REPORT No. 84

DATA ON THE DESIGN OF PLYWOOD FOR AIRCRAFT

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PURPOSE OF THE STUDY.

This report makes available data which will aid the designer in determining the plywood that is best adapted to various aircraft parts. It gives the results of investigations made by the Forest Products Laboratory of the United States Forest Service at Madison, Wis., for the Army and Navy Departments, and is one of a series of reports on the use of wood in aircraft prepared by the Forest Products Laboratory for publication by the National Advisory Committee for Aeronautics.

The object of the study was to determine, through comprehensive tests, the mechanical and physical properties of plywood and how these properties vary with the density, number, thickness, arrangement of the plies and direction of grain of the plies. While the data were sought primarily and immediately with a view to obtaining information needed by aircraft designers, the results have a broader field of application.

USE OF PLYWOOD IN AIRPLANES.

Plywood is being used extensively in airplanes for fuselage sides, bulkheads, engine bearers, wing rib webs, gusset and thrust plates, flooring, diaphragms, and at times for partially covering wings, in particular at the leading edges. In some machines stabilizer, elevator, and rudder surfaces are covered with thin plywood. Its use as a substitute for linen in covering wings has, however, not yet found favor, chiefly on account of the excess weight over linen.

From the standpoint of general engineering design the selection of veneer species and thickness introduces elements quite distinct from those involved in the design of an ordinary structural member of wood. More variables are involved, for in addition to the properties of the various species there are added unique properties due to number of plies and thickness and direction of the grain of the various plies. For the designer of aircraft certain further and special considerations enter into the problem. In the first place, strength with a minimum weight is required, while in the design of most stationary structural members weight is a minor consideration. Again, the forces acting on the different parts of an airplane are usually very complex, and both their magnitude and direction can in many cases only be approximated. The position and magnitude of the loads for which stationary structural members must be designed are, on the other hand, usually known with greater precision.

The complexity of the forces acting on airplane parts usually makes the designer's problem one of determining relatively superior constructions rather than of exact computation of required dimensions. Nevertheless, the actual size of some plywood parts of an airplane may be worked out with a reasonable degree of accuracy by using the strength data included in this bulletin. An example of comparatively exact design is afforded in the construction of large trussed wing ribs in which it is desired to know the dimensions of the tension members of wood. The table of tensile strength of veneer will serve for this purpose, although the details of fastening also require consideration.

DEFINITION OF PLYWOOD.

Much confusion has been caused by the indiscriminate use of the terms "veneer" and "plywood." The former term should be restricted to the relatively thin sheets of wood cut with special veneer machinery from the surface of a log revolving in a massive lathe or by slicing or sawing from the face of a log, known, respectively, as rotary, sliced, and sawed veneer. "Plywood," on the other hand, refers to the combination of several plies or sheets of veneer glued together, usually so that the grain of any one ply is at right angles to the grain of the adjacent ply or plies.

PROPERTIES OF ORDINARY WOOD COMPARED WITH PLYWOOD.

Wood, as is well known, is a nonhomogeneous material, with widely different properties in the various directions relative to the grain. This difference must be recognized in all wood construction, and the size and form of parts and placement of wood should be such as to utilize to the best advantage the difference in properties along and across the grain. It is the strength of the fibers in the direction of the grain that gives wood its relatively high modulus of rupture and tensile and compressive strength parallel to the grain. Were it a homogeneous material such as cast iron, having the same strength properties in all directions that it has parallel to the grain, it would be unexcelled for all structural parts where strength with small weight is desired. As it is, the tensile strength of wood may be 20 times as high parallel to the grain as perpendicular to the grain, and its modulus of elasticity from 15 to 20 times as high. In the case of shear the strength is reversed, the shearing strength perpendicular to the grain being much greater than parallel to the grain. The low parallel-to-the-grain shearing strength makes the utilization of the tensile strength of wood along the grain difficult, since failure will usually occur through shear at the fastening before the maximum tensile strength of the member is reached.

The large shrinkage of wood across the grain with changing moisture content may introduce distortions in a board that decrease its uses where a broad, flat surface is desired. The shrinkage from the green to the oven-dry condition across the grain for a flat-sawed board is about 8 per cent and for quarter-sawed board about 4½ per cent, while the shrinkage parallel to the grain is practically negligible for most species.

It is not always possible to proportion a solid plank so as to develop the necessary strength in every direction and at the same time utilize the full strength of the wood in all directions of the grain. In such cases it is the purpose of plywood to meet this deficiency by cross banding, which results in a redistribution of the material.

In building up plywood a step is made in obtaining equality of properties in two directions, parallel and perpendicular to the edge of a board. The greater the number of plies used for a given panel thickness, the more nearly homogeneous in properties is the finished panel. Thus, in an airplane engine mounting made of 15-ply veneer, the mechanical properties of the panel parallel and perpendicular to the grain of the faces are almost the same. Broadly speaking, what is gained in one direction is lost in the other. For a very large number of plies we may assume that the tensile strength in the two directions is the same and that it is equal to the average of the parallel-to-the-grain and perpendicular-to-the-grain values of an ordinary board. This is not always exactly true, since the maximum stress of the plies in both directions may not be reached at the same time. Internal stresses due to change of moisture content may also tend to unbalance the strength ratio.

SCOPE AND METHOD OF TESTS.

The results and conclusions which follow are based on tests of about 34 species. In general, 8 thicknesses of plywood were tested, as follows: 3/30, 3/24, 3/20, 3/16, 3/12, 3/10, 3/8, and 3/6 inch.

Most of the tests were on panels composed of three plies of equal thickness of the same species, with the grain of successive plies at right angles. In addition tests were made on plywood of various numbers of plies; having various ratios between the core and the total panel thickness; having the plies glued at angles other than 90° with each other; and on plywood in which the core and the faces were not of the same species.

Bending tests.—As a rule bending tests were made on specimens measuring 5 by 12 inches, although some of the thinner specimens were cut to a length of 6 inches. In half of the tests the grain of the faces was parallel to the direction of application of the load, and in half perpendicular.

Figure 1 shows the method of conducting the column-bending test. The ends of the test piece were rounded to approximately a semicircle. Deflections were measured at the center of the specimen as shown in the photograph. The product of the load and the corresponding deflection was recorded as the bending moment. For some of the thicker specimens it was not satisfactory to test in column bending on account of separation of the plies. These specimens were tested as a beam in ordinary cross bending.

The formula for computing the column-bending modulus is given at end of report. The results of the tests are included in Table 1.

In most cases in column bending the direct compressive stress at the maximum moment is only a small fraction of the bending or flexural stress, so that the column-bending modulus may be used with little error in all computations in a capacity similar to the bending strength or modulus of rupture of plain timber tested in cross bending. Like the modulus of rupture, it is not an actual stress but a measure of the strength in bending.

Tension tests.—Tests were made to determine the tensile strength of plywood both parallel and perpendicular to the grain of the faces. Specimens 3 by 12 inches in size were used, the center portion being trimmed down to approximately an inch wide. They were held by ordinary flat grips, and tested in direct tension to rupture.

Plywood tension members, while not very common, are in use and the data may be applied in computations. The tensile strength is the average stress over the section at failure.

The results of the tensile tests are included in Table 1 and 4.

