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The Effect of Synthetic Resin Adhesives on the Strength and Physical Properties of Wood Veneer Laminates

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THE EFFECT OF SYNTHETIC RESIN ADHESIVES ON THE STRENGTH AND PHYSICAL PROPERTIES OF WOOD VENEER LAMINATES

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PROPERTIES OF AMERICAN BEECH IN TENSION AND COMPRESSION PERPENDICULAR TO THE GRAIN AND THEIR RELATION TO DRYING

INTRODUCTION

ALTHOUGH a full discussion of the developments in drying theory, applied to wood, is outside the scope of this bulletin, the salient points leading to the present status of the theory, as it pertains to drying degrade, will be critically reviewed.

The beginning of kiln drying and the origin of wood drying theory are uncertain. However, the artificial drying of wood was not adopted on a wide-spread commercial scale until the twentieth century. Modern forced-draft, temperature- and humidity-controlled kilns were developed from heated rooms or hot boxes as the drying process became better understood.

In the United States, the development of a comprehensive and workable theory of kiln drying for wood must be largely credited to H. D. Tiemann (*32*).[1] Tiemann's concepts, which were published in some detail in 1917, are the basis of modern drying theory. His theory includes an appreciation of the nature of wood-liquid relations and of the development of stresses in drying wood as a function of shrinkage, set, structure, permeability, and moisture gradients. He also recognized that high temperature and/or moisture content result in a loss of cohesive strength in the wood and also exert a plasticizing effect.

The ideal kiln schedule is one which will enable the stock to be dried economically for its end use in the shortest possible time with the least possible defect. In order to achieve the optimum kiln schedule for a species, a range of initial drying conditions is tried, and selection is made of the combination which affords the least degrade commensurate with the fastest drying time. The extent of the changes within the kiln schedule and their frequency are also determined by the occurrence, or absence, of drying defects. The change points are determined to a large degree by the presence or absence of drying defects and the stress condition of the lumber. This work is facilitated by a knowledge of the moisture content distribution and stress condition within the drying lumber.

On the basis of the above approach, kiln schedules were gradually de-

[1] Italic numbers in parentheses refer to references cited at the end of this paper.

resulting from resin impregnation and extreme veneer compression have been the subject of thorough investigation, an arbitrary and unfounded dividing line has segregated these modified wood products from plywood and laminated wood fabricated in the conventional manner. The inadequacy of this segregation has been demonstrated by at least two American investigators (42,47), and German wood technologists *(31)* have suggested the recognition in plywood design of the improvement in mechanical properties accompanying the laminating process. However, adequate information for design purposes concerning the changes in strength and elastic properties imparted to plywood and laminated wood by the adhesive and gluing process is largely lacking.

This paper describes an investigation designed to establish the extent to which the tensile and flexural strength and certain elastic properties of laminates[2] of thin yellow poplar *(Liriodendron tulipifera* L.) veneer are influenced by the fundamental properties of synthetic resin glue lines. Although the study is limited to the properties of veneer-resin systems assembled from one species and six commercially important types of synthetic resin adhesive, the information disclosed can be considered basic to most veneer-resin laminates and the theories and techniques involved should prove useful in further fundamental glue-line studies.

2. In the remainder of this paper, *plywood* refers to a construction in which the grain of adjacent veneer sheets is perpendicular, *laminated wood* refers to a construction in which the grain of adjacent veneer sheets is parallel, and *laminate* refers to a veneer construction in either plywood or laminated wood form.

FACTORS INFLUENCING THE STRENGTH OF VENEER-RESIN SYSTEMS

MOST of the physical and mechanical properties of commercially important native woods are well known and the variability associated with certain environmental influences and structural characteristics can be reliably predicted. Inasmuch as the wood components predominate in conventional plywood and laminated wood, accepted methods of predicting the mechanical properties of these types of veneer-resin systems are based entirely on the strength and elasticity of the wood from which they are assembled. Freas (*18*), Hoff (27), Hearmon (23), and others (*16, 20, 35, 41*, 64) cite mathematical techniques for computing the strength and elastic properties of laminates which assume a material of composite cross section comprising well defined layers of known mechanical properties. Freas (*18*) has suggested the necessity for incorporating a form factor in the modified flexure formula for plywood beams to establish closer conformity between theoretical and experimental results. With this factor, the computed flexural strength is decreased from that based entirely on wood components. Poletika (*47*) and Norton (*42*) have both observed an improvement of certain strength properties in laminated wood fabricated from ⅛-inch veneer which they attribute to the influence of the adhesive. That this improvement has not also been found in plywood suggests a basically different mechanical behavior of these two types of construction.

Among the factors which may alter the properties of wood in systems of veneer laminates are (1) polymerization of the resin in the transient capillaries of the cell wall, (2) compression of veneer during the laminating process, and (3) deposition of resin between veneer sheets and in the gross capillary structure of the wood. In addition, mechanical factors inherent to composite cross section assemblies of orthotropic materials may be operative. Clues to the possible influences of certain factors acting independently and in combination may be available through investigations of the properties of modified woods.

Research directed toward improving the dimensional stability of wood has led to impregnation of the cell walls with water-soluble synthetic resins in a virtually unpolymerized state after which the impregnant is polymerized within the fine capillary structure (*13, 51*, 56). The results of numerous investigations (*10, 11*, 52, *54*, 56) indicate that resin impregnation, in addition to its influence in reducing hygroscopicity, improves hardness and compression perpendicular to the grain very appreciably, compression parallel to the grain to a somewhat lesser extent, and modulus of elasticity and shearing strength slightly. Tensile strength, toughness, and impact strength are significantly reduced. Erickson and Faulkes (*11*) and others (*38*) have found that wood impregnated with a given amount of phenol formaldehyde is, in general, somewhat superior in strength to that impregnated with an equal amount of urea formaldehyde. In several publications, Stamm and Seborg (52, *54*, 56) have indicated that compressive strength is the only mechanical property appreciably improved and that cell-wall impregnation is not necessary for this; similar results could be achieved by using any impregnant that would form hard, solid materials in the coarse capillary structure.

Specific gravity of wood is dependent upon the amount of cell-wall substance per unit volume and is, therefore, an index of many strength properties (63). It is recognized that wood is plasticized by moisture (*26, 50, 51,* 59, *60*) and heat, particularly above 350°F. which is the approximate minimum temperature for lignin flow (*26,50*). Many investigators and authors (*19*, *31*, 36, *50*, 52) have observed that the strength of wood, compressed under conditions which minimize rupture of the cell walls, is increased in approximate proportion to the increase in density.

The advantage of dimensional stability imparted to wood by deposition of resin-forming constituents in the fine capillary structure of the cell walls has been combined with the improvement in mechanical properties accompanying densification in the development of resin-impregnated, compressed wood. Impregnating resins facilitate compression by plasticizing the cell walls and, after polymerization, prevent appreciable recovery. Although most thermosetting synthetic resins have been used for impregnation, phenol formaldehyde has proven most successful and, consequently, has been most widely investigated for this purpose (*1a*, 55). Erickson (*1a*) has found that resin impregnation and compression produce a general increase in mechanical properties both parallel and perpendicular to the grain. Ultimate compressive strength is increased to a greater degree than density, and tensile and flexural properties are improved approximately in proportion to the degree of compression. This conclusion is generally supported by other investigators and authors (*11, 12, 15, 19, 36, 45*).

The improvement of mechanical properties of wood by densification through high-pressure bonding of veneer in the form of plywood and laminated wood has been widely investigated in the United States and other countries. Numerous writers (4, 22, 24, 28,37, *41*, 48) have described general methods of fabricating high density plywood and have compared its properties with those of other forms of modified wood. Although the influence of cell-wall penetration by the adhesive is implied by some investigators (*19*, *30*, 45), the extent of true impregnation has not been clearly established. Several investigators and authors (3, *19*, *44*) have indicated that the compression of high-density laminates is associated with the penetration of the adhesive into the veneer and that the properties of the laminates are partially dependent upon the bonding of cell walls which have been ruptured in the pressing process (52). Harlow *(21)*, however, has shown through microscopical studies that the zone of maximum penetration is immediately adjacent to the bonding line with the zone of maximum compression located closer to the center of the veneer. Most investigators agree that strength increases are consistent with increases in specific gravity.

That the line of distinction between conventional plywood or laminated veneer and the improved wood forms is poorly defined is clearly stated by Kollmann *(31)* and Gunn (*19*) who point out that the German laminated-veneer product, *Scbicbtbolz*, increases in uniformity, compression, impregnation, and density with decreasing veneer thickness, and that mechanical properties are improved with disproportionate increases in density. Further, Kollmann *(31)* indicates that tensile strength of plywood is improved as a consequence of the adhesive, and that conventional equations for computing the tensile strength should be modified by a factor dependent upon the extent of adhesive penetration. He does not elaborate on this subject, however. Also, as previously mentioned, both Norton (42) and Poletika (47) have observed an improvement over solid wood in the strength of laminated beams made up of layers of 1/8-inch veneer. Experimental evidence of further improvement in assemblies of thinner veneers is not available.

PROCEDURE

DESIGN OF THE EXPERIMENT

SINCE 1935, when synthetic resin first attained commercial importance as a wood adhesive in the United States, a great variety of general types has been formulated, and those types which have found acceptance in the wood-using industry have been manufactured by many different companies. Although the principal chemical constituents of a given type are essentially the same, the proportions of chemicals, catalysts, hardeners, and inert ingredients, and manufacturing variables may differ appreciably. Consequently, it is doubtful if the chemical behavior of any two proprietary compounds is identical.

An investigation of all commercially important synthetic resin adhesives would exceed the limits of practicality. Therefore, the study was limited to the influence of one widely used representative of each of six general types of adhesive which are of industrial importance. Although the results apply specifically only to these adhesives used under conditions identical to those of the study, they should serve as indices of the behavior of the general types which are represented.

The adhesives chosen for the study were:

1. Resorcinol-formaldehyde liquid adhesive, Penacolite G-II31, manufactured by Koppers Company, Inc., Pittsburgh.
2. Resorcinol-phenol-formaldehyde liquid adhesive, Penacolite G-1215, manufactured by Koppers Company, Inc., Pittsburgh.
3. Powder-type phenol-formaldehyde adhesive, Amberlite PR-14, manufactured by Rohm and Haas, Philadelphia.
4. Film-type phenol-formaldehyde adhesive, Tego Film, manufactured by Rohm and Haas, Philadelphia.
5. Urea-formaldehyde powder adhesive, Urac 110, manufactured by American Cyanamid Co., New York.
6. Melamine-formaldehyde powder adhesive, Melmac 401, manufactured by American Cyanamid Co., New York.

The formulations used were those current in 1949-50 when the experimental phase of this study was conducted.

It is recognized that many species of wood differ appreciably in gluing properties (44) and also in the rate of diffusion of impregnating resins (56). It is, therefore, highly improbable that a given adhesive imparts the same change in strength properties to all woods. This study is confined to the influence of the aforementioned adhesives on the strength properties of laminated wood and plywood made from rotary-cut yellow poplar veneer. It is reasonable to believe that trends established in this investigation can be considered indicative of those that would result from a similar study employing other species.

Any effect of an adhesive on the static-bending and tensile strength and elastic properties of laminated wood and plywood should become increasingly pronounced if, in successive panels, the veneer thickness is decreased while the adhesive application and the bonding procedure are held constant. In order to establish the limits of the influence of the adhesive and the gluing process, veneer thicknesses of 1/10, 1/20, 1/40, and 1/60 inch were used. Three plywood and three laminated wood panels of each veneer thickness were assembled with each adhesive. In each, a sufficient number of veneer sheets was used to give a total panel thickness of approximately 3/10 inch. Two static-bending and two tension specimens were randomly selected from each panel. Thus, six plywood and six laminated-wood tension and bending specimens were prepared from panels of each of four veneer thicknesses. This totals 24 beams and 24 tension specimens for each type of assembly (plywood and laminated wood) and each adhesive, representing three complete replications. In all, 288 beams and 288 tension specimens were prepared for testing. The design was selected to permit a simultaneous statistical analysis of variance, for each strength property, between assemblies of different veneer thicknesses and assemblies bonded with different adhesives. In this regard, extreme care was exercised to control to the greatest possible extent all other sources of variation.

SELECTION OF VENEER

All veneer used in the study was rotary-cut yellow poplar from the Southern Appalachian region. Temperatures below 212°F. were used in drying. All veneer considered for panel construction was tight, straight-grained stock, free from visible defect and any abnormal coloring which could be indicative of wood-staining or wood-destroying fungi (25).

In order to evaluate accurately the influence of the adhesive and the gluing process, it was desirable to fabricate all panels from veneer sheets of closely comparable strength and elastic properties. Inasmuch as density is the most reliable non-destructive index of the strength properties of clear wood (31,63), the specific gravity of all veneer sheets from which the panels were fabricated was determined so that all assemblies could be matched in average specific gravity. This was accomplished by a method patterned after techniques perfected at the Forest Products Laboratory (43).

The specific gravity based on oven-dry weight and oven-dry volume of the veneer sheets formed a normal distribution pattern with a mean value of 0.46; hence, all panels were assembled with an average specific gravity of 0.46. In every case, face veneers were of average density, and interior sheets were randomly distributed with respect to specific gravity. A complete record was retained of the specific gravity and thickness of veneer sheets to be used in each panel.

FABRICATION OF PANELS

The length and width of the panels assembled for test purposes were limited to 10 x 10 inches, the platen dimensions of the available hot press. In order that all properties of the different assemblies could be directly compared, all panels were constructed with a sufficient number of veneer sheets to give an approximate panel thickness of 3/10 inch, the minimum thickness of conventional plywood assembled from the thickest veneer class. Three, 7, 13, and 17 plies were used respectively in panels of 1/10-, 1/20-, 1/40-, and I/60-inch veneer.

Adhesives were mixed in accordance with instructions issued by the manufacturers with the exception of the urea resin which was hot pressed without the recommended hardener so that the assembly time could be extended to prevent blistering in panels of the thinner veneers.

Adhesive properties and gluing procedures are tabulated on page 9.

The amount of liquid adhesive mix per glue line was regulated with a calibrated ladle which was checked periodically with a torsion balance. The adhesive was uniformly spread with a hand-operated, rubber roller, and each successive veneer was placed on the spread surface of the preceding one before the adhesive was applied to insure accurate grain alignment and prevent excessive curling. Veneer to be bonded with the film-type phenol resin was conditioned to 10 percent moisture content whereas all other gluing was at approximately 7 percent. Assemblies were separated with I-inch stickers during the closed assembly period after which they were pressed individually in a hand-operated, hydraulic hot press equipped with a thermostat and pressure gauge. After the pressing operation, panels were conditioned in stickered piles for one

	Adhesive					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
Resin (Parts by weight)	50	50	40	—	100	70
Hardener (Parts by weight)	20	20	—	—	—	—
Water or incorporated solvent (Parts by weight)	50	50	60	—	65	35
Spread (Pounds per 1000 sq. ft. of glue line)	50	50	30	1 sheet	50	50
Closed assembly time	30 min	30 min	24 hrs	—	48 hrs	48 hrs
Pressure (Psi)	150	150	150	150	150	150
Temperature (Degrees F.)	200	200	300	300	280	280
Pressing time (Minutes)	10	10	10	10	12	12

week in a humidity cabinet controlled at 100°F. dry-bulb temperature and 75 percent relative humidity (equilibrium moisture content of 12 percent). Bonds satisfying the requirements for Type II hardwood plywood described in Commercial Standard 35–49 (*62*) were attained in all cases.

Preparation of Test Specimens

After trimming the panels to eliminate any variability that might occur in that part pressed near the edges of the platens, two 1 x 10-inch beams and two 5/8 x 10-inch tension blanks, all of panel thickness, were cut at random from each. In all cases the grain direction of the face veneers was oriented parallel to the longitudinal axis of the specimen. The beams underwent no further machining whereas the tension blanks were shaped into specimens proportionately reduced from that specified in A.S.T.M. Designation: D 805–47, *Standard Methods of Testing Plywood, Veneer, and Other Wood and Wood-Base Materials* (*1*). Prior to testing, the specimens were conditioned to constant weight in a humidity cabinet in which ¼-inch yellow poplar veneer strips attained a moisture content of 12 percent.

PROCEDURE FOR TESTING LAMINATED WOOD

All mechanical tests were conducted with a Baldwin-Southwark, electrically powered, hydraulically operated testing machine. Beams were supported on sensitively self-aligning knife edges equipped with semi-cylindrical, metal, bearing members which were designed to minimize crushing at the points of reaction. In all cases, spans were controlled to maintain a constant span-to-depth ratio of approximately 27 to 1. Loads, applied at mid-span in a direction normal to the plane of the glue line, were imposed through a hard maple bearing block, dimensioned to A.S.T.M. specifications, at rates computed to produce a maximum fiber strain of 0.0015 inch per inch per minute (*1*). Deflections, measured directly beneath the load to 0.001-inch precision, were recorded to failure at regular load intervals of a magnitude selected to give approximately fifteen readings below the proportional limit. Tension specimens were held in self-aligning Templin grips and loaded to failure at 0.07 inch per minute. The increase in rate of loading over that specified in A.S.T.M. Designation: 805-47 (0.035 inch per minute) was found to have no significant influence on the elasticity or the ultimate tensile strength. Information pertinent to computations of unit stress values and analysis of results was recorded.

Unit values were computed in the conventional manner for ultimate tensile stress and the static-bending properties of fiber stress at proportional limit, modulus of rupture, modulus of elasticity, work to proportional limit, and work to maximum load. In addition, the specific gravity and apparent moisture content were determined from a sample taken from each beam in the vicinity of the failure.

THE INFLUENCE OF SHEAR ON THE DEFORMATION OF LAMINATES IN BENDING

It is recognized that tensile, compressive, and shearing stresses are simultaneously operative in a flexed beam (*18*, 32, 39). However, in conventional equations expressing Young's modulus in bending, strain resulting from shearing stresses is not considered. The proportion of shearing strain to tensile and compressive strain in beams is dependent upon the ratios of span to depth and of bending elasticity to rigidity (*32*, *61*). Inasmuch as the modulus of rigidity of wood is but 0.01 to 0.07 of Young's modulus parallel to the grain, the shearing deformation in solid and laminated wood beams of practical lengths and depths may be significant. Consequently, for testing laminates, the American Society for Testing Materials has specified a standard ratio of span to depth of 14 to 1 for laminated wood beams and a ratio of 48 to 1 for plywood beams.

