numerical value for density in grams per cubic centimeter is the same as the numerical value for specific gravity, the terms "specific gravity" and "density" are used interchangeably to avoid monotony in the text.

The trees ranged from 11 to 23 inches in diameter at breast height, averaging about 15 inches. The average age was about 80 years. No particular attempt was made to select trees which would yield a maximum of clear material, but trees that were obviously of extremely low quality were excluded. Most of the logs were sawn into 1¼ inch round-edge boards varying in length from 8 to 16 feet. In addition, three timbers, 4½ inches square and 16 feet long, were obtained. More than 3,000 board feet of material were available for the study.

The lumber was stacked for seasoning in a ventilated shed with sawn yellow poplar stickers, spaced two feet apart in the pile. The ends of all boards were covered with two liberal coats of a suspension of aluminum powder in spar varnish.

When the lumber reached a moisture content of about 20 per cent, it was rough planed and, for the purpose of determining yield, each piece was graded according to the rules of the National Hardwood Lumber Association and its board foot volume obtained. Edging and end trimming was assumed to have been done before assigning a grade or determining volume. In addition, a sketch of each piece showing all visible defects was made.

Each board was also inspected for yield of material suitable for laminating. As a basis for this estimate, it was arbitrarily decided that the minimum width should be three inches, the minimum length, 50 inches, and that the following defects should be prohibited:

a. Knots or knot holes over ¾ inch in diameter
b. Any form of decay
c. Cross grain with a slope steeper than one in twelve
d. Bark pockets larger than ¾ square inch in area
e. Surface checks longer than four inches
f. Splits and shakes
g. Wane

Preparation of Material for Laminating

Two basic sizes of material were prepared for the study. Most of the lumber was cut into pieces 3 inches wide and 36 inches long. A limited amount of stock was sawn 6 inches wide by 72 inches long. After cutting to the above sizes, one inch was trimmed off each end for subsequent specific gravity determination. The material was then re-piled with stickers for further seasoning. Table 1 gives the finished dimensions, number of items, and thickness and number of laminae of the several types of test specimens used in the study.

TABLE 1. DESCRIPTION OF TEST SPECIMENS[1]

Type of Test and Name of Specimen	Dimensions[2] of Specimen, Inches			Number of Specimens	Composition of Specimens			
					Face Laminae		Core Laminae	
	Width	Depth	Length		Number	Thickness Inches	Number	Thickness Inches
Static Bending								
Standard Beams	2.00	2.00	30.0	50	2	.666	1	.666
					2	.500	2	.500
					2	.250	6	.250
					2	.125	14	.125
Special Beams	2.25	2.25	34.0	133	2	.750	1	.750
					2	.500	2	.625
					2	.250	2	.875
					2	.125	3	.666
Large Beams	4.50	4.50	64.0	3	2	.750	4	.750
				2	2	.250	5	.800
				2[3]	.	. . .	. .	. . .
Compression Parallel to Grain								
Short Columns	2.00	2.25	8.0	47	2	.750	1	.750
Compression Perpendicular to Grain								
Standard Compression Specimens	2.00	2.00	6.0	40	2	.625	1	.750
Shear Parallel to Grain								
Shear Blocks	2.00	1.50	2.0	55	2	.750	0	. . .
Durability (Exposure)	2.00 2.25	2.00 2.25	3.5 3.5	153	All combinations listed under Standard and Special Beams were investigated.			

1. All test specimens were of clear material except the large laminated beams, for the composition of which see page 29.
2. The final dimensions of specimen at time of test.
3. Not laminated.

Segregation Into Specific Gravity Classes

One of the principal relationships studied was the effect of the density of individual laminae on the overall strength and stiffness of the laminated member. It was necessary, therefore, to know the specific gravity of each lamina to permit holding this factor constant while the effect of other variables was studied.

No information was available on the average value and range of specific gravity of Connecticut red oak. The average specific gravity for the species, based on trees sampled in five widely scattered regions of the country, is recorded as 0.66 on the basis of oven-dry weight and oven-dry volume (12). In the present study it was found that, on the same basis, the mean of 1,252 specific gravity determinations was 0.670. The range in specific gravity was from 0.55 to 0.76.

For the purposes of the investigations, three arbitrary specific gravity classes were established. All pieces with a specific gravity of less than 0.63 were designated as low density; those ranging from 0.63 to 0.69, inclusive, as average density; those exceeding 0.69, as high density material. Forty-four per cent of the samples tested for specific gravity fell into the average density class; 28 per cent each into the low and high density classes.

The average number of rings per inch was found to be 9.7, which compares very closely with the published average (12) of 10 rings per inch for the species.

Method of Fabrication

All stock to be glued was planed to the desired thickness and used within 36 hours to prevent excessive warping. Since synthetic adhesives, especially urea-formaldehyde, will not produce good bonds when the matching surfaces are not in close contact, a maximum tolerance of .005 inch was maintained while planing.

The rough-laminated blanks were from ¾ to 1 inch wider and 2 inches longer than the final finished dimension. Specimens tested to determine strength in static bending, compression parallel to the grain, compression perpendicular to the grain, and shear are illustrated in Figures 1, 2, 3 and 4, respectively.

The moisture content of the material at the time of gluing varied from 6 to 15 per cent. The individual laminae in a given assembly, however, did not differ in moisture content by more than 2 per cent.

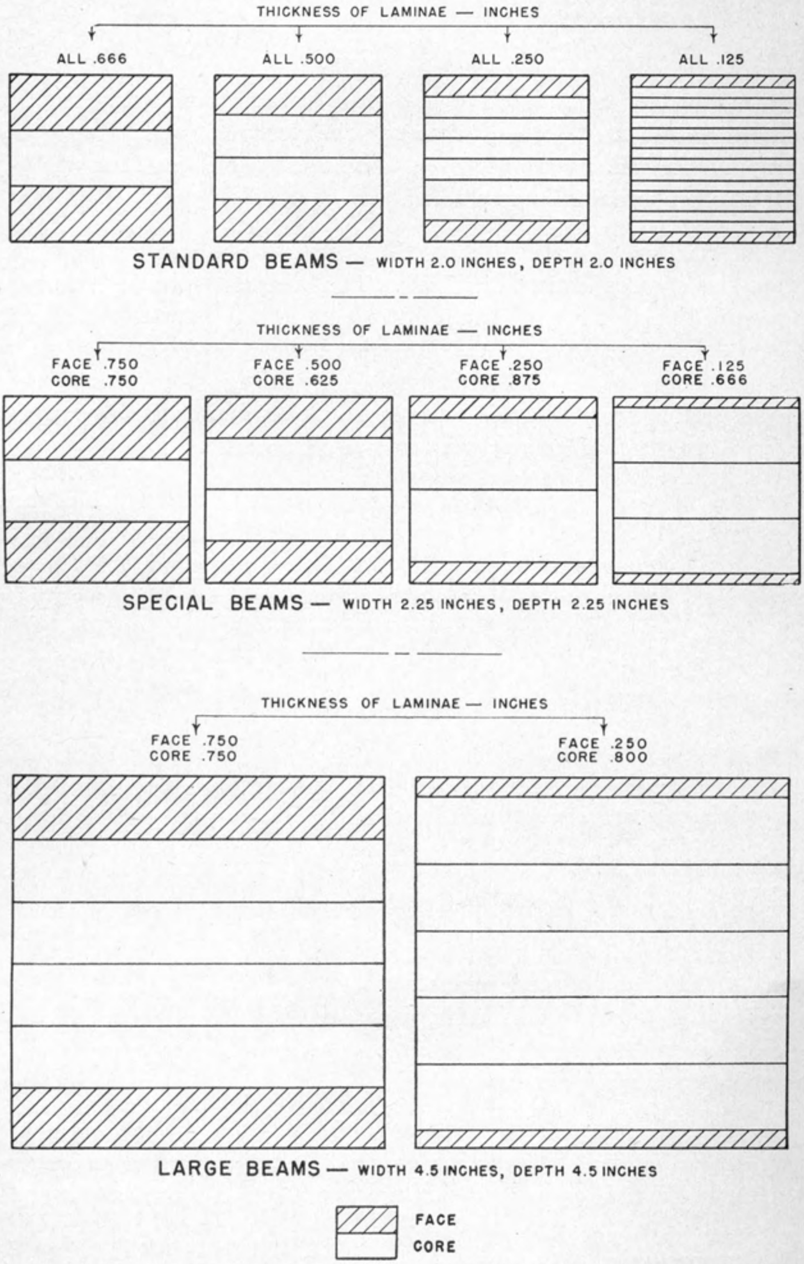

FIGURE 1

Cross sectional views of standard, special and large beams showing arrangement and thickness of laminae.

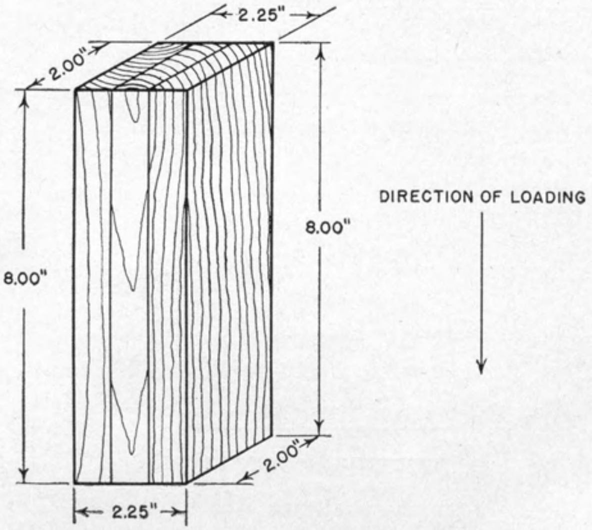

FIGURE 2

Isometric drawing of a laminated short column showing dimensions and arrangement of laminae. All laminae 0.75 inch thick.