Splitting test.—For splitting tests square pieces 3¼ by 3¼ inches were used. Upon the center of the test piece a conical spear (shown in fig. 2) was first dropped from a height of one-half inch. The spear was 8 inches long and 2 inches in diameter at the upper end and with the rod weighed 11.22 pounds. Carrying the test piece upon its point it was then dropped from increasing heights with an increment of one-half inch until failure due to splitting occurred. The resistance of the material to splitting is represented by its "splitting energy;" the formula for its computation is given near end of report.

The splitting energy is a measure of resistance to splitting at the screw or bolt fastenings of veneer panels. It is merely a factor for comparing different panels, and as a numerical quantity can not be used in design.

A comparison of the relative resistance to splitting of various three-ply panels will be found in Table 1.

Warping tests.—Warping may consist of cupping or twisting, or a combination of these two actions. Pieces of plywood 12 inches square were used for warping tests.

To determine cupping, a straightedge was placed over a median line drawn on the specimen perpendicular to the grain of the faces (see fig. 3), and the recession of the point deflected farthest from the straightedge was measured. This recession was recorded as the cupping of the panel.

To determine twisting, the panel was placed upon a flat surface so that three corners were resting upon the surface. The distance from the surface to the fourth corner was measured as shown in figure 4 and recorded as the "twist in 12 inches."

Information of the kind obtained in this test is of value in selecting a panel for structural parts where flat, undistorted surfaces are important. The results indicate roughly the comparative resistance to external conditions that tend to warp or distort a panel. The smaller the cupping and twisting under test, the more desirable the panel for flat work.

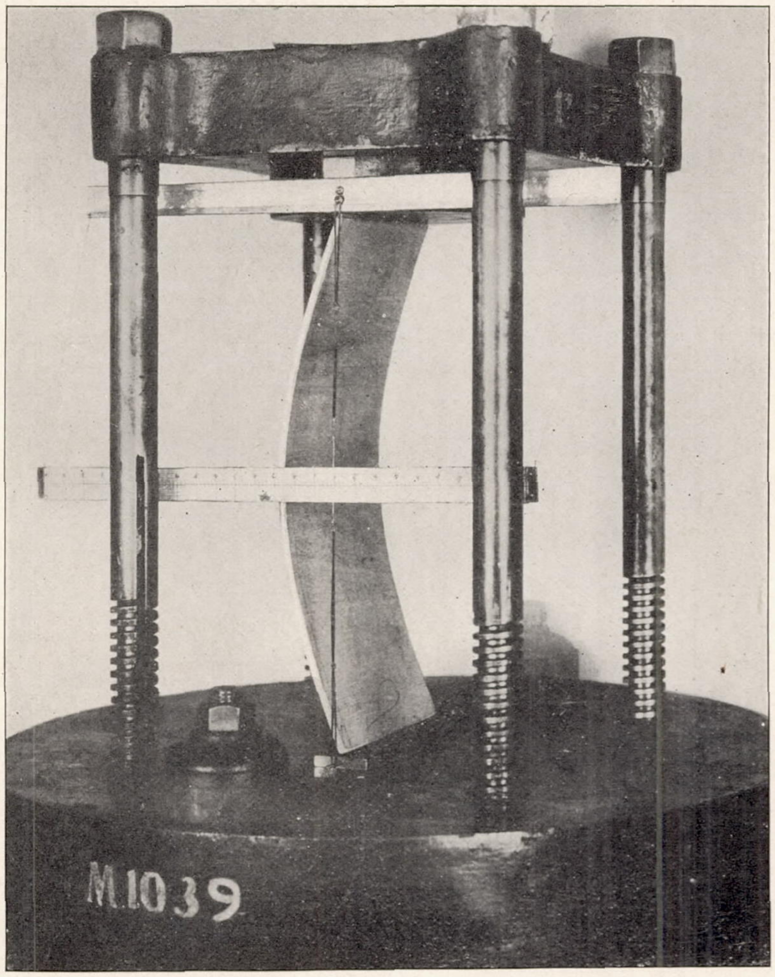

FIG. 1.—COLUMN-BENDING TEST.

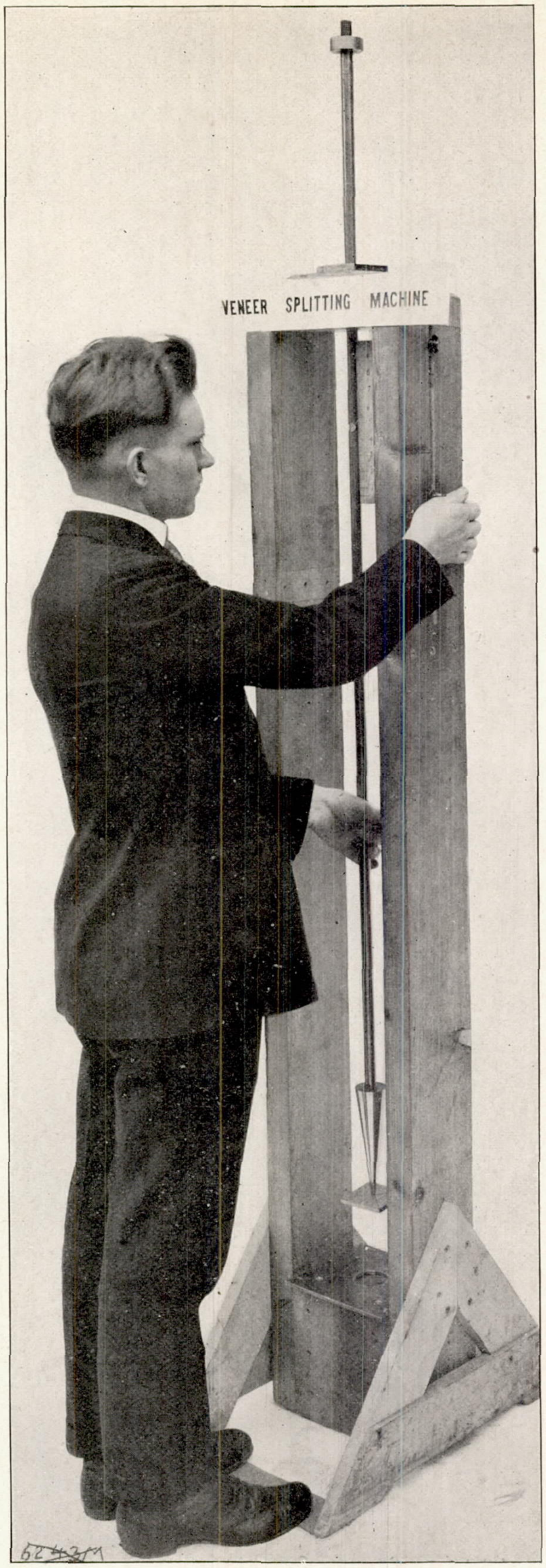

FIG. 2.—SPLITTING TEST.