For many species of solid wood, the moduli of elasticity and rigidity are both available and can be used to predict the influence of shearing deformation on beam deflection. Newlin and Trayer (*39*) have illustrated the importance of this consideration in computing the deflection of wood beams with solid, I, and box sections, and Freas (*18*) has presented a method of computing the bending deflection of plywood beams of certain specific constructions in which the influence of shear may be important. There is, however, insufficient information available for predicting the influence of shearing strain on the observed Young's modulus or deflection of wood laminates generally.

As previously mentioned, panels to be tested were 10 x 10 inches in surface dimensions, and 3/10 inch in thickness. Thus, the maximum practicable span-to-depth ratio in the test beams could be but 27 to 1. This deviation from the accepted plywood standard would be expected to yield results which could not be directly compared with other work because of excessive shearing deformation in the plywood beams. Further, the values determined by tests entailing but one span-to-depth ratio are seriously limited in utility unless they can be adjusted to apply validly to similar beams of any desired span. Therefore, an investigation of the influence of shearing strain on the bending deformation of glued veneer laminates appeared highly desirable.

According to Timoshenko (*61*), additional deflection resulting from shearing strain in a cantilever beam can be considered by the modified equation for determining bending deflection as follows:

$$D = \frac{PL^3}{3EI}\left[1 + \frac{3}{10}\left(\frac{h^2}{L^2}\right)\frac{E}{G}\right]$$

D = Total deflection in inches
P = Load in pounds
L = Span in inches
h = Depth in inches

E = Young's modulus in pounds per square inch
I = Moment of inertia about the neutral axis in inches to the fourth power
G = Modulus of rigidity in pounds per square inch

The effective modulus of elasticity of a cantilever beam with a given depth-to-span ratio is expressed by the equation,

$$E' = \frac{PL^3}{3EI}.$$

Therefore, by substitution, the relationship between the true modulus of elasticity devoid of shearing influences and an experimentally determined value (E′) at a given ratio of depth to span may be expressed by the equation,

$$E = E'\left[1 + \frac{3}{10}\left(\frac{h^2}{L^2}\right)\frac{E}{G}\right].$$

The transposed form,

$$E' = \frac{E}{1 + \frac{3}{10}\left(\frac{h^2}{L^2}\right)\frac{E}{G}},$$

expresses the effective modulus of elasticity of a cantilever beam as a hyperbolic function of the depth-to-span ratio, the asymptote parallel to the axis of the abscissa of which is the pure modulus of elasticity in bending (E). The equation remains valid for a simple, center-loaded beam if the square of the ratio of depth to one-half the span

$$\left(\frac{h}{\frac{1}{2}L}\right)^2$$

is substituted for the term

$$\left(\frac{h^2}{L^2}\right).$$

Thus, when the moduli of elasticity (E) and rigidity (G) are known, the effective modulus of elasticity (E′) at any ratio of depth to span

$$\left(\frac{h}{L}\right)$$

can be readily determined. Further, an experimentally determined effective modulus of elasticity value at any ratio of depth to span can be used in the equation to compute either the pure Young's modulus or the modulus of rigidity if one of the latter constants is known.

In materials of homogeneous cross section, the modulus of elasticity (E) determined from a beam with an infinitely small ratio of depth to span should approximate that determined from tension or compression. However, in materials of composite cross section such as plywood, or possibly laminated wood, where layers of different elastic properties parallel the neutral plane, the pure modulus of elasticity in tension or compression differs appreciably from that in bending. Also, methods of computing the effective modulus of rigidity relating stress in a plane parallel to the laminae to strain in the plane parallel to the sides of a beam of composite cross section, such as plywood, are not available. Consequently, usable methods of determining these unknown constants are requisite to the prediction of the effective modulus of elasticity or deflection of a plywood or laminated wood strip with any desired ratio of depth to span.

A linear transformation of a hyperbolic relationship can be made by expressing

$$\frac{x}{y}$$

as a function of x. By this method, the hyperbolic relationship,

$$E' = \frac{E}{1 + \frac{3}{10}\left(\frac{h}{\frac{1}{2}L}\right)^2 \frac{E}{G}}, \qquad (1)$$

can be transformed to the rectilinear relationship,

$$\frac{(\frac{1}{2}L)^2}{E'} = \frac{0.3}{G} + \frac{1}{E}(\tfrac{1}{2}L)^2.$$

In this particular instance L is defined as the ratio of span to depth. In the graphic representation of this equation, the intercept of the curve with the axis of the ordinate represents the term,

$$\frac{0.3}{G},$$

and the slope represents the reciprocal of the asymptote which is the pure Young's modulus devoid of shearing influences. Thus, the two unknown constants, E and G, can be determined by an experimentally established curve.

In order to confirm this theory and provide a valid method for adjusting test values to conform to values expected of beams of any desired ratio of span to depth, a secondary experiment was conducted. One beam was taken from each of two laminated veneer panels of each veneer thickness bonded with the resorcinol-phenol-formaldehyde adhesive. In addition, two specimens of unmodified yellow poplar with a specific gravity of 0.47 were selected for comparison. This provided two beams, representing two replications, for laminates of each veneer thickness and for solid wood. The specimens, conditioned to approximately 10 percent moisture content, were center-loaded within one-half the computed proportional limit as simple beams with span-to-depth ratios of 26:1, 22:1, 18:1, and 14:1. The deflection at mid-span was taken during each loading to 0.001-inch accuracy at sufficient intervals to establish load-deformation curves. The effective Young's modulus values collected for each specimen were found to approximate closely the theoretical hyperbolic trend as illustrated in Figure 1. The pure Young's modulus in bending and the effective modulus of rigidity of each specimen were

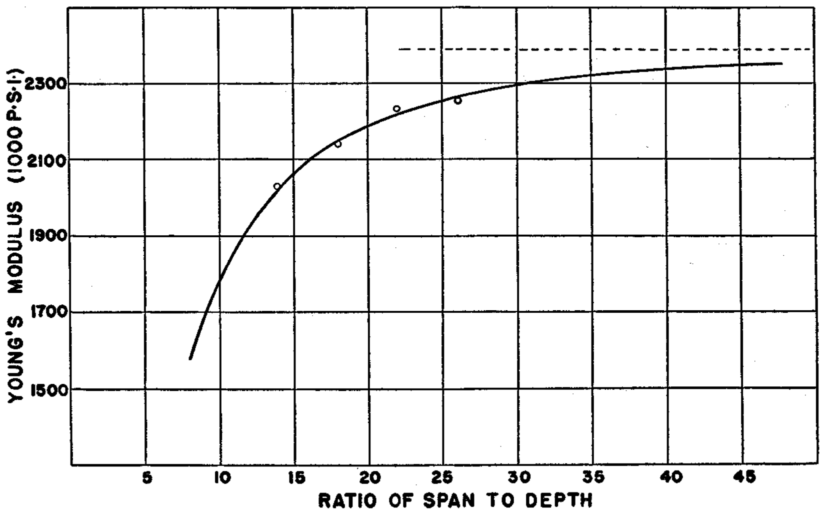

FIGURE 1. Relationship between Young's modulus in static bending of laminated wood and the ratio of span to depth.

graphically determined from the rectilinear transformation of the hyperbolic relationship as illustrated in Figure 2.

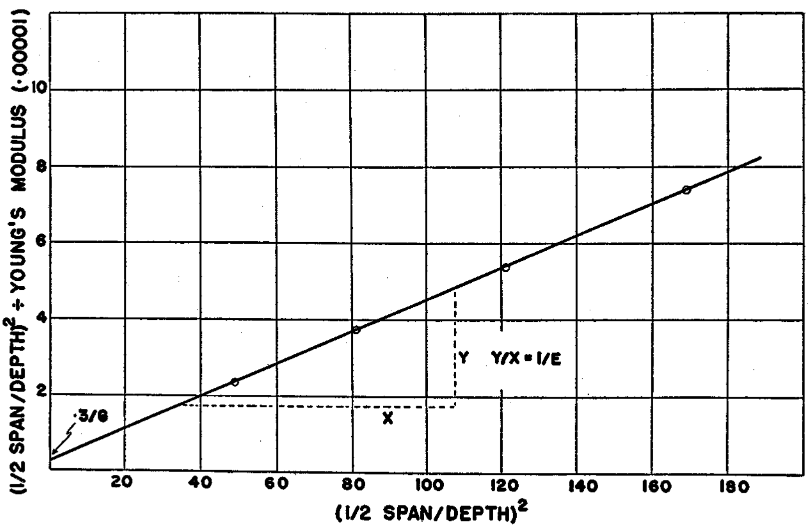

FIGURE 2. Rectilinear transformation of the relationship between Young's modulus in static bending of laminated wood and the ratio of span to depth.

Although close conformity of experimental data to the theoretical hyperbolic trend indicates that the theory is valid for solid and modified woods, the technique does not provide a convenient method of determining the two unknown constants for plywood construction. A direct method of determining one of the two was, therefore, desired. Inasmuch as shearing stresses are theoretically nonexistent in any portion of a span in which the bending moment is constant, the possibility of determining Young's modulus devoid of shearing influence from the deformation between loads at third points of a simple beam is suggested. The difference, δ, between the deflection at mid-span and that under either load, computed according to the second area-moment proposition (*32*) may be expressed by the equation,

$$\delta = \frac{PL^3}{36Ebh^3},$$

in which P is the total load. Thus, the experimental determination of

δ provides a simple, direct method of determining the unknown pure Young's modulus in bending (E).

In order to evaluate the effectiveness of this direct method, each beam for which the hyperbolic relationship of elasticity to depth-to-span ratio had been determined was loaded within one-half the computed proportional limit, with equal loads imposed precisely at third points through a specially designed device. During three successive loadings, deflections were taken to o.oool-inch accuracy at mid-span and under each load. The difference between the deflection at the center and the average of the deflections at load points was used as δ in the computation of pure Young's modulus which is theoretically comparable to the asymptote of the previously established hyperbola. It was found that the similarity of values determined by the two methods was exceptionally close; discrepancies exceeded 3 percent of the directly determined value only in the case of one control beam. Thus, the validity of the application to glued veneer beams of the theory of strain energy relations according to Timoshenko was established, and a direct method of determining pure Young's modulus in bending was proved to be without significant error.

The modulus of rigidity values determined from the intercepts of the linearly transposed hyperbolas (Figure 2), which are the effective moduli of the various composite cross sections tested, were extremely variable. Since complex differences resulting from adhesive concentration, adhesive-wood interfaces, and lathe checks undoubtedly exist between different planes paralleling the neutral axis, and since Drow and McBurney (9) observed appreciable variation in modulus of rigidity values for solid yellow poplar, the high degree of variability shown by this property is not considered unreasonable.

A statistical analysis of variance failed to establish significant differences in modulus of rigidity values between laminates of different veneer thicknesses. Therefore, the most accurate expression of modulus of rigidity for laminates of all veneer thicknesses is the mean of all values obtained which proved to be 57,000 pounds per square inch. An average modulus of rigidity of 85,000 pounds per square inch for deformation in the longitudinal-radial plane caused by stresses in the longitudinal-tangential plane was determined for the two solid wood controls. Tests at the Forest Products Laboratory, Madison, disclosed no correlation between specific gravity and modulus of rigidity and provided an average modulus value of 105,000 pounds per square inch for solid yellow poplar stressed in the same plane as the control specimens. Therefore, it is indicated that the modulus of rigidity of laminated veneer may be lower than that of solid wood.

The foregoing experiment indicates that modulus of rigidity values, provided by testing beams at different ratios of depth to span, can be used in a form of equation (1) to adjust an effective modulus of elasticity value determined experimentally from beams with any known ratio of depth to span to a pure value devoid of shearing influences. Similarly, a pure Young's modulus value, determined from the deformation of a beam between loads at third points, can be used to compute the effective modulus of rigidity of beams tested at any ratio of depth to span. This makes possible the adjustment of Young's modulus values determined at any depth-to-span ratio to the anticipated value at any other ratio. Thus, a usable method is provided for determining the unknown plywood constants, modulus of rigidity and modulus of elasticity in pure bending, so that effective Young's modulus values at any ratio of depth to span can be predicted from test values.

Procedure for Testing Plywood

Before plywood beams were tested to destruction, one of the two specimens machined from each panel was used to determine the pure Young's modulus in bending by the third-point loading method described in the foregoing section. The beams were then center-loaded to failure in a manner similar to that described for testing laminated wood and similar unit stress values were computed by the conventional equations. In addition, the effective modulus of rigidity of each specimen for which the pure Young's modulus in bending had been determined was computed by the equation,

$$G = \frac{0.3\, h^2\, EE'}{(\frac{1}{2}L)^2\,(E - E')},$$

a form of the hyperbolic equation (1) presented in the previous section.

Plywood tension specimens were tested similarly to the laminated wood specimens except that data for load-strain curves were collected for one specimen from each of two panels of each veneer thickness bonded with the film-type phenol resin, the powder-type phenol resin, and the resorcinol resin. For this, SR–4 electrical strain-gauge equipment was used (Plate I). The ultimate tensile strength of each specimen and, in addition, Young's modulus of specimens for which strain data were available were computed in the conventional manner.

RESULTS OF TESTS AND METHODS OF ANALYSIS

A SUMMARY of the unit tensile and bending strength and elastic properties determined from the tests together with specific gravity values are presented in the appendix, Tables 29 through 41. With the exceptions of modulus of rigidity, pure modulus of elasticity in bending, and modulus of elasticity in tension, each tabulated value is the arithmetic mean of six values, two from each of the three replications. The tabulated modulus of rigidity and pure modulus of elasticity values for plywood in Tables 35 through 40 are the arithmetic means of three values, one from each replication, whereas those for modulus of elasticity in tension (Table 41) are the means of two replicated values.

Although major causes for variability of wood such as specific gravity and moisture content may be controlled, unavoidable factors such as variations in percentages of structural elements and dissimilarity in the microstructure of cell walls give rise to uncontrolled differences in physical and mechanical properties. In an investigation of the influence of deliberately applied factors on these properties, it is desirable to differentiate mathematically between inherent variability and that associated with treatment. This study was so designed that the data could be examined statistically with multiple-treatment analyses of variance and t-tests as described in standard texts of statistical analysis (*53*). The values for each property established through testing were analyzed separately to determine the probability of the differences in values being caused by differences in adhesives or veneer thicknesses.

PHYSICAL PROPERTIES OF LAMINATED WOOD AND PLYWOOD

Apparent Moisture Content

ALTHOUGH all test specimens were conditioned to constant weight in a humidity cabinet in which yellow poplar veneer strips attained 12 percent moisture content, the specific gravity samples of laminated wood were weighed prior to oven drying in order to determine the apparent moisture content of the wood-adhesive system. The specific gravity of the polymerized adhesive was appreciably greater than the wood in the assembly, and films of the adhesives could be expected to reach equilibrium at moisture content percentages varying from 3 percent in the case of phenol formaldehyde to 12 percent in the case of melamine formaldehyde when subjected to the relative humidity used in conditioning test specimens (*14*). Thus, a trend of decreasing apparent moisture content accompanying decreasing veneer thickness could be expected with most adhesives. Contrary to expectations, however, a trend of increasing apparent moisture content accompanied decreasing veneer thickness for laminates bonded with all adhesives except the film-type phenol resin, suggesting the probability that the polymerized adhesives contain volatiles which are driven off in oven drying. Among these are possibly uncombined formaldehyde, which was driven off in sufficient quantity to create a strong odor, and moisture trapped in small bubbles in the glue line. The effect was found to persist to a somewhat lesser degree 18 months after pressing.

Specific Gravity

Although all panels were assembled from veneer selected and distributed to give an approximate average specific gravity of 0.46 for the wood component, panels of thinner veneers contained higher percentages of adhesive (Plate II) which, in the polymerized condition, can be expected to approximate in specific gravity cast resins of similar chemical composition. These range from 1.25 to 1.53 (*2*). Consequently, it is logical to expect a trend of increasing specific gravity to accompany a decrease in veneer thickness. This is clearly shown in Table 1. Assemblies containing the greatest amount of resin solids were in all cases the most dense.

Specific gravity differences between plywood and laminated wood

TABLE I. MEAN SPECIFIC GRAVITY VALUES OF PLYWOOD AND LAMINATED WOOD[1]

Veneer Thickness (inch)	*Adhesive:* Resorcinol resin		Resorcinol-phenol resin		Powder-type phenol resin		Film-type phenol resin		Melamine resin		Urea resin	
	Construction: Laminated Wood (Lam.) or Plywood (Ply.)											
	Lam.	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*
1/10	0.50	0.50	0.51	0.50	0.48	0.49	0.47	0.46	0.51	0.52	0.54	0.51
1/20	0.62	0.56	0.61	0.55	0.55	0.56	0.51	0.49	0.60	0.58	0.67	0.57
1/40	0.78	0.67	0.72	0.62	0.64	0.63	0.54	0.54	0.75	0.73	0.87	0.68
1/60	0.97	0.76	0.84	0.72	0.71	0.69	0.57	0.57	0.90	0.79	0.90	0.74

1. Specific gravity based on oven-dry weight and oven-dry volume.

assemblies of the thinner veneers may be partially explained by a basic difference in the two types of construction. When veneer sheets less than *1/20* inch in thickness were spread with liquid adhesives, sufficient solvent was added to saturate the fibers. In laminates bonded with solvent-dispersed adhesives, the resin polymerized when the wood was in a more or less expanded condition. Plywood panels could be expected, in some cases at least, to retain essentially their fully swollen dimensions, whereas laminated wood was free to shrink without the restraint imposed by cross-ply construction during subsequent oven-drying of specific gravity specimens. Lesser differences in specific gravity could be expected in the case of laminates bonded with dry film or with those adhesives from which the solvent was partially evaporated before pressing. According to the Forest Products Laboratory, Madison (*14*) and Kollmann (32), shrinkage of plywood in depth is essentially the same as that of solid wood. Therefore, in the oven-dry condition, the weight per unit volume of plywood can be expected to be less than that of laminated wood by approximately the percent of tangential shrinkage associated with the change in moisture content from that at which the adhesive polymerized to the oven-dry condition. Limited experimentation with assemblies of 1/40-inch yellow birch indicated that this theory is valid.