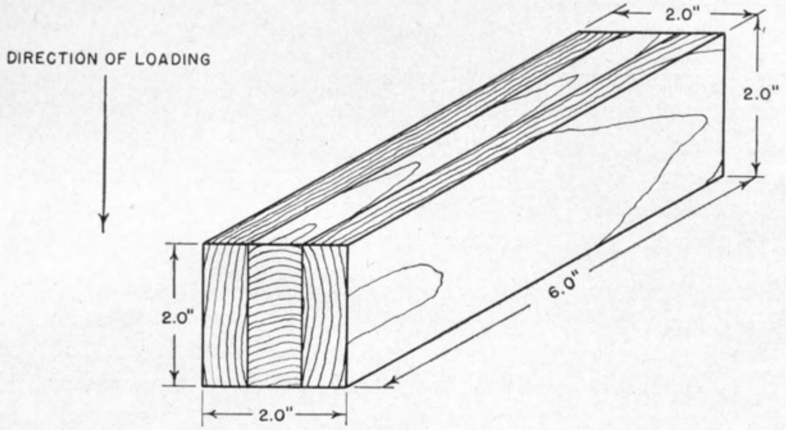

FIGURE 3

Isometric drawing of specimen for testing compression perpendicular to the grain. Face laminae 0.625 inch thick, core lamina 0.750 inch thick.

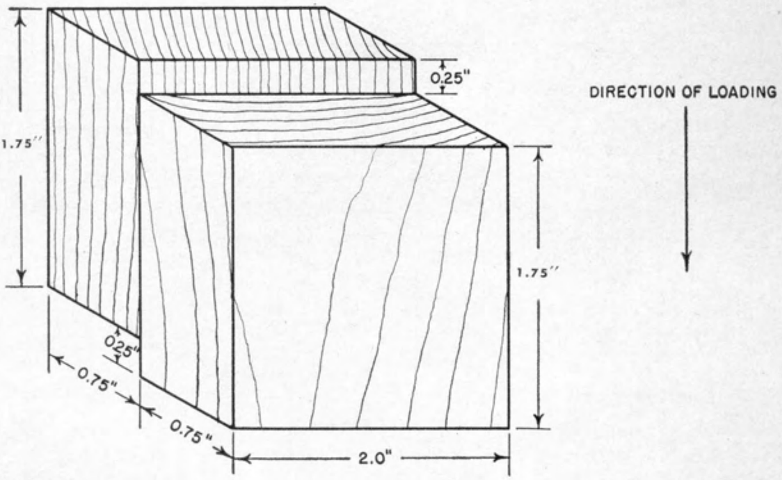

FIGURE 4

Isometric drawing of a shear specimen showing dimensions and arrangement of laminae. Both laminae 0.750 inch thick. Glued surface 3.0 square inches.

All the specimens used for strength tests, with the exception of five beams, were glued with Plaskon 250-2, a urea-formaldehyde type resin. All of the exposure specimens and five beams for strength tests were glued with Penacolite G-1124, a resorcinol-formaldehyde type resin. Both adhesives were mixed according to manufacturer's recommendations.

Glue spreads recommended by adhesive manufacturers are usually based on density of the wood. Red oak, however, although a relatively dense wood, is included, for glue spreading purposes, among woods of lower density because of its high porosity. The spread of adhesive used per 1,000 square feet of glue line was 50 pounds for the urea-formaldehyde and 60 pounds for the resorcinol-formaldehyde.

Most synthetic resin adhesives permit only a limited open and closed assembly time. The actual period varies with the specific adhesive but the range within a given type (urea or resorcinol) is relatively small. In all gluing operations with urea resin, the joints were assembled immediately after glue application and not more than 15 minutes of closed assembly time was allowed before pressure application. When a resorcinol adhesive was used, the open assembly time was five minutes followed by 30 minutes of closed assembly before pressure was applied.

A rigid frame screw press or rocker-head clamps were used for applying pressure which in all cases was 200 pounds per square inch.

The urea adhesive required a minimum curing temperature of 70°F. and all the specimens bonded with it were under pressure for at least 14 hours. The resorcinol adhesive was cured for eight hours in a small chamber in which the temperature at the glue line was maintained at 140°F. and the relative humidity controlled to keep the assembly at 12 per cent moisture content.

A minimum of one week was allowed for the conditioning of all glued members. With the urea-bonded blanks, conditioning served to permit a complete polymerization of the resin and to equalize the moisture content of the assembly (water is added to the wood with the resin). The conditioning period with resorcinol resin was exclusively for moisture equalization since the temperature employed assures a proper cure.

Details of various methods of fabrication may be found in a number of references on laminating (3, 4, 6, 8, 9, 20).

Testing and Evaluation Procedures

The mechanical tests were conducted according to the general procedures recommended by the American Society for Testing Materials (1, 2). All the tests, with the exception of the large beams, were made on a Baldwin-Southwark 60,000 pound hydraulic machine or on an Olsen 30,000 pound mechanical machine. The large beams were tested on a 150,000 pound Olsen mechanical machine.

Standard formulae were used to calculate the unit strength values which were adjusted to a 12 per cent moisture content according to the equation method (12).

Durability was evaluated by accelerated laboratory tests and by outdoor exposure. The laboratory test consisted of three cycles of alternate soaking and drying. The specimens were soaked in tap water for 15 days and then allowed to dry at room temperature until shrinkage stresses had caused a maximum of end-checking. This usually took six to seven days. All the glue lines at the ends of each block were then examined and total surface length of delamination, which developed if the glue bond was not as strong as the wood itself, was measured to an accuracy of 0.01 inch. After measurement, the specimens were again immersed to start the second cycle.

The outdoor exposure specimens were placed on the flat roof of a building and delamination measured once a month in the same manner as for the cyclic exposure tests.

The results of all tests were evaluated by means of appropriate statistical methods. Analysis of variance, factorial analysis of variance, various tests of significance, and regression analysis were some of the methods used. A description of these treatments can be found in any standard reference on statistical methods.

STRENGTH AND DURABILITY TESTS

The efficient utilization of red oak depends on a number of factors which have not been completely investigated. Some of these factors are directly related to strength, others involve a combination of strength and durability. The subsequent sections analyze the significance of some of these factors and draw conclusions as to their effect.

Flexural Properties

EFFECT OF GROWTH RING PLACEMENT

No information was available as to the effect of placement of growth rings, relative to the load applied, on the flexural properties of solid or laminated red oak, that is, whether the load is applied to the flat-grained, quarter-sawed, or some intermediate surface. It was, consequently, necessary to evaluate this factor before other portions of the study could be performed. To minimize variability of the material, only laminae from the average density class were used.

Three classes of growth ring placement were established for the individual laminae: flat (F), edge (E), and 45 degrees (45). A maximum variation of 15 degrees from the designated placement was permitted. An edge lamina, for example, was defined as one with annual rings forming an angle of 75° to 105° with the face.

The laminae were assembled into beams with the following ring placement combinations: F-F-F, E-E-E, 45-45-45, F-E-F and E-F-E. Five standard sized beams, composed of three defect-free pieces (Table 1), were tested for each of the above combinations. Average values are presented in Table 2.

A statistical analysis of variance indicated that there was no significant difference among the properties shown by the various combinations indicating that arrangement of growth rings in the fabrication of laminated beams has no influence on their strength and stiffness. Consequently, all later assemblies used for mechanical tests were fabricated without reference to growth ring placement.

TABLE 2. EFFECT OF GROWTH RING PLACEMENT ON FLEXURAL PROPERTIES

Type of Specimen	Specific [1] Gravity	Modulus [1] of Rupture p. s. i. [2]	Fiber Stress [1] at Proportional Limit p. s. i.	Modulus [1] of Elasticity p. s. i.
F-F-F	0.66	13,850	7,590	1,670,000
E-E-E	0.66	13,840	7,720	1,624,000
45-45-45	0.65	13,710	7,300	1,718,000
F-E-F	0.67	13,300	7,130	1,748,000
E-F-E	0.66	13,430	7,210	1,660,000

1. In this and all subsequent tables, specific gravity values are on the basis of oven-dry weight and oven-dry volume; strength and stiffness values are adjusted to 12 per cent moisture content.
2. p. s. i. = lbs. per square inch.

AVERAGE STRENGTH OF SMALL LAMINATED BEAMS

This section presents, on the basis of a limited number of specimens and a representative sampling of material, the average flexural properties of red oak beams fabricated from ¾-inch stock, straight-grained and free from defects. Lumber of this thickness is commonly used in commercial laminating.

Since the initial segregation into specific gravity classes showed that approximately 25 per cent of the available material was classed as low density, 50 per cent as average density, and 25 per cent as high density, this distribution was used as the basis for determining the proportion of high, average, and low density beams to be tested. By selecting and fabricating the material to be tested in this manner, it was possible to obtain from a small number of samples an average value which was considered to be as valid as one obtained from a much larger number of beams fabricated from randomly selected material. Twenty special beams (Table 1), five fabricated of high density, five of low density, and ten of average density material were tested. Average values

TABLE 3. FLEXURAL PROPERTIES OF SOLID AND LAMINATED RED OAK

Type of Material	Specific Gravity	Modulus of Rupture p. s. i.	Fiber Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
Solid [1]	0.66	14,300	8,500	1,820,000
Laminated	0.67	14,750	7,150	1,771,000

1. Values from Tech. Bul. 479, U. S. Dept. of Agr. (12).

based on these 20 beams are compared with published averages (12) for solid air-dry material in Table 3. The average flexural properties of solid and laminated small clear beams are reasonably similar.

EFFECT OF ADHESIVES ON THE STRENGTH OF LAMINATED BEAMS

Tests of closely matched standard size laminated beams, glued under the same conditions as were used in fabricating mechanical and exposure specimens, were conducted to check the assumption that the strength of beams was not affected by the two adhesives used. Five beams, composed of three high density laminae, each .666 inch thick (Table 1), were bonded with each adhesive and tested. The average values obtained are given in Table 4.

TABLE 4. THE EFFECT OF TYPE OF ADHESIVE ON FLEXURAL PROPERTIES

Adhesive	Specific Gravity	Modulus of Rupture p. s. i.	Fiber Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
Urea	0.71	17,240	8,180	2,050,000
Resorcinol	0.72	16,960	8,490	2,013,000

A statistical analysis indicated that no significant difference in strength could be attributed to the type of adhesive used.