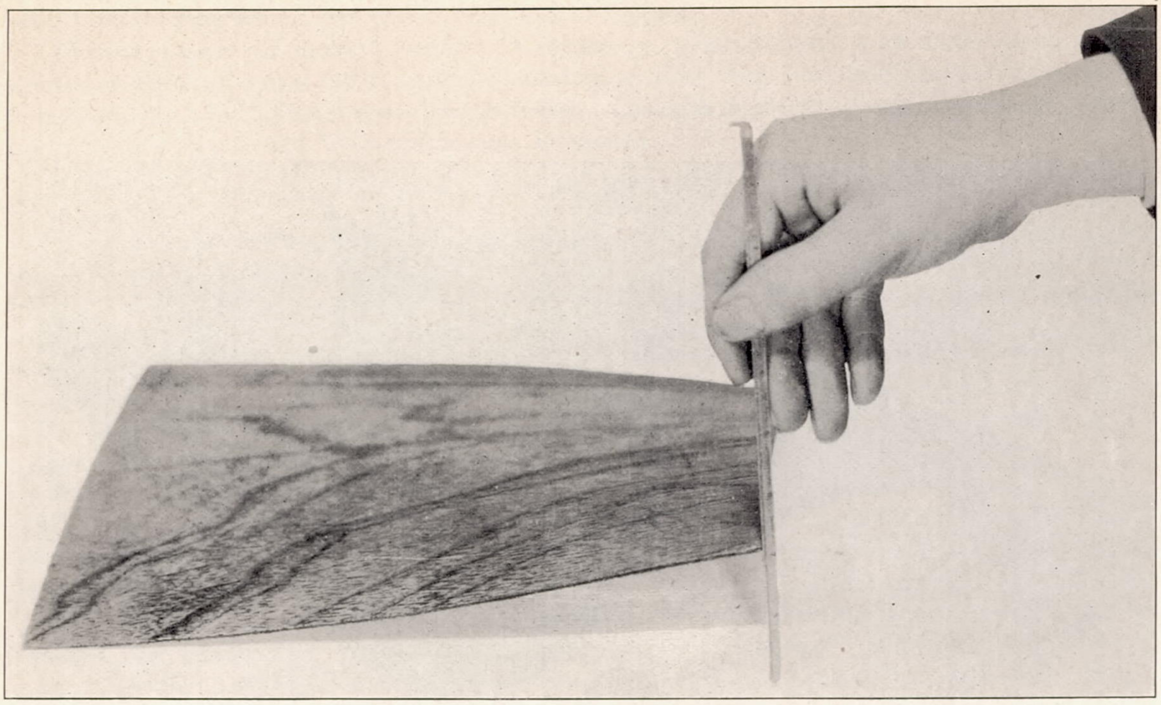

FIG. 3.—METHOD OF MEASURING CUPPING.

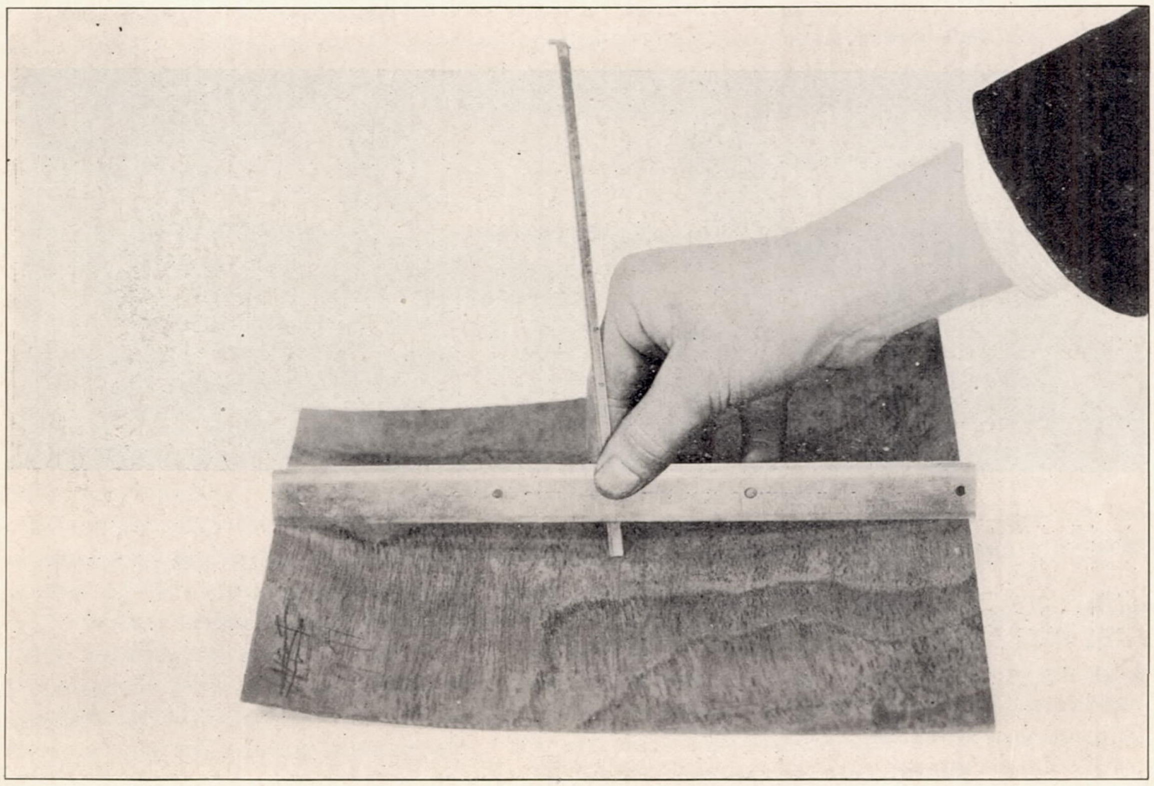

FIG. 4.—METHOD OF MEASURING TWISTING.

Thickness factor K_w.—This factor serves to obtain the thickness of a ply of any species equal in weight to a ply of yellow birch of unit thickness. It is obtained by dividing the density[1] of birch by the density of the species for which the thickness is desired. For yellow poplar, for example, the thickness of a ply equal in weight to a 1/16-inch ply of birch is $1.54 \times 1/16 = 0.096$ inches.

Uses and properties of various species.—On the basis of their mechanical properties, the veneer species commonly used for the face stock of plywood for airplanes may be grouped as follows:

Group 1.—Beech, birch (sweet or yellow), hard maple, black walnut.

Group 2.—White elm,[2] red gum, soft maple, mahogany (African or true), sycamore.

Group 3.—Basswood, Spanish cedar, fir (grand, noble, or silver), cotton gum, western hemlock, sugar pine, white pine, yellow poplar, redwood, spruce (red, white, or Sitka).

Where a flat panel, high bending strength, or high column strength with minimum weight are desired, species of group 3 should be used as face stock. Some of these species, such as spruce, can not be finished properly without a considerable amount of sanding, and all but light sanding is undesirable because it may unbalance the construction. In fuselage bulkheads or other hidden parts where finish is secondary, any of the species of group 3 should be satisfactory for face veneer as well as for core stock.

Hardness, resistance to abrasion, and strength of fastening increase considerably with increasing density of wood, so that where any one or all of these factors are of importance the heavier woods beginning with group 1 should be used.

Where finish is desired species of group 1 or group 2 should be used.

Where the plywood must be steamed, or soaked and bent into a form in which it is to remain, species of group 1 or group 2 should be used.