Inasmuch as the maximum difference in specific gravity between plywood and laminated wood assemblies attributable to restraint of shrinkage can be but approximately 7 percent, differences exceeding this must be recognized as a possible source of error in comparing the mechanical properties of the two types of assemblies.

The loss of volatile constituents from thin veneer laminates in oven drying and the influence of restraint on weight per unit volume of plywood is of significance. Specific gravity and moisture content values determined in the conventional manner may lead to error in computations of strength and weight of assemblies. Perhaps specific gravity based on weight and volume of laminates in equilibrium with the humidity conditions under which they are to be used and equilibrium moisture content values based on those attained by solid wood under identical conditions would be more suitable.

It has been demonstrated by numerous investigators that the plasticity of wood in compression perpendicular to the grain is increased by treatment with impregnating resins and film-type phenolic resins (19, 31, 45, 55,56) as well as by heat and moisture (19, 26, 31, 37,50, 51, 59, 60). Consequently, it is reasonable to expect all synthetic resin adhesives to impart to the veneer in an assembly a degree of plasticity which will result in permanent compression of the wood components. In order to analyze intelligently the influence of the laminating process, it is necessary to differentiate between the increase in specific gravity which results from the addition of the adhesive and that which accompanies veneer compression.

When the veneer of which plywood and laminated wood assemblies were composed was segregated into specific gravity classes, the average thickness of each sheet was determined and recorded. The thickness of each specimen was also recorded. In order to compute the net retention of compression and thereby to determine the average specific gravity of the wood in each assembly, it was necessary only to determine the effective glue-line thickness of each class of laminate. This was accomplished by microscopical measurements of randomly selected samples of material.

When viewed through a microscope, the surface of veneer is very irregular because of severed vessels and other cells and the occurrence of torn tissue and lathe checks. Consequently, numerous voids of approximately 0.003-inch and less in depth occur between veneer surfaces. When the assembly is compressed, a high percentage of adjacent surface areas is brought into intimate contact and an interlocking or dovetailing effect is of frequent occurrence. With the exception of the urea formaldehyde, the liquid adhesives were forced into the irregularities of the veneer surfaces, and consequently did not appreciably increase the panel thickness (Plate III). The urea adhesive did not exhibit the flow properties of the others, however. Although contact was made between surfaces at a limited number of points, the average thickness of the adhesive layer was 0.001 inch in laminates of 1/10-, 1/20-, and 1/40-inch veneer, and 0.0015 inch in those of 1/60-inch veneer. In the case of the film-type phenolic resin, the microscopic examination revealed that the tissue paper on which the adhesive is carried remained intact and separated all parts of adjacent surfaces by an average of 0.001 inch.

The average veneer compression retained in each class of panel bonded with each adhesive was computed by subtracting the measured thickness of the pressed assembly from the sum of the veneer thicknesses plus the total effective thickness of the glue lines. The percentage compression thus determined was considered the average percentage increase in specific gravity of the wood component. Computed mean specific gravity values of wood in plywood and laminated wood assemblies of each veneer thickness bonded with each adhesive are presented in Table 2. It may be observed that the computed specific gravity value for the wood in plywood panels bonded with any given adhesive differs no more than 0.03 from that of laminated wood. This indicates that the mechanical properties of plywood and laminated wood can be compared without serious error being introduced by differences in compression of veneer in the two types of assemblies.

TABLE 2. COMPUTED AVERAGE SPECIFIC GRAVITY VALUES OF WOOD IN PLYWOOD AND LAMINATED WOOD ASSEMBLIES[1]

Veneer Thickness (inch)	*Adhesive: Resorcinol resin*		*Resorcinol-phenol resin*		*Powder-type phenol resin*		*Film-type phenol resin*		*Melamine resin*		*Urea resin*	
Construction: Laminated Wood (Lam.) or Plywood (Ply.)	*Lam.*	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*	*Lam.*	*Ply.*
1/10	0.46	0.46	0.47	0.47	0.47	0.46	0.47	0.47	0.47	0.47	0.47	0.47
1/20	0.47	0.47	0.47	0.47	0.49	0.51	0.47	0.47	0.48	0.49	0.49	0.47
1/40	0.47	0.48	0.47	0.49	0.52	0.53	0.48	0.48	0.50	0.50	0.50	0.47
1/60	0.47	0.50	0.48	0.50	0.53	0.54	0.49	0.48	0.51	0.50	0.50	0.50

1. Specific gravity based on oven-dry weight and oven-dry volume.

The trend of increasing veneer compression accompanying decreasing veneer thickness suggests strongly that the synthetic resin adhesives investigated impart a degree of plasticity to the wood components of the assemblies. The most distinct trend was shown by both plywood and laminated wood bonded with the powder-type phenol resin. Although laminates bonded with other adhesives did not display pronounced differences in compression, those bonded with the melamine resin appeared to be consistently slightly higher than assemblies bonded with the other four adhesives. Inasmuch as the probable moisture content at the time of pressing differed very little for laminates bonded with the powder-type phenol resin, the melamine resin, and the urea resin, and the pressing temperature of those bonded with the powder-type phenol resin was but 20° higher, it is strongly suggested that the phenolic resin imparted a greater degree of plasticity to the wood than the other two adhesives. Because of the complexity of the influence of heat and moisture content and the slight differences in compression of veneer, definite conclusions concerning the plasticizing effect of the other adhesives are not permitted.

MECHANICAL PROPERTIES OF LAMINATED WOOD

Fiber Stress at Proportional Limit in Static Bending

FIBER stress at proportional limit values for laminates of all veneer thicknesses bonded with all adhesives except the resorcinol resin were greater than would be predicted from the veneer alone. An analysis of variance indicated that values for laminates bonded with the resorcinol and resorcinol-phenol resins were significantly lower than those for laminates bonded with the other four adhesives. Although a clearly defined trend of increasing strength accompanying decreasing veneer thickness was not established in any case, this pattern of influence was indicated for assemblies bonded with the melamine resin.

The influence of lamination is illustrated in Table 3 which presents ratios of fiber stress at proportional limit of laminated veneer to that of unmodified wood from which the panel was assembled. The latter value (6,940 pounds per square inch) was derived by adjusting the average value of the species (*34*) to the predicted value at the average specific gravity of the veneer sheets for beams of 0.3-inch depth. For this, established relationships of strength to specific gravity (*63*) and form of cross section (*40*) were used.

TABLE 3. RATIOS OF VALUES FOR FIBER STRESS AT PROPORTIONAL LIMIT IN STATIC BENDING OF LAMINATED VENEER TO THAT OF SOLID WOOD

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.00	1.04	1.16	1.12	1.12	1.09
1/20	1.10	1.12	1.20	1.13	1.13	1.24
1/40	0.99	1.05	1.18	1.24	1.19	1.25
1/60	0.94	1.06	1.16	1.30	1.39	1.21

Fiber stress at proportional limit of yellow birch has been found to improve 27 to 31 percent by impregnation with urea and phenolic resins, whereas modulus of rupture is unaffected or slightly decreased. Further, when impregnation is accompanied by compression, modulus of rupture has been found to improve to an appreciably lesser extent than fiber stress at proportional limit (*11*). In contrast to wood-impregnating resin systems, the laminated yellow poplar exhibited an increase in the ratio of modulus of rupture to fiber stress at proportional limit in bending. The ratio for solid yellow poplar with the specific gravity of 0.46 is 1.51. Average ratios for laminates of the four veneer thicknesses bonded with the six adhesives are presented in Table 4. Of significance is the pattern of increasing ratios accompanying decreasing veneer thickness below 1/20 inch in all laminates except those bonded with the film-type phenol resin. This clearly shows that, unlike resin-impregnated woods, the properties of laminated wood are influenced by factors which increase modulus of rupture to a much greater degree than fiber stress at proportional limit.

TABLE 4. RATIOS OF MODULUS OF RUPTURE TO FIBER STRESS AT PROPORTIONAL LIMIT FOR LAMINATED VENEER

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.71	1.77	1.65	1.60	1.78	1.73
1/20	1.71	1.63	1.68	1.67	1.80	1.63
1/40	1.87	1.78	1.74	1.58	1.89	1.87
1/60	2.17	1.84	1.85	1.66	1.95	1.88

It has been shown that veneer compression contributed to the increase in specific gravity accompanying the laminating process. If veneer compression is assumed to be uniform throughout the cross section, the influence of the increase in specific gravity of the wood in the assembly can be computed from the established relationship between strength and density (*63*). Table 5 presents ratios of average fiber stress at proportional limit values of laminated veneer to those calculated for solid yellow poplar beams which are 0.3 inch in depth with the same specific gravity as the wood in the pressed laminates. It may be observed from Table 5 that factors other than specific gravity influenced the fiber stress at proportional limit of laminated veneer bonded with the film-type phenol resin, the melamine resin, and the urea resin, and that the pattern of influence of the laminating process was altered only in the case of assemblies bonded with the powder-type phenol resin.

TABLE 5. RATIOS OF VALUES FOR FIBER STRESS AT PROPORTIONAL LIMIT IN STATIC BENDING OF LAMINATED VENEER TO THOSE OF SOLID WOOD OF THE SAME SPECIFIC GRAVITY AS THE VENEER IN THE LAMINATES

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.00	1.02	1.16	1.09	1.09	1.05
1/20	1.07	1.07	1.10	1.09	1.07	1.14
1/40	0.96	1.02	0.97	1.17	1.17	1.16
1/60	0.91	1.00	0.92	1.18	1.19	1.12

Inasmuch as the behavior in fiber stress at proportional limit of veneer laminates bonded with all adhesives could not be accounted for by uniform compression of the veneer in the assembly, it is logical to assume that the properties reflect the influence of a veneer-resin complex which differs from solid wood in its response to stress. It follows that laminated veneer is a material of composite cross section composed of alternate zones of normal wood and wood-adhesive systems.

According to the theory of mechanics of materials of composite cross sections (*27*), the normal stress, S, at any point in the cross section of a beam composed of laminae which differ in strength and elastic properties is expressed by the equation,

$$S = \frac{ME_yY}{EI} \qquad (2)$$

in which E is the effective modulus of elasticity of the beam, E_y is the modulus of elasticity in the plane of stress, Y is the distance of the plane of stress from the neutral axis, and I is the moment of inertia about the neutral axis. Of significance is the fact that the maximum stress does not necessarily occur in the outermost fiber but in the plane where the product, E_yY, is maximum.

The fiber stress at proportional limit of the laminate, S′, can be expressed by the equation,

$$S' = \frac{MY}{I}.$$

By substituting S′ for this expression in the equation,

$$S = \frac{ME_yY}{EI},$$

and transposing terms, the equation,

$$S' = \frac{E}{E_y} S, \qquad (3)$$

can be derived. This can be used to compare the experimentally determined and theoretical values to gain basic information concerning the influence of the adhesive on the proportional limit of the wood-resin system. If it is assumed that the limit of proportionality is first reached by the outermost fiber, S′ and E are average values for fiber stress at proportional limit and modulus of elasticity respectively which were determined from tests, and S and E_y are respectively the average value for fiber stress at proportional limit and modulus of elasticity of the wood of which the assembly was composed. Theoretical average values computed in this manner are compared in Table 6 with those determined experimentally. The deviation of the theoretical from the experimental values is expressed as a percentage of the latter.

TABLE 6. THE DEVIATION OF THEORETICAL FROM EXPERIMENTAL FIBER STRESS AT PROPORTIONAL LIMIT VALUES (PERCENTAGE OF THE EXPERIMENTAL VALUE)

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	−12	−8	−12	−15	−11	−16
1/20	− 4	−5	− 5	− 6	− 4	−13
1/40	+ 8	+6	− 1	−15	+ 3	−10
1/60	+25	+6	+ 2	−14	− 5	− 1

Values presented in Table 6 indicate that if the limit of proportionality was reached first in the outermost fiber, either the fiber stress at proportional limit was reduced or the modulus of elasticity of the outermost fiber was increased with decreasing veneer thickness in all laminates except those bonded with the film-type phenol resin. Inasmuch as the effective modulus of elasticity of the laminate was improved, the possibility that a sufficient amount of adhesive had penetrated to the outermost fibers to improve their elasticity without appreciably increasing their proportional limit cannot be discounted. It appears more probable, however, that the limit of proportionality was first reached in the glue-line zone in laminates of the thinner veneers bonded with some adhesives. The fiber stress at proportional limit of any laminate consisting of layers parallel to the loaded face which differ in strength and elastic properties is limited by the layer with the lowest ratio of fiber stress at proportional limit to the product of its modulus of elasticity and distance from the neutral axis. If the adhesive increases the modulus of elasticity of the material in the vicinity of the glue line to a significantly greater extent than it does the proportional limit stress, that zone can be expected to limit the proportionality of the laminate. This condition was indicated for laminates of 1/20-, 1/40-, and 1/60-inch veneer bonded with all adhesives except the film-type phenol resin, in which the trend of the values in Table 6 suggests that the outermost fiber was limiting.

The efficient use of wood as a structural material is, in many cases, dependent upon its exceptional strength on a weight basis. A convenient expression of this property is specific strength, the strength at the specific gravity, 1.00. The strength of solid wood may be adjusted to the predicted value at the specific gravity, 1.00, by the conventional equation,

$$\frac{S}{S'} = \left(\frac{G}{G'}\right)^n,$$

in which S is the predicted strength at the specific gravity, G (1.00), S′ is the known strength at the specific gravity, G′, and n is an exponent appropriate to the variation of a particular strength property within a species. In the case of fiber stress at proportional limit, the value for n is 1.50. Based on specific values computed in this manner for comparative purposes, laminates bonded with the film-type phenol resin were more efficient in fiber stress at proportional limit than those bonded with any other adhesive. They were superior to solid wood at all thickness levels, whereas laminates bonded with the other five adhesives decreased appreciably with decreasing veneer thickness. Below the 1/10-inch veneer-thickness level of laminates bonded with liquid adhesives, only those of 1/20-inch veneer bonded with the powder-type phenol resin were equal to solid wood in specific fiber stress at proportional limit.

MODULUS OF RUPTURE

The modulus of rupture values of laminates of all veneer thicknesses bonded with all six adhesives were appreciably superior to the average value of yellow poplar similar in density to the unpressed veneer (10,400 pounds per square inch), and were improved to a significantly greater extent than was fiber stress at proportional limit. Values for laminates bonded with the resorcinol and resorcinol-phenol adhesives could not be separated statistically and were lower than for those bonded with the other four adhesives. Laminates bonded with the film-type phenol, powder-type phenol, urea, and melamine resins, in order of increasing strength, all differed significantly. Further, statistical analysis indicated that, except for the resorcinol-phenol-bonded laminates, strength increased with decreasing veneer thickness, the trend being most distinctly shown by laminates bonded with melamine formaldehyde. Improvement in modulus of rupture values by the laminating process is shown in Table 7 in which ratios of modulus of rupture of laminated veneer to that of unmodified wood are presented.

TABLE 7. RATIOS OF VALUES FOR MODULUS OF RUPTURE OF LAMINATED VENEER TO THAT OF SOLID WOOD

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.14	1.23	1.27	1.20	1.30	1.24
1/20	1.26	1.21	1.35	1.26	1.36	1.35
1/40	1.23	1.24	1.37	1.31	1.50	1.56
1/60	1.36	1.27	1.44	1.44	1.81	1.51

Uncompressed, resin-impregnated wood, in which compressive strength is appreciably improved and tensile strength is slightly reduced, is equal or somewhat inferior to solid wood in modulus of rupture. In contrast to wood-impregnating resin systems, laminated veneer still showed appreciable improvement over its wood components in modulus of rupture after the influence of veneer compression had been eliminated (Table 8). The trend of increasing strength accompanying

TABLE 8. RATIOS OF VALUES FOR MODULUS OF RUPTURE OF LAMINATED VENEER TO THOSE OF SOLID WOOD OF THE SAME SPECIFIC GRAVITY AS THE VENEER IN THE LAMINATES

Veneer Thickness (inch)	Adhesive					
	Resorcinol resin	Resorcinol-phenol resin	Powder-type phenol resin	Film-type phenol resin	Melamine resin	Urea resin
I/IO	IoU	1.20	1.27	1.17	1.26	1,20
1/20	1.23	1.18	1.23	1.22	1.28	1.23
1/40	1.23	1.21	1.15	1.24	1.33	1.38
1/60	1.33	1.20	1.18	1.31	1.55	1.34

decreasing veneer thickness was altered only for laminates bonded with the powder-type phenol resin.

It is recognized that only stress values below the proportional limit in a given lamina of a beam of composite cross section can be determined accurately by equation (2). However, an equation based on this principle is recommended for the computation of modulus of rupture of plywood (*18*), so it is reasonable to expect it to apply it to laminated wood beams where the zones of different properties are not so clearly defined. If the modulus of rupture of laminated veneer is limited by the outermost fiber, equation (3),

$$S' = \frac{E}{E_y} S,$$

should be valid when S' and E are modulus of rupture and modulus of elasticity values from test and S and E_y are the values for unmodified yellow poplar. Table 9 presents the percentage deviation of the theoretical average modulus of rupture

$$\left(\frac{E}{E_y} S\right)$$

from the average test value (S') for each veneer-thickness class bonded with each adhesive.

It is of significance that in no case is the theoretical value as high as the actual value. This indicates that factors other than an improvement in stiffness of the assembly influenced the modulus of rupture of laminates of all veneer thicknesses. An examination of load-deformation curves for

TABLE 9. THE DEVIATION OF THEORETICAL FROM EXPERIMENTAL MODULUS OF RUPTURE VALUES
(PERCENTAGE OF THE EXPERIMENTAL VALUE)

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	−22	−22	−20	−20	−23	−26
1/20	−16	−11	−16	−15	−18	−20
1/40	−13	− 9	−14	−18	−17	−26
1/60	−12	−10	−17	−21	−26	−25
Average	−15.7	−15.5	−16.8	−18.5	−21.0	−24.2

assemblies of different veneer thicknesses revealed that further conclusions drawn from the data presented in Table 9 may be seriously misleading. When the beams deflected within the limits of proportionality, the laminates of the thinner veneers were stiffer, whereas at loads approaching the maximum there was little difference in the slope of the load-deformation curves for laminates for all veneer thicknesses.