EFFECT OF THICKNESS OF LAMINAE

The study of the effect of thickness of laminae on the strength and stiffness of beams was divided into two parts. In one, laminae of the same thickness were used throughout the beam; in the other, the ratio

TABLE 5. THE EFFECT OF THICKNESS OF LAMINAE ON FLEXURAL PROPERTIES[1]

Thickness of Laminae Inches	Specific Gravity	Modulus of Rupture p. s. i.	Fiber Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
¾	.68	14,740	7,740	1,712,000
½	.68	15,040	8,040	1,898,000
¼	.67	14,720	6,580	1,912,000
⅛	.71	15,600	8,700	1,944,000

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[1] Each value based on tests of five beams.

of thickness of face laminae to thickness of core laminae was varied (Figure 1). In both cases average density material was used.

The results of tests of beams with laminae of uniform thickness are summarized in Table 5.

An analysis of variance indicated that beams composed entirely of ⅛ inch plies were stronger and stiffer than those with thicker laminae. No statistical difference in strength was established among the other three thicknesses.

The conclusion is that thickness of the individual laminae as such does not affect the strength and stiffness of beams. However, in the case of veneer thicknesses, in which the ratio of adhesive to wood is high, the strength and stiffness of the assembled beam are actually increased because of the effect of the adhesive.

The average results of the tests on the set of beams in which face and core thicknesses were varied are summarized in Table 6.

TABLE 6. THE EFFECT OF THICKNESS OF FACE LAMINAE ON FLEXURAL PROPERTIES[1]

Thickness of Face Laminae Inches	Specific Gravity	Modulus of Rupture p. s. i.	Fiber Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
¾	.68	14,550	8,030	1,694,000
½	.68	14,280	6,520	1,963,000
¼	.69	15,250	7,520	2,047,000
⅛	.68	14,500	6,600	1,730,000

1. Each value based on tests of four beams.

A statistical analysis of the data indicated that the thickness of the face material did not, of itself, influence the strength and stiffness of beams of uniform density.

EFFECT OF VARIATIONS IN DENSITY

Native red oak lumber has been shown to have a relatively wide range in specific gravity. The next phase of the study was undertaken to determine whether combinations of laminae can be arranged to produce a structural product which would be superior to one made of material selected completely at random. Specifically, the placement of stronger, denser wood in regions of maximum stress was studied.

The material was clear and straight-grained and was selected from the three density classes previously discussed. To evaluate all possible conditions, combinations incorporated all three density classes in both the faces and cores making nine density combinations. In addition, three thicknesses of face laminae (¾ inch, ½ inch and ¼ inch) were used in each density combination. There were, consequently, 27 different assemblies each replicated four times. The beams were all of special size (Table 1).

The average results are presented in Table 7.

TABLE 7. THE EFFECT OF DENSITY AND FACE AND CORE THICKNESS ON FLEXURAL PROPERTIES

Density Combination	Face Thickness Inches	Specific Gravity	Modulus of Rupture p. s. i.	Fiber Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
L-L-L[1]	¾	0.62	12,000	5,760	1,576,000
L-L-L	½	0.61	12,500	5,380	1,559,000
L-L-L	¼	0.61	12,300	5,050	1,514,000
L-A-L	¾	0.64	12,900	6,460	1,528,000
L-A-L	½	0.67	12,500	6,500	1,719,000
L-A-L	¼	0.67	12,300	5,230	1,663,000
L-H-L	¾	0.67	13,300	6,530	1,631,000
L-H-L	½	0.69	14,200	7,420	1,815,000
L-H-L	¼	0.69	15,000	6,310	1,895,000
A-L-A	¾	0.67	15,000	7,350	1,804,000
A-L-A	½	0.65	13,900	7,020	1,808,000
A-L-A	¼	0.66	15,000	7,890	2,040,000
A-A-A	¾	0.68	14,600	8,030	1,694,000
A-A-A	½	0.67	14,300	6,520	1,963,000
A-A-A	¼	0.68	15,300	7,520	2,046,000
A-H-A	¾	0.69	14,400	7,340	1,730,000
A-H-A	½	0.70	14,300	6,810	1,828,000
A-H-A	¼	0.70	14,300	7,400	1,978,000
H-L-H	¾	0.69	15,300	7,890	1,810,000
H-L-H	½	0.65	15,000	7,330	1,715,000
H-L-H	¼	0.65	14,400	7,270	1,941,000
H-A-H	¾	0.68	15,200	7,780	1,947,000
H-A-H	½	0.68	14,900	7,770	1,748,000
H-A-H	¼	0.69	14,500	6,820	1,984,000
H-H-H	¾	0.72	16,200	7,590	1,907,000
H-H-H	½	0.71	15,900	9,180	1,969,000
H-H-H	¼	0.72	15,700	7,660	2,163,000

[1] L-L-L = low density faces on a low density core. H and A signify high and average density, respectively.

The data in Table 7 were analyzed statistically and it was found that the density of the face and core laminae had a significant influence on strength and stiffness. Although the thickness of the components of the different beams did not, of itself, influence flexural properties, a combination of density, thickness and location did have an effect.

THEORY OF COMPOSITE BEAMS

The results presented in the preceding section provide a means of testing the theory of bending in composite beams of native red oak. The accuracy of the theory is checked by comparison of theoretical values for strength and stiffness with results actually obtained.

The stresses in rectangular laminated beams, in which all laminae are of comparable quality, may be calculated by methods used for solid material. Thus, for stresses in extreme fiber the conventional stress equation can be used (17):

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

in which:

S = maximum stress in outer fiber of face lamina, p. s. i.
M = bending moment, pound-inches
c = ½ depth of beam, inches
I = moment of inertia, inches ^{4}

In a beam of rectangular cross section, $I = \dfrac{bd^3}{12}$ when b is the breadth and d the depth of the beam in inches.

A modification of the usual method of calculation is necessary if faces and core differ in strength or stiffness. Since in a beam maximum stress is in the extreme fiber, top and bottom, it is apparent that the selection of stronger, stiffer material for the face laminae is beneficial to the overall strength of the beam. The ratio of thickness of core laminae to thickness of face laminae may be arranged so that the face laminae fail first, so that the core fails first, or so that face and core fail simultaneously. The discussion below, however, is based on the assumption that failure will occur in the face before it does in the core, although it is also applicable when face and core fail simultaneously.

The basic concept of mechanics involved is that a rectangular beam with faces and core which differ in modulus of elasticity behaves, in effect, like an I beam. By means of the method of "equivalent areas" (10) a beam with a theoretical or transformed I section may be conceived as having one of two forms:

(a) The width of the core (web) may be held constant and the width of the faces (flanges) increased by the factor $n = \frac{E_f}{E_c}$

in which

E_f = modulus of elasticity of the face laminae, p. s. i.

E_c = modulus of elasticity of the core material, p. s. i.

In this case the transformed beam may be considered equivalent in strength to an I beam of the same dimensions, assembled of core material throughout.

(b) The width of the faces may be held constant and the width of the core decreased by the factor, $\frac{1}{n} = \frac{E_c}{E_f}$

In this case the transformed beam has the characteristics of an I beam of the same dimensions assembled of face material throughout.

Obviously, the moments of inertia of the transformed beams will be different from each other and from that of the untransformed beam. If the stress properties of the face material are under consideration, the moment of inertia of a beam transformed as described under (a) must be reduced by the factor, $\frac{1}{n}$, as shown immediately below in the calculation of modulus of rupture for a beam transformed in this manner. If the stress properties of the core are under consideration, no such reduction of the moment of inertia of the transformed beam is necessary. See calculation of horizontal shear stress on page 28.

If the transformation is accomplished as described in (b), conditions will be reversed, i.e., the moment of inertia will be used as derived when determining stresses in the face material. It must, however, be increased by the factor, n, when working with stresses in the core.

The several steps in the procedure for deriving a calculated modulus of rupture of a beam transformed as indicated in (a) are outlined below.

Calculated Modulus of Rupture

(a) Determine whether the ratio of thickness of face to thickness of core is such that failure will occur first in the face laminae by the equation

$$d_c = \frac{F_c\ E_f\ d_f}{E_c\ F_f} \qquad (18)$$

in which

d_c = distance from neutral plane to outermost fiber of core laminae, inches

F_c = maximum allowable fiber stress in core laminae, p. s. i.

E_f = modulus of elasticity of face laminae, p. s. i.

d_f = distance from neutral plane to outermost fiber of face laminae, inches

E_c = modulus of elasticity of core laminae, p s. i.

F_f = maximum allowable stress in face laminae, p. s. i.

(It follows that $d_f - d_c$ equals the minimum allowable face thickness in inches)

(b) Keeping the width of the web (core) constant, compute the width of the "flange" from the equation $w = b \dfrac{E_f}{E_c}$

in which

w = transformed width of face laminae (flanges), inches

b = actual width of face laminae, inches

(c) Compute the moment of inertia of the transformed section from the equation

$$I_t = \frac{wd^3}{12} - \frac{(w-b)\,(d-f)^3}{12}$$

in which

I_t = moment of inertia of transformed section, inches ^{4}

d = depth of beam, inches

f = combined thickness of face laminae, inches

(d) Reduce I_t for determination of stress in faces by the equation

$$I_{tr} = I_t \frac{1}{n} = I_t \frac{E_c}{E_f}$$

in which

I_{tr} = reduced moment of inertia of the transformed section, inches ^{4}

(e) Compute bending moment for the transformed section from the equation

$$M = \frac{S_f\, I_{tr}}{c}$$

in which

S_f = maximum allowable stress in outer fiber of face laminae, p. s. i.

(f) Derive the concentrated center load on a simple beam at failure from the equation

$$P = \frac{4M}{L}$$

in which

P = maximum load at failure, pounds

L = span of the beam, inches

(g) Determine the calculated modulus of rupture from the equation

$$R = \frac{1.5\ PL}{bd^2}$$

in which

R = modulus of rupture (calculated), p. s. i.