Where failure of an airplane part is likely to occur from buckling, as in plywood fuselages in which the shell carries considerable stress, it is recommended that the plywood be made entirely of low-density species, such as those in group 3. Numerous tests on plywood columns have shown that three-ply columns of low-density species, such as are included in group 3, carry from 2 to 2.5 times the load of three-ply columns of the same weight of species included in group 1. Buckling is a form of column failure, and for that reason greater resistance to buckling per unit weight would be expected from the use of low-density veneer.

SIZE, WEIGHT, AND THICKNESS OF COMMERCIAL VENEER.

The average length of sawed veneer sheets is about 14 feet, and the maximum 24 feet; the average length of sliced veneer is about 10 feet, and the maximum 18 feet; rotary-cut veneer averages about 6 feet, with a maximum of 16 feet. Sawed veneer is seldom cut less than 1/28 inch thick. Sliced veneer of some species may be cut as thin as 1/100 inch, but is seldom cut thicker than 1/16 inch. Rotary-cut veneer of some species may be cut from 1/100 inch to almost 1/2 inch in thickness. Sawed and sliced veneer sheets are limited in width by the diameter of the log, whereas rotary cut veneer may be any width consistent with easy handling.

Except for the 1/100 inch veneer, all the thicknesses listed in Table 3 are commercial. Table 3 may be used in computing the weight of veneer sheets of any size and thickness, and of plywood made of any combination of the species listed. A sample computation is given near end of report.

JOINTS IN PLYWOOD PANELS.

There are three types of joints commonly used for joining plywood panels: (*a*) Riveted joints, (*b*) glued joints in individual plies, and (*c*) glued joints extending through the entire thickness of plywood. These will be considered in detail.

Riveted joints.—The most satisfactory joints of the riveted type are made with tubular rivets. Tension tests have shown quite conclusively that it is very difficult to obtain more than

[1] The density data for the domestic species used in computing K_w are those given in United States Department of Agriculture Bulletin 556, "Mechanical Properties of Woods Grown in the United States," and do not include the weight of the glue.

[2] White elm should not be used where a high finish is desired. However, it has exceptional bending qualities.

50 per cent efficiency with a single row of rivets. Efficiencies somewhat higher than 50 per cent may probably be obtained if two or more rows of rivets are used. In such cases the rivets should be staggered. The size of the rivet seems to have little effect upon the strength of the joint, providing the proper spacing is used. The distance between centers of rivets should be about equal to twice the outside diameter of the rivets. It is obvious that for such spacing very many rivets are required, and that the labor in making the joint is very great.

Joints in individual plies.—Two pieces of plywood may be fastened together by means of glued joints in individual plies. Joints in individual plies take a variety of forms. (See fig. 7.) Strength, ease of manufacture, and efficiency considered, the simple scarf joint appears to be the most desirable of the group. The simple butt joint should not be used where strength is important. The edge joint is satisfactory if carefully made. The slope of the scarf in the simple scarf joint should be within the range of from 1 in 20 to 1 in 30.

The use of joints in individual plies has an advantage over the other types, in that the joints in the plies may be staggered, so that a single defective joint only partially weakens the entire panel. The preparation of a joint of this type requires less time and labor than a riveted joint, but more than a scarf joint extending through the entire thickness of the panel.

Joints extending through the entire thickness of plywood.—Two types of scarf joints extending through the entire plywood thickness are shown in figure 8. These are known as the straight scarf joint and the Albatross scarf joint. It will be seen that in the Albatross joint the face ply of the one panel does not meet the face ply of the second panel, or only partially meets it.

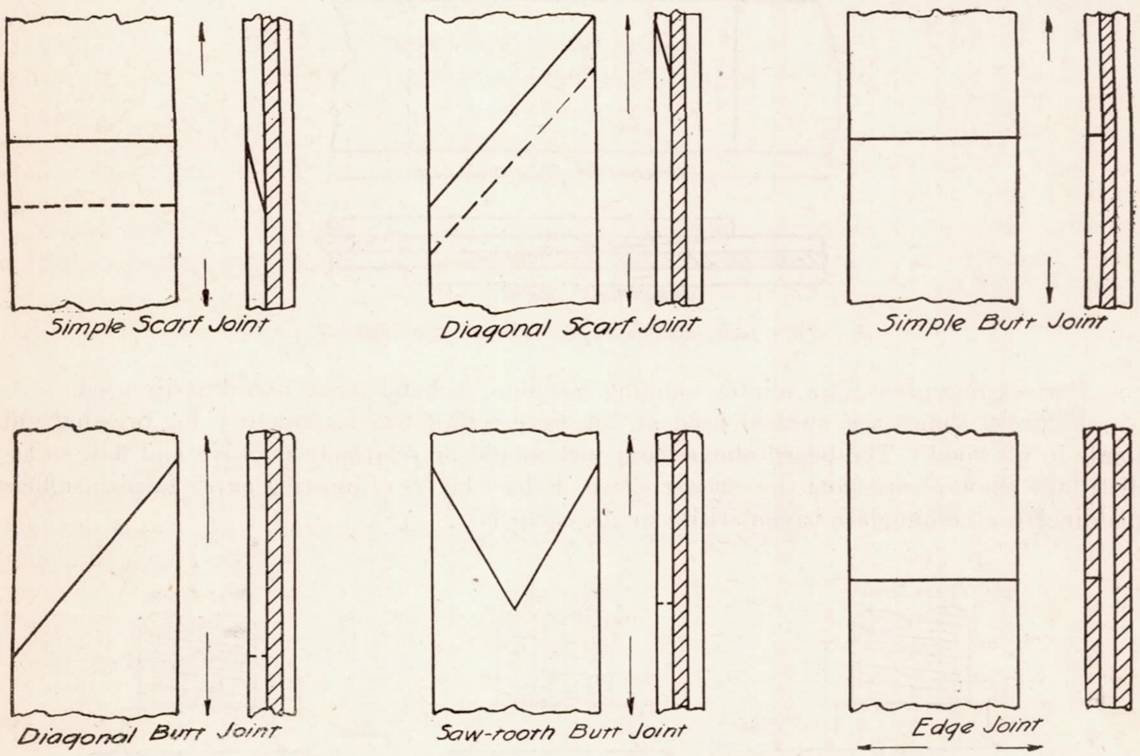

FIG. 7. Joints in the face veneer of 3-ply panels. Arrows indicate direction of face grain.

In place of being glued to wood that has the grain running in the same direction, the face ply of one panel is glued to the core of the other panel, the grain of the core being at right angles to the grain in the face. Joints in which the grain of the two pieces joined is at right angles are not so strong as joints in which the direction of grain in the two pieces is the same.

Tests indicate quite conclusively that in tension the straight scarf joint is superior. An efficiency of over 90 per cent may be obtained with this type of joint for a slope of scarf as low as 1 in 10. On account of the variations in the effectiveness of the gluing by different manufacturers it is recommended that a slope of scarf greater than this be used. A slope between 1 in 20 and 1 in 30 is recommended.

Severe weakening of scarf joints is often caused by sanding the face plies at the joint Observations on joints thus sanded showed that in some cases more than half of the face ply was ground away. Inasmuch as the strength of a three-ply panel when bent parallel to the direction of the grain of the faces lies almost entirely in the face plies, it is obvious that a reduction in the thickness of the face plies will materially affect the strength of a panel. Consequently, it is recommended that the scarf joint be lightly sanded by hand if at all, so as not to decrease the thickness of the face veneer.