The greater resistance of laminated veneer to bending stresses than would be predicted from solid wood properties and the increasing strength shown when veneer thickness decreased indicate that the outermost fibers had an improved resistance to stress. Since it is reasonable to expect the zone into which the adhesive penetrated to be improved in compressive strength, an effective lateral support offered to the outermost fibers by the area of the glue line is strongly suggested. This theory is supported by the appearance of the bending failures in laminates of 1/40- and 1/60-inch veneer in which compression failures obvious to the unaided eye did not occur. As will be shown later, an improvement in tensile strength for laminates of thinner veneers is conclusively proven by the study. That the tension failures on the convex face of the beams were progressively more finely splintering in laminates of successively thinner veneers also indicates an improvement in the tensile strength of laminae in beams composed of thin veneer. This may contribute to the improvement in modulus of rupture over that which could be predicted from the properties of unmodified veneer.

The specific strength values of laminates, computed by the equation,

$$\frac{S}{S'} = \left(\frac{G}{G'}\right)^n,$$

in which n is 1.50, indicate that laminates bonded with the phenolic adhesives had the most favorable modulus of rupture on a weight basis. Beams of all four veneer thicknesses bonded with the film-type phenol resin and of 1/10- and 1/20-inch veneer bonded with the powder-type phenol resin were equally or more efficient than solid wood and compared favorably with those of 1/10-inch veneer bonded with the other four adhesives. For laminates bonded with all adhesives except the film-type phenol resin, however, there was a trend of decreasing specific strength accompanying decreasing veneer thickness.

Modulus of Elasticity in Static Bending

The test results indicate that the modulus of elasticity of laminated veneer is greater than that of solid wood of the same species. Of the assemblies investigated, those bonded with the melamine resin were significantly superior to laminates bonded with the powder-type phenol resin which were, in turn, superior to those bonded with the other four adhesives. Although, when laminates bonded with all adhesives were considered, a general pattern of increasing stiffness accompanied decreasing veneer thickness, distinct trends for individual veneer-adhesive systems were demonstrated only by laminates bonded with the resorcinol and melamine resins. The improvement in modulus of elasticity associated with the laminating process is shown in Table 10.

TABLE 10. RATIOS OF VALUES FOR YOUNG'S MODULUS IN STATIC BENDING AT THE SPAN-TO-DEPTH RATIO OF 27 : 1 OF LAMINATED VENEER TO THAT OF SOLID WOOD

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	0.88	0.96	1.02	0.96	0.99	0.95
1/20	1.07	1.08	1.14	1.08	1.12	1.13
1/40	1.08	1.14	1.18	1.08	1.25	1.15
1/60	1.20	1.15	1.19	1.13	1.34	1.14

The influence of the laminating process on Young's modulus was less striking than its effect on modulus of rupture. Further, when the effect of veneer compression was eliminated, the improvement in stiffness of laminates bonded with the phenolic and urea adhesives was insignificant. Moderate increases in modulus of elasticity which cannot be explained by increased veneer density were exhibited by laminates bonded with the other three adhesives. This is illustrated in Table II which presents average ratios of Young's modulus values of laminated veneer to those of solid yellow poplar having the same specific gravity as the wood in the assemblies.

TABLE II. RATIOS OF VALUES FOR YOUNG'S MODULUS IN STATIC BENDING AT THE SPAN-TO-DEPTH RATIO OF 27 : 1 OF LAMINATED VENEER TO THOSE OF SOLID WOOD OF THE SAME SPECIFIC GRAVITY AS THE VENEER IN THE LAMINATES

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	0.85	0.94	1.02	0.94	0.97	0.89
1/20	1.04	1.05	1.07	1.05	1.05	1.06
1/40	1.08	1.10	1.02	1.02	1.13	1.04
1/60	1.16	1.09	1.00	1.07	1.18	1.03

Inasmuch as the modulus of elasticity of the adhesives can be assumed to be similar to that of cast molding powders which are lower in this property than solid wood (2,6,49), the glue film between the veneers could be expected to reduce slightly the Young's modulus of the laminates. Consequently, the resin can contribute to the elasticity of the system only by effectively filling the porous structure of the veneer or by combining with the wood to yield a material with properties differing from those of either component. Since impregnation of the cell wall of wood with commonly used impregnating resins has been found to improve the modulus of elasticity only 4 to 10 percent, and improvements of 16 and 18 percent were exhibited by thin veneer laminates bonded with two of the six adhesives, a possible basic difference is indicated between wood-impregnating-resin and wood-adhesive systems in Young's modulus as well as modulus of rupture and fiber stress at proportional limit.

As in the case of modulus of rupture and fiber stress at proportional limit, specific values can also be computed for comparative purposes for Young's modulus in bending. In this case, the value for the exponent n in the equation,

$$\frac{S}{S'} = \left(\frac{G}{G'}\right)^{n},$$

is 1.25. Laminated assemblies of the study, based on specific values, were in no case as efficient as solid wood. Laminates bonded with the phenolic adhesives were consistently higher than other assemblies in specific modulus of elasticity; however, the efficiency of laminates bonded with all adhesives decreased appreciably with decreasing veneer thickness.

The modulus of rigidity of laminates bonded with the resorcinol-phenol-formaldehyde adhesive was determined through the study described on pages 10 to 17 and found to be constant for assemblies of all veneer thicknesses. The mean effective modulus of rigidity value of 57,000 pounds per square inch, approximately 54 percent of the corresponding value for solid wood, was determined for laminates in the longitudinal-radial plane. Thin veneer laminates appear to differ in this property from other forms of improved wood. The moduli of rigidity of impreg, compreg, and staypak are all reported to be superior to normal laminated wood (*16*), and according to Gunn (*19*), *Schichtholz* improves in this property as veneer thickness decreases. It is possible that the low value observed for thin veneer laminates reflects the heterogeneous nature of the glue-line area which results from irregular surfaces of the veneer sheets and consequent variations in thickness of adhesive deposits between laminae. Stress concentrations under such conditions are conceivable which could effectively increase the shearing strain for a given average unit stress.

Because of the low modulus of rigidity of the veneer laminates investigated, the influence of horizontal shearing strain on bending deformation can be expected to be greater in laminated than solid wood. By using the average modulus of rigidity of the laminated assemblies and the effective modulus of elasticity at the span-to-depth ratio at which the beams were tested, Young's modulus in bending devoid of the influence of horizontal shear can be computed by the form of equation (1),

$$E = \frac{E'}{1 - 0.3E'\left(\frac{2h}{L}\right)^2 \frac{1}{G}} \tag{4}$$

in which, E = Pure modulus of elasticity determined from tests of simple beams with the span-to-depth ratio of

$$\frac{L}{h},$$

G = Effective modulus of rigidity of laminated veneer (57,000 psi).

These values can then be used in equation (1),

$$E' = \frac{E}{1 + 0.3\left(\frac{2h}{L}\right)^2 \frac{E}{G}},$$

to compute the effective Young's modulus to be anticipated at any ratio of span to depth. The effect of span-to-depth ratio on Young's modulus for 1/10-, 1/20-, 1/40-, and 1/60-inch veneer laminates bonded with the resorcinol-phenol-formaldehyde adhesive is graphically illustrated in Figure 3. Similar curves can be expected for laminates bonded with the other adhesives.

Work to Proportional Limit in Static Bending

A theoretical value for work to proportional limit, which is directly dependent upon fiber stress at proportional limit and inversely dependent upon modulus of elasticity, may be computed by the equation,

$$W_{pl} = \frac{S^2}{18E'} \tag{5}$$

in which, W_{pl} = Work to proportional limit,
S = Fiber stress at proportional limit,
E′ = Effective modulus of elasticity in bending.

The theoretical work to proportional limit value for a solid yellow poplar beam with the ratio of span to depth of 27 to 1 and the specific gravity of 0.46 is 1.50 inch-pounds per cubic inch. Test values of all classes of laminated veneer which were investigated except those for 1/40- and

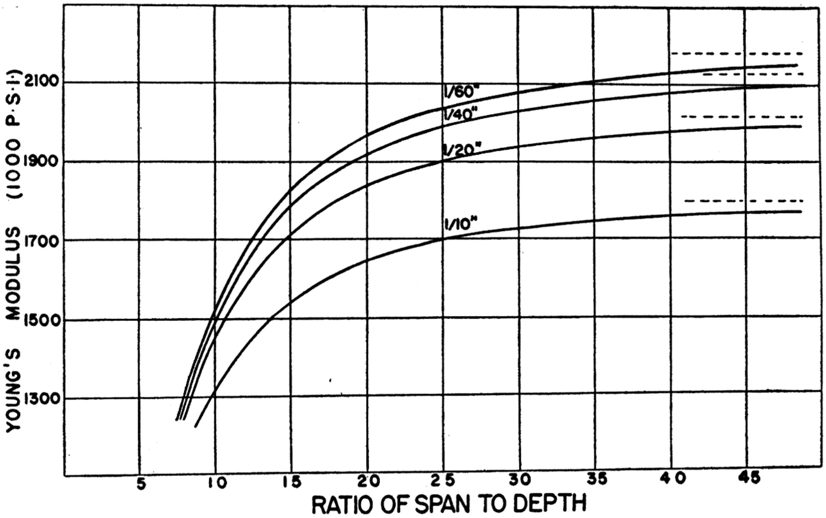

FIGURE 3. Effect of span-to-depth ratio on Young's modulus of laminated veneer.

1/60-inch veneer bonded with the resorcinol and resorcinol-phenol adhesives were superior to the theoretical value for the wood from which they were assembled (Table 12).

TABLE 12. RATIOS OF VALUES FOR WORK TO PROPORTIONAL LIMIT IN STATIC BENDING OF LAMINATED VENEER TO THAT OF SOLID WOOD

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.16	1.09	1.34	1.45	1.30	1.27
1/20	1.15	1.17	1.23	1.16	1.15	1.40
1/40	0.89	0.99	1.20	1.44	1.15	1.37
1/60	0.75	1.01	1.14	1.56	1.44	1.29

Statistical analysis indicated that assemblies bonded with the film-type phenol resin were highest in work to proportional limit and were followed in decreasing order by those bonded with (1) the urea, melamine, or powder-type phenol resins, and (2) the resorcinol or resorcinol-phenol resins. Only laminates bonded with the resorcinol resin exhibited differences of sufficient magnitude to suggest a trend of decreasing work values accompanying decreasing veneer thickness.

The appropriate exponent to be used in adjusting work to proportional limit values for the influence of specific gravity is not available from the literature. However, the theoretical value, 1.75, can be derived from the adjustment of the numerator and denominator of the general expression,

$$\frac{S^2}{18E}.$$

When the influence of the increases in specific gravity is isolated, the test results indicate that factors other than veneer compression led to a decrease in work to proportional limit accompanying decreasing veneer thickness for laminates bonded with the resorcinol, resorcinol-phenol, powder-type phenol, and urea resins. Further, the slight trend of improvement with decreasing veneer thickness for laminates bonded with the other two adhesives shown in Table 12 may be largely accounted for by the increase in veneer specific gravity. This is illustrated in Table 13.

TABLE 13. RATIOS OF VALUES FOR WORK TO PROPORTIONAL LIMIT IN STATIC BENDING OF LAMINATED VENEER TO THOSE OF SOLID WOOD OF THE SAME SPECIFIC GRAVITY AS THE VENEER IN THE LAMINATES

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.16	1.05	1.30	1.41	1.25	1.23
1/20	1.11	1.13	1.15	1.24	1.07	1.26
1/40	0.87	0.95	0.95	1.34	1.00	1.13
1/60	0.72	0.94	0.89	1.41	1.19	1.06

Inasmuch as the fiber stress at proportional limit for resin-impregnated wood is improved with little increase in modulus of elasticity, a decided increase in work to proportional limit over that of the wood in the system can be expected. Ratios presented in Table 13 support the conclusion drawn from other mechanical properties that wood-adhesive and wood-impregnating-resin systems differ basically in their mechanical behavior.

Work to Maximum Load in Static Bending

Work to maximum load in static bending, a measure of the energy required to stress a beam to failure with a static or slowly applied load, was improved by the laminating process for assemblies of all veneer thicknesses bonded with all adhesives except those of 1/20-inch veneer bonded with the film-type phenol resin. A trend toward increasing work values accompanying decreasing veneer thickness below 1/20 inch was common to laminates bonded with all adhesives. The influence of the laminating process is shown in Table 14. Although it is recognized that the size of the specimen may influence work values, methods of isolating the effect of beam size are not available. Therefore, work to maximum load values of the veneer laminates are of necessity compared with the average for 2 x 2-inch beams of yellow poplar with the specific gravity of 0.46 (7.18 inch-pounds per cubic inch).

TABLE 14. RATIOS OF VALUES FOR WORK TO MAXIMUM LOAD IN STATIC BENDING OF LAMINATED VENEER TO THAT OF SOLID WOOD

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.20	1.45	1.23	1.20	1.24	1.21
1/20	1.20	1.04	1.20	0.98	1.31	1.06
1/40	1.30	1.23	1.30	1.17	1.40	1.51
1/60	1.68	1.56	1.54	1.39	1.79	1.42

Of all strength properties investigated, work to maximum load is most influenced by specific gravity; in the equation

$$\frac{S}{S'} = \left(\frac{G}{G'}\right)^n,$$

the exponent n is 2.0. The tests, however, indicated that the increase in specific gravity resulting from veneer compression was not alone responsible for the improvement in work to maximum load. It may be seen from Table 15 that other factors also contributed appreciably to this property. Inasmuch as impregnation with phenolic and urea resins reduces work to maximum load of wood by 53 and 57 percent respectively, and when impregnation is accompanied by extreme compression, urea-impregnated wood is reduced 20 percent and phenol-formaldehyde-impregnated wood is increased but 31 percent, tests of work to maximum load accentuate the basic difference between veneer laminates and resin-impregnated wood systems.

TABLE 15. RATIOS OF VALUES FOR WORK TO MAXIMUM LOAD IN STATIC BENDING OF LAMINATED VENEER TO THOSE OF SOLID WOOD OF THE SAME SPECIFIC GRAVITY AS THE VENEER IN THE LAMINATES

Veneer Thickness (inch)	Adhesive: Resorcinol resin	Resorcinol-phenol resin	Powder-type phenol resin	Film-type phenol resin	Melamine resin	Urea resin
1/10	1.21	1.40	1.23	1.16	1.13	1.16
1/20	1.15	1.00	1.07	0.96	1.20	0.95
1/40	1.37	1.18	1.02	1.07	1.19	1.12
1/60	1.62	1.42	1.15	1.27	1.45	1.20

Ultimate Tensile Strength

Solid wood exhibits its greatest strength in tension parallel to the grain. Stern (*57*) has reported the average strength in tension parallel to the grain for solid yellow poplar with the average specific gravity of 0.43 to be 13,080 pounds per square inch. In a later publication (*58*), he has shown that within the limits of his study, tensile strength is a rectilinear function of specific gravity. Consequently, the average strength of yellow poplar with the specific gravity of 0.46 could be expected to be 14,000 pounds per square inch.

As in solid wood, thin veneer laminates were found to be stronger in tension parallel to the grain than in bending strength. Further, with the exception of laminates bonded with the urea resin, the study indicates that tensile strength may be improved by reducing the veneer thickness (Table 16). The statistical analysis indicated that laminates bonded with the resorcinol-phenol resin were superior in tensile strength to all others and that those bonded with the resorcinol and powder-type phenol resins were stronger in tension than laminates bonded with the other three adhesives. Only laminates of veneer thickness 1/20-inch and less bonded with the resorcinol, resorcinol-phenol, and powder-type phenol resins exhibited a well defined trend of increasing tensile strength accompanying decreasing veneer thickness, although 1/60-inch veneer laminates bonded with the other adhesives, with the exception of the urea resin, were superior to those of thicker veneer.

TABLE 16. RATIOS OF VALUES FOR ULTIMATE TENSILE STRENGTH PARALLEL TO THE GRAIN OF LAMINATED VENEER TO THAT OF SOLID WOOD

Veneer Thickness (inch)	Adhesive					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	0.95	1.22	1.11	1.00	1.11	0.88
1/20	1.07	1.20	0.99	0.91	1.05	1.10
1/40	1.34	1.41	1.25	0.98	0.89	1.15
1/60	1.45	1.54	1.40	1.27	1.33	1.07

With the elimination of the influence of specific gravity, the improvement in tensile strength was somewhat less pronounced, but the basic trends remained unaltered (Table 17). Laminates bonded with urea resin were not appreciably stronger in tension parallel to the grain than solid wood. However, if compression of veneer were to account for the improvement in 1/60-inch veneer laminates bonded with the resorcinol-phenol resin, the wood in the assembly would have to be compressed approximately 56 percent.

TABLE 17. RATIOS OF VALUES FOR ULTIMATE TENSILE STRENGTH PARALLEL TO THE GRAIN OF LAMINATED VENEER TO THOSE OF SOLID WOOD OF THE SAME SPECIFIC GRAVITY AS THE VENEER IN THE LAMINATES

Veneer Thickness (inch)	Adhesive					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	0.93	1.20	1.11	0.98	1.09	0.86
1/20	1.05	1.17	0.93	0.90	1.01	1.04
1/40	1.34	1.38	1.11	0.94	0.82	1.06
1/60	1.42	1.48	1.21	1.19	1.20	1.00

Inasmuch as veneer compression could account for only a relatively small percent of the improvement in tensile strength of laminates of the thinner veneers, other influences are indicated. If the tensile strength of the adhesive is assumed to be similar to that of a cast, cellulose-filled molding powder of the same basic type of resin, which is less than that of unmodified yellow poplar (*2*, *6*, *49*), it can contribute to the tensile strength of the system only by effectively filling the porous structure of the wood without reducing the strength of the cell walls or by improving the shearing resistance of wood, forcing all the cellular elements in a given cross section to fail in tension. Examination of the tension failures indicates that the latter influence is predominant.