Example 1[1] shows the derivation of a calculated modulus of rupture, using static bending data obtained in this study.

Specifications of the beam:

Span (L)	31.5 inches
Width (b)	2.25 inches
Depth (d)	2.25 inches
Thickness of individual faces $(\frac{f}{2})$	0.25 inch
Thickness of core	1.75 inches
Modulus of elasticity, high density face material (E_f)	2,014,000 p. s. i.
Modulus of elasticity, low density core material (E_c)	1,550,000 p. s. i.
Modulus of rupture, high density face material (F_f, S_f)	15,900 p. s. i.
Modulus of rupture, low density core material (F_c)	12,200 p. s. i.

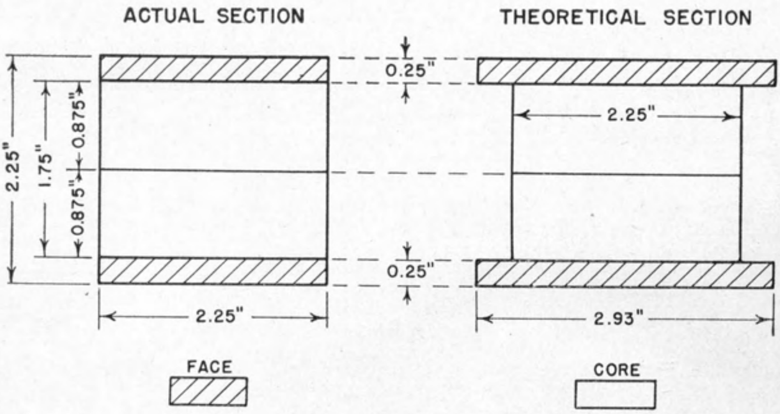

FIGURE 5

Cross section of a special beam showing transformation to a theoretical I section.

(a) Minimum allowable thickness of face laminae

$$d_c = \frac{F_c\ E_f\ d_f}{E_c\ F_f} = \frac{12{,}200 \times 2{,}014{,}000 \times 1.125}{1{,}550{,}000 \times 15{,}900} = 1.121 \text{ inches}$$

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[1] In this and all subsequent illustrative examples, computations are to slide rule accuracy only.

$d_f - d_c = 1.125 - 1.121 = 0.004$ inch

Since the face laminae of the beam are 0.25 inch thick, failure will occur first in the faces.

(b) Minimum width of flanges

$$w = b \frac{E_f}{E_c} = 2.25 \text{ x } \frac{2{,}014{,}000}{1{,}550{,}000} = 2.93 \text{ inches} \quad \text{(See Figure 5)}$$

(c) Moment of inertia, transformed section

$$I_t = \frac{wd^3}{12} - \frac{(w-b)\ (d-f)^3}{12} = \frac{2.93 \text{ x } 2.25^3}{12} -$$

$$\frac{(2.93 - 2.25)\ (2.25 - 0.50)^3}{12} = 2.47 \text{ inches}^4$$

(d) Reduced moment of inertia

$$I_{tr} = I_t \frac{E_c}{E_f} = 2.47 \frac{1{,}550{,}000}{2{,}014{,}000} = 1.90 \text{ inches}^4$$

(e) Bending moment, transformed section

$$M = \frac{S_f\ I_{tr}}{c} = \frac{15{,}900 \text{ x } 1.90}{1.125} = 26{,}900 \text{ pound-inches}$$

(f) Concentrated center load

$$P = \frac{4M}{L} = \frac{4 \text{ x } 26{,}900}{31.5} = 3{,}420 \text{ pounds}$$

(g) Calculated modulus of rupture

$$R = \frac{1.5\ PL}{bd^2} = \frac{1.5 \text{ x } 3{,}420 \text{ x } 31.5}{2.25 \text{ x } (2.25)^2} = 14{,}200 \text{ p.s.i.}$$

Calculated values for modulus of rupture, obtained as outlined in the example above, were derived for all beams listed in Table 7 which had faces and core of dissimilar materials. These values are compared in Table 8 with actual values for modulus of rupture obtained from static bending tests.

The differences between actual and calculated values range from approximately 1 to 12 per cent. The range in values due to inherent vari-

TABLE 8. ACTUAL VERSUS CALCULATED VALUES FOR MODULUS OF RUPTURE[1]

		Modulus of Rupture		
Density Combinations	Face Thickness Inches	Actual p. s. i.	Calculated p. s. i.	Difference Between Actual & Calculated per cent
L-A-L	¾	12,900	12,400	+4.0
L-H-L	¾	13,300	12,600	+5.6
A-L-A	¾	15,000	14,500	+3.4
A-H-A	¾	14,400	14,600	—1.4
H-L-H	¾	15,300	15,700	—2.5
H-A-H	¾	15,200	15,800	—3.8
L-A-L	½	12,500	12,700	—1.6
L-H-L	½	14,200	12,700	+11.8
A-L-A	½	13,900	14,100	—1.4
A-H-A	½	14,300	14,900	—4.0
H-L-H	½	15,000	15,200	—1.3
H-A-H	½	14,900	15,700	—5.1
L-A-L	¼	12,300	13,400	—8.2
L-H-L	¼	15,000	13,900	+7.9
A-L-A	¼	15,000	13,500	+11.1
A-H-A	¼	14,300	15,100	—5.3
H-L-H	¼	14,400	14,200	+1.4
H-A-H	¼	14,500	15,400	—5.8

[1] The actual values used in computing calculated values for modulus of rupture (Table 8) and modulus of elasticity (Table 9) were as follows:

High density material	
Modulus of elasticity	2,014,000 p. s. i.
Modulus of rupture	15,900 p. s. i.
Average density material	
Modulus of elasticity	1,901,000 p. s. i.
Modulus of rupture	14,700 p. s. i.
Low density material	
Modulus of elasticity	1,550,000 p. s. i.
Modulus of rupture	12,200 p. s. i.

ability of wood (based on beams tested in this study which were composed of uniform material throughout) was 3 to 7 per cent. Thus, it would seem that the differences between the actual and calculated values are probably due to natural variation in wood properties rather than to error in the theory.

The application of the foregoing method of analysis in estimating the strength of combinations of face and core thickness other than those shown in Table 8 is justified by these results.

The variation in properties within a single species is usually not great enough to demonstrate the possibilities of composite structure to best advantage. This can be better shown by considering two kinds of wood having quite different properties. A calculation, similar to Example 1, was made for a 2 x 6 inch beam, fabricated of average density oak faces of minimum allowable thickness on an average density hemlock core. This showed that, with the oak faces constituting slightly more than 10 per cent of the depth, the modulus of rupture of the composite beam was 28 per cent greater than an all-hemlock beam of the same dimensions.

Calculated or Apparent Modulus of Elasticity

Conventional methods of mechanics can be used to compute the modulus of elasticity of laminated beams composed of uniform material throughout. The equation used for this computation, in a simple beam, centrally loaded, is

$$E = \frac{P'L^3}{4bd^3y} \qquad (17)$$

in which

E = modulus of elasticity, p. s. i.
P' = load at proportional limit, pounds
L = span, inches
b = width, inches
d = depth, inches
y = deflection at center, inches

When a laminated beam is composed of two or more materials which differ in stiffness, an equation which incorporates the stiffness of each material used is required. The general form of the equation is

$$E_a = \frac{1}{I}\sum_{i=1}^{i=n} E_i \, I_i \qquad (5)$$

in which

E_a = "apparent" modulus of elasticity, p. s. i.[1]
I = moment of inertia of whole beam, inches ^{4}
E_i = modulus of elasticity of i^{th} lamination, p. s. i.
I_i = moment of inertia of i^{th} lamination, inches ^{4}
n = number of laminae

For a laminated beam of only two materials, the general equation may be reduced to the form

---

[1] "Apparent" modulus of elasticity is modulus of elasticity of the combination considered as a homogeneous material.

$$E_a = \frac{E_f\, I_f + E_c\, I_c}{I} \qquad (5)$$

in which

E_a and I are as noted above
E_f = modulus of elasticity of face material, p. s. i.
I_f = moment of inertia of faces, inches ^{4}
E_c = modulus of elasticity of core material, p. s. i.
I_c = moment of inertia of core, inches ^{4}

In Example 3 the above equation is used to derive the apparent modulus of elasticity of a beam of the same specifications as stated for Example 1 as follows:

Moment of inertia, whole beam, $I = \dfrac{bd^3}{12} = \dfrac{2.25 \text{ x } 2.25^3}{12} = 2.14$ inches ^{4}

Moment of inertia, core, $I_c = \dfrac{b\,(d-f)^3}{12} = \dfrac{2.25 \text{ x } 1.75^3}{12} = 1.01$ inches ^{4}

Moment of inertia of the faces, $I_f = I - I_c = 2.14 - 1.01 = 1.13$ inches ^{4}

Apparent modulus of elasticity of the combination, E_a =

$$\frac{2{,}014{,}000 \text{ x } 1.13 + 1{,}550{,}000 \text{ x } 1.01}{2.14} = 1{,}791{,}000 \text{ p. s. i.}$$

Values for calculated or apparent modulus of elasticity are compared in Table 9 with actual values from static-bending tests for those beams in Table 7 which were assembled with unlike materials in faces and core.

The differences between the actual and calculated values of modulus of elasticity are greater than were found for modulus of rupture. The maximum difference was about 18 per cent and is less than the maximum variation of 20 per cent obtained in testing a comparable number of beams which were laminated from material in one density class. This indicates that the theoretical method of computing modulus of elasticity is reliable.