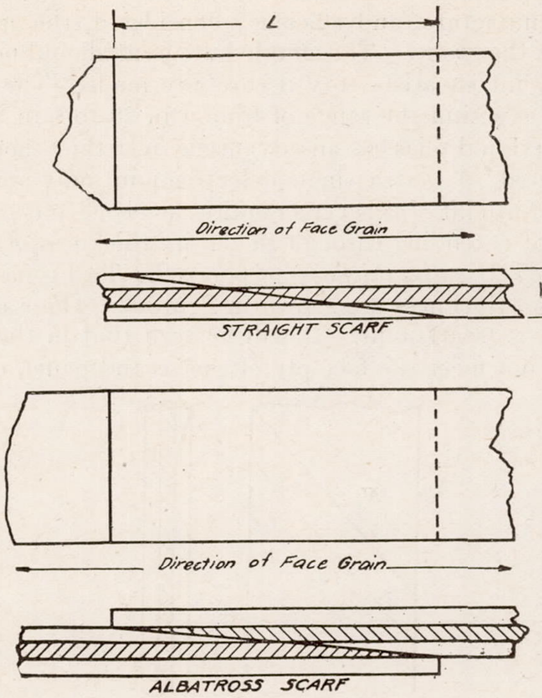

FIG. 8. Joints extending through the panel. Slope of scarf$=\frac{L}{T}$.

For scarfing plywood a jointer, sanding machine, or hand plane is ordinarily used.

Figure 9 shows the method used at the Forest Products Laboratory for pressing glued joints in plywood. The board above the panel should be relatively massive and flat, so as to distribute the pressure from the screws. Two or three layers of blotting paper furnish sufficient padding to accommodate irregularities in the surface.

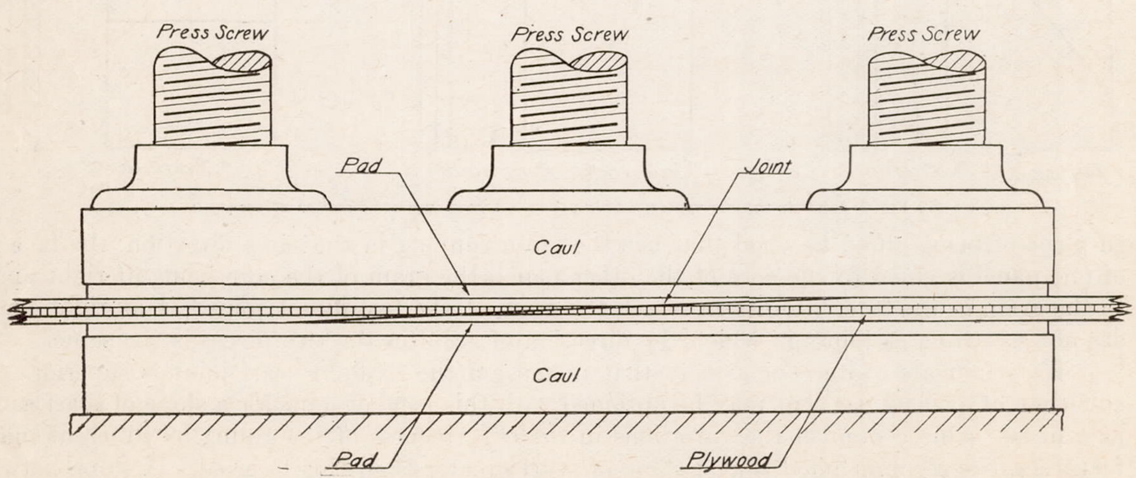

FIG. 9. Method of pressing glued joint.

FORMULAS USED IN COMPUTATION OF STRENGTH DATA.

Column-bending modulus.—The term "column-bending modulus" applies to the stress obtained by adding the direct compression stress at the maximum moment to the flexural stress at the maximum moment. The following formula applies:

$$S=\frac{P}{A}+\frac{6M}{bd^2} \text{ where}$$

S = Column-bending modulus.
A = Area of cross section of test piece.
P = Load at maximum moment.
M = Maximum bending moment.
b = Width of test piece.
d = Thickness of test piece.

Modulus of rupture.—The modulus of rupture is the computed stress in the outermost fibers of the plywood, when tested in crossbending as a simple beam. The following formula applies for center loading:

$$MR=\frac{1.5P\times L}{bd^2} \text{ where}$$

MR = Modulus of rupture.
P = Maximum load at center.
L = Span of test piece.
b = Width of test piece.
d = Thickness of test piece.

Tensile strength.—The term "tensile strength" applies to the stress obtained by dividing the load at rupture by the minimum cross-section area of the specimen.

$$S=\frac{P}{A} \text{ where}$$

S = Tensile strength.
P = Maximum load in tension.
A = Total cross-sectional area at minimum section.

Modulus of elasticity.—The moduli of elasticity of all column-bending and cross-bending specimens were computed by substitution in the following formulas:

For column bending,

$$E=\frac{PL^2}{\pi^2 I}$$

For cross bending (center loading),

$$E=\frac{P^1L^3}{48fI} \text{ where}$$

E = Modulus of elasticity of the plywood.
P = Maximum load sustained in column bending.
P^1 = Any load within the elastic limit of the plywood.
L = Length of the plywood column or the length of the span in cross bending.
I = Moment of inertia of the cross section of the specimen.
f = Deflection corresponding to P^1.

Splitting energy.—The total work done or the splitting energy W was computed by adding together the distances through which the spear fell, h_1, h_2, etc., and multiplying by the weight (11.2 pounds) of spear and rod.

$$M=11.2\ (h_1+h_2+h_3+\cdots)$$

EXPLANATION OF TABLE 1.

The data of this table may be used to compute the thickness of three-ply wood members of various species when the forces acting on these members are known. The strength in bending is given by the column-bending modulus, which may be used in computations in a capacity similar to the modulus of rupture of ordinary wood. The direction in which the external forces act on the member relative to the direction of the face grain of the plywood must be taken into consideration in using the data. The strength values correspond to the moisture contents listed.

TABLE 1.—*Strength of various species of three-ply panels.*

All plies in any one panel were of the same thickness and of the same species—grain of successive plies at right angles. In most cases eight thicknesses of plywood, ranging from 3/30 inch to 3/6 inch were tested.