In unmodified wood, it is probable that portions of a given cross section differ appreciably in tensile strength and that failures in weaker areas in different positions with respect to the longitudinal axis of the specimen are connected by diagonal shearing failures so that the stronger areas are ineffective in contributing lateral support. This type of failure was exhibited by laminates of 1/10- and 1/20-inch veneer. In laminates of 1/40- and 1/60-inch veneer, the tension failures tended to be increasingly more transverse, with failures in 1/60-inch veneer specimens essentially perpendicular to the direction of applied stress (Plate IV). Thus, it is indicated that the adhesive penetrating into the veneer tends to improve its resistance to shear which forces the failure to occur in the cross section of lowest average tensile strength. A similar influence of the adhesive on the tensile strength of plywood is reported by Kollmann (*31*).

Inasmuch as cell-wall impregnation with synthetic resins reduces the ultimate tensile strength parallel to the grain, it must be concluded that adhesives do not appreciably penetrate into the fine structure of the cell wall. Kitazawa (*29*) has shown that the penetrability of room-temperature setting adhesives is primarily a function of the slope of grain into the glue line and that, although the adhesive enters into the pit cavity, an appreciable amount does not pass through pit-pairs from one cell to another. Microscopical examination of the test material of the present study showed, however, that a resorcinol adhesive may pass through a fiber pit-pair and enter the cavity of an adjacent cell (Plate III). Since two cells rarely separate along the plane of the middle lamella (*17*), it appears possible for the adhesive deposits in the pit cavities to serve as connectors or keys within the cell wall thereby improving its resistance to shear.

It is probable that the superiority in tensile strength of laminates bonded with the resorcinol and resorcinol-phenol resins reflects the high percent of resin solids, an extensive degree of penetration, and a minimum concentration of stresses because of the low Young's modulus and proportional limit. The erratic behavior of melamine-bonded laminates may be explained by the sensitivity of those composed of thinner veneers to stress concentrations because of the substantial increase in Young's modulus and proportional limit values. Lack of penetration is probably reflected in low values for urea-bonded laminates, whereas the relatively small improvement imparted by the phenolic adhesives may result from the low resin-solids content of the wood-adhesive systems.

Since tensile strength is a rectilinear function of specific gravity, the specific strength may be expressed as the quotient of the unit value divided by specific gravity. Based on specific strength, the tensile strength of thin veneer laminates bonded with the resorcinol-phenol and phenol resins was improved with little sacrifice in strength-weight efficiency. Laminates of 1/60-inch veneer bonded with the film-type phenol resin were more efficient than solid wood.

Summary

The phase of the study relating to laminated wood revealed that the tensile and flexural strength and elastic properties investigated were generally improved by the laminating process with increasing improvement accompanying decreasing veneer thickness. Properties were not similarly influenced by all adhesives nor were all properties proportionately altered by any one adhesive.

Of the properties investigated, fiber stress at proportional limit was least influenced, being only moderately improved or slightly reduced when the influence of veneer compression was eliminated, whereas modulus of rupture, work to maximum load, and ultimate tensile strength were improved to the greatest extent. Test results indicate that in thin veneer laminates, (1) Young's modulus in static bending is improved as a result of increased stiffness in the area of the glue line, (2) the proportional limit is first exceeded by a zone in the vicinity of the glue line, (3) modulus of rupture is increased as a result of lateral support offered to the outermost fibers by deeper-lying ones which are influenced by the laminating process, and (4) improvement in ultimate tensile strength reflects improvement in resistance to shear and conse-

quently the development of a greater proportion of the intrinsic fiber tensile strength.

The study indicates that the increase in strength must be attributed to (1) veneer compression, (2) a filling of a portion of the porous structure with the adhesive which develops sufficient strength to reinforce the composite structure similar to filling a steel tube with brass, and (3) an improved resistance to longitudinal shear stress without improvement in rigidity, by keying together the cellular elements into which the adhesive has penetrated, probably as a result of the filling of pits and lathe checks with the adhesive. Extensive cell-wall penetration is not indicated.

MECHANICAL PROPERTIES OF PLYWOOD

Elastic Properties

When a plywood prism is stressed in bending, its deformation is dependent not only on the elastic properties of individual plies in the direction of the principal stress but also on their thickness and location in the cross section. An accepted expression of the effective modulus of elasticity of a prism of composite cross section of well defined layers differing appreciably in elastic properties is

$$E_e = \frac{1}{I} \sum E_i I_i, \qquad (6)$$

in which I is the moment of inertia of the entire cross section about the neutral axis, E_i is the Young's modulus of the i^{th} ply, and I_i is the moment of inertia of the i^{th} ply about the neutral axis of the prism (*16*, *27*). The theoretical value obtained by this equation is that of a beam devoid of shearing stresses. Theoretical values for plywood beams, oriented so that the face ply is stressed parallel to the grain, of the four veneer-thickness classes included in this study, were computed. Calculations were based on average actual veneer thicknesses for each class of assembly and average Young's modulus values for unmodified yellow poplar of the specific gravity of the unpressed veneer at 12 percent moisture content with the following results: 1,730,000, 1,300,000, 1,150,000, and 1,050,000 pounds per square inch, respectively, for panels of nominal 1/10-, 1/20-, 1/40-, and 1/60-inch veneer.

In conventional plywood beams of rotary-cut veneer, horizontal shearing stresses deform alternate layers in the tangential-radial plane. Inasmuch as the modulus of rigidity in the tangential-radial plane is only 0.01 of Young's modulus parallel to the grain, shearing deformation in beams with low ratios of span to depth may be expected to influence bending deflection appreciably. Beams in this study were tested at the ratio of 27 to 1 whereas a ratio of 48 to 1 is recommended by the American Society for Testing Materials. It was, therefore, necessary to make adjustments for shearing deformation in order to compare modulus of elasticity values for plywood to theoretical values computed from laminated and solid wood.

In order to determine the influence of shearing deformation, sufficient data were collected to compute the modulus of rigidity of one beam from each panel as described on pages 10 to 17. An analysis of variance indicated that neither veneer thickness nor adhesive influenced modulus of rigidity; therefore, the mean of all values, 14,400 pounds per square inch, is the best estimate of the effective modulus of rigidity for all assemblies. This constant value may then be used in equation (4),

$$E = \frac{E'}{1 - 0.3E'\left(\frac{2h}{L}\right)^2 \frac{1}{G}},$$

to determine the pure modulus of elasticity in bending from tests of beams with any ratio of span to depth. Similarly, pure Young's modulus values computed in this manner can be used in equation (1),

$$E' = \frac{E}{1 + 0.3\left(\frac{2h}{L}\right)^2 \frac{E}{G}},$$

to predict the effective Young's modulus at any ratio of span to depth (Figure 4). The relative influence of shearing deformation on Young's modulus of plywood and laminated wood is clearly illustrated in the comparison of Figures 3 and 4, both of which are based on laminates bonded with the resorcinol-phenol-formaldehyde adhesive.

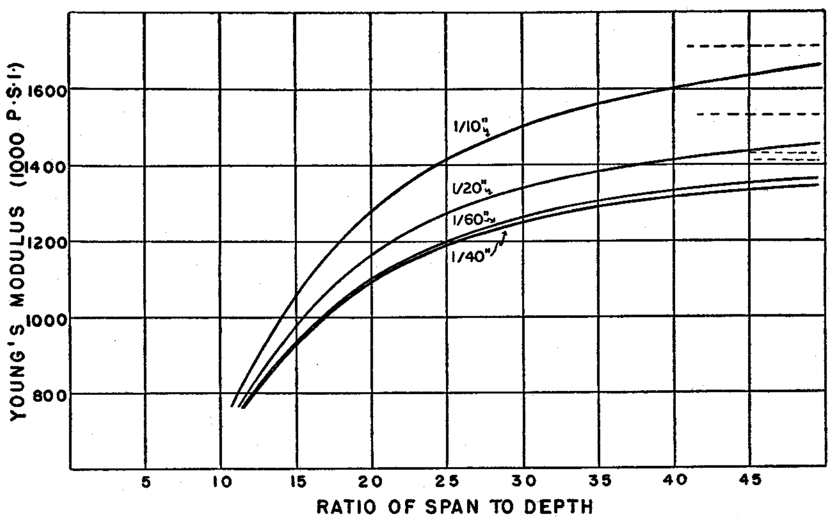

FIGURE 4. Effect of span-to-depth ratio on Young's modulus of plywood.

An analysis of variance of Young's modulus values adjusted to eliminate the influence of shearing deformation indicated that only veneer thickness influenced this property for plywood. In keeping with the theory of the mechanics of cross-ply construction, a trend toward decreasing values of Young's modulus accompanied decreasing veneer thickness when the total thickness of panel remained constant. Plywood of veneer thickness less than 1/10 inch bonded with all adhesives, however, was higher in Young's modulus than theoretical values computed from the properties of unmodified wood (Table 18).

TABLE 18. RATIOS OF VALUES FOR PURE MODULUS OF ELASTICITY IN STATIC BENDING OF PLYWOOD TO THEORETICAL VALUES BASED ON THE PROPERTIES OF SOLID WOOD

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	0.97	1.00	1.02	0.99	1.06	0.97
1/20	1.28	1.18	1.26	1.17	1.25	1.22
1/40	1.29	1.23	1.35	1.23	1.35	1.28
1/60	1.33	1.36	1.34	1.23	1.34	1.42

The superiority of the modulus of elasticity of plywood to theoretical values for this property predicted from the properties of the wood from which it was assembled is graphically illustrated in Figure 5. Inasmuch as the statistical analysis indicated that plywood was similarly influenced by all six adhesives, the use of empirical correction constants is suggested for adjusting theoretical values based on the properties of unmodified wood to values which more closely approximate those of plywood assemblies. Average ratios of values for pure Young's modulus in bending of plywood assemblies to those predicted from solid wood for 1/10-, 1/20-, 1/40-, and 1/60-inch veneer classes were respectively 1.00, 1.23, 1.29, and 1.34. It is obvious that the precision with which Young's modulus of the plywood included in this study can be predicted could be improved appreciably by the use of these empirical correction constants to modify the values resulting from conventional computations.

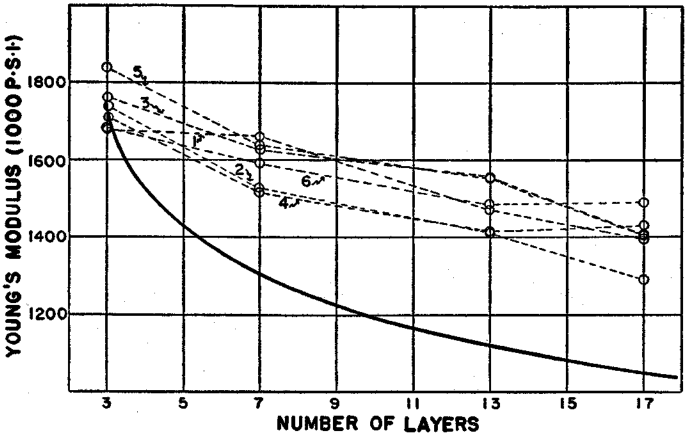

FIGURE 5. Average experimental values for pure Young's modulus of plywood beams of approximately 0.3 inch in depth compared with theoretical values based on the properties of unmodified wood. Theoretical values illustrated by the unbroken curve, are independent of veneer thickness when assemblies are square-laid plywood with all layers of the same thickness. Experimental values, connected by broken lines, are identified by numbers representing the adhesive with which the assemblies were bonded as follows: (1) resorcinol resin, (2) resorcinol-phenol resin, (3) powder-type phenol resin, (4) film-type phenol resin, (5) melamine resin, (6) urea resin.

The modulus of rigidity in the longitudinal-radial plane for laminated wood of all veneer thicknesses bonded with the resorcinol-phenol adhesive was found to be 57,600 pounds per square inch. Inasmuch as the modulus of rigidity of plywood was uninfluenced by the adhesive, it is probable that it was also constant in laminated wood. With this assumption, it is possible to compute the pure Young's modulus for laminated wood for assemblies of each veneer thickness bonded with each adhesive for which test values of beams with the ratio of span to depth of 27 to 1 are available. These computations were made similarly to corresponding ones for plywood (Page 45) by using equation (4). It was found that pure Young's modulus values were approximately 6 percent higher than experimental ones.

If Young's modulus is influenced by the laminating process similarly in plywood and laminated wood, theoretical values for plywood which are computed from the pure Young's modulus of laminated wood bonded with the same adhesive should approximate test values corrected for shearing influences. Such computations based on the properties of laminated wood were made, using equation (6). It was assumed that the ratio of Young's modulus in a tangential direction to that in a longitudinal direction remained the same as for unmodified wood. Table 19 compares plywood test values, adjusted to eliminate the influence of horizontal shear, with the computed values.

TABLE 19. RATIOS OF VALUES FOR PURE MODULUS OF ELASTICITY IN STATIC BENDING OF PLYWOOD TO THOSE COMPUTED FROM THE PROPERTIES OF LAMINATED WOOD

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.06	0.99	0.96	0.98	1.02	0.99
1/20	1.13	1.05	1.06	1.04	1.09	1.04
1/40	1.16	1.06	1.10	1.11	1.04	1.09
1/60	1.04	1.12	1.06	1.03	0.96	1.16

Although computed values for assemblies of veneer thinner than 1/10 inch were slightly lower than adjusted test values and discrepancies as great as 16 percent of the theoretical value occurred in two cases, no well defined trends of difference were established. Average ratios for laminates of 1/10-, 1/20-, 1/40-, and 1/60-inch veneer were 1.00, 1.08, 1.09, and 1.06, respectively. A comparison of Tables 18 and 19 clearly shows that values for Young's modulus computed from the properties of laminated wood conform much more closely to actual values than do those computed in the conventional manner. Therefore, when the elastic properties of laminated veneer are known, the Young's modulus, and consequently the deflection, of plywood strips of any ratio of span to depth can be computed within close limits of accuracy.

Young's modulus in tension parallel to the grain of the face veneer was determined for plywood of the four veneer thicknesses bonded with the film- and powder-type phenol and the resorcinol-phenol resins. An analysis of variance failed to reveal significant differences between thickness levels although theoretical values computed by the conventional summation equation,

$$E_e = \frac{1}{T} \sum E_i T_i,$$

in which T is the overall panel thickness and E_i and T_i are the Young's modulus and thickness of the i^{th} ply, were respectively 1,200,000, 1,020,000, 966,000, and 950,000 pounds per square inch for veneer thicknesses of 1/10, 1/20, 1/40, and 1/60 inch. Although the variability between similar samples was high, the mean values for each class of specimen, with the exception of the plywood of 1/10-inch veneer, were increasingly superior to theoretical values as veneer thickness decreased (Table 20).

TABLE 20. RATIOS OF VALUES FOR YOUNG'S MODULUS OF PLYWOOD IN TENSION PARALLEL TO THE GRAIN OF THE FACE LAMINAE TO THEORETICAL VALUES BASED ON THE PROPERTIES OF SOLID WOOD

Veneer Thickness (inch)	*Adhesive*		
	Resorcinol-phenol resin	*Powder-type phenol resin*	*Film-type phenol resin*
1/10	0.91	0.93	0.98
1/20	1.14	1.25	1.16
1/40	1.29	1.34	1.18
1/60	1.53	1.33	1.23

Tests of laminated veneer indicated that its Young's modulus is increased as a result of increased stiffness in the vicinity of the glue line and that consequently it is a material of composite cross section. Unlike solid wood, then, laminated wood could be expected to be somewhat higher in modulus of elasticity in tension parallel to the grain than in pure bending. The difference, however, should not be great so that theoretical values for Young's modulus of plywood based on the pure values for laminated wood devoid of shearing influences should correspond reasonably closely to plywood test values. Table 21 indicates that this is true.

Although theoretical and experimental values are not in perfect agreement, discrepancies exceeding 10 percent occur only in plywood of 1/10-inch veneer bonded with the powder-type phenol resin and 1/60-inch veneer bonded with the resorcinol-phenol resin. Since the experimental means are based on but two specimens, the variability between

TABLE 21. RATIOS OF VALUES FOR YOUNG'S MODULUS OF PLYWOOD IN TENSION PARALLEL TO THE GRAIN OF THE FACE LAMINAE TO THEORETICAL VALUES BASED ON THE PURE MODULUS OF ELASTICITY IN BENDING OF LAMINATED VENEER

Veneer Thickness (inch)	*Adhesive*		
	Resorcinol-phenol resin	*Powder-type phenol resin*	*Film-type phenol resin*
1/10	0.90	0.86	0.92
1/20	0.97	0.99	0.99
1/40	1.03	1.02	0.99
1/60	1.24	1.02	1.02

actual and theoretical values is considered excessive only in the case of the 1/60-inch veneer bonded with the resorcinol-phenol adhesive. Therefore, it is indicated that the elasticity of plywood in tension can be computed with reasonable accuracy from values for pure Young's modulus in bending of laminated wood, whereas computations based on the properties of solid wood may lead to serious error.

Fiber Stress at Proportional Limit in Static Bending

When a prism is stressed in flexure, the stress in any plane paralleling the neutral axis is the product of its modulus of elasticity and strain, and where the modulus of elasticity is constant throughout the cross section, the strain and consequently the stress is proportional to its distance from the neutral axis. In strips of conventionally constructed plywood, however, plies oriented with the grain parallel to the span differ significantly in Young's modulus from adjacent ones, the grain of which is perpendicular to the span. Consequently, stresses in planes other than those in the center ply are not proportional to the distance from the neutral axis; they are governed by the modulus of elasticity of the ply as well as its location. The internal unit stress in a rectangular lamina with low modulus of elasticity is equivalent to the stress that would occur in a substitute lamina of high elastic modulus if the latter were reduced in width by an amount inversely proportional to the increase in modulus of elasticity (*32*). This principle gives rise to methods of computing the stress in wood beams of composite cross section.