Shear Stress

When two materials, which differ markedly, are combined in a laminated beam, the shear stress in the weaker core may become the factor limiting the strength of a timber. An approximate check of the shear stress in a beam of a given combination can be obtained through an ad-

TABLE 9. ACTUAL VERSUS CALCULATED VALUES FOR MODULUS OF ELASTICITY IN STATIC BENDING[1]

Density Combinations	Face Thickness Inches	Modulus of Elasticity Actual p. s. i.	Calculated p. s. i.	Difference Between Actual & Calculated per cent
L-A-L	¾	1,528,000	1,562,000	−2.2
L-H-L	¾	1,631,000	1,568,000	+4.0
A-L-A	¾	1,804,000	1,888,000	−4.5
A-H-A	¾	1,730,000	1,904,000	−9.1
H-L-H	¾	1,810,000	1,997,000	−9.4
H-A-H	¾	1,947,000	2,009,000	−3.1
L-A-L	½	1,719,000	1,608,000	+6.9
L-H-L	½	1,815,000	1,627,000	+11.5
A-L-A	½	1,808,000	1,845,000	−2.0
A-H-A	½	1,828,000	1,923,000	−4.9
H-L-H	½	1,715,000	1,935,000	−11.4
H-A-H	½	1,748,000	1,995,000	−12.4
L-A-L	¼	1,663,000	1,715,000	−3.0
L-H-L	¼	1,895,000	1,768,000	+7.2
A-L-A	¼	2,040,000	1,733,000	+17.7
A-H-A	¼	1,978,000	1,956,000	+1.1
H-L-H	¼	1,941,000	1,791,000	+8.4
H-A-H	¼	1,984,000	1,961,000	+1.2

1. See footnote to Table 8.

aptation of the conventional equation for shear:

$$S_s = \frac{VQ}{Ib} \qquad (10)$$

in which

S_s = horizontal shearing stress at a given plane[1] of a given cross section of the beam, p. s. i.

V = total shear at the cross section, pounds

Q = statical moment of that part of the cross section between the plane where shearing stress is computed and the nearest surface of the beam, inches ^{3}

I = moment of inertia of the whole cross section with respect to the neutral axis, inches ^{4}

b = width of the cross section at the point where S_s is being computed, inches.

The above equation can be adapted for use with laminated beams composed of two materials by transforming the cross section into a theoretical I beam section as described under (a), page 20. Substituting

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[1] S_s may be computed for any area lying between and parallel to the faces of a beam. In the example below it is computed for the neutral plane.

the moment of inertia and the statical moment of the transformed I beam, the above equation may be written

$$S_s = \frac{VQ_t}{I_t b}$$

in which Q_t and I_t are the statical moment and the moment of inertia, respectively, of the transformed section.

If a beam with specifications identical with those of the beam in Example 1 is used, then

$$V = \frac{P}{2} = \frac{3{,}420}{2} = 1{,}710 \text{ pounds}$$

$I_t = 2.47$ inches^4 *
$b = 2.25$ inches

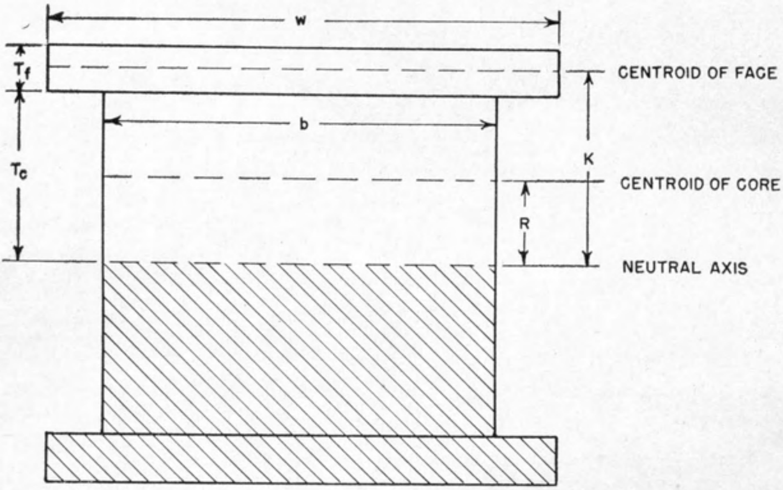

FIGURE 6

Showing dimensions required for computation of horizontal shear in a beam with high density faces and a low density core.

The statical moment of the transformed section may be expressed by the equation

$$Q_t = w \times T_f \times K + b \times T_c \times R \qquad \text{(See Figure 6)}$$

in which

b = actual width of cross section = 2.25 inches
w = transformed width of "flange" = 2.93 inches
T_f = thickness of face lamina = 0.25 inch
K = distance from neutral axis of beam to centroid of face lamina = 1.0 inch

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* Since shearing stress, S_s, is being computed for core material, I_t is the same as for the transformed section in Example 1. No reduction is necessary (see page 20).

T_c = distance from neutral axis of beam to extreme fiber of core = 0.875 inch (d_c in Example 1)

R = distance from neutral axis of beam to centroid of core = 0.4375 inch

($\frac{d_c}{2}$ in Example 1)

$$Q_t = 2.93 \times 0.25 \times 1.0 + 2.25 \times 0.875 \times 0.4375 = 1.595 \text{ inches}^3$$

The value for horizontal shear at the neutral plane is consequently

$$S_s = \frac{1{,}710 \times 1.595}{2.47 \times 2.25} = 492 \text{ p. s. i.}$$

If this value is compared with 2,175 p. s. i., the average shear strength obtained from block shear tests as reported in a subsequent section, it would appear that, in this combination of materials, the core was in no danger of failing in shear. However, comparison of horizontal shear stress in a beam with stress obtained from block shear tests is not completely valid, since it has been shown that, when beams fail in horizontal shear, they do so at loads considerably less than would be expected on the basis of block shear tests.

Flexural Properties of Large Beams

Seven large beams (see Table 1) were tested for comparison with small beams laminated from clear material and to test the I beam theory described in the previous section. Two were solid (unlaminated) and of a quality comparable with the highest structural grade of red oak. Three were built up of ¾ inch plies of average density material of a quality considered suitable for laminating (see page 7). Two were composed of ¼ inch high density faces on a laminated core of low density material, all laminae being of a quality considered suitable for laminating. The results are presented in Table 10.

Although based on a limited number of tests, the results indicate that flexural properties of laminated beams are slightly higher than those of the solid controls. After adjustment by the proper height factor (11), strength and stiffness values were similar to those of small clear specimens.

Theoretical strength and stiffness were calculated for the beams with a high-low-high density combination, using the actual values given in the footnote to Table 8, with results as follows:

Calculated modulus of rupture, 13,300 p. s. i.
Calculated modulus of elasticity, 1,689,000 p. s. i.

TABLE 10. FLEXURAL PROPERTIES OF LARGE BEAMS

Type of Beam	Specific Gravity	Modulus of Rupture p. s. i.	Fiber Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
Solid Control #1	0.68	13,600	6,400	1,600,000
Solid Control #2	0.69	14,100	7,160	1,680,000
Average	0.68	13,850	6,780	1,640,000
Average Laminated #1	0.69	14,500	7,200	1,970,000
Average Laminated #2	0.67	14,300	6,900	1,850,000
Average Laminated #3	0.69	14,400	7,300	2,000,000
Average	0.68	14,400	7,130	1,940,000
High-Low-High Laminated #1	0.65	13,800	6,860	1,760,000
High-Low-High Laminated #2	0.63	13,400	6,260	1,890,000
Average	0.64	13,600	6,560	1,825,000

Although only two large composite beams were tested, a comparison of calculated values with the actual values shown in Table 10 indicates that the method of theoretical analysis is reasonably applicable to beams of larger size.

Compressive Properties

COMPRESSION PARALLEL TO THE GRAIN

The strength of Connecticut red oak as a short column, in either solid or laminated form, had not been previously determined and tests were made to provide average strength values as a basis for comparison.

Average Compressive Strength of Clear Laminated Red Oak

Columns were assembled from three ¾-inch plies and were the size indicated under short columns in Table 1. Five columns were made from low, five from high, and ten from average density clear material. The average strength and stiffness values derived from tests of these columns are considered representative of laminated native red oak not segregated for specific gravity.

They are compared in Table 11 with the published averages for solid red oak.

The strength and stiffness of locally grown red oak in compression parallel to the grain is apparently lower than the generally accepted average for the species. No known variable was introduced during pro-

TABLE 11. AVERAGE STRENGTH AND STIFFNESS OF SOLID AND LAMINATED RED OAK IN COMPRESSION PARALLEL TO THE GRAIN

Type of Beam	Specific Gravity	Maximum Crushing Strength p. s. i.	Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
Solid[1]	0.66	6,760	4,580	1,820,000
Laminated	0.67	4,890	3,440	1,743,000

1. Values from Tech. Bul. 479, U. S. Dept. of Agr. (12).

cessing which would account for the lower strength and stiffness of the Connecticut material.

Effect of Density Combinations

The effect of variations in density of the laminae of a column have not been studied previously for red oak. This phase of the study was designed to evaluate this factor.

In contrast to the study of beams, only one thickness of lamina (¾ inch) was used throughout the columns which were all 2 x 2¼ inches in cross section (Table 1). The orthogonality of density combinations was maintained in that high, average and low density materials were used in all possible locations in the faces and cores. Nine such combinations, each with four replicates, were tested with results as shown in Table 12.

TABLE 12. COMPRESSIVE PROPERTIES OF LAMINATED COLUMNS WITH CLEAR MATERIAL OF DIFFERENT DENSITY COMBINATIONS

Density Combination[1]	Specific Gravity	Maximum Crushing Strength p. s. i.	Fiber Stress at Proportional Limit p. s. i.	Modulus of Elasticity p. s. i.
L-L-L	0.62	4,510	3,180	1,555,000
L-A-L	0.65	4,720	3,440	1,747,000
L-H-L	0.67	4,850	3,450	1,574,000
A-L-A	0.65	4,880	3,410	1,707,000
A-A-A	0.68	4,960	3,210	1,713,000
A-H-A	0.69	5,180	3,640	1,780,000
H-L-H	0.67	4,830	3,110	1,634,000
H-A-H	0.69	4,860	4,080	2,038,000
H-H-H	0.71	5,200	3,740	1.983.000

1. L-A-L signifies low density faces on an average density core. H and A indicate high and average density, respectively.

A statistical analysis indicated that the placement of laminae has no significant effect on the strength and stiffness of a short column. The effect of each lamina on the compressive properties of the column was directly proportional to its density.

The overall influence of different densities on maximum crushing strength is apparently not very great in red oak (approximately 25 per cent between the extremes of low and high density material). The range in specific gravity was from 0.62 to 0.71.