Species.	Average specific gravity of plywood based on oven-dry weight and volume at test.	Average moisture (per cent).	Column bending.						Tensile strength.				Splitting resistance.	
			Column-bending modulus.				Modulus of elasticity.							
			Parallel.[1]		Perpendicular.[1]		Parallel.[1]	Perpendicular.[1]	Parallel.[1]		Perpendicular.[1]			
			No. of tests.	Lbs. per sq. in.	No. of tests.	Lbs. per sq. in.	1,000 lbs. per sq. in.	1,000 lbs. per sq. in.	No. of tests.	Lbs. per sq. in.	No. of tests.	Lbs. per sq. in.	No. of tests.	Per cent of birch.[2]
Ash, black	0.49	9.1	120	7,760	120	1,770	1,070	96	120	6,180	120	3,940	240	3
Ash, commercial white	.60	10.2	200	9,930	200	2,620	1,420	143	200	6,510	200	4,350	400	71
Basswood	.42	9.2	200	7,120	200	1,670	1,210	85	200	6,880	200	4,300	400	63
Beech	.67	8.6	120	15,390	120	2,950	2,150	167	120	13,000	120	7,290	240	94
Birch, yellow	.67	8.5	195	16,000	200	3,200	2,260	197	200	13,210	200	7,700	400	100
Cedar, Spanish	.41	13.3	115	6,460	115	1,480	1,030	84	115	5,200	115	3,340	230	60
Cherry[3]	.56	9.1	115	12,260	115	2,620	1,630	152	115	8,460	115	5,920	230	80
Chestnut	.43	11.7	40	5,160	40	1,110	740	75	40	4,430	40	2,600	80	74
Cottonwood[4]	.46	8.8	120	8,460	120	1,870	1,440	109	120	7,280	120	4,240	240	85
Cypress, bald	.45	8.0	113	8,890	113	1,850	1,220	95	113	6,160	113	3,980	148	49
Douglas fir[5]	.48	8.6	176	9,340	200	1,940	1,530	126	200	6,188	200	3,910	374	63
Elm, cork	.62	9.4	65	12,710	65	2,500	1,980	136	65	8,440	65	5,500	130	99
Elm, white	.52	8.9	160	8,680	160	1,970	1,220	109	160	5,860	160	3,990	320	75
Fir, true[6]	.40	8.5	24	9,200	24	1,811	1,580	100	24	5,670	24	3,770	48	60
Gum[7]	.54	10.6	40	8,090	40	1,920	1,280	113	35	6,960	35	4,320	70	55
Gum, cotton	.50	10.3	80	7,760	80	1,580	1,300	111	80	6,260	80	3,760	160	60
Gum, red	.54	8.7	182	9,970	182	2,070	1,590	120	182	7,850	182	4,930	364	80
Hackberry	.54	10.2	80	8,100	80	1,880	1,150	99	80	6,920	80	4,020	160	84
Hemlock, western	.47	9.7	119	9,250	119	1,960	1,580	112	119	6,800	119	4,580	238	63
Magnolia[8]	.58	8.8	80	10,830	80	2,600	1,700	138	80	9,220	80	5,730	120	85
Mahogany, African[9]	.52	12.7	20	8,070	20	2,000	1,260	144	20	5,370	20	3,770	....	....
Mahogany, Philippine[10]	.53	10.7	25	10,160	25	2,310	1,820	169	25	10,670	25	5,990	50	90
Mahogany, true	.48	11.4	35	8,500	35	1,940	1,250	117	35	6,390	35	3,780	....	....
Maple, soft[11]	.57	8.9	120	11,540	120	2,420	1,750	145	120	8,180	120	5,380	240	106
Maple, hard[12]	.68	8.0	202	15,600	202	3,340	2,110	189	192	10,190	202	6,530	404	114
Oak, commercial red	.59	9.3	115	8,500	115	2,070	1,290	120	115	5,480	115	3,610	230	70
Oak, commercial white	.64	9.5	195	10,490	195	2,310	1,340	118	195	6,730	195	4,200	390	85
Pine, sugar	.42	9.4	65	8,050	70	1,670	1,310	90	70	5,430	70	3,690	140	47
Pine, white	.42	5.4	40	10,130	40	2,050	1,570	111	40	5,720	40	3,340	80	31
Poplar, yellow	.50	9.4	165	8,860	165	1,920	1,540	115	155	7,390	165	4,720	330	51
Redwood	.42	9.7	105	8,230	105	1,550	1,180	108	105	4,770	105	2,960	210	48
Spruce, Sitka	.42	8.3	121	7,710	121	1,690	1,370	105	121	5,650	121	3,410	224	78
Sycamore	.56	9.2	163	11,040	163	2,340	1,630	130	163	8,030	163	5,220	326	77
Walnut, black	.59	9.1	110	12,660	110	2,770	1,740	141	110	8,250	110	5,260	220	77
Yucca species	.49	7.3	33	2,960	33	900	560	44	33	2,210	33	1,700	66	14

[1] Parallel and perpendicular refer to the direction of the grain of the faces relative to the direction of the application of the force.
[2] The relative splitting resistance of the various panels tested depends largely on the holding strength of glue.
[3] Probably black cherry.
[4] Probably (common) cottonwood.
[5] Coast type.
[6] Probably white fir.
[7] Probably black gum.
[8] Probably (evergreen) magnolia.
[9] Probably Khaya sp.
[10] Probably tanguile.
[11] Probably silver maple.
[12] Sugar or black maple.

NOTE.—In some of the species listed above the tests are rather limited in number. Since there is considerable variation in the strength of wood, further tests on additional material would be expected to modify the values appreciably in some cases.

Explanation of Table 2.

When substituting one species for another in airplane plywood it is desirable to know the thickness of veneer which will give either the same bending strength or the same weight as the original material. The thickness factors K_s and K_w given in Table 2 will be found useful for this purpose. For instance, the thickness of basswood veneer required to afford approximately the same bending strength as one-tenth inch yellow poplar, may be obtained by multiplying the thickness of the yellow poplar by the ratio of the thickness factor (K_s) of basswood to that of yellow poplar. The factor K_w may be used in a similar computation to obtain the thickness of one species required to equal the weight of another.

Table 2.—*Thickness factors for veneer.*

Giving: (1) Veneer thickness for the same total bending strength as birch (K_s); (2) Veneer thickness for the same weight as birch (K_w).

Species.	D Average specific gravity of species [11] based on oven-dry weight and air-dry volume.	Specific gravity of glued plywood as tested based on oven-dry weight and volume at test.	Moisture content of plywood as tested.	S Unit bending strength compared with birch.[1]	K_s Thickness factor for the same total bending strength as birch. $\sqrt{\frac{100}{S}}$	K_w Thickness factor for the same weight as birch. $\frac{.63}{D}$
			Per cent.	*Per cent.*		
Ash, black	0.50	0.49	9.1	52	1.39	1.26
Ash, commercial white	.58	.60	10.2	72	1.18	1.09
Basswood	.38	.42	9.2	48	1.44	1.66
Beech	.63	.67	8.6	94	1.03	1.00
Birch, yellow	.63	.67	8.5	100	1.00	1.00
Cedar, Spanish	.34	.41	13.3	43	1.52	1.85
Cherry [2]	.51	.56	9.1	80	1.12	1.24
Chestnut	.44	.43	11.7	34	1.72	1.43
Cottonwood	.43	.46	8.8	56	1.34	1.47
Cypress, bald	.44	.45	8.0	57	1.32	1.43
Douglas fir [3]	.51	.48	8.6	60	1.29	1.24
Elm, cork	.66	.62	9.4	78	1.13	.95
Elm, white	.51	.52	8.9	58	1.31	1.24
Fir, true [4]	.38	.40	8.5	57	1.32	1.66
Gum [5]	.52	.54	10.6	55	1.35	1.21
Gum, cotton	.52	.50	10.3	49	1.43	1.21
Gum, red	.49	.54	8.7	64	1.25	1.29
Hackberry	.54	.54	10.2	55	1.35	1.17
Hemlock, western	.42	.47	9.7	60	1.29	1.50
Magnolia [6]	.51	.58	8.8	74	1.16	1.24
Mahogany, African [7]	.46	.52	12.7	56	1.34	1.37
Mahogany, Philippine [8]	.57	.53	10.7	68	1.21	1.10
Mahogany, true	.49	.48	11.4	57	1.32	1.29
Maple, soft [9]	.48	.57	8.9	74	1.16	1.31
Maple, hard [10]	.62	.68	8.0	100	1.00	1.02
Oak, commercial red	.63	.59	9.3	59	1.30	1.00
Oak, commercial white	.69	.64	9.5	69	1.20	.91
Pine, sugar	.37	.42	9.4	51	1.40	1.70
Pine, white	.39	.42	5.4	64	1.25	1.61
Poplar, yellow	.41	.50	9.4	58	1.31	1.54
Redwood	[12] .36	.42	9.7	50	1.41	1.75
Sycamore	.50	.56	9.2	71	1.19	1.26
Spruce, Sitka	.38	.42	8.3	50	1.41	1.66
Walnut, black	.57	.59	9.1	83	1.10	1.10
Yucca species	....	.49	7.3	23	2.09	....