A commonly accepted method of applying the principle of equivalent areas described by Freas (*18*) and others (*16*, *20*, *27*) is to modify the moment of inertia term of the flexure formula by the ratio of the effective modulus of elasticity of the plywood as determined from the summation equation (E_e) to the modulus of elasticity of the plies with the grain paralleling the span (E_L). The flexure formula then becomes

$$S = \frac{MC}{KI}\left(\frac{E_L}{E_e}\right),$$

in which K is an empirically determined form factor. Freas (*18*) suggests the K value of 0.85 for stresses to rupture for plywood of the type used in this study where the outer plies are parallel to the span. Since the unit stress values of the test beams were computed by the flexure formula,

$$S' = \frac{MC}{I},$$

theoretical values can be expressed by the equation

$$S' = KS\frac{E_e}{E_L} \tag{7}$$

in which S is the fiber stress at proportional limit in bending of yellow poplar with the grain paralleling the span. Theoretical fiber stress at proportional limit values computed in this manner from the properties of the wood from which the plywood was assembled were 5,700, 4,260, 3,740, and 3,470 pounds per square inch respectively for plywood strips assembled from 1/10-, 1/20-, 1/40-, and 1/60-inch veneer. These values are compared with experimental ones in Table 22.

In computing the theoretical values for fiber stress at proportional limit, the value used for S was that determined from beams with the span-to-depth ratio of 14 to 1 in which approximately 10 percent of the deformation resulted from shearing strain. However, in the test beams, the span-to-depth ratio was such that approximately 15 percent of the deformation resulted from shearing strain. This may limit somewhat the application of conventional theoretical computations to the test material. If the effective modulus of elasticity (E_e) in the equation presented in the preceding paragraph were adjusted to include deformation resulting from shear, ratios of experimental to theoretical values would be increased by approximately 0.18. Consequently, the ratios are important primarily as relative values to be used in analyzing the influence of the veneer thickness and adhesive on fiber stress at proportional limit of plywood strips.

TABLE 22. RATIOS OF VALUES FOR FIBER STRESS AT PROPORTIONAL LIMIT IN STATIC BENDING OF PLYWOOD TO THEORETICAL VALUES BASED ON THE PROPERTIES OF SOLID WOOD

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	0.76	0.95	0.90	0.95	0.94	0.90
1/20	1.00	0.95	1.25	1.18	0.99	1.13
1/40	1.01	0.92	1.26	1.16	1.00	1.11
1/60	0.99	0.98	1.15	1.15	0.91	1.36

The analysis of variance indicated that the assemblies bonded with the resorcinol, resorcinol-phenol, and melamine resins were similar in fiber stress at proportional limit and inferior in this property to those bonded with the other three adhesives. Only laminates of 1/20-, 1/40-, and 1/60-inch veneer bonded with the powder- and film-type phenol and urea resins were appreciably stronger than would be anticipated from the properties of solid wood (Figure 6).

Theoretical computations of fiber stress at proportional limit of plywood from the properties of laminated wood are complicated by the fact that the analysis of laminated wood test data indicated that fiber stress at proportional limit was reached first in the area of the glue line in assemblies bonded with all adhesives with the possible exception of the film-type phenol resin. Further, shearing strain in plywood was much greater than that in laminated wood. Without precise information concerning the strength, elasticity, and effective thickness of the area of the glue line and information concerning the influence of shear, theoretical computations which may be expected to compare closely with experimental values cannot be made. Trends of variance resulting from computations entailing certain assumptions may be useful, however, in analyzing factors influencing strength.

Computations of theoretical plywood fiber stress at proportional limit were made under the assumptions that (1) the outermost ply has uniform properties of laminated wood of the same veneer thickness and (2) the outermost fiber is uninfluenced by the laminating process and limits this strength property of plywood. Under the first assumption, in equation (7),

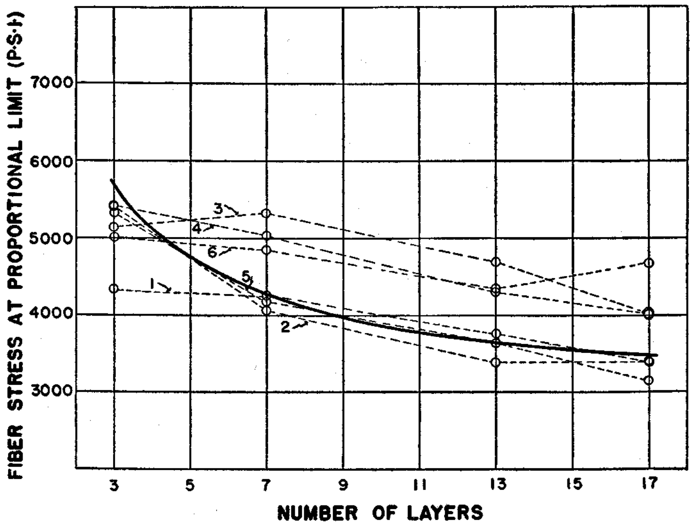

FIGURE 6. Average experimental values for fiber stress at proportional limit of plywood beams of approximately 0.3 inch in depth compared with theoretical values based on the properties of unmodified wood. Theoretical values, illustrated by the unbroken curve, are independent of veneer thickness when assemblies are square-laid plywood with all layers of the same thickness. Experimental values, connected by broken lines, are identified by numbers representing the adhesives with which the assemblies were bonded as follows: (1) resorcinol resin, (2) resorcinol-phenol resin, (3) powder-type phenol resin, (4) film-type phenol resin, (5) melamine resin, (6) urea resin.

$$S' = KS \frac{E_e}{E_L},$$

S and E_L are respectively fiber stress at proportional limit and Young's modulus of laminated wood of the same veneer thickness as the plywood under consideration, whereas under the second assumption they are those properties of unmodified wood of the same specific gravity as in the unpressed assembly. In each case E_e is the effective modulus of elasticity of the plywood strip which was determined experimentally. Values resulting from both methods of calculation are compared with experimental values in Table 23.

It may be observed from Table 23 that in neither case was agreement between experimental and theoretical values good. When the assumption

TABLE 23. RATIOS OF EXPERIMENTAL TO THEORETICAL FIBER STRESS AT PROPORTIONAL LIMIT VALUES OF PLYWOOD IN WHICH THEORETICAL VALUES ARE COMPUTED BY (1) ASSUMING OUTERMOST PLIES ARE LIMITING AND (2) ASSUMING OUTERMOST FIBERS ARE LIMITING

	Adhesive											
Veneer Thickness (inch)	*Resorcinol resin*		*Resorcinol-phenol resin*		*Powder-type phenol resin*		*Film-type phenol resin*		*Melamine resin*		*Urea resin*	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
1/10	0.82	0.95	1.03	1.13	0.92	1.05	0.96	1.11	0.93	1.06	0.92	1.07
1/20	0.89	0.92	0.93	0.95	1.12	1.19	0.98	1.19	0.84	0.93	0.99	1.09
1/40	1.00	0.92	0.93	0.87	1.09	1.10	0.92	1.07	0.89	0.85	0.95	1.04
1/60	1.05	0.85	0.92	0.87	1.02	1.00	0.92	1.07	0.74	0.77	1.10	1.13

was made that the outermost fiber is limiting (column 2), a general trend of decrease in ratios of experimental to theoretical values with decreasing veneer thickness for laminates of veneer less than 1/10 inch resulted except in the case of assemblies bonded with urea formaldehyde, thus strengthening the conclusion drawn from laminated beam data that the area of the glue line is first to be stressed in excess of the proportional limit. Although no trends were evident from calculations based on the assumption that the unmodified outermost fiber is limiting, experimental and theoretical values were too divergent to warrant the conclusion that this assumption is valid. Either theory, however, leads to a value which is more reliable than that computed in the conventional manner. It may be noted that if the form factor were omitted, all ratios would be appreciably lower.

The ratio of theoretical values based on the properties of solid wood for modulus of rupture to fiber stress at proportional limit for plywood of all veneer thicknesses is 1.70. However, as in the case of laminated wood, the ratios for experimental values for plywood increased appreciably as veneer thickness decreased which clearly illustrates that modulus of rupture of plywood was improved to a much greater degree than fiber stress at proportional limit (Table 24). Inasmuch as laminated wood data indicated similar comparative values, it is strongly suggested that the proportional limit of a zone in the area of the glue line is first exceeded in laminates of thinner veneers whereas modulus of rupture is dependent upon the reinforced strength of the outermost fibers.

TABLE 24. RATIOS OF MODULUS OF RUPTURE TO FIBER STRESS AT PROPORTIONAL LIMIT FOR PLYWOOD

Veneer Thickness (inch)	*Adhesive*					
	Resorcinol resin	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.97	1.80	1.76	1.71	1.90	1.73
1/20	2.05	2.23	1.77	1.71	2.27	1.99
1/40	2.36	2.31	1.93	2.02	2.57	2.08
1/60	2.56	2.73	2.30	2.20	3.18	2.21

Modulus of Rupture

As in the case of fiber stress at proportional limit, an accepted equation to be used in computing the modulus of rupture of plywood is

$$S = \frac{MC}{KI}\left(\frac{E_L}{E_e}\right),$$

which, for computations of theoretical values for the test strips becomes equation (7),

$$S' = KS\frac{E_e}{E_L},$$

in which S' is the modulus of rupture of the assembly and S is the modulus of rupture of the outermost ply. Computed values for assemblies of 1/10-, 1/20-, 1/40-, and 1/60-inch veneer were respectively 8,550, 6,600, 5,670, and 5,180 pounds per square inch.

Of all the strength properties evaluated, modulus of rupture of plywood was improved over theoretical values based on the properties of solid wood to the most pronounced degree. Plywood test values of assemblies of 1/20-inch and thinner veneer were higher than theoretical values and a distinct trend of improvement over theoretical values accompanied decreasing veneer thickness (Figure 7). The statistical analysis indicated that the improvement in strength of laminates of thinner veneers was sufficiently great to obscure the theoretical trend of decreasing strength accompanying decreasing veneer thickness when assemblies bonded with all adhesives were considered. The analysis further indicated that the laminates bonded with the urea and melamine adhesives were

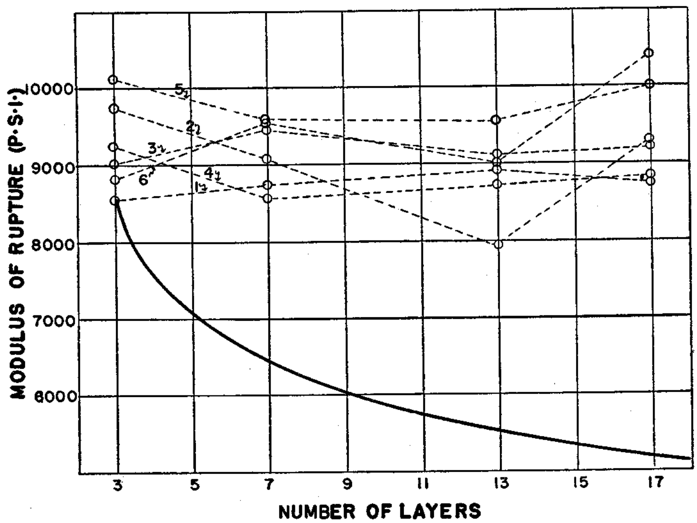

FIGURE 7. Average experimental values for modulus of rupture of plywood beams of approximately 0.3 inch in depth compared with theoretical values based on the properties of unmodified wood. Theoretical values, illustrated by the unbroken curve, are independent of veneer thickness when assemblies are square-laid plywood with all layers of the same thickness. Experimental values, connected by broken lines, are identified by numbers representing the adhesive with which the assemblies were bonded as follows: (1) resorcinol resin, (2) resorcinol-phenol resin, (3) powder-type phenol resin, (4) film-type phenol resin, (5) melamine resin, (6) urea resin.

strongest, those bonded with the powdered phenolic adhesive were intermediate, and those bonded with the film-type phenolic, resorcinol-phenol, and resorcinol adhesives were weakest. Experimental and theoretical values are compared in Table 25.

The analysis of data from tests of laminated wood indicated that modulus of rupture was improved largely as a result of the lateral support afforded to the outermost fibers by the deeper-lying areas which were increased in tensile and compressive strength by the laminating process. The data further suggested that the improvement in Young's modulus resulted from increased stiffness in the area of the glue line. Since an improvement in the modulus of rupture of plywood may result from an improvement in the ratio of the effective modulus of elasticity of the assembly to that of the limiting fiber, an improvement in the ulti-

TABLE 25. RATIOS OF VALUES FOR MODULUS OF RUPTURE OF PLYWOOD TO THEORETICAL VALUES BASED ON THE PROPERTIES OF SOLID WOOD

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.00	1.14	1.06	1.08	1.18	1.03
1/20	1.32	1.37	1.43	1.30	1.45	1.45
1/40	1·57	1.40	1.61	1·54	1.68	1.60
1/60	1.69	1·79	1.78	1.70	1·94	2.01

mate strength of the limiting fiber, or a combination of the two, it is not surprising that the values for the test material so greatly exceeded the theoretical ones computed in the conventional manner.

If the laminating process influenced the modulus of rupture of plywood and laminated wood similarly, it should be possible to predict values for plywood from those of laminated wood of the same veneer thickness bonded with the same adhesive by assuming that the outermost fiber of plywood has the same bending strength as laminated wood of the same components and the elasticity of the unmodified wood from which the plywood was assembled. Since laminated-wood data did not conclusively prove that Young's modulus was increased only in the glue-line area, theoretical plywood values were computed for comparative purposes with the assumptions that the elasticity of the outermost fiber is that of (I) laminated wood of the same veneer thickness bonded with the same adhesive and (2) the average value for unmodified veneer from which the plywood was assembled. In each case the strength of the outermost fiber was considered to be that of laminated wood of the same components and the effective Young's modulus was that from plywood test. The agreement between values computed by each assumption and those from tests is shown in Table 26.

Ratios presented in Table 26 strongly indicate that the improvement in modulus of elasticity of thin veneer laminates is confined to the area of the glue line, whereas the ultimate strength of the outermost fiber is appreciably greater than that of solid wood. When this assumption was made, the ratios of experimental to theoretical values exhibited no well defined trends, and serious discrepancies between experimental and

TABLE 26. RATIOS OF EXPERIMENTAL TO THEORETICAL VALUES FOR MODULUS OF RUPTURE OF PLYWOOD

Veneer Thickness (inch)	Adhesive: Resorcinol resin (1)*	Resorcinol resin (2)†	Resorcinol-phenol resin (1)	Resorcinol-phenol resin (2)	Powder-type phenol resin (1)	Powder-type phenol resin (2)	Film-type phenol resin (1)	Film-type phenol resin (2)	Melamine resin (1)	Melamine resin (2)	Urea resin (1)	Urea resin (2)
1/10	0.95	1.08	1.04	1.09	0.98	1.02	1.02	1.06	1.01	1.02	0.92	1.00
1/20	1.07	0.99	1.11	1.04	1.18	1.03	1.14	1.06	1.13	1.01	1.20	1.06
1/40	1.24	1.15	1.20	1.07	1.21	1.02	1.17	1.08	1.21	0.97	1.07	0.93
1/60	1.25	1.05	1.37	1.19	1.27	1.06	1.22	1.08	1.24	0.94	1.25	1.04

*Ratios of experimental values to those computed by the equation,

$$S' = KS\frac{E_e}{E_L},$$

in which K is 0.85, E_e is the experimental modulus of elasticity of the plywood assembly and E_L and S are respectively the average experimental modulus of elasticity and modulus of rupture of laminated wood of the same veneer thickness bonded with the same adhesive.

†Ratios of experimental values to those computed by the equation,

$$S' = KS\frac{E_e}{E_L},$$

in which K is 0.85, E_e is the experimental modulus of elasticity of the plywood assembly, E_L is the modulus of elasticity of solid yellow poplar with the specific gravity of 0.46 and S is the modulus of rupture of laminated wood of the same veneer thickness bonded with the same adhesive.

theoretical values resulted only in the case of 1/40-inch veneer plywood bonded with the resorcinol adhesive and 1/60-inch veneer bonded with the resorcinol-phenol adhesive. Agreement would have been somewhat poorer if the effective Young's modulus of the assembly devoid of shearing influences had been used instead of test values. When it was assumed that the elasticity of the outermost fiber is similar to that of the laminated veneer, theoretical values became increasingly less than actual ones as veneer thickness decreased.

It has been shown in previous sections that the pure modulus of elasticity of plywood can be computed with reasonable accuracy from the modulus of elasticity of laminated wood of similar veneer thickness bonded with the same adhesive and that this value can be adjusted to the effective value (E_e) for any ratio of span to depth. Thus it is apparent that modulus of rupture of thin-veneer plywood can be more accurately predicted from a combination of the properties of laminated wood of the same veneer thickness bonded with the same adhesive and of solid wood than from the properties of solid wood alone.

Work to Proportional Limit and Work to Maximum Load in Static Bending

As in the case of laminated wood, a theoretical value for work to proportional limit of a simple, center-loaded plywood beam may be expressed by equation (5),

$$W_{pl} = \frac{S^2}{18E},$$

in which S is fiber stress at proportional limit and E is modulus of elasticity. For theoretical values of plywood, S in the above equation is the fiber stress at proportional limit of the plywood strip computed in the conventional manner and E is the effective modulus of elasticity (E_e) computed by the summation method and adjusted to include the influence of horizontal shear. Theoretical values are 1.23, 0.90, 0.76, and 0.71 inch-pounds per cubic inch respectively for plywood of 1/10-, 1/20-, 1/40-, and 1/60-inch veneer. Experimental values for plywood bonded with the resorcinol, resorcinol-phenol, and melamine resins were statistically similar and somewhat lower than these, whereas values for plywood bonded with the other three adhesives were significantly superior statistically in this property and (with the exception of those for assemblies of 1/10-inch veneer) were as high or higher than the theoretical values. No consistent trends of deviation from theoretical values were exhibited by plywood bonded with any adhesive.

Work to maximum load of plywood is dependent upon the flexural strength and the deformation of a beam under its maximum load. Inasmuch as bending deflections can be predicted only within the range of proportionality, theoretical values of work to maximum load cannot be computed. It might be expected, however, that work to maximum load of plywood would be appreciably lower than that of solid wood with the grain paralleling the span and that a decrease in this property would accompany a decrease in veneer thickness. It is of significance, therefore, that only plywood bonded with the film-type phenol resin was appreciably inferior to solid wood on the basis of work values determined for the latter from 2 x 2-inch specimens. Although it is recognized that work values of beams of different cross-sectional dimensions are not strictly comparable, it would appear that the desirable properties of thin veneer plywood bonded with all adhesives studied except the film-type phenol resin can be attained without sacrifice of shock resistance.