THEORY OF COMPOSITE COLUMNS

The analysis of stresses in laminated columns of uniform material throughout, is computed from the equation

$$S_c = \frac{P}{A} \qquad (12)$$

in which

S_c = maximum crushing strength, p. s. i.
P = maximum load, pounds
A = area of cross section, square inches

However, when two materials with unlike properties are combined, their respective moduli of elasticity must be considered.

The equation developed for the calculation of stress parallel to the face plies of plywood lends itself to use with laminated columns composed of two unlike materials. This equation is

$$\frac{P}{A} = F_a = E_a \frac{F_l}{E_l} \qquad (5)$$

in which

F_a = average crushing stress in the column, p. s. i.
F_l = maximum crushing strength of the "limiting"[1] lamina, p. s. i.
E_l = modulus of elasticity of the "limiting" lamina, p. s. i.
E_a = "apparent"[2] modulus of elasticity of the column, p. s. i.

$\frac{F_l}{E_l}$ = factor for determining the "limiting" lamina

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1. The "limiting" lamina is that with the lowest ratio of crushing strength (F_l) to modulus of elasticity (E_l).

2. For definition of "apparent" modulus of elasticity, see page 25.

It is evident from the equation that two values must be determined

(a) The apparent modulus of elasticity
(b) The factor for the limiting lamina

The general equation for E_a for plywood is

$$E_a = \frac{1}{A} \sum_{i=1}^{i=n} E_i A_i \qquad (5)$$

in which

A = total cross sectional area under stress, square inches
E_i = modulus of elasticity of the i^{th} lamina, p. s. i.
A_i = cross sectional area of the i^{th} lamina, square inches

When the column is composed of only two materials the above equation may be reduced to the form

$$E_a = \frac{E_f A_f + E_c A_c}{A} \qquad (5)$$

in which E and A refer to modulus of elasticity and cross sectional area, respectively, and subscripts f and c refer to face and core.

The application of the two equations for deriving F_a and E_a for a short column composed of two high density face laminae and one low density core lamina is illustrated for a column with the following specifications:

Thickness of each lamina = 0.75 inch
Width of all laminae = 2.00 inches
Modulus of elasticity of high density face material (E_f) = 1,983,000 p. s. i.
Modulus of elasticity of low density core material (E_c) = 1,555,000 p. s. i.
Maximum crushing strength of high density face material (F_f) = 5,200 p. s. i.
Maximum crushing strength of low density core material (F_c) = 4,510 p. s. i.
Area of face laminae under compression (A_f) = 3.0 square inches
Area of core lamina under compression (A_c) = 1.5 square inches
Total area under compression (A) = 4.5 square inches

Determination of E_a

$$E_a = \frac{E_f A_f + E_c A_c}{A} = \frac{1{,}983{,}000 \times 3.0 + 1{,}555{,}000 \times 1.5}{4.5} = 1{,}840{,}000 \text{ p. s. i.}$$

Determination of limiting lamina and the factor, $\frac{F_l}{E_l}$

For low density material $\frac{F_c}{E_c} = \frac{4{,}510}{1{,}555{,}000} = .00290$

$$\text{For high density material } \frac{F_f}{E_f} = \frac{5{,}200}{1{,}983{,}000} = .00262$$

The high density faces have the lowest ratio of maximum crushing strength to stiffness and are, therefore, the "limiting" laminae. Consequently

$$\frac{F_l}{E_l} = .00262$$

$$\frac{P}{A} = F_a = E_a \frac{F_l}{E_l} = 1{,}840{,}000 \text{ x } .00262 = 4{,}820 \text{ p. s. i.}$$

In order to check the reliability of the theory just described, values for F_a (theoretical average crushing stress) and E_a (apparent or theoretical modulus of elasticity) were computed for all columns in Table 12 which were composed of unlike materials in faces and core. The comparisons of actual and calculated values are given in Tables 13 and 14.

TABLE 13. ACTUAL VERSUS CALCULATED VALUES FOR MAXIMUM CRUSHING STRENGTH IN COMPRESSION PARALLEL TO THE GRAIN

	Maximum Crushing Strength		
Density Combination	Actual [1] p. s. i.	Calculated p. s. i.	Difference Between Actual & Calculated per cent
L-A-L	4,720	4,670	+1.0
L-H-L	4,850	4,460	+8.7
A-L-A	4,880	4,820	+1.2
A-H-A	5,180	4,720	+9.7
H-L-H	4,830	4,820	+0.2
H-A-H	4,860	4,960	−2.0

[1] Values from Table 12.

It is apparent from an examination of Table 13 that there is reasonably good agreement between actual and theoretical values in only four out of the six cases cited. Of the other two cases, the theoretical value for L-H-L (4,460 p. s. i.) is lower than the actual value for L-L-L of 4,510 p. s. i. (Table 11); the theoretical value for A-H-A (4,720 p. s. i.) is lower than the actual value for A-A-A of 4,960 p. s. i. (Table 11). This leaves reasonable doubt as to the validity of the theory under the conditions described.

On the other hand, the actual and theoretical (or apparent) values for modulus of elasticity (Table 14) are in as close agreement as can

TABLE 14. ACTUAL VERSUS CALCULATED VALUES FOR MODULUS OF ELASTICITY IN COMPRESSION PARALLEL TO THE GRAIN

	Modulus of Elasticity		
Density Combination	Actual[1] p. s. i.	Calculated p. s. i.	Difference Between Actual & Calculated per cent
L-A-L	1,747,000	1,605,000	+8.8
L-H-L	1,574,000	1,699,000	−7.3
A-L-A	1,707,000	1,660,000	+2.8
A-H-A	1,780,000	1,803,000	−1.3
H-L-H	1,634,000	1,840,000	−11.2
H-A-H	2,038,000	1,891,000	+7.8

1. Values from Table 12.

be reasonably expected considering the normal variation in wood, and the method of calculation is considered reliable.

COMPRESSION PERPENDICULAR TO THE GRAIN

In preparing the compression specimens, the specific gravity distribution previously described was used as a basis for determining the number of high, average and low density specimens to be tested, i.e., 10 specimens of high density, 20 of average and 10 of low density clear material. The material was not segregated for growth ring placement. From tests of samples assembled in this manner, an average value similar to that for static bending and compression parallel to the grain was obtained. Alternate specimens were tested parallel and perpendicular to the glue line.

The mean fiber stress at proportional limit of the prisms loaded perpendicular to the glue line was 1,380 p. s. i. and that of the specimens loaded parallel to the glue line, 1,448 p. s. i. A statistical analysis showed that there was no significant difference in strength as a result of the two directions of loading. The average of all tests, 1,414 p. s. i., was slightly higher than the published average (12) of 1,250 p. s. i. for the species.

SHEAR PARALLEL TO THE GRAIN

The determination of average block shear strength of glued joints was made from 40 test specimens prepared from material selected from the three specific gravity classes in the manner previously described. In addition, the shear strength of the wood parallel and perpendicular to the glue joints was determined. This phase of the study was undertaken to show that the strength of well glued joints is as high as that of solid wood. In making up the test specimens, close matching was obtained by assigning alternate pieces in the same blank for the two directions of loading. Twenty specimens were tested parallel and 20 perpendicular to the glue line.

The average of the tests parallel to the glue line was 2,130 p.s.i., and that of tests perpendicular to the glue line was 2,220 p.s.i. A statistical analysis of the two means did not establish any significant difference between them.

Glue Joint Durability of Laminated Products

Numerous systems of studying glue line durability in laminated products have been proposed and used. All attempt to approximate actual service conditions (16). Because of the relatively recent advent of synthetic resins, only the results of comparatively short outdoor service exposure tests are available on adhesives of this class. A recent Forest Products Laboratory publication (15) shows, however, that the results of certain of the accelerated laboratory exposure tests apparently are a good indication of the results obtained in outdoor exposure.

Two tests of the durability of resorcinol-bonded joints were made on blocks composed of three laminae and of the size shown in Table 1. One was based on an accelerated laboratory exposure test and the other on outdoor exposure. In the fabrication of the test specimens, two conditions were studied; one was the effect of growth ring placement on glue joint durability and the other was the effect of density of individual laminae. Both phases incorporated different thicknesses of laminae as outlined in the previous discussion of mechanical tests (see Table 1).

Examination of the data indicated that there were relatively large amounts of delamination in combinations in which plain and edge grain pieces were glued together. One such combination (flat-edge-flat) showed an average delamination for all face thickness combinations of 2.2 per cent in the accelerated and 12.3 per cent in the weather tests. The other (edge-flat-edge) combination showed 6.3 per cent delamination in the accelerated and 12.6 per cent in the outdoor exposure tests. As the face lamina was decreased in thickness, there was a slight decrease in the amount of delamination in both these combinations. The remaining combinations of growth rings, including edge to edge, flat to flat, and either edge or flat to 45°, did not show appreciable delamination.

After reviewing the results of the accelerated and weather exposure tests, it was apparent that the former gave a good indication of expected delamination, even though the actual amount was considerably less than for the weather tests. Measurement of specimens which had been exposed for a year indicated that only slight increases in delamination took place after six months.

The conclusions, which can be derived on the basis of this and other investigations of glue line durability, are: for interior use, urea-formaldehyde resin joints, with random placement of growth rings, are satisfactory; for outdoor service, high quality resorcinol adhesives, bonded at elevated temperatures and with proper orientation of growth rings, will produce reliable joints.

APPLICATION OF RESULTS

When laminated and solid small, clear specimens are of comparable quality, they may be considered, for practical purposes, to have the same strength and stiffness. In laminated construction, however, it is possible to improve the properties of the product by locating better quality material in zones of maximum stress.

The advantages of laminating for structural use become more apparent in the case of relatively large timbers. The increasing scarcity of large, knot-free logs indicates that the building up of large members from lumber cut from relatively small logs can become important.

Working Stresses

In the design of wood structures involving large members, it is necessary to adjust the basic values for strength and stiffness, determined from small standard size specimens, by a number of factors.