[1] Average of the column bending moduli parallel and perpendicular to grain compared to birch, based on tests of 3-ply wood, each ply one-third of the total panel thickness.
[2] Probably black cherry.
[3] Coast type.
[4] Probably white fir.
[5] Probably black gum.
[6] Probably (evergreen) magnolia.
[7] Probably Khaya species.
[8] Probably tanguile.
[9] Probably silver maple.
[10] Probably sugar or black maple.
[11] Values of domestic species taken from U. S. Department of Agriculture Bulletin 556, Mechanical Properties of Woods Grown in the United States.
[12] Based on tests not included in Bulletin 556.

Explanation of Table 3.

This table gives the approximate weight of individual sheets of veneer in ounces per square foot, making possible the computation of the weight of plywood built up of any combination of thicknesses and veneer species listed and of any number of plies. The approximate weights of two common water-resistant plywood glues in ounces per square foot of glued surface are also given.

It should be remembered that the weight of wood is quite variable, and that large differences from the figures are to be expected, particularly with small quantities of material.

Example: To get the weight of a square foot of 5-ply wood consisting of 1-ply of 1/12-inch basswood, 2 plies of 1/16-inch basswood, and 2 plies of 1/20-inch yellow birch for faces, at 12 per cent moisture, glued with casein glue.

$$\text{Weight} = [(1\times 2.64)+(2\times 1.98)+(2\times 2.62)]\ 1.12+(4\times 0.4)=14.9 \text{ ounces.}$$

The example above is slightly in error through neglecting the change in volume between the moisture content at 12 per cent and the moisture listed in the table.

TABLE 3.—*Oven dry weights of veneer of veneer of various species and thicknesses.*

[In ounces per square foot of 1-ply; veneer thickness in inches.]

Species.	Specific gravity based on oven-dry weight and air-dry volume.	Air-dry moisture content (per cent).	1/100	1/80	1/64	1/60	1/55	1/48	1/40	1/32	1/28	1/24	1/20	1/16	1/12	1/10	1/8	1/6	3/16	1/4
Ash, black	0.50	10.4	0.42	0.52	0.65	0.69	0.76	0.87	1.04	1.30	1.49	1.74	2.08	2.60	3.47	4.16	5.20	6.94	7.81	10.41
Ash, commercial white	.58	8.9	.48	.60	.75	.80	.88	1.00	1.21	1.51	1.72	2.01	2.41	3.02	4.02	4.82	6.04	8.05	9.05	12.06
Basswood	.38	8.4	.32	.40	.49	.53	.58	.66	.79	.99	1.13	1.32	1.58	1.98	2.64	3.16	3.96	5.28	5.94	7.92
Beech	.63	11.2	.52	.66	.82	.87	.95	1.09	1.31	1.64	1.87	2.19	2.62	3.28	4.37	5.24	6.56	8.74	9.84	13.12
Birch, yellow	.63	9.6	.52	.66	.82	.87	.95	1.09	1.31	1.64	1.87	2.19	2.62	3.28	4.37	5.24	6.56	8.74	9.84	13.12
Butternut	.39	7.6	.32	.41	.51	.54	.59	.68	.81	1.02	1.16	1.35	1.62	2.03	2.71	3.25	4.06	5.42	6.09	8.12
Cedar, Spanish	.37	7.3	.31	.38	.48	.51	.56	.64	.77	.96	1.10	1.28	1.54	1.92	2.56	3.08	3.85	5.13	5.77	7.70
Cherry, black	.51	9.2	.42	.53	.66	.71	.77	.88	1.06	1.33	1.52	1.77	2.12	2.65	3.54	4.25	5.31	7.08	7.97	10.62
Chestnut	.44	8.6	.37	.46	.57	.61	.67	.76	.92	1.14	1.31	1.52	1.83	2.29	3.05	3.67	4.58	6.10	6.87	9.16
Cottonwood (common)	.43	4.7	.36	.45	.56	.60	.65	.75	.90	1.12	1.28	1.49	1.79	2.24	2.98	3.58	4.47	5.97	6.71	8.96
Cypress bald	.44	9.0	.37	.46	.57	.61	.67	.76	.92	1.14	1.31	1.52	1.83	2.29	3.05	3.67	4.58	6.10	6.86	9.16
Douglas fir (Washington and Oregon)	.51	6.2	.42	.53	.66	.71	.77	.88	1.06	1.33	1.51	1.77	2.12	2.65	3.53	4.24	5.30	7.08	7.96	10.6
Douglas fir (Montana and Wyoming)	.44	9.4	.37	.46	.57	.61	.67	.76	.92	1.15	1.31	1.53	1.83	2.29	3.05	3.66	4.58	6.10	6.87	9.16
Elm, white	.51	8.8	.42	.53	.66	.71	.77	.88	1.06	1.33	1.52	1.77	2.12	2.65	3.54	4.25	5.31	7.08	7.97	10.62
Gum, black	.52	7.2	.43	.54	.68	.72	.79	.90	1.08	1.35	1.55	1.80	2.17	2.71	3.61	4.33	5.42	7.32	8.12	10.82
Gum, cotton	.52	6.1	.43	.54	.68	.72	.79	.90	1.08	1.35	1.55	1.80	2.17	2.71	3.61	4.33	5.42	7.32	8.12	10.82
Gum, red	.49	11.3	.41	.51	.64	.68	.74	.85	1.02	1.28	1.46	1.70	2.04	2.55	3.40	4.08	5.10	6.80	7.66	10.20
Hackberry	.54	9.2	.45	.56	.70	.75	.82	.94	1.12	1.40	1.61	1.87	2.25	2.81	3.75	4.49	5.63	7.50	8.44	11.24
Hemlock, western	.42	8.6	.35	.44	.55	.58	.64	.73	.87	1.09	1.25	1.46	1.75	2.18	2.91	3.50	4.37	5.83	6.56	8.74
Magnolia (evergreen)	.51	8.8	.42	.53	.66	.71	.77	.88	1.06	1.33	1.51	1.77	2.12	2.65	3.53	4.24	5.30	7.08	7.96	10.6
Mahogany, Central American	.49	7.9	.41	.51	.65	.68	.75	.85	1.02	1.28	1.46	1.70	2.04	2.55	3.50	4.08	5.10	6.80	7.66	10.20
Mahogany, African	.46	8.0	.38	.48	.60	.64	.70	.80	.96	1.19	1.37	1.59	1.91	2.39	3.19	3.83	4.78	6.38	7.17	9.57
Maple, silver	.48	8.2	.40	.50	.62	.67	.73	.83	1.00	1.25	1.43	1.67	2.00	2.50	3.33	4.00	5.00	6.66	7.50	7.00
Maple, sugar	.62	10.5	.52	.65	.81	.86	.94	1.08	1.29	1.61	1.85	2.15	2.58	3.23	4.30	5.16	6.46	8.60	9.69	12.91
Oak, commerical red	.64	10.7	.53	.67	.83	.89	.97	1.11	1.33	1.66	1.90	2.22	2.66	3.33	4.44	5.32	6.66	8.88	9.99	13.3
Oak, commerical white	.68	11.0	.57	.71	.88	.94	1.03	1.18	1.41	1.77	2.02	2.36	2.83	3.54	4.72	5.66	7.08	9.43	10.61	14.1
Pine, longleaf	.66	9.2	.55	.69	.86	.92	1.00	1.15	1.37	1.72	1.96	2.29	2.75	3.44	4.58	5.50	6.88	9.16	10.32	13.75
Pine, sugar	.37	11.4	.31	.39	.48	.51	.56	.64	.77	.96	1.10	1.28	1.54	1.93	2.57	3.08	3.85	5.14	5.78	7.70
Pine, shortleaf	.54	11.0	.45	.56	.70	.75	.82	.94	1.12	1.40	1.60	1.87	2.25	2.81	3.74	4.49	5.62	7.49	8.43	11.2
Pine, western yellow	.41	10.8	.34	.43	.53	.57	.62	.71	.85	1.07	1.22	1.42	1.71	2.13	2.84	3.41	4.27	5.69	6.40	8.54
Pine, white	.39	9.9	.33	.41	.51	.54	.59	.68	.81	1.02	1.16	1.35	1.62	2.03	2.71	3.25	4.06	5.42	6.09	8.12
Poplar, yellow	.41	6.1	.34	.43	.53	.57	.62	.71	.85	1.07	1.22	1.42	1.71	2.13	2.84	3.41	4.27	5.69	6.40	8.54
Spruce, Sitka	.38	8.9	.32	.40	.49	.53	.58	.66	.79	.99	1.13	1.32	1.58	1.98	2.64	3.16	3.96	5.28	5.94	7.94
Sycamore	.50	9.2	.42	.52	.65	.69	.76	.87	1.04	1.30	1.49	1.73	2.08	2.60	3.47	4.16	5.20	6.94	7.82	10.41
Tanguile (Philippine mahogany)	.54	11.8	.45	.56	.70	.75	.82	.94	1.12	1.40	1.60	1.87	2.25	2.81	3.74	4.49	5.62	7.49	8.42	11.20
Walnut, black	.57	4.8	.47	.59	.74	.79	.86	.99	1.19	1.48	1.70	1.98	2.37	2.97	3.96	4.75	5.94	7.92	8.91	11.87