ULTIMATE TENSILE STRENGTH

There are two theories relating to the computation of the ultimate stress of square-laid plywood in tension. Of these, the most widely accepted is the theory of maximum stress which assumes that failure will result when plies paralleling the direction of applied force, acting independently of the perpendicular plies, are stressed to the point of failure (*16*, *27*). Thus, for plywood of one species and uniform veneer thickness as investigated in this study, the ultimate tensile stress may be expressed by the equation,

$$S = \frac{1}{T} n \, (T_L S_L)$$

in which T is the overall thickness of the assembly, n is the number of layers with grain paralleling the direction of applied stress, and T_L and S_L are respectively the thickness and ultimate tensile stress of an individual ply paralleling the direction of stress. According to the other theory, deformation is essentially proportional to load until failure occurs and the contribution of the perpendicular plies to the stiffness of the assembly may be considered. The ultimate strength is limited by the ply that fails with the least strain. Thus, the ultimate strain of the plywood,

$$\frac{S}{E_e},$$

in which S is the ultimate unit tensile stress and E_e is the effective modulus of elasticity, is equal to

$$\frac{S_L}{E_L},$$

in which S_L and E_L are respectively the ultimate tensile stress and modulus of elasticity of the limiting ply; or

$$S = \frac{S_L}{E_L} E_e .$$

Theoretical values computed by the two methods differ insignificantly.

As in the case of the other properties evaluated, the ultimate tensile strength was not accurately predicted from this property of unmodified wood (Table 27). When all veneer thicknesses were considered, panels bonded with the resorcinol-phenol and powder-type phenol resins exhibited the greatest strength, those bonded with the resorcinol resin were intermediate, and those bonded with the film-type phenol, melamine, and urea resins were low. Further, a general trend of improvement accompanied decreasing veneer thickness. The behavior of assemblies of different veneer thicknesses was in general extremely erratic, however (Figure 8).

If the theory of maximum stress is assumed, the ratios presented in Tables 27 and 16 should be approximately the same providing that ply-

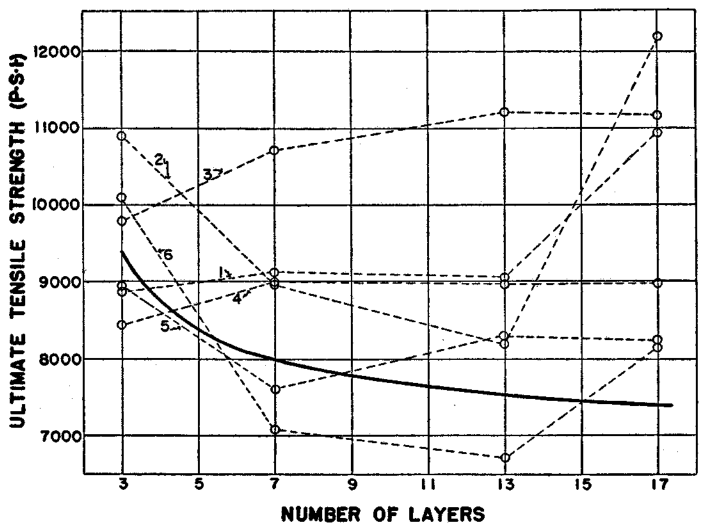

FIGURE 8. Average experimental values for ultimate tensile strength of plywood beams of approximately 0.3 inch in depth compared with theoretical values based on the properties of unmodified wood. Theoretical values, illustrated by the unbroken curve, are independent of veneer thickness when assemblies are square-laid plywood with all layers of the same thickness. Experimental values, connected by broken lines, are identified by numbers representing the adhesives with which the assemblies were bonded as follows: (1) resorcinol resin, (2) resorcinol-phenol resin, (3) powder-type phenol resin, (4) film-type phenol resin, (5) melamine resin, (6) urea resin.

TABLE 27. RATIOS OF VALUES FOR ULTIMATE TENSILE STRENGTH OF PLYWOOD TO THOSE BASED ON THE PROPERTIES OF SOLID WOOD

Veneer Thickness (inch)	Adhesive					
	Resorcinol resin	Resorcinol-phenol resin	Powder-type phenol resin	Film-type phenol resin	Melamine resin	Urea resin
1/10	0.95	1.17	1.05	0.90	0.96	1.09
1/20	1.14	1.12	1.33	1.12	0.95	0.89
1/40	1.20	1.09	1.49	1.19	1.10	0.89
1/60	1.47	1.64	1.51	1.21	1.11	1.10

wood and laminated wood were similarly influenced in the process of fabrication. With very few exceptions, however, differences between ratios are appreciable, indicating clearly that theoretical plywood values based on the tensile strength of laminated wood cannot agree precisely with experimental results. The accuracy of predicting plywood values according to the theory of maximum stress can, however, be appreciably improved by using the tensile strength of laminated wood instead of solid wood in the equation,

$$S' = \frac{1}{T} n(T_L S_L),$$

the results of which are given in Table 28. It may be noted that where ratios presented in Tables 27 and 16 are similar, those in Table 28 are approximately 1.00, indicating that the theory of maximum stress is valid.

If it is assumed that the pure modulus of elasticity of laminated wood in bending and tension is similar, theoretical values for ultimate tensile strength of plywood can be computed according to the theory of maximum strain by the equation,

$$S = \frac{S_L}{E_L} E_e,$$

in which S_L and E_L are respectively the ultimate tensile stress and pure modulus of elasticity in bending of laminated wood of corresponding veneer thickness and adhesive and E_e is the effective modulus of elasticity of the plywood computed from the properties of laminated wood. There is little difference between values computed according to the two

TABLE 28. RATIOS OF EXPERIMENTAL VALUES FOR ULTIMATE TENSILE STRENGTH OF PLYWOOD TO THEORETICAL ONES COMPUTED ACCORDING TO THE THEORY OF MAXIMUM STRESS

	Adhesive					
Veneer Thickness (inch)	*Resorcinol resin*	*Resorcinol-phenol resin*	*Powder-type phenol resin*	*Film-type phenol resin*	*Melamine resin*	*Urea resin*
1/10	1.00	0.96	0.94	0.90	0.86	1.23
1/20	1.06	0.94	1.35	1.23	0.90	0.80
1/40	0.90	0.77	1.19	1.21	1.23	0.77
1/60	1.00	1.06	1.08	0.95	0.84	1.03

theories, indicating that either can be used with approximately the same accuracy. By either method, the greatest improvement in computations of ultimate tensile strength of plywood from the properties of laminated wood was for assemblies of 1/40- and 1/60-inch veneer.

Summary

As in the case of laminated wood, the tensile and flexural strength and elastic properties determined for conventional plywood of thin yellow poplar veneer were generally increasingly greater as veneer thickness decreased than would be predicted from the solid wood components. The experiment suggests that the properties of plywood and laminated wood are basically influenced similarly by the process of bonding with synthetic resin adhesives; the effect, however, is reflected somewhat differently in the flexural properties of the two types of construction due to the mechanics of materials of composite cross section.

The study indicates that the properties of plywood can be predicted more accurately from similar properties of laminated wood of the same veneer thickness bonded with the same adhesive than from unmodified wood. It appears that theoretical computations of fiber stress at proportional limit based on the properties of laminated veneer are limited in accuracy by the fact that, as in laminated construction, proportionality is first exceeded by a zone in the vicinity of the glue line. Satisfactory Young's modulus values for plywood can be computed from values for laminated wood by assuming that the elastic properties of veneer assemblies are improved uniformly throughout the cross section. However, theoretical values for modulus of rupture must be based on the assumption that the outermost ply can resist a stress similar to that resisted by a laminated strip of the same combination of adhesive and veneer thickness, but is not uniformly improved in stiffness, the outermost fiber being the same as solid wood in this respect. Except for assemblies bonded with the film-type phenol resin, work values indicate that improvement in plywood flexural strength is not accompanied by a decrease in shock resistance. Ultimate tensile strength of plywood can be predicted more accurately from values for laminated veneer than solid wood properties by assuming that strength is uniformly improved throughout the cross section by the laminating process, but agreement between actual and theoretical values is generally not completely satisfactory.

CONCLUSIONS

POSITIVE conclusions from the foregoing study must necessarily be limited to the specific materials used under the conditions of the investigation. Certain facts and theories which have been brought out by the investigation, however, enhance our understanding of the basic behavior of veneer-adhesive systems and open avenues for study which can lead to an improvement in the precision of design techniques.

The study has led to the following conclusions:

Synthetic resin adhesives increase the specific gravity of laminates of thin veneer by the addition of resin solids and the plasticizing of the cell walls which results in residual compression. When the adhesive spread is held constant, the specific gravity and percent of compression increase as veneer thickness decreases.

The oven-dry weight per unit volume of plywood is reduced as a result of lateral restraint of the cross plies and may be appreciably less than that of laminated wood of the same veneer thickness. Also, certain volatile constituents of the adhesives which are not released during normal conditioning may be driven off in oven-drying leading to abnormally high weight losses for given conditions of moisture content and, consequently, to misleading moisture content values when determined by the oven-drying method.

In both plywood and laminated wood construction, the modulus of elasticity of a zone in the vicinity of the glue line is improved because of compression of veneer and penetration of the adhesive into the cellular structure. As a result of this effect, moderate improvement is shown in the modulus of elasticity of the laminates in both bending and tension.

The additional deflection of beams of thin veneer in both plywood and laminated wood form resulting from deformation in horizontal shear can be accurately predicted from equations established from the theory of strain energy in bending when the pure modulus of elasticity and modulus of rigidity are known. Consequently, the effective modulus of rigidity can be indirectly determined from the effective modulus of elasticity of a center-loaded beam at any ratio of span to depth and the pure modulus of elasticity in bending computed from the difference in deformation at mid-span and load points of a beam loaded at third points. The average effective modulus of rigidity thus determined can be used to compute the pure Young's modulus of beams tested at any ratio of span to depth, and to predict from these values the effective Young's modulus at any other ratio of span to depth.

The modulus of rigidity in the longitudinal-radial plane of laminated veneer and in the combined tangential-radial and longitudinal-radial plane of plywood stressed in the plane of the glue line is independent of veneer thickness and adhesive and is slightly lower than the value for solid wood in similar planes.

Young's modulus of plywood in tension or in bending at any ratio of span to depth can be computed more reliably from the elastic properties of laminated veneer of the same thickness bonded with the same adhesive than from those of solid wood.

Fiber stress at proportional limit in both plywood and laminated wood is first exceeded in a zone in the vicinity of the glue line except in laminates bonded with the film-type phenol resin. Constructions of thin veneer are improved only slightly in this property by the laminating process.

When compared with values based on the properties of solid wood, modulus of rupture of plywood and laminated veneer increases significantly with decreasing veneer thickness. Ratios of modulus of rupture to fiber stress at proportional limit for both types of construction increase appreciably as veneer thickness decreases, indicating the marked difference in the degree to which the two properties are influenced.

Modulus of rupture of veneer laminates is improved largely as the result of lateral support in compression and tension offered to the outermost fibers by the area of the glue line. The basic influence is similar for laminated wood and plywood. Consequently, modulus of rupture values for plywood can be computed with reasonable accuracy from values for laminated wood of the same veneer thickness bonded with the same adhesive by assuming that the stress that can be resisted by the outermost ply is the same as that for laminated wood, the modulus of elasticity of the outermost fiber is unchanged by the laminating process, and the modulus of elasticity of the assembly is that computed from the elastic properties of laminated wood and adjusted for the influence of horizontal shear.

Work to proportional limit in static bending is only slightly improved in both types of construction by some adhesives. Work to maximum load of laminated wood, however, bonded with the six adhesives studied increases above that of solid wood, determined from specimens which are 2 x 2 inches in cross section, as veneer thickness decreases below 1/20 inch. Work to maximum load of plywood bonded with all adhesives studied except the film-type phenol resin is greater than the average for standard specimens of solid wood. Although the difference in dimensions of the test beams and standard small clear specimens limits somewhat the conclusions to be drawn from comparative values for work to maximum load, the results suggest that thin veneer plywood is superior to solid wood in shock resistance.

When compared with values based on the properties of solid wood, the ultimate tensile strength of veneer laminates in both plywood and laminated wood form increases as veneer thickness decreases below 1/20 inch. The failures of laminated wood indicate that the increase results from an improvement in resistance to longitudinal shear thereby forcing the assembly to fail more nearly in simple tension in one cross-sectional plane.

Although the agreement between experimental and theoretical tensile strength values is not completely satisfactory, plywood values may be predicted more closely from the ultimate tensile strength of laminated wood than from solid wood properties. Theoretical values can be predicted with equal accuracy from the theories of maximum stress and maximum strain.

Laminates bonded with phenolic adhesives have the greatest strength-weight efficiency, but this efficiency is superior to that of solid wood only in ultimate tensile strength and modulus of rupture for laminated veneer bonded with the phenolic adhesives.

The influence on the properties of wood of synthetic resin adhesives differs basically from that of impregnating resins of small molecular size. The mechanical properties of veneer laminates indicate that wood adhesives do not appreciably impregnate the cell wall.

Improvement in the mechanical properties of veneer-adhesive systems above those of solid wood may be attributed to (1) veneer compression in the vicinity of the glue line, (2) deposits of polymerized adhesive in the porous structure of the veneer, and (3) deposits of polymerized adhesive in pits and torn areas of the cell wall, thereby improving resistance to longitudinal shear.

The strength properties evaluated are in many cases improved to different degrees by the various adhesives but in no case are all strength properties improved to the same relative degree by any given adhesive.

The thickness of the veneer in laminated wood assemblies bonded with the synthetic resin adhesives included in the investigation has an important influence on most strength and elastic properties. With the exception of modulus of rigidity, the mechanical properties included in the study increase as veneer thickness decreases. The efficiency of design of plywood and laminated veneer structures could be greatly enhanced by the perfection of techniques which would permit the consideration of the improvement imparted to thin veneer laminates by fundamental glue-line properties. This study has demonstrated that the properties of plywood can be predicted with reasonable accuracy when the properties of laminated wood of the same veneer thickness are known. Before this method can be used extensively in design practice, however, further investigation is needed to provide methods of predicting the influence of fundamental glue-line properties on the strength of laminated veneer.

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APPENDIX

TABLE 29. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF LAMINATED YELLOW POPLAR VENEER BONDED WITH THE RESORCINOL RESIN

		Static Bending					Tension Parallel to Grain
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Ultimate Tensile Strength (psi)*
1/10	0.50	6,950	11,700	1,560	1.74	9.33	13,300
1/20	0.62	7,670	13,100	1,900	1.73	9.29	15,000
1/40	0.78	6,850	12,800	1,920	1.34	10.22	18,700
1/60	0.97	6,520	14,200	2,130	1.11	13.10	20,400

TABLE 30. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF LAMINATED YELLOW POPLAR VENEER BONDED WITH THE RESORCINOL-PHENOL RESIN

		Static Bending					Tension Parallel to Grain
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Ultimate Tensile Strength (psi)*
1/10	0.51	7,240	12,800	1,710	1.63	11.30	17,100
1/20	0.61	7,750	12,600	1,910	1.76	8.10	16,700
1/40	0.72	7,280	13,000	2,010	1.46	9.56	19,800
1/60	0.84	7,270	13,300	2,060	1.55	12.10	21,600

TABLE 31. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF LAMINATED YELLOW POPLAR VENEER BONDED WITH THE POWDER-TYPE PHENOL RESIN

		Static Bending					Tension Parallel to Grain
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Ultimate Tensile Strength (psi)*
1/10	0.48	8,050	13,300	1,810	2.01	9.56	15,500
1/20	0.55	8,370	14,100	2,040	1.91	9.34	13,900
1/40	0.64	8,220	14,300	2,120	1.79	10.20	17,600
1/60	0.71	8,050	14,900	2,120	1.70	11.80	19,600

TABLE 32. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF LAMINATED YELLOW POPLAR VENEER BONDED WITH THE FILM-TYPE PHENOL RESIN

		Static Bending					Tension Parallel to Grain
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Ultimate Tensile Strength (psi)*
1/10	0.47	7,820	12,500	1,710	2.18	9.39	14,000
1/20	0.51	7,820	13,100	1,920	1.74	7.77	12,800
1/40	0.54	8,630	13,700	1,920	2.16	9.11	13,800
1/60	0.57	9,010	15,000	2,010	2.34	10.80	17,800

TABLE 33. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF LAMINATED YELLOW POPLAR VENEER BONDED WITH THE MELAMINE RESIN

Veneer Thickness (inch)	*Specific Gravity*	*Static Bending*					*Tension Parallel to Grain*
		Fiber Stress at Proportional Limit (psi)	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Ultimate Tensile Strength (psi)*
1/10	0.51	7,800	13,500	1,770	1.95	9.64	15,600
1/20	0.60	7,900	14,200	1,990	1.73	10.20	14,700
1/40	0.75	8,300	15,600	2,230	1.73	10.90	12,500
1/60	0.90	9,700	18,900	2,390	2.17	14.00	18,700

TABLE 34. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF LAMINATED YELLOW POPLAR VENEER BONDED WITH THE UREA RESIN

Veneer Thickness (inch)	*Specific Gravity*	*Static Bending*					*Tension Parallel to Grain*
		Fiber Stress at Proportional Limit (psi)	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Ultimate Tensile Strength (psi)*
1/10	0.54	7,460	12,900	1,620	1.91	9.41	12,400
1/20	0.67	8,650	14,100	2,010	2.10	8.21	15,500
1/40	0.87	8,670	16,300	2,050	2.05	10.80	16,200
1/60	0.90	8,360	15,800	2,030	1.94	11.00	15,000

TABLE 35. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF YELLOW POPLAR PLYWOOD BONDED WITH THE RESORCINOL RESIN

		Static Bending							
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E') (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Pure Modulus of Elasticity (E)* (1000 psi)*	*Modulus of Rigidity† (psi)*	*Ultimate Tensile Strength (psi)*
1/10	0.50	4,340	8,600	1,400	0.81	8.76	1,670	10,200	8,850
1/20	0.56	4,260	9,040	1,400	0.77	7.84	1,660	15,600	9,130
1/40	0.67	3,770	8,910	1,250	0.67	8.73	1,480	15,700	9,060
1/60	0.76	3,420	8,780	1,230	0.57	8.02	1,400	15,100	10,900

TABLE 36. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF YELLOW POPLAR PLYWOOD BONDED WITH THE RESORCINOL-PHENOL RESIN

		Static Bending							
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E') (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Pure Modulus of Elasticity (E)* (1000 psi)*	*Modulus of Rigidity† (psi)*	*Ultimate Tensile Strength (psi)*
1/10	0.50	5,420	9,740	1,460	1.14	9.92	1,740	10,500	10,900
1/20	0.55	4,060	9,080	1,300	0.70	8.30	1,530	14,000	8,980
1/40	0.62	3,430	7,940	1,210	0.52	7.06	1,410	15,500	8,200
1/60	0.72	3,410	9,300	1,230	0.53	9.57	1,430	12,600	12,200

*Pure modulus of elasticity average values are based on three tests, one from each of three replications.
†Modulus of rigidity average values are based on three computed values.