Working stresses for solid material of structural grade are based on the strength of clear green wood, modified by suitable reduction factors. The use of green strength is logical for solid material because the members are often placed in service green. Seasoning defects, which occur during the drying of large size timbers, tend to offset the advantages normally associated with reduced moisture content. It is not logical, however, to use the green strength of the wood as a basis for the determination of working stresses in laminated material because the wood is thoroughly seasoned in the form of relatively thin lumber and selected for quality before assembly.

The working stresses derived below for laminated red oak, except that for horizontal shear in beams, are based on air-dry strength and stiffness values determined in this study. The procedure used followed that recommended by the U. S. Forest Products Laboratory (7, 19). In the application of the various reduction factors to the basic strength and stiffness values, the worst possible conditions were assumed. For example, it was assumed that the maximum of permissible defects appeared in every lamina, whereas in actual practice it is quite possible that only a few of the pieces would include such defects.

FLEXURAL WORKING STRESSES

The defects which were prohibited in the material designated as suitable for laminating a high quality product are given on page 7. Limitations in these defects are necessary for good gluing practice since grosser defects may produce inferior glue lines.

Working stress for extreme fiber in bending was derived by use of the formula:

$$f = M.R._{12} \times F_1 \times F_2 \times F_3 \times F_4 \times F_5$$

in which

f = allowable stress in extreme fiber in bending, p. s. i.

$M.R._{12}$ = modulus of rupture of clear laminated beams at 12 per cent moisture content = 14,750 p. s. i.[1]

F_1 = reduction factor for variability in the strength of clear wood = 0.75 (7)

F_2 = reduction factor for normal duration of load = 0.67 x 1.10 = 0.74 (7) (14)

F_3 = reduction factor for accidental overloading = 0.60 (7)

F_4 = reduction for defects = 0.69 (7)

F_5 = reduction for 1 in 10 scarf joints = 0.85 (21)

Substituting in the formula

$$f = 14{,}750 \times .75 \times .74 \times .60 \times .69 \times .85 = 2{,}880 \text{ p. s. i.}$$

A comparison with structural grades of solid red oak shows that the unit working stress for laminated material was approximately 50 per cent higher than for the best structural grade of beams and stringers, 1,900 p. s. i., (14) and 100 per cent higher than for a comparable structural grade, 1,450 p. s. i., (14) in which the permissible slope of grain was 1 in 12. If the slope of grain limitation imposed on the laminated material were to be increased to 1 in 15 or 1 in 18, the disparity between unit working stresses of solid and laminated material would be even more pronounced.

No reduction factors are commonly applied to the value for modulus of elasticity in the standard procedure of developing working stresses. It was felt, however, that a reduction for the maximum permissible slope

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[1] From Table 3.

of grain (1 in 12) should be made. Since the chance of all the laminae having this slope of grain is remote, this assumption is intentionally conservative. Based on available data (12) relating to the influence of cross grain on stiffness, a reduction in stiffness of 9 per cent was applied and the working value for modulus of elasticity becomes 1,771,000[1] x .91 = 1,600,000 p. s. i.

The third property which is needed in the design of beams is the allowable unit stress in horizontal shear. For large green members, a very severe reduction factor is used to compensate for possible subsequent seasoning checks. In laminated construction, seasoning checks have been eliminated in the selection of material. For the sake of conservatism, the dry shear strength of red oak (1,780 p. s. i.)[2] was reduced by the same factor as is used for green material. This factor was determined by dividing the basic stress in horizontal shear for red oak (185 p. s. i) (7) by the green shear strength of this species (1,210 p. s. i.) (12) which resulted in a factor of .153. Application of this factor to the dry shear strength (1,780 x .153) gives an allowable working stress for dry material of 272 p. s. i.

A comparison of allowable stresses in static bending for solid and laminated material, based on the preceding discussion is presented in Table 15.

TABLE 15. COMPARISON OF WORKING STRESSES IN BENDING FOR SOLID AND LAMINATED RED OAK

Material	Extreme Fiber in Bending p. s. i.	Modulus of Elasticity p. s. i.	Horizontal Shear p. s. i.
Solid, 1,450 f, B & S[1]	1,450	1,500,000	120
Laminated	2,880[2]	1,600,000[2]	272

1. 1,450 pound fiber stress grade of beams and stringers (14).
2. Derived from values in Table 3.

The working stresses for laminated beams shown in Table 15 are possibly too conservative but even so they show that a distinct advantage in flexural strength can be obtained by using laminated material.

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[1] From Table 3.

[2] Average dry shear strength of red oak as given in U. S. Dept. of Agr. Tech. Bul. 479 (12) was used as the base value in this computation, rather than an average of the shear values shown on page 36, because the tests conducted in the course of the present study were of the glue block type rather than the conventional block-shear test for solid wood.

COMPRESSIVE WORKING STRESSES

The same general procedure used in deriving working stresses in static bending was applied to obtain compressive working stresses parallel to the grain. It was necessary, however, to assign different values to the factors; their source was identical with that used in static bending.

The reduction factor for variability (F_1) was 0.80; that for duration of load (F_2) was 0.74; that for factor of safety (F_3), 0.67; and that for defects (F_4), 0.82. No reduction for scarf joint is necessary in compression parallel to the grain. By multiplying the maximum crushing strength of red oak (4,890 p. s. i.)[1] by the above factors, the allowable working stress in compression parallel to the grain was found to be 1,590 p. s. i.

The same reduction factor (9%) for slope of grain as was used in static bending was applied to the value for modulus of elasticity from Table 11 (1,743,000 p. s. i.) to give a value for working modulus of elasticity of 1,590,000 p. s. i.

In deriving the allowable stress in compression perpendicular to the grain, only one adjustment was necessary, namely, a factor of 0.67 for variability. This factor, applied to the average value for fiber stress at proportional limit of 1,414 p. s. i. (see page 35), gave an allowable stress of 950 p. s. i.

The working stresses in compression for laminated red oak are compared in Table 16 with those of solid material of similar structural grade.

TABLE 16. COMPARISON OF COMPRESSIVE WORKING STRESSES FOR SOLID AND LAMINATED RED OAK

Material	Compression Parallel to the Grain p. s. i	Modulus of Elasticity in Compression Parallel to the Grain p. s. i	Compression Perpendicular to the Grain p. s. i
Solid, 1,325C, P&T [1]	1,325	1,500,000	600
Laminated	1,590 [2]	1,590,000 [2]	950

1. 1,325 pound stress grade of posts and timbers (14).
2. Derived from values in Table 11.

General Design Considerations

The use of working stresses in design requires consideration of the ultimate service conditions under which the member will be used. In the

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[1] From Table 11.

discussion of glue line durability it was pointed out that consideration must be given to the orientation of the growth rings of the individual laminae if the members are to be subjected to outdoor exposure conditions. If the components of a member are so arranged that all are either predominantly flat sawn, quarter sawn, or at 45 degrees to the glue line, the full working stresses can be used. For uses in which the member is not subjected to weathering, arrangement of growth rings in adjacent laminations is of little importance.

The allowable stresses which have been developed for laminated red oak are applicable to service conditions in which the moisture content of the wood is approximately 12 per cent or less. They may be modified for use at high moisture content by reducing the allowable stresses by the ratio of $\frac{\text{strength green}}{\text{strength air dry}}$. These reduction factors are presented in Table 17 and are based on the published green and air dry values of red oak (12).

TABLE 17. FACTORS FOR REDUCING ALLOWABLE STRESSES FOR LAMINATED WOOD WHEN USED UNDER CONDITIONS MORE OR LESS CONTINUOUSLY DAMP OR WET

Kind of Stress	Per cent of Air-Dry Allowable Stress
Stress in extreme fiber in bending	58
Stress in compression perpendicular to the grain	61
Stress in compression parallel to the grain	51
Stress in horizontal shear	69
Modulus of elasticity	74

When the laminated member is to be used under service conditions where a deterioration hazard exists, the material had best be treated with a suitable preservative to prevent possible decay.

The preceding discussion is based upon the use of average strength values. In precise design problems, where a beam includes material of different densities in the various stress zones, it would be necessary to assign unit working stresses to material of each density class.

ECONOMIC ASPECTS OF LAMINATING

Yield of Material Suitable for Laminating

Of some 2,500 board feet of material which was sawn as 1¼ inch round edged lumber, approximately 60% (or 1,495 board feet) was found to be of a quality considered suitable for laminating according to the standards described on page 7. The defect limitations were chosen because of their extensive use in the production of high grade laminated timbers for marine use. In laminated products which are not subject to severe exposure or to maximum stresses, larger defects can undoubtedly be permitted with correspondingly higher yields than those indicated. Table 18 gives the yield of laminating material by standard lumber grades.

TABLE 18.

	Yields of Laminating Stock Expressed as a Percentage of:	
Lumber Grade	(1) Laminating Stock Recovered from All Grades	(2) Lumber Contained in the Grade
First and Seconds	36	89
Selects	21	78
No. 1 Common	27	50
No. 2 Common	13	47
No. 3A Common	2	31
No. 3B Common	1	9

In Column 1 the laminating material recovered from each lumber grade is indicated as a percentage of that recovered from all grades. In Column 2 the material suitable for laminating is indicated as a percentage of the total volume of the grade from which it was obtained. The bulk of the laminating material, 84 per cent, came from No. 1 Common and better grades. The highest yields are from the Firsts and Seconds. However, if advantage is to be taken of quality improvement through laminating, and if a greater proportion of the lumber produced from typical New England logs is to be utilized, it would appear advisable to use No. 2 Common or better. If the latter practice is followed, 97 per cent of the material suitable for laminating would be recovered (Table 18).

Yields of Solid Material of Structural Stress Grade Quality

Sketches of defects in each board were used to reconstruct the log by means of phantom drawings for determining the yield of solid structural material.

Each was analyzed for maximum yield of solid structural material on the basis of reduction into beams and stringers and into posts and timbers. The size limitations specified by the National Hardwood Lumber Association were observed. This meant that the minimum width of the beams and stringers was 5 inches; the minimum depth, 8 inches, and the minimum length, 6 feet. The minimum cross sectional dimension of posts and timbers was 4 inches and the minimum length 6 feet.