Weight of glue per square foot of single glue line, blood albumen about 0.3 ounce; casein about 0.4 ounce.

Explanation of Table 4.

This table lists the tensile strength of three-ply wood of various common veneer species and the approximate strength of single-ply wood. The strength figures, given in pounds per square inch, correspond to the moisture contents listed.

Sample computation: To obtain the tensile strength of three-ply wood consisting of two 1/20-inch birch faces and a 1/16-inch basswood core.

Tensile strength parallel to face grain $=2\times 1/20\times 19{,}820=1{,}982$ pounds per inch of width.

Tensile strength perpendicular to face grain $=1\times 1/16\times 10{,}320=645$ pounds per inch of width.

This computation neglects the tensile strength of the ply or plies perpendicular to the grain, which is comparatively small, and the results are therefore slightly in error.

The mechanical properties of wood are quite variable, and the strength of individual pieces may be expected to differ considerably from the average values given.

Table 4.—*Tensile strength of plywood and veneer.*

Species.	Number of tests.	Moisture content at test.	Specific gravity [1] of plywood.	Tensile strength [2] of 3-ply wood parallel to grain of faces.	Tensile strength [3] of single-ply veneer 1½ (d).
		Per cent.		*Pounds per square inch.*	*Pounds per square inch.*
	(a)	(b)	(c)	(d)	(e)
Ash, black	120	9.1	0.49	6,180	9,270
Ash, commercial white	200	10.2	.60	6,510	9,760
Basswood	200	9.2	.42	6,880	10,320
Beech	120	8.6	.67	13,000	19,500
Birch, yellow	200	8.5	.67	13,210	19,820
Cedar, Spanish	115	13.3	.41	5,200	7,800
Cherry [4]	115	9.1	.56	8,460	12,690
Chestnut	40	11.7	.43	4,430	6,640
Cottonwood [5]	120	8.8	.46	7,280	10,920
Cypress, bald	113	8.0	.45	6,160	9,240
Douglas fir [6]	200	8.6	.48	6,180	9,270
Elm, cork	65	9.4	.62	8,440	12,660
Elm, white	160	8.9	.52	5,860	8,790
Fir, true [7]	24	8.5	.40	5,670	8,510
Gum [8]	35	10.6	.54	6,960	10,440
Gum, cotton	80	10.3	.50	6,260	9,390
Gum, red	182	8.7	.54	7,850	11,780
Hackberry	80	10.2	.54	6,920	10,380
Hemlock, western	119	9.7	.47	6,800	10,200
Magnolia [9]	80	8.8	.58	9,220	13,830
Mahogany, African [10]	20	12.7	.52	5,370	8,060
Mahogany, Philippine [11]	25	10.7	.53	10,670	16,000
Mahogany, true	35	11.4	.48	6,390	9,580
Maple, soft [12]	120	8.9	.57	8,180	12,270
Maple, hard [13]	192	8.0	.68	10,190	15,290
Oak, commercial red	115	9.3	.59	5,480	8,220
Oak, commercial white	195	9.5	.64	6,730	10,100
Pine, sugar	110	8.0	.42	5,530	8,300
Pine, white	40	5.4	.42	5,720	8,580
Poplar, yellow	155	9.4	.50	7,390	11,080
Redwood	105	9.7	.42	4,770	7,160
Spruce, Sitka	121	8.3	.42	5,650	8,480
Sycamore	163	9.2	.56	8,030	12,040
Walnut, black	110	9.1	.59	8,250	12,380
Yucca species	33	7.3	.49	2,210	3,320

[1] Specific gravity based on oven-dry weight and volume at test.
[2] Based on total cross-sectional area.
[3] Based on assumption that center ply carries no load.
[4] Probably black cherry.
[5] Probably (common) cottonwood.
[6] Coast type.
[7] Probably white fir.
[8] Probably black gum.
[9] Probably (evergreen) magnolia.
[10] Probably Khaya species.
[11] Probably tanguile.
[12] Probably silver maple.
[13] Sugar or black.
Data based on tests of 3-ply panels with all plies in any one panel same thickness and species.

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