TABLE 37. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF YELLOW POPLAR PLYWOOD BONDED WITH THE POWDER-TYPE PHENOL RESIN

Veneer Thickness (inch)	Specific Gravity	Static Bending: Fiber Stress at Proportional Limit (psi)	Static Bending: Modulus of Rupture (psi)	Static Bending: Modulus of Elasticity (E′) (1000 psi)	Static Bending: Work to Proportional Limit (in.-lb. per cu. in.)	Static Bending: Work to Maximum Load (in.-lb. per cu. in.)	Static Bending: Pure Modulus of Elasticity (E)* (1000 psi)	Modulus of Rigidity† (psi)	Ultimate Tensile Strength (psi)
1/10	0.49	5,130	9,030	1,460	1.01	8.07	1,760	14,300	9,800
1/20	0.56	5,350	9,470	1,360	1.17	7.12	1,640	11,200	10,700
1/40	0.63	4,730	9,110	1,300	0.97	8.02	1,550	11,300	11,200
1/60	0.69	4,100	9,250	1,220	0.69	8.58	1,410	9,600	11,200

TABLE 38. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF YELLOW POPLAR PLYWOOD BONDED WITH THE FILM-TYPE PHENOL RESIN

Veneer Thickness (inch)	Specific Gravity	Static Bending: Fiber Stress at Proportional Limit (psi)	Static Bending: Modulus of Rupture (psi)	Static Bending: Modulus of Elasticity (E′) (1000 psi)	Static Bending: Work to Proportional Limit (in.-lb. per cu. in.)	Static Bending: Work to Maximum Load (in.-lb. per cu. in.)	Static Bending: Pure Modulus of Elasticity (E)* (1000 psi)	Modulus of Rigidity† (psi)	Ultimate Tensile Strength (psi)
1/10	0.46	5,390	9,240	1,450	1.12	6.48	1,720	18,600	8,440
1/20	0.49	5,090	8,580	1,290	1.10	5.61	1,520	14,100	8,990
1/40	0.54	4,340	8,740	1,230	0.80	6.13	1,410	23,400	8,960
1/60	0.57	4,010	8,810	1,150	0.79	6.27	1,290	14,700	8,950

*Pure modulus of elasticity average values are based on three tests, one from each of three replications.
†Modulus of rigidity average values are based on three computed values.

TABLE 39. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF YELLOW POPLAR PLYWOOD BONDED WITH THE MELAMINE RESIN

		Static Bending							
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Pure Modulus of Elasticity (E)* (1000 psi)*	*Modulus of Rigidity† (psi)*	*Ultimate Tensile Strength (psi)*
1/10	0.52	5,330	10,100	1,530	1.09	8.75	1,840	14,500	8,940
1/20	0.58	4,230	9,590	1,370	0.72	7.44	1,630	18,800	7,620
1/40	0.73	3,710	9,510	1,320	0.61	7.18	1,550	19,200	8,320
1/60	0.79	3,150	10,000	1,250	0.47	9.10	1,410	11,100	8,260

TABLE 40. AVERAGE STRENGTH AND ELASTIC PROPERTIES OF YELLOW POPLAR PLYWOOD BONDED WITH THE UREA RESIN

		Static Bending							
Veneer Thickness (inch)	*Specific Gravity*	*Fiber Stress at Proportional Limit (psi)*	*Modulus of Rupture (psi)*	*Modulus of Elasticity (E′) (1000 psi)*	*Work to Proportional Limit (in.-lb. per cu. in.)*	*Work to Maximum Load (in.-lb. per cu. in.)*	*Pure Modulus of Elasticity (E)* (1000 psi)*	*Modulus of Rigidity† (psi)*	*Ultimate Tensile Strength (psi)*
1/10	0.51	5,100	8,820	1,420	1.17	8.67	1,680	14,700	10,200
1/20	0.57	4,840	9,770	1,340	0.98	7.95	1,590	17,800	7,090
1/40	0.68	4,360	9,080	1,270	0.83	5.65	1,480	13,000	6,720
1/60	0.74	4,700	10,400	1,260	1.01	8.37	1,490	10,900	8,190

*Pure modulus of elasticity average values are based on three tests, one from each of three replications.
†Modulus of rigidity average values are based on three computed values.

APPENDIX

TABLE 41. AVERAGE MODULUS OF ELASTICITY VALUES OF PLYWOOD IN TENSION PARALLEL TO THE GRAIN

	Adhesive		
Veneer Thickness (inch)	*Resorcinol-phenol resin (psi)*	*Powder-type phenol resin (psi)*	*Film-type phenol resin (psi)*
1/10	1,090,000	1,110,000	1,180,000
1/20	1,160,000	1,270,000	1,180,000
1/40	1,240,000	1,300,000	1,140,000
1/60	1,450,000	1,260,000	1,170,000

PLATE SECTION

PLATE I

Equipment for testing laminates in tension showing method for gripping specimens and electrical strain indicator.

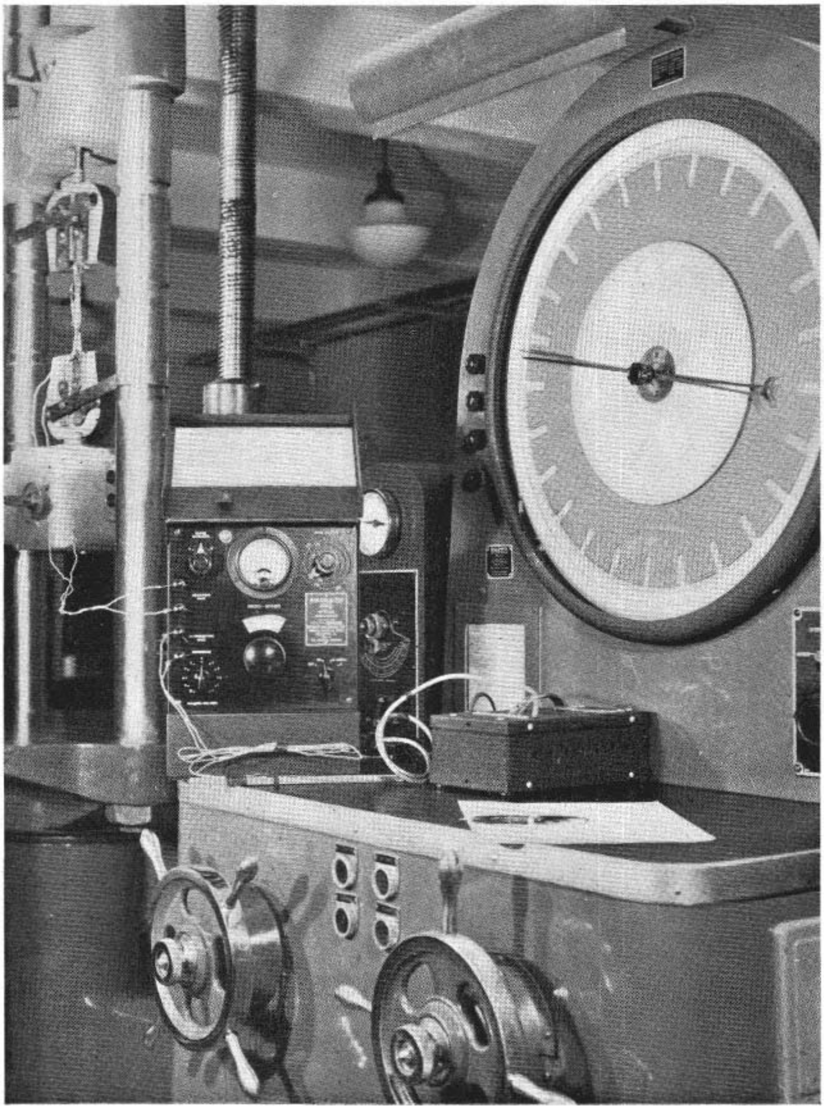


PLATE II

Cross sections of laminated veneer (IOX) showing the relative proportion of resin to wood in laminates of different veneer thicknesses and the crinkling and interlocking of rays at the glue line.

r. I/ Ia-inch veneer.
2. I/ 2o-inch veneer.
3. I/ 4o-inch veneer.
4. I/ 60-inch veneer.

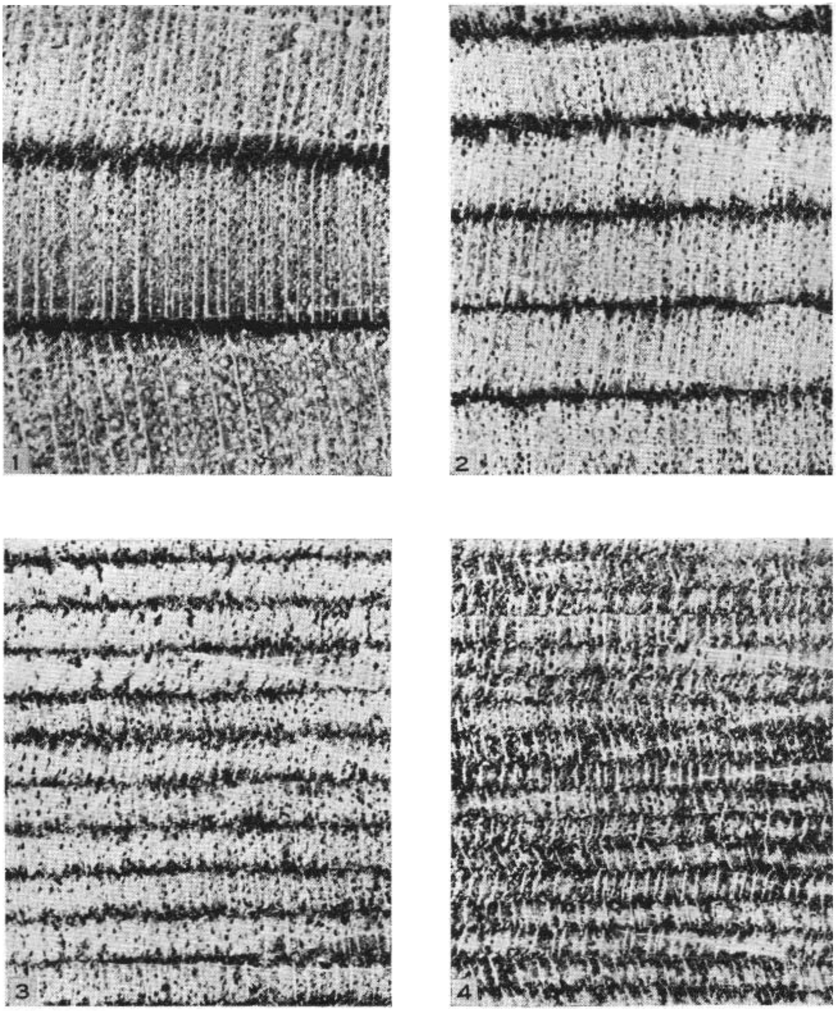

1
2
3
4

PLATE III

Photomicrograph of resorcinol glue line in laminated assembly of I/ IO-inch veneer showing the penetration of the adhesive and the deformation and dovetailing of the cellular elements (150X).

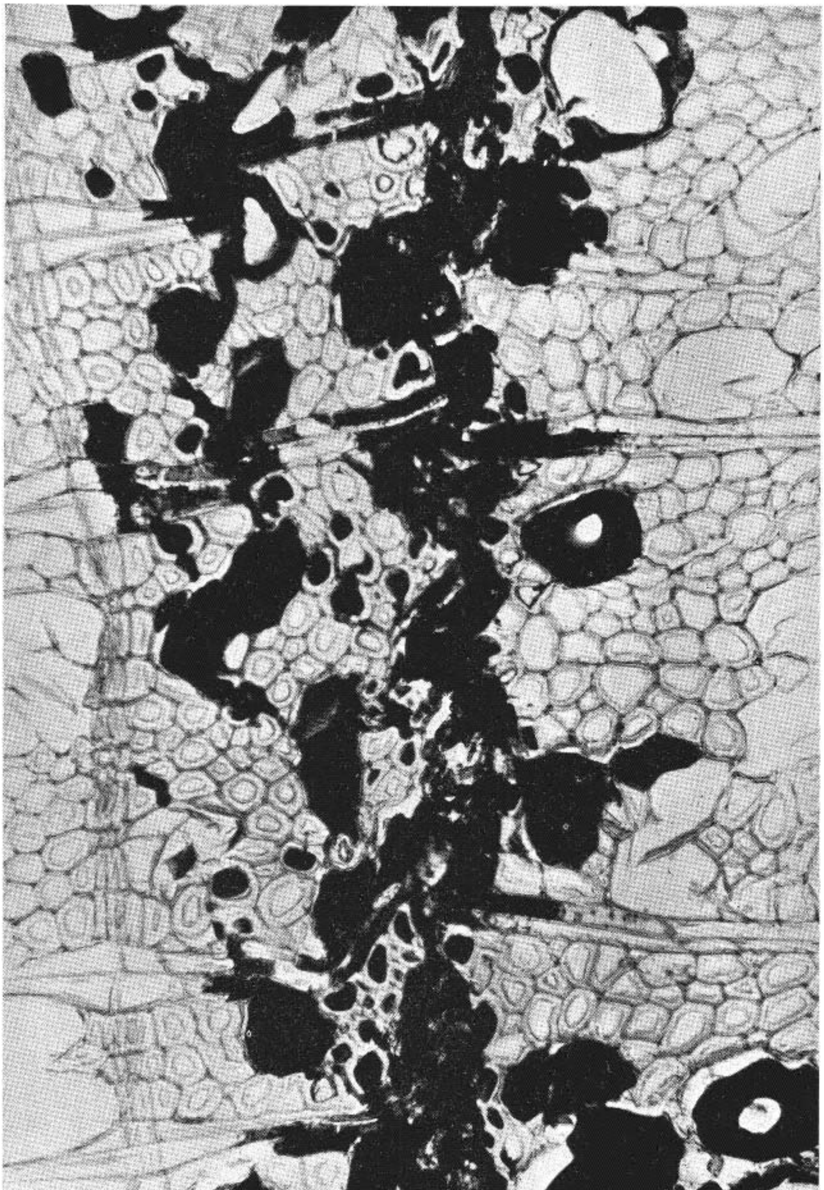
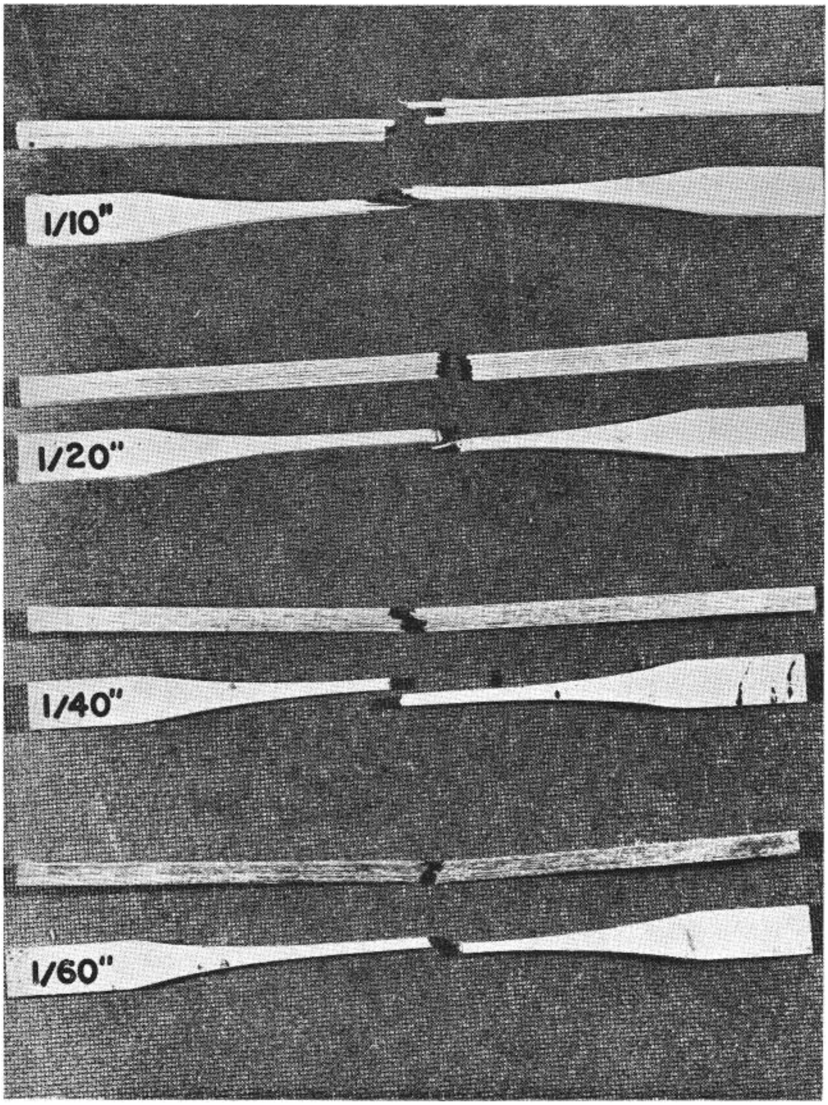


PLATE IV

Typical failures of laminated veneer in tension parallel to the grain showing decreasing splintering accompanying decreasing veneer thickness.


1/10"
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1/60"

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