In general, the largest possible member of structural size was assumed for any given log. In a few cases, however, several smaller members were assumed when it was evident that the total yield in board feet could be thus increased. The length of the members was assumed to be the maximum length of suitable quality obtainable from the log.

The defect limitations permitted in each grade were those recommended by the National Hardwood Lumber Association, except that it was not possible to reconstruct the amount of seasoning defects which might have occurred had the log actually been sawn into structural members. The grade of the structural members was, therefore, established by omitting consideration of seasoning defects, the presence of which would tend to lower the grade or reduce the yield of structural material obtainable.

The total yield of solid material of structural grade from the 20 trees, subject to the limitations discussed, would have been 1,144 board feet. This is less than half of the total quantity of 1¼ inch lumber which was actually obtained. The breakdown by grades was as follows:

Beams and Stringers ranging from 5″ x 8″ x 10′ to 8″ x 10″ x 16′
National Hardwood Lumber Association (1948)

Grade	*Board Feet*
1900#	241
1700#	344
1450#	214
1300#	97

Posts and Timbers ranging from 5″ x 5″ x 12′ to 6″ x 6″ x 14′
National Hardwood Lumber Association (1948)

Grade	*Board Feet*
1325#	164
1200 #	54
1075#	30

Most of the material of structural grade was obtained from the first log. The second and third logs usually had defects sufficiently large to prevent the cutting of material of structural grade. The 25 second and third logs contributed only 309 board feet to the total yield of structural material.

Comparison of the Yields of Solid and Laminated Material

It is not possible to compare the reconstructed yield of solid material of structural grade (1,144 board feet) with the recovery from the same logs of material considered suitable for laminating (1,495 board feet) since there is some loss from scarfing and trimming during the laminating process.

To evaluate the fabrication losses of material, it was necessary to select some arbitrary standard size for comparison. It was decided to use the minimum cross sectional dimensions permitted in structural beams and stringers (5 inches by 8 inches) and a length of 16 feet, containing 53⅓ board feet.

Assuming the final planed thickness to be 1 inch, eight laminae would be required to produce the necessary depth. Since the gross width of these must be 5½ inches to permit edge trimming of the glued member, the trimming loss amounts to approximately 5.3 board feet.

An inspection of the lumber indicated that the distribution of lengths available was such that five scarf joints would be required to produce a timber 16 feet long. If a 1 in 10 scarf were used, 50 additional inches of board (1.9 board feet) would be needed.

Losses from trimming and scarfing would, consequently, amount to 7.2 board feet necessitating the use of approximately 13.5 per cent more material than is contained in the finished beam.

Of the 1,495 board feet of lumber considered suitable for laminating, a net of 86.5 per cent, or 1,290 board feet, would be available for laminating timbers of the type described above. This is 146 board feet more than the theoretical amount of structural grade lumber calculated from the phantom drawings.

The yield of solid structural timbers was probably somewhat optimistic because of failure to consider seasoning defects. Also, since higher stress values can be assigned to laminated material, the size of a beam or column for a given loading can be smaller than if a solid structural member is specified. In addition, solid members are limited to the length of a log whereas laminated members have no length limitation.

Fabrication Costs

The actual cost of laminating is subject to many factors which are beyond the scope of this bulletin but it is possible to give a brief outline of the operations involved in assembling timbers from rough sawn, seasoned lumber, one inch thick.

A representative sequence of operations is as follows:

1. All boards rough planed to uniform thickness.
2. Defects removed by cross-cutting and by ripping.
3. Edge gluing.
4. Fabrication and gluing of scarf joints.
5. Finish planing.
6. Glue spreading and assembly of laminae.
7. Clamping, curing and unclamping.
8. Trimming and finishing to size.

The approximate direct labor requirements of this sequence of operations may be summarized on the basis of 1,000 board feet of finished 5″ x 8″ x 16′ beams as follows:

Labor Requirements	*Man Hours*
Rough planing	3.3
Cross-cutting and ripping	5.2
Edge gluing	4.8
Fabrication and gluing of scarf joints	12.1
Finish planing	3.0
Laminating, glue spreading, assembly and curing	6.8
Trimming and finishing of glued member	3.5
Total	38.7

To the above time estimate must be added the cost of raw material, seasoning, glue cost, depreciation and overhead. Carter et al (3) indicate that the cost of producing 1,000 board feet of finished laminated product would be approximately $300.00. This value is subject to a great deal of fluctuation. It is apparent that laminating is advantageous primarily for timbers of large size or complex shapes or as long straight or curved timbers for bridges, arches and barn rafters. Laminated wood also finds extensive application in the manufacture of such articles as skis, tennis rackets, oars and other articles where special properties must be built into the finished product.

CONCLUSIONS[1]

1. The average specific gravity and average rate of growth of locally grown wood are very similar to the published averages for the species.
2. The correlation between specific gravity and number of rings per inch is very poor.

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[1] The conclusions below apply only to Connecticut grown red oak investigated under the conditions described in the accompanying text.

3. The strength and stiffness of laminated beams is not affected by arrangement of the growth rings relative to the load applied.
4. When composed throughout of material of the same specific gravity, laminated beams (with individual laminae more than ⅛ inch thick) and solid beams have essentially the same flexural properties.
5. The thickness of laminae, of itself, does not significantly affect the strength or stiffness of beams. However, beams composed entirely of laminae, which are ⅛ inch or less in thickness, are stronger and stiffer than beams laminated of thicker plies.
6. The thickness of the face lamina does not, of itself, affect the flexural properties of beams.
7. Laminated beams, composed of face and core laminae which differ in strength and stiffness, behave in effect like I beams. Calculated values for strength and stiffness of such beams compare quite closely with values obtained from actual tests.
8. The flexural properties of large laminated beams, when adjusted by the proper form factors, are similar to those of laminated standard size test beams.
9. The average crushing strength and stiffness of laminated short columns is somewhat lower than the published averages for the species. The reason for this is unknown.
10. Placement of laminae of different crushing strength and stiffness in the faces and core of a short column affect the crushing strength and stiffness of the entire column in direct proportion to the cross sectional area of the two kinds of material; the position of each (whether in face or core) has no apparent significance.
11. Calculated values for modulus of elasticity in compression parallel to the grain, derived according to the principle of "limiting lamina", are in good agreement with actual values. Values similarly calculated for maximum crushing strength show rather poor agreement with actual values.
12. There is no significant difference in shear strength parallel to the grain when laminated test blocks are loaded parallel and perpendicular to the glue line.
13. For inside use, the position of growth rings in adjacent laminae is of no significance; under outdoor exposure conditions a lamina which is predominantly flat grained should not be placed adjacent to one which is predominantly edge grained.

14. Working stresses for laminated members should be higher than for solid structural members of the same size and grade.

15. Approximately 60 per cent of the lumber from representative locally grown trees is suitable for laminating into high grade structural timbers. The laminating stock recovered in the form of a finished product is higher in quantity and of better quality than the structural grade material recovered from the same logs.

16. Locally grown red oak seems well adapted for laminating into high grade structural timbers of large size or of special shape which, in solid form, are either unobtainable or are available only at high cost.

LITERATURE CITED

1. AMERICAN SOCIETY FOR TESTING MATERIALS. Standard methods of testing small clear specimens of timber. A. S. T. M. Designation D-143-48. 1948.

2. .... Standard tests of timbers in structural sizes. A. S. T. M. Designation D-198-27. 1927.

3. CARTER, R. M., AND J. C. RETTIE. Highlights of wood laminating. Northeast. Wood Util. Council. Bul. **22.** 1948.

4. FOREST PRODUCTS LABORATORY. Wood aircraft inspection and fabrication. ANC 19. 1943.

5. .... Design of wood aircraft structures. ANC 18. 1944.

6. .... Wood: a manual for its use in wooden vessels. In cooperation with Research and Standards Branch, Bur. of Ships, Navy Dept. 1945.

7. .... Recommendations for basic stresses. Report No. R-1715. 1948.

8. HANRAHAN, F. J. Glued laminated lumber construction. Mech. Eng. **65:** 905-913. 1943.

9. KNAUSS, A. C., AND M. L. SELBO. Laminating of structural timber products by gluing. For. Prod. Lab. Report No. D 1635. 1947.

10. LAURSON, P. B., AND W. J. COX. Mechanics of materials. John Wiley and Sons. New York. 1947.

11. MARKWARDT, L. J. Form factors and methods of calculating the strength of wood in beams. For. Prod. Lab. Report No. R1184. 1938.

12. ...., AND T. R. C. WILSON. Strength and related properties of woods grown in the United States. U.S. Dept. of Agr. Tech. Bul. **479.** 1935.

13. MC KEAN, H. B. Mechanical properties and design procedure for glued laminated beams composed of two wood species. Univ. of Mich., School of Forestry and Conservation. Bul. **11.** 1944.

14. NATIONAL LUMBER MANUFACTURERS ASSOCIATION. National design specification for stress grade lumber and its fastenings. Revised 1948.

15. TRUAX, T. R., AND M. L. SELBO. Results of accelerated tests and long term exposure on glue joints of laminated beams. A. S. M. E. Wood Ind. Div. Paper. December, 1948.

16. WANGAARD, F. F. Summary of information on the durability of wood working glues. For. Prod. Lab. Report No. 1530. Revised. 1946.

17. .... The mechanical properties of wood. John Wiley & Sons. New York. 1950.

18. ...., AND N. V. POLETIKA. Lamination of Connecticut red oak. Northeast. Wood Util. Council. Bul. **22.** April, 1948.

19. WILSON, T. R. C. Guide to the grading of structural timbers and the determinations of working stresses. U. S. Dept. of Agr. Misc. Pub. No. **185.** 1934.

20. .... The glued laminated wooden arch. U. S. Dept. of Agr. Tech. Bul. **691.** 1939.

21. ...., AND W. S. COTTINGHAM. Tests of glued laminated wood beams and columns and development of principles of design. For. Prod. Lab. Report No. R1687. 1